Which Weather Data Should You Use for Energy Simulations of Commercial Buildings?

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ABSTRACT

Users of energy simulation programs have a wide variety of weather data from which to choose–from locally recorded weather data to preselected 'typical' years, often a bewildering range of options. In the last five years, several organizations have developed new typical weather data sets including WYEC2, TMY2, CWEC, and CTZ2. Unfortunately, neither how these new data influence energy simulation results nor how they compare to recorded weather data is well documented.

This paper presents results from the DOE-2.1E hourly energy simulation program for a prototype office building as influenced by local measured weather data for multiple years and several weather data sets for eight U.S. locations. We compare the influence of the various weather data sets on simulated annual energy use and costs and annual peak electrical demand, heating load, and cooling load. Statistics for temperature, heating and cooling degree-days, and solar radiation for the different locations and data sets are also presented. Where possible, the author explains the variation relative to the different designs used in developing each data set. The variation inherent in actual weather data and how it influences simulation results is also shown. Finally, based on these results, the question is answered: which weather data should you use?

INTRODUCTION

In the last five years, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), National Renewable Energy Laboratory (NREL), WATSUN Simulation Laboratory, and California Energy Commission (CEC) have released new or updated typical weather data sets for use in simulating building energy performance: WYEC2, TMY2, CWEC, and CTZ2, respectively. Each of these data sets contain a year of hourly data (8,760 hours) synthesized to represent long-term statistical trends and patterns in weather data for a longer period of record. Each developer designed its data sets to meet a particular need. ASHRAE designed the WYEC2 data set to represent typical weather patterns. NREL updated the TMY data sets to represent the most recent period of record available for use in work that require solar radiation data. WATSUN Simulation Laboratory created the CWEC weather data sets for use by the National Research Council (NRC) Canada in developing and complying with their new National Energy Code for Buildings. The CEC updated their CTZ weather data to make them better represent design conditions within each climate region and for use in demonstrating compliance with the California Title 24 energy standards. All groups intended their weather data sets to be usable with energy performance simulation programs. A recent study by Haberl (1995) compared measured weather data in calibrated DOE-2 simulations versus TMY data.

For each of the four weather data sets—WYEC2, TMY2, CWEC, and CTZ2—the developers used standard methodologies to determine which data would be used from the actual weather data period of record. The methods were virtually the same in the four cases—the true differences are related to the different weights applied to weather variables in the selection process. But these methods do not attempt to evaluate either the impact on energy simulation results of the new data sets or how these data sets compare to actual weather data or other existing typical data sets. In this paper, we focus on the TMY2 and WYEC2 data sets, comparing results with actual weather data through energy simulation results.

WEATHER DATA SETS

Over the past 20 years, several groups have developed hourly weather data sets specifically designed

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for use in building energy simulations. One of the earliest is Test Reference Year (TRY) (NCDC 1976). TRY contains dry-bulb temperature, wet-bulb temperature, dew point, wind direction and speed, barometric pressure, relative humidity, cloud cover and type, and a placeholder for solar radiation; however, no measured or calculated solar data are included. When used for building energy simulations, the simulation program must calculate the solar radiation based on the cloud cover and cloud type information available in the TRY data. Simulation programs may not deal with the complex interactions, use simplified methods, or methods that are out of date. Another weakness of the TRY data set was the method used to select data. The TRY data are an actual historic year of weather, selected using a process where years in the period of record (~1948-1975) which had months with extremely high or low mean temperatures were progressively eliminated until only one year remained. This tended to result in a particularly mild year that, either by intention or default, excludes extreme conditions. TRY data are available for 60 locations in the United States.

To deal with the limitations of TRY, particularly the lack of solar data, the National Climatic Data Center (NCDC) worked together with Sandia National Laboratory (SNL) to create a new data set, Typical Meteorological Year (TMY). TMY include, in addition to the data contained in TRY, total horizontal and direct normal solar radiation data for 234 U.S. locations (NCDC 1981). Twenty-six locations have measured solar data; solar data for the other 208 locations were calculated from cloud cover and type. This eliminated the need for the simulation programs to separately calculate solar data. Data in this set consist of 12 months selected from an approximately 23-year period of record (~1952-1975, available data varies by location) to represent typical months. The method used is similar to that used for the TRY, but individual months are selected rather than entire years. The TMY months were selected based on a monthly composite weighting of solar radiation, dry-bulb temperature, dew point, and wind velocity as compared to the long-term distribution of those values. Months that were closest to the weighted long-term distribution were selected. The resulting TMY data files each contain months from a number of different years.

In the late 1970s, the CEC developed a data set specifically for use in complying with the new Title 24 building energy regulations. They mapped the climatic regions of California, dividing it into 16 regions. CEC then created a weather data set, California Thermal Zones (CTZ), with a weather file for each region. The CTZ are based on the TMY format with several CTZ files derived from a specific TMY location. In 1992, the CEC updated their CTZ data set, creating CTZ2 (CEC 1992), with data in the new ASHRAE WYEC2 format. In creating the CTZ2, the temperatures from the original CTZ data set were adjusted to make the temperature profile match the ASHRAE design conditions for the particular location (ASHRAE 1993). More recently, the CEC developed a method to adjust the CTZ2 data to another location (CEC 1994). Essentially this procedure modifies the temperature in the existing CTZ2 weather file to match the design conditions for another city.

From 1970 through 1983, ASHRAE commissioned research projects RP-100, RP-239, and RP-364 (Crow 1970, 1980, 1983) to create a weather data set to represent more typical weather patterns than either a single representative year or an assemblage of months. This weather data set, known as Weather Year for Energy Calculations (WYEC) (ASHRAE 1985), uses the TRY format but it includes solar data (measured where available, otherwise calculated based on cloud cover and type). The basic method used to select data for WYEC was to determine, for each month of the year, the single, real month of hourly data whose mean dry-bulb air temperature was closest to the average dry-bulb temperature for that month in the 30-year period of record. If the mean dry-bulb air temperature for the individual month was within 0.2 F of the mean for the 30 months in the period of record, that individual month was used unless it included unusual or extreme weather patterns or events. If an unusual weather event was found in that month, the next closest month was examined for unusual patterns—until a month was found. If none of the 30 months in the period of record was within 0.2 F of the mean dry -bulb temperature, then the month with a mean closest to the mean of the 30 months was selected. Then, individual days from other months were substituted when those days helped bring the mean for the month closer to the 30-year mean. This process continued until one or more substitute days brought the now modified month mean dry bulb temperature to within 0.2 F of the 30-year mean. In general, no WYEC file needed more than 3 substitute days for any month to match the 30-year mean. WYEC data for 51 locations (46 locations in the United States and five in Canada) were completed in late 1983.

In the early 1990s, ASHRAE began to update the WYEC data set. Beginning with the format for the TMY data set, the WYEC data set format was first extended by including calculated hourly illuminance data and data quality and source flags. Other major changes included updating the calculated solar radiation data and adjusting the data from solar time to local time. A recently updated models for calculating solar radiation from cloud cover data (Perez et al. 1990, 1991) was used to recalculate the solar radiation components and illuminance data. The updated WYEC data set became known as WYEC2, for WYEC version 2 (ASHRAE 1997a). In addition, the 26 TMY locations with measured solar data were updated to include illumination data and to correct the time shift. NREL, working with ASHRAE, processed the existing WYEC and TMY data to create the 77 final WYEC2 format files (Stoffel and Rymes 1997, 1998).

In 1993, NREL created a new long-term solar radiation data set based on the 1961-1990 period of record known as the National Solar Radiation Data Base

(NSRDB) (Maxwell 1990). In conjunction with the National Climatic Data Center (NCDC), they published a combined set of hourly weather and solar data for the 1961-1990 period of record. These data are known as Solar and Meteorological Surface Observational Network (SAMSON) (NCDC 1993) and include 30 years of hourly data for 239 locations, most of those in the original TMY data set. As with the TMY data set, only 26 locations have measured solar data for at least a portion of the 30-year period of record. For the remaining 213 locations, solar radiation values were calculated from cloud cover based on the Perez model (1990, 1991). Separately, NREL updated the TMY data set based on the new period of record (1961-1990) available in SAMSON—creating the TMY2 data set (NREL 1995).

In 1992, NRC Canada commissioned the WATSUN Simulation Laboratory at the University of Waterloo to create an hourly weather data set for Canadian locations. They used the long-term data set developed by the Atmospheric Environment Service, Environment Canada in a TMY methodology, formatting the resultant data set in the WYEC2 format. WATSUN created data for 49 locations (WATSUN 1992).

In Europe, a data set for European locations (European Test Reference Year) (Commission of the European Community 1985) was created using a methodology similar to that used by NCDC and SNL to derive the TMY. Petrakis (1995) recently recommended revised procedures for generating Test Meteorological Years from observed data sets in Europe.

SIMULATION METHODOLOGY

For the work described in this paper, the author simulated an office building using the DOE-2.1E energy simulation program (Winkelmann et al. 1994). The building model was kept identical for all weather data sets with HVAC equipment sizing based on design conditions in the ASHRAE *Handbook—Fundamentals* (ASHRAE 1993). The office building modeled is a 48,000 ft^2, three-story building typical of recent envelope-dominated, low-rise buildings built in the U.S. For lighting, efficient 0.8 W/ft^2, T-8 fluorescent, 2-lamp, 2 x 4 fixtures with electronic ballasts and occupancy sensors were assumed. Office equipment was assumed at a level of 1.0 W/ft^2 for computers, laser printers, photocopiers, and facsimile machines. The building envelope assumed a 40% fenestration-to-wall ratio with glazing varying by location—primarily single-pane, tinted/reflective in southern locations and double-pane, tinted in northern locations. The minimum occupied outside air ventilation rate was 20 cfm/person. The air system simulated was a VAV reheat system with an enthalpy-controlled outside air economizer. The central plant included 0.55 kW per ton centrifugal chillers and a 90% efficiency gas-fired boiler. Energy costs were calculated by DOE-2.1E from local utility rates.

Actual hourly weather data (SAMSON, 1961-1990, 30-year period of record) and typical weather data sets with hourly data (TRY, TMY, TMY2, WYEC, and WYEC2) were used in the simulations. Eight U.S. locations were selected to cover a range of typical climatic patterns: Denver, Los Angeles, Miami, Minneapolis, New York, Phoenix, Seattle, and Washington, D. C.

For each of the eight locations, Table 1 first shows the 99% (winter) and 2-1/2% (summer) design temperature values from Chapter 24 of the *1993 ASHRAE Handbook—Fundamentals* (ASHRAE 1993). The second line for each location shows the new annual 99.6% (heating) and 1% (cooling) design temperatures for each location from Chapter 26 of the *1997 ASHRAE Handbook—Fundamentals* (ASHRAE 1997b). Note that for Washington, D.C., the design temperatures from the 1993 *Fundamentals* are for Washington National Airport—there were no design conditions for Washington Dulles Airport in the 1993 *Fundamentals*. The design conditions listed in Table 1 for Washington Dulles Airport are from nearby Sterling, Virginia. The next portion of Table 1 for each location includes maximum, average, median, and minimum values for the 99% (winter) and 2-1/2% (summer) design temperatures, heating and cooling degree-days, and solar radiation calculated from the 1961-1990 SAMSON data. For the SAMSON data:

- Maximum refers to the highest value in the 30-year set, i.e., the maximum winter design temperature is the winter design temperature for the warmest year in the 30-year set.
- Average is the average of the annual values for the 30 years.
- Median is the median of the annual values for the 30 years.
- Minimum is the lowest value among the 30 years, i.e., the minimum winter design temperature is the design winter temperature for the coldest year of the 30.

Similar statistics derived from the typical weather data sets are also shown in Table 1. In Table 1 and Figures 9 through 24, ‘WYEC2 (TMY)’ means WYEC2 data derived from TMY files and ‘WYEC2 (WYEC)’ means WYEC2 data derived from WYEC files. Note that not all weather data types were available for all locations; no TRY or WYEC2 (TMY) data were available for Denver and no WYEC2 (TMY) data were available for Los Angeles and Minneapolis. WYEC2 (TMY) data were only available for locations with measured solar data (the original 26 SOLMET locations). These data are left blank for consistent presentation among locations in Table 1 and Figures 9-24.

RESULTS

Figures 1 through 8 show the office building simulation results using the 30 years of SAMSON weather data in terms of annual end-use energy performance and

TABLE 1
Statistics for Weather File Types and SAMSON Weather Data

Location		Statistic or File Type	Winter 99% Dry bulb Temperature (F)	Summer 2.5% Dry bulb Temperature (F)	Annual Heating Degree-Days, 65 F	Annual Cooling Degree-Days, 65 F	Daily Average Direct Normal Solar (Btu/h)/ft^2	Daily Average Horizontal Solar (Btu/h)/ft^2
Denver Colorado		1993 HOF	-5	91				
		1997 HOF (99.6/1%)	-3	90				
	1961-	Maximum	8	93	6780.5	934.5	1897.2	1525.0
		Average	-3	91	6015.5	650.3	1714.8	1450.8
		Median	-2	91	6042.3	668.8	1743.5	1453.3
		Minimum	-15	84	4936.5	279.5	1376.1	1348.6
		TRY	--	--	--	--	--	--
		TMY	-4	90	6114	566	2044.3	1591.2
		TMY2	-2	91	6007	623	1743.2	1467.0
		WYEC	-4	91	5941	631	1875.7	1573.2
		WYEC2 (TMY)						
		WYEC2 (WYEC)	-3	91	5936	631	1612.2	1514.9
Los Angeles California		1993 HOF	41	80				
		1997 HOF (99.6/1%)	43	81				
	1961-	Maximum	47	84	1915.5	933.5	1694.8	1632.7
		Average	42.6	78.8	1401.6	591.7	1532.1	1568.1
		Median	42.0	78.5	1376.3	535.5	1546.4	1564.8
		Minimum	39	74	976.5	284.5	1365.2	1499.7
		TRY	42	78	1518.0	391.5	1331.5	1392.2
		TMY	42	78	1506.5	466.5	1693.7	1611.6
		TMY2	43	77	1291.0	469.5	1563.6	1579.4
		WYEC	41	77	1704.0	459.0	1662.6	1608.8
		WYEC2 (TMY)	--	--	--	--	--	--
		WYEC2 (WYEC)	41	77	1704.0	459.0	1373.2	1553.6
Miami Florida		1993 HOF	44	90				
		1997 HOF (99.6/1%)	46	90				
	1961-	Maximum	54	92	345.0	4741.0	1453.7	1630.9
		Average	44.4	89.4	190.5	4138.7	1254.0	1532.0
		Median	44.5	89.0	194.8	4119.5	1274.2	1531.5
		Minimum	37	87	17.5	3438.0	990.8	1344.4
		TRY	44	89	147.0	4262.5	863.7	1367.5
		TMY	43	89	188.5	4031.0	1231.7	1482.0
		TMY2	48	89	141.0	4126.5	1307.2	1557.2
		WYEC	42	89	227.0	4005.0	1047.6	1478.0
		WYEC2 (TMY)	43	89	188.5	4032.5	1071.0	1477.5
		WYEC2 (WYEC)	42	89	227.0	4005.0	1049.9	1470.2
Minneapolis Minnesota		1993 HOF	-16	89				
		1997 HOF (99.6/1%)	-16	88				
	1961-	Maximum	-5	95	9105.0	1124.5	1574.6	1343.9
		Average	-15.7	87.9	8002.9	695.9	1265.6	1234.0
		Median	-16.5	88.0	8077.3	688.3	1250.4	1228.7
		Minimum	-24	84	6435.0	401.0	1041.1	1167.2
		TRY	-25	90	8345.5	911.5	1069.0	1160.2
		TMY	-17	90	8095.0	759.5	1182.3	1169.6
		TMY2	-15	86	7985.5	634.0	1299.1	1257.0
		WYEC	-20	88	8070.5	750.5	1123.3	1170.8
		WYEC2 (TMY)	--	--	--	--	--	--
		WYEC2 (WYEC)	-19	88	8070.0	750.5	1135.4	1161.4

TABLE 1 (Continued)
Statistics for Weather File Types and SAMSON Weather Data

Location	Statistic or File Type		Winter 99% Dry bulb Temperature (F)	Summer 2.5% Dry bulb Temperature (F)	Annual Heating Degree-Days, 65 F	Annual Cooling Degree-Days, 65 F	Daily Average Direct Normal Solar (Btu/h)/ft^2	Daily Average Horizontal Solar (Btu/h)/ft^2
New York New York	1993 HOF		11	89				
	1997 HOF (99.6/1%)		13	89				
	1961-	Maximum	21	92	5465.0	1324.5	1215.0	1321.9
		Average	10.1	87.9	4977.6	1067.1	1095.7	1265.3
		Median	10.5	88.0	5009.3	1082.0	1095.0	1268.6
		Minimum	3	84	3976.5	751.5	933.8	1182.7
	TRY		14	86	4520	1059	963.7	1180.8
	TMY		13	84	5058	824	953.2	1092.1
	TMY2		9	87	5090	1002	1069.8	1268.5
	WYEC		14	87	4941	1034	786.6	1094.6
	WYEC2 (TMY)		13	84	5052	825	854.5	1090.5
	WYEC2 (WYEC)		14	87	4941	1034	789.7	1066.7
Phoenix Arizona	1993 HOF		31	107				
	1997 HOF (99.6/1%)		34	108				
	1961-	Maximum	41	111	2043.5	5125.0	2331.0	1866.8
		Average	33.9	107.8	1210.2	4052.2	2154.8	1817.8
		Median	34.0	108.0	1222.3	4112.5	2171.1	1826.4
		Minimum	27	104	649.0	3087.0	1844.1	1669.0
	TRY		30	106	1476	3390	1892.0	1679.2
	TMY		31	106	1391	3641	2187.2	1873.0
	TMY2		34	108	1154	3815	2187.7	1839.0
	WYEC		32	107	1356	3661	2159.6	1870.0
	WYEC2 (TMY)		31	106	1389	3644	2232.6	1868.5
	WYEC2 (WYEC)		32	107	1356	3661	2199.1	1863.6
Seattle Washington	1993 HOF		21	80				
	1997 HOF (99.6/1%)		23	81				
	1961-	Maximum	31	86	5674.5	338.0	1106.6	1140.5
		Average	23.7	81.5	4927.7	162.9	932.5	1055.2
		Median	25.5	82.0	4844.8	167.8	947.4	1056.4
		Minimum	13	76	4338.0	52.0	664.3	1000.1
	TRY		27	84	5373.5	142.0	675.7	933.8
	TMY		24	81	5299.5	106.0	878.2	1031.8
	TMY2		29	80	4867.0	127.0	966.4	1061.5
	WYEC		24	81	5295.5	106.0	878.8	1030.8
	WYEC2 (TMY)		20	81	5222.5	97.0	916.5	1054.0
	WYEC2 (WYEC)		20	81	5222.5	97.0	908.1	1047.2
Washington, D. C. (Dulles Airport) (Sterling, Virginia)	1993 HOF (National)		14	91				
	1997 HOF (99.6/1%)		9	90				
	1961-	Maximum	18	95	5538.0	1470.0	1367.4	1402.8
		Average	7.0	89.9	5017.3	1042.4	1173.7	1303.2
		Median	6.5	90.0	5034.8	1019.8	1172.3	1311.1
		Minimum	0	87	3993.0	766.5	1020.8	1177.4
	TRY (National)		13	91	4112.5	1525.5	1025.0	1231.9
	TMY		7	90	4865.5	1054.0	1131.2	1215.3
	TMY2		8	89	5233.0	1044.0	1171.4	1300.5
	WYEC		7	90	4865.5	1062.5	1023.2	1213.5
	WYEC2 (TMY)		12	90	4236.0	1425.0	1000.0	1212.3
	WYEC2 (WYEC)		12	90	4236.0	1425.0	982.6	1201.7

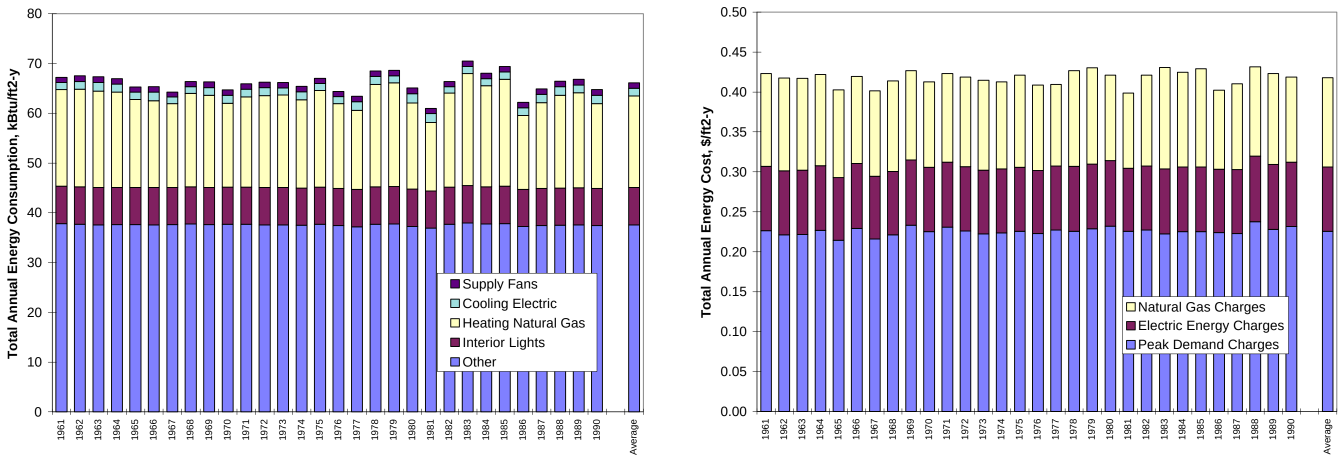

Figure 1 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in Denver, Colorado.*

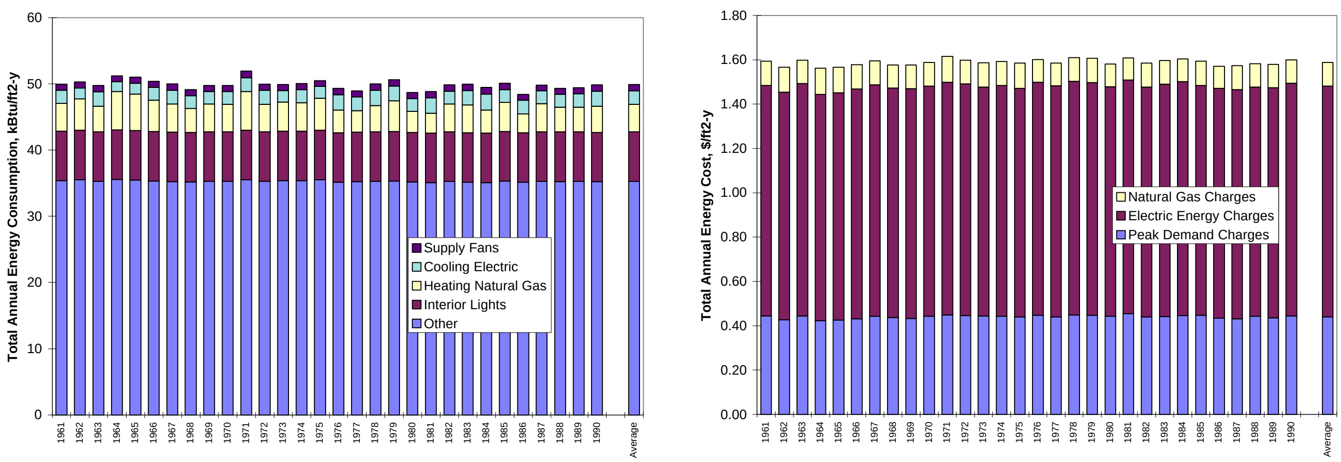

Figure 2 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in Los Angeles, California.*

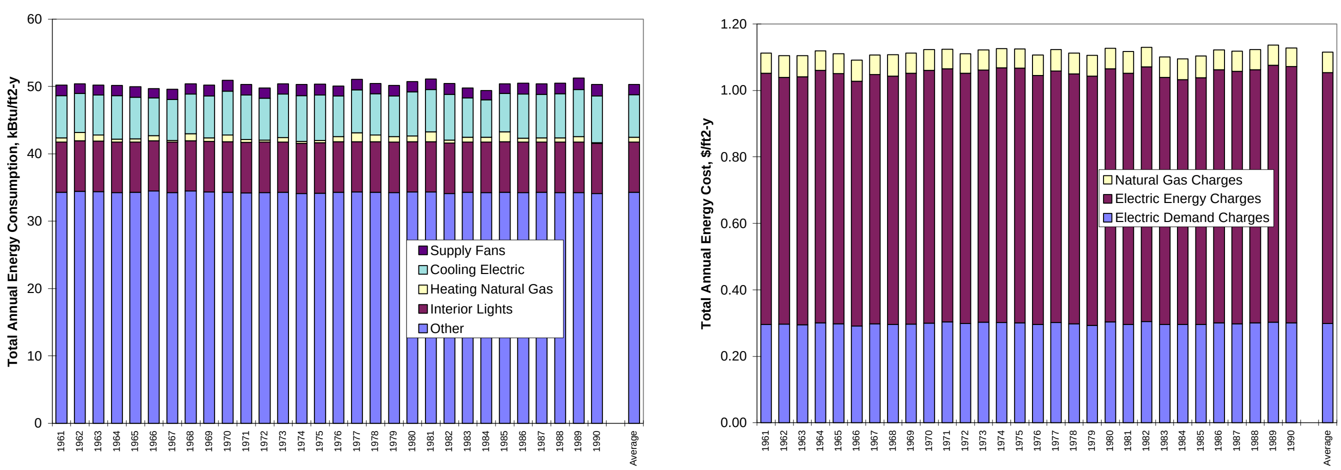

Figure 3 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in Miami, Florida.*

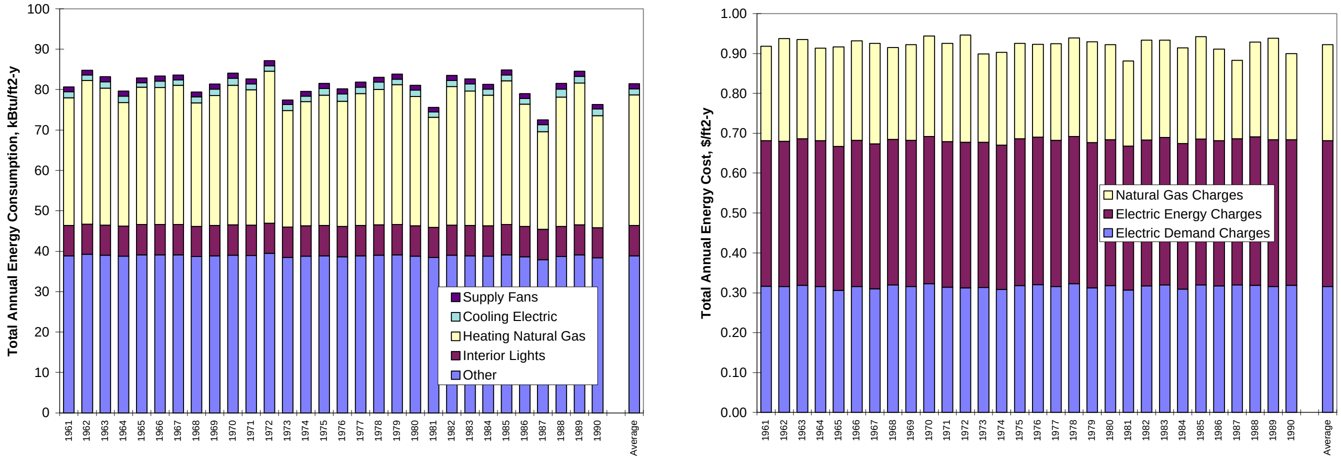

Figure 4 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in Minneapolis, Minnesota.*

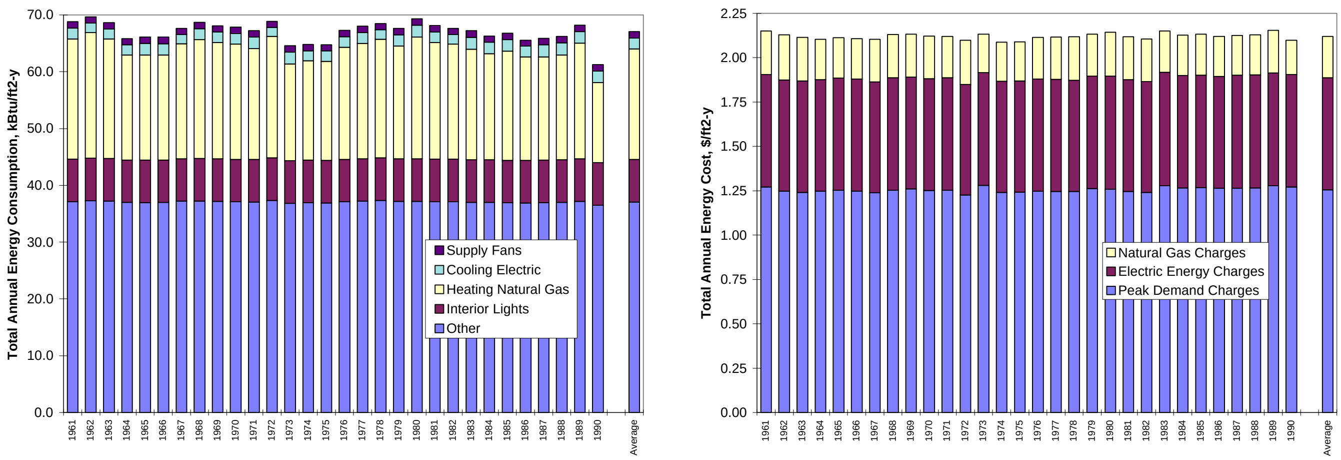

Figure 5 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in New York, New York.*

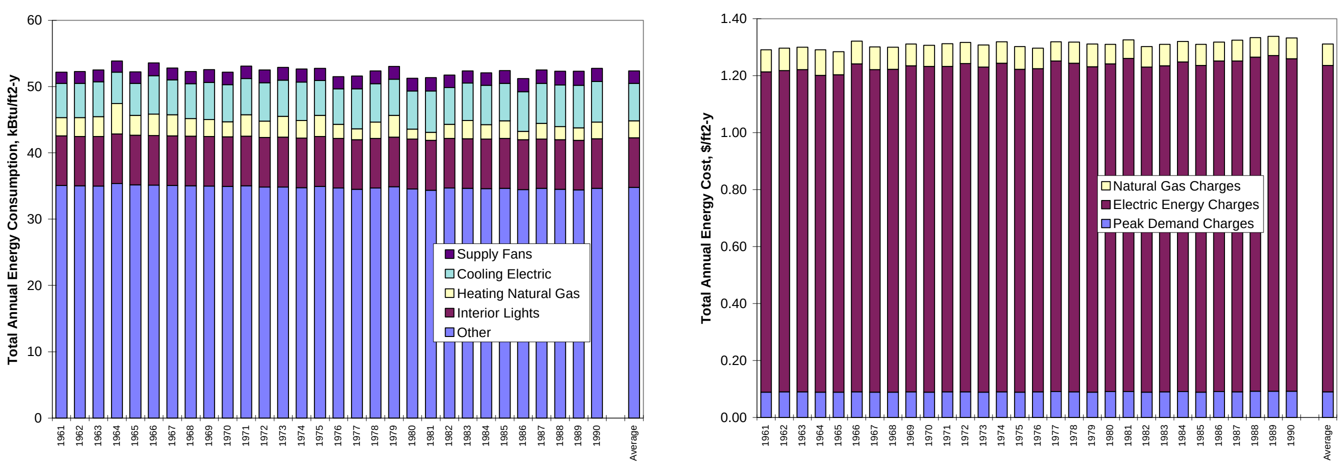

Figure 6 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in Phoenix, Arizona.*

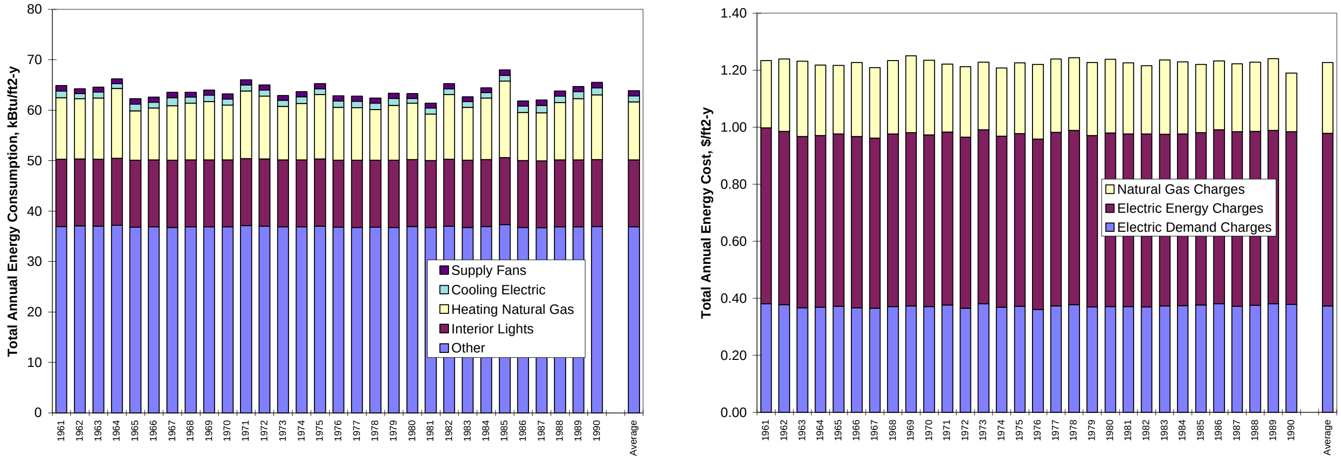

Figure 7 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in Seattle, Washington.*

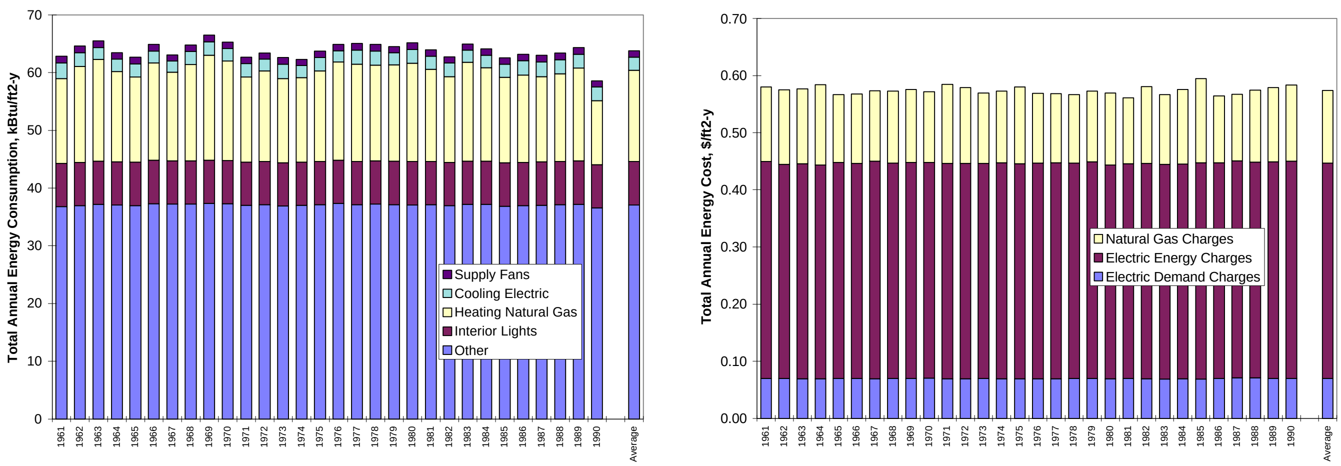

Figure 8 *Effect of Actual Weather Variation on Annual Energy Consumption and Costs in Washington, DC*

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energy costs by fuel type for the eight locations. The left graph in each figure show the component end-use (heating, cooling, lighting, fans, and other) energy performance (in thousands of Btu/ft^2-yr) for each of the 30 years. The right-hand bar shows the average energy performance for the 30 years. The right graph shows the components (natural gas and electricity energy and demand charges) of total annual energy costs (in \$/ft^2-yr) as simulated for each of the 30 years. The right-hand bar shows the average energy costs for the 30 years. Table 2 presents the average, minimum, and maximum annual energy consumption and costs (summarized from Figures 1 through 8) along with average, minimum, and maximum annual peak electric demand, and annual peak cooling and heating loads.

Figures 1 through 8 demonstrate that buildings in locations that are either heating-dominated (Minneapolis) or have a significant amount of both heating and cooling (Denver, New York, Seattle, and Washington, D.C.) exhibit a higher relative variation in annual energy consumption year-to-year. Milder or cooling-dominated climates (Los Angeles, Miami, and Phoenix) demonstrate relatively less overall variation in year-to-year energy consumption. However, as shown in the summary data in Table 2, the range of annual energy performance across the eight locations only varies from –11% to 7% for the SAMSON 30-year period of record. Annual energy cost is a function of the three components shown on the right-hand portion of the figures: natural gas costs (usually based on natural gas consumption), and electric energy and demand charges. Local utility rates weight electricity consumption and peak demand differently depending on what is more expensive to the utility, consumption or peak demand. Throughout the eight locations, the annual energy costs vary widely, from a low of \$0.42 for Denver to a high of \$2.12 for New York. Overall, the year-to-year variation in annual energy cost for the eight locations is less than half the variation in energy consumption noted

TABLE 2
Variation in Simulated Annual Energy Consumption, Energy Costs, Peak Electric Demand, and Peak Loads for SAMSON Weather Data

Location	Average (Min/*Max* percent change from average)				
	Total Annual Energy		Annual Peak		
	Consumption, kBtu/ft^2-yr	Costs, \$/ft^2-yr	Electric Demand, W/ft^2	Cooling Load, (Btu/h)/ft^2	Heating Load, (Btu/h)/ft^2
Denver, Colorado	**66.1** (-7.7%/*6.7%*)	**0.42** (-4.6%/*3.3%*)	**4.1** (-2.3%/*1.4%*)	**17.6** (-8.8%/*9.0%*)	**32.5** (-16.1%/*8.9%*)
Los Angeles, California	**49.9** (-3.0%/*4.0%*)	**1.59** (-1.7%/*1.7%*)	**4.1** (-4.7%/*4.9%*)	**19.5** (-21.2%/*34.1%*)	**20.1** (-21.7%/*21.4%*)
Miami, Florida	**50.3** (-1.8%/*1.8%*)	**1.11** (-2.1%/*1.9%*)	**4.7** (-1.1%/*1.0%*)	**28.0** (-8.2%/*8.9%*)	**15.6** (-74.8%/*75.3%*)
Minneapolis, Minnesota	**81.4** (-11.0%/*7.0%*)	**0.92** (-4.4%/*2.6%*)	**4.4** (-4.5%/*2.2%*)	**24.0** (-18.7%/*19.5%*)	**36.9** (-6.4%/*11.9%*)
New York, New York	**67.0** (-8.7%/*4.0%*)	**2.12** (-1.5%/*1.6%*)	**4.4** (-2.3%/*2.0%*)	**24.0** (-11.9%/*15.2%*)	**32.0** (-13.5%/*14.9%*)
Phoenix, Arizona	**52.4** (-2.3%/*2.9%*)	**1.31** (-2.1%/*2.1%*)	**4.7** (-1.7%/2.6%)	**28.0** (-7.6%/*10.7%*)	**19.4** (-54.9%/*34.5%*)
Seattle, Washington	**63.9** (-3.9%/*6.5%*)	**0.58** (-2.3%/*3.6%*)	**4.0** (-3.5%/*2.1%*)	**18.1** (-17.8%/*18.5%*)	**25.7** (-11.3%/*19.5%*)
Washington, D. C.	**63.8** (-8.1%/*4.3%*)	**1.23** (-3.0%/*2.0%*)	**4.5** (-3.7%/*1.7%*)	**24.5** (-14.4%/*16.7%*)	**30.6** (-13.6%/*13.4%*)

above, only –4.6% to 3.6%. Interestingly, annual peak electrical demand variation is similar to that for energy costs, -4.7% to 4.9%. Similar to annual energy consumption, the least variation is apparent in cooling-dominated climates (Miami and Phoenix). But climates with a mix of heating and cooling (Denver, New York, Seattle, and Washington) showed less variation in peak demand. Unlike energy consumption, peak demand varies considerably more in Los Angeles, a location with relatively mild but variable weather conditions. Similar to Los Angeles, Seattle has higher variation in electric demand. Because the simulated building is gas-heated, electrical demand variation is less than that of energy consumption in heating-dominated climates such as Minneapolis.

Figures 9 through 16 compare similar results for the weather data type sets in terms of energy performance and energy cost for the eight locations. The weather data type sets are contrasted with average, minimum, and maximum values shown in Table 2 (from the SAMSON 30-year simulations in Figures 1 through 8). The left graph in each figure shows total energy performance (thousands of Btu/ft^2-yr) for each of the weather data file types. The three lines on the graph are the maximum, average, and minimum energy performance from the SAMSON simulations (Table 2 and Figures 1 through 8). The right graph shows the total annual energy costs (\$/ft^2-yr) as simulated for the weather data file types. The three lines on the right graph show the maximum, average, and minimum energy costs from the simulations of 30 years of SAMSON data (from Table 2 and Figures 1 through 8). Table 3 presents summary information from Figures 9 through 16 for annual energy consumption and costs, and annual peak electric demand and cooling and heating loads. For annual energy consumption and costs and peak electric demand, the table shows the average value for the 30-year SAMSON simulations from Table 2 along with the percentage change from the average value for each weather data type. The two right-hand columns show the variation exhibited in annual peak heating and cooling loads calculated from the simulations. The values in the design size rows are the peak cooling or heating requirement for HVAC equipment sizing based on design conditions in the *1993 ASHRAE Handbook—Fundamentals* (ASHRAE 1993). The values in the SAMSON and the weather data type rows are the percent change from the design size values.

The variation of energy consumption for the weather data types shown in Figures 9 through 16 and summarized in Table 3 is less than that shown for the 30-year period of record. The range of variation across the eight locations is -2.3% to 5.4%; excluding the TRY results, the range of variation among the weather data types is –1.9% to 3.2%. Because the TRY period of record (~1945-1973) and the

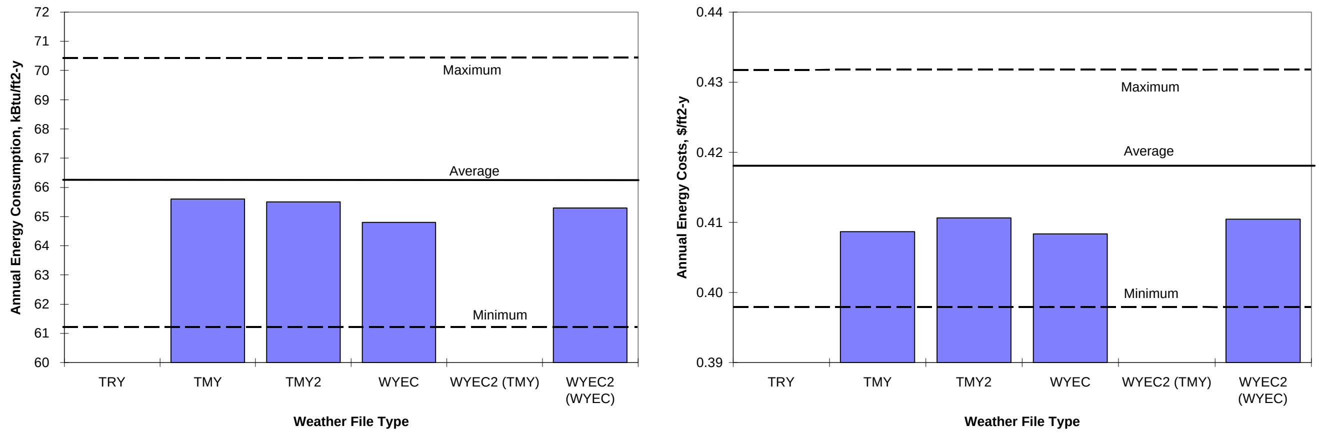

Figure 9 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in Denver, Colorado.*

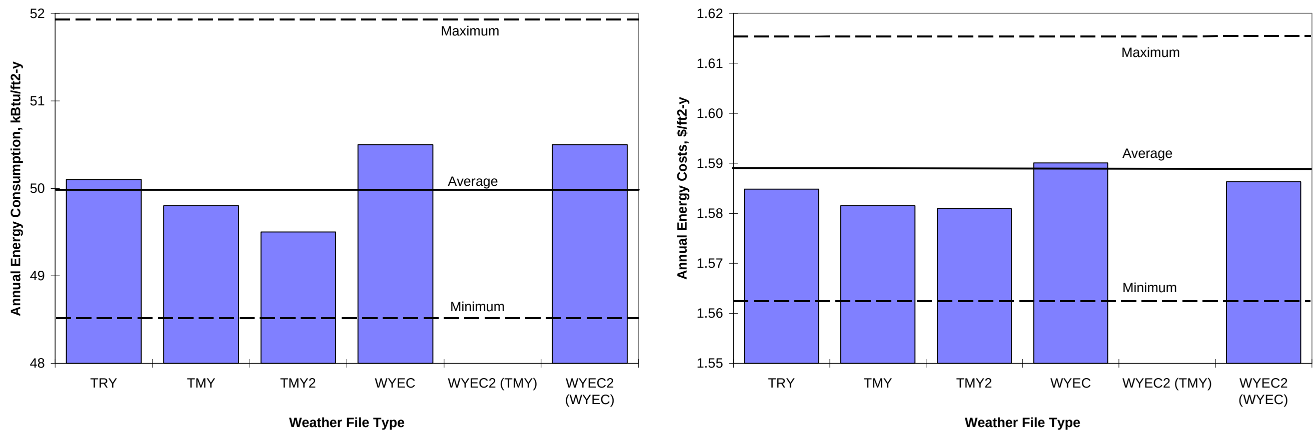

Figure 10 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in Los Angeles, California.*

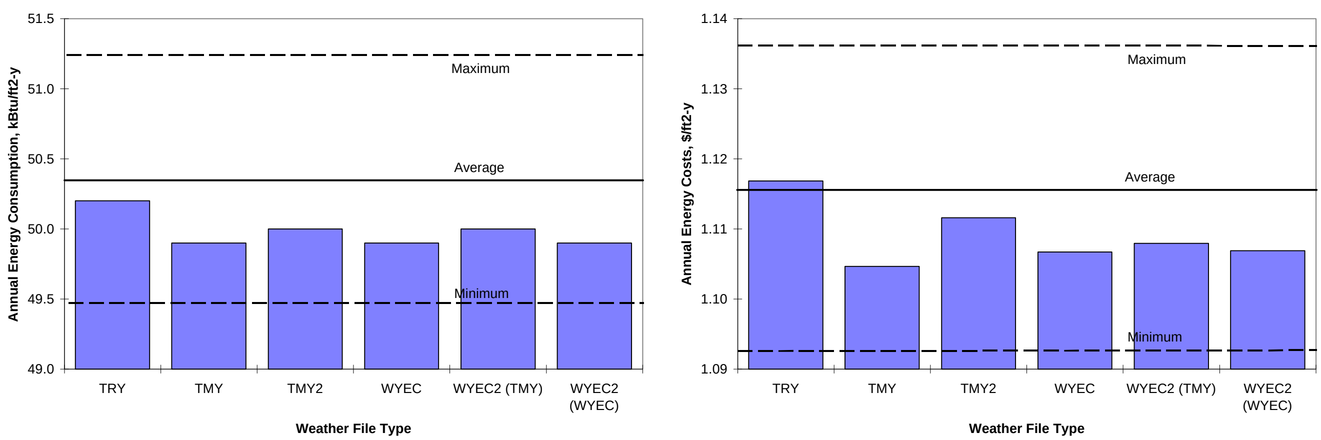

Figure 11 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in Miami, Florida.*

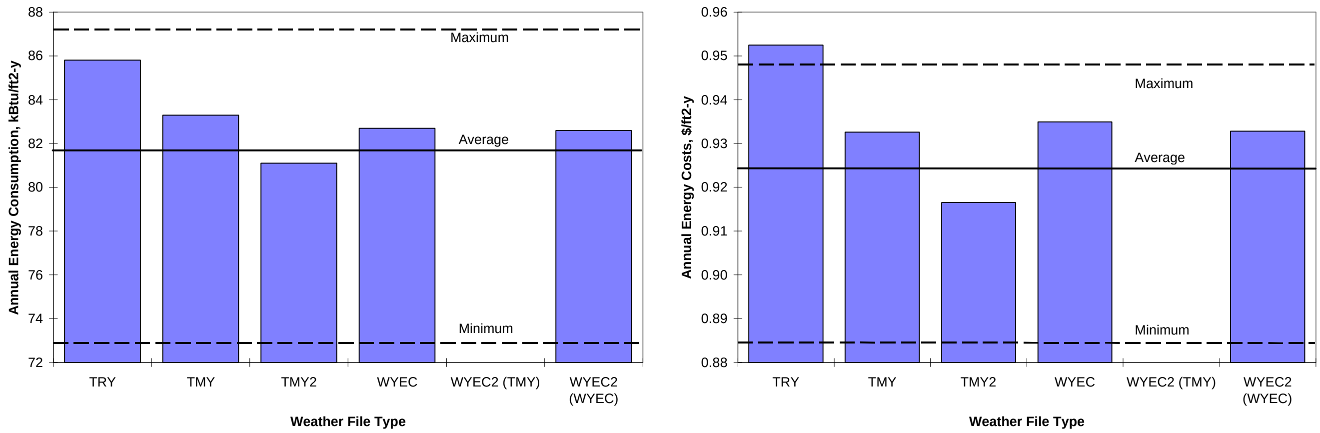

Figure 12 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in Minneapolis, Minnesota.*

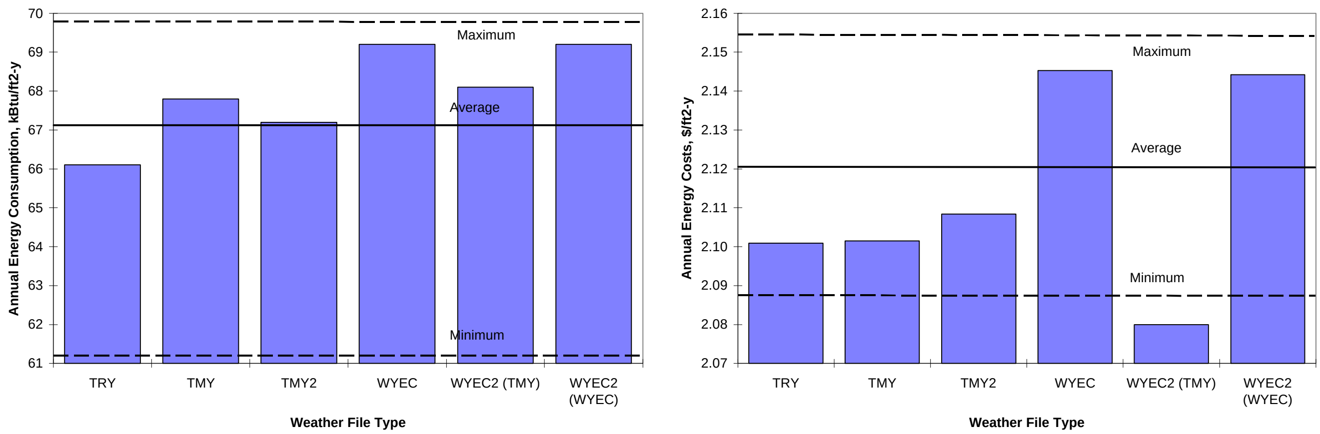

Figure 13 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in New York, New York.*

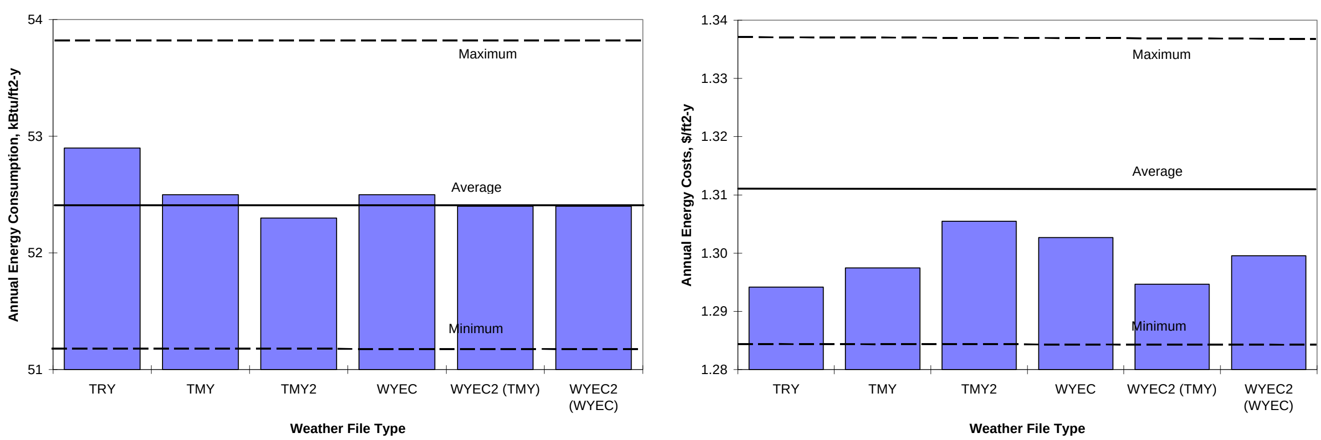

Figure 14 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in Phoenix, Arizona.*

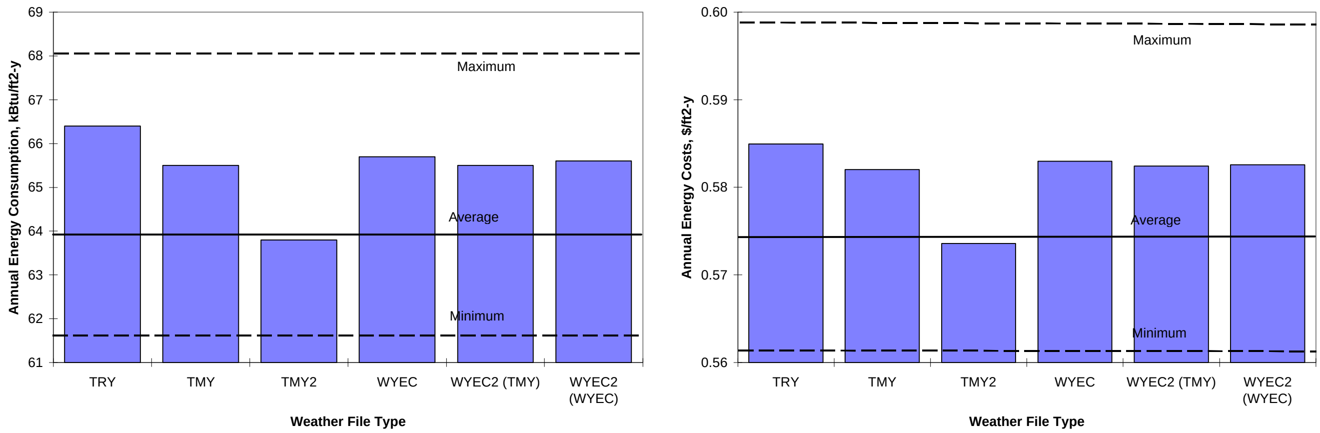

Figure 15 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in Seattle, Washington.*

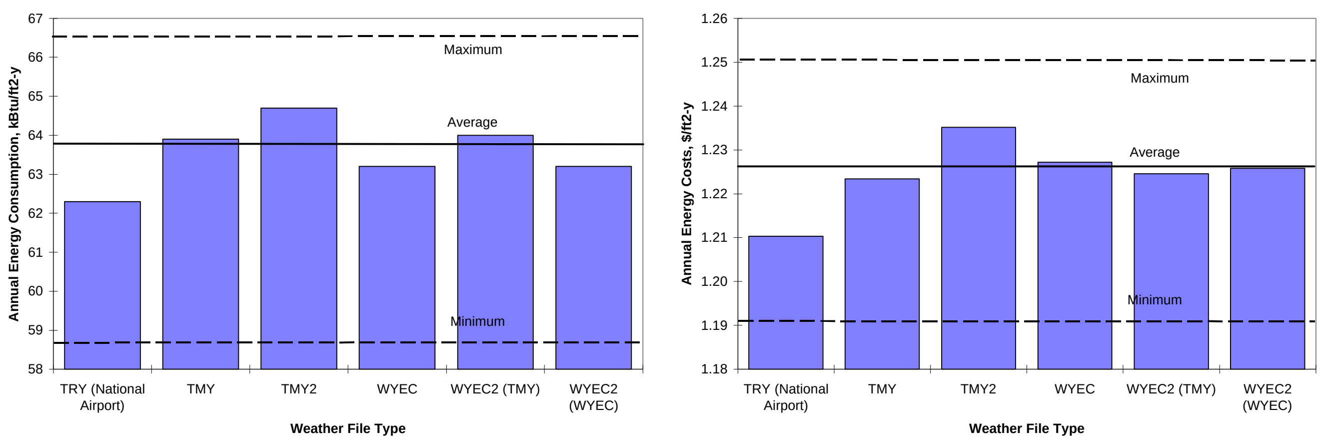

Figure 16 *Comparison of Annual Energy Consumption and Costs for Weather File Types and SAMSON Weather Data in Washington, DC.*

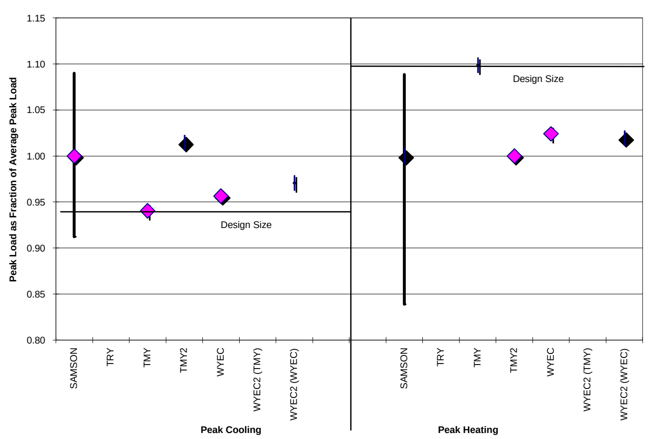

Figure 17 *Comparison of Annual Peak Loads in Denver, Colorado.*

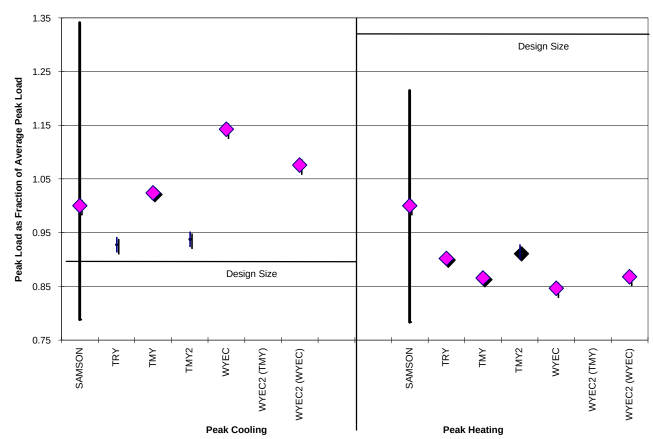

Figure 18 *Comparison of Annual Peak Loads in Los Angeles, California.*

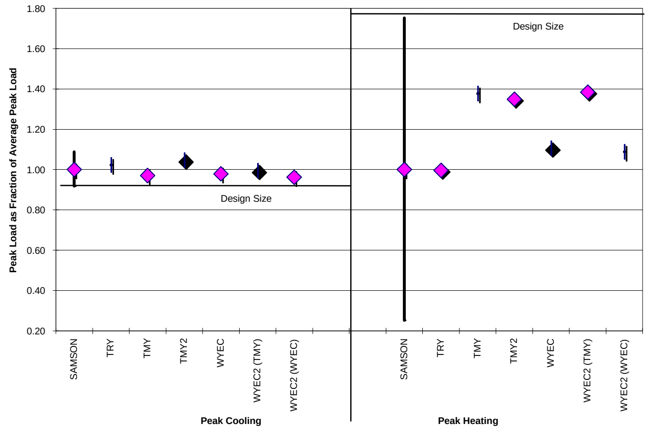

Figure 19 *Comparison of Annual Peak Loads in Miami, Florida.*

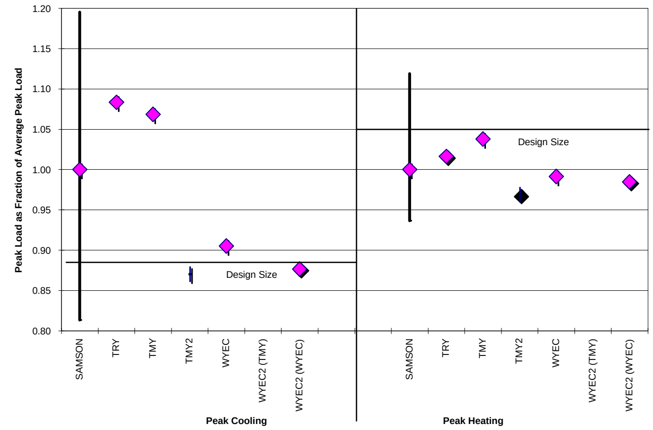

Figure 20 *Comparison of Annual Peak Loads in Minneapolis, Minnesota.*

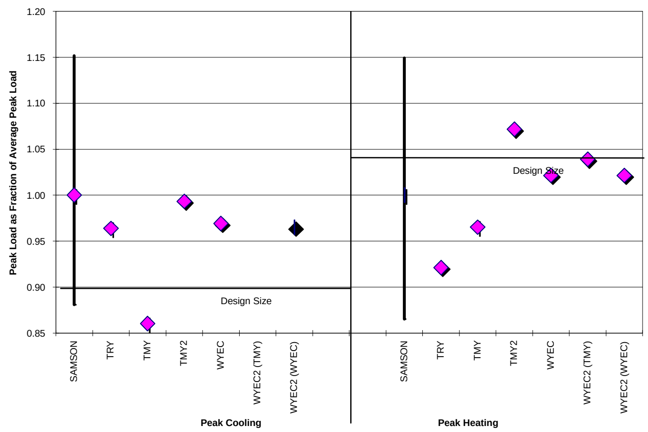

Figure 21 *Comparison of Annual Peak Loads in New York, New York.*

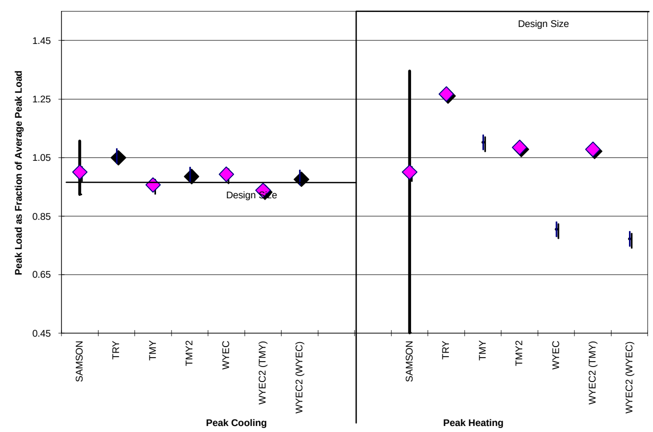

Figure 22 *Comparison of Annual Peak Loads in Phoenix, Arizona*

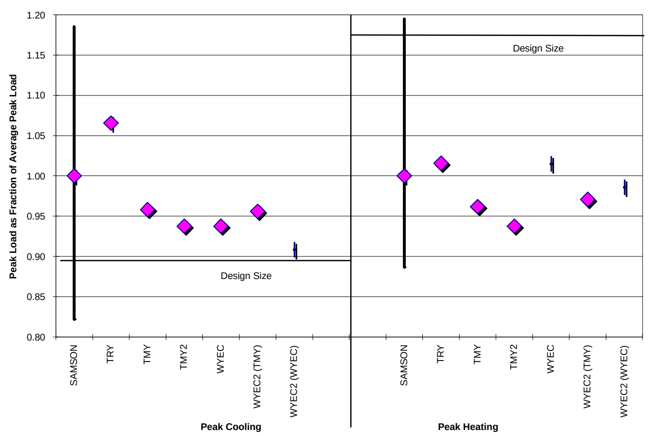

Figure 23 *Comparison of Annual Peak Loads in Seattle, Washington.*

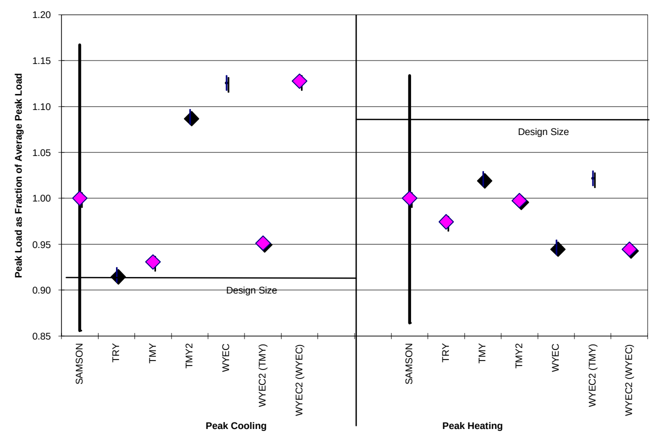

Figure 24 *Comparison of Annual Peak Loads in Washington, DC*

TABLE 3
Comparison of Simulated Annual Energy Consumption, Energy Costs, Peak Electric Demand, and Peak Loads for Weather Data Files Types and SAMSON Weather Data

Location	Weather File Type	Total Annual Energy		Annual Peak		
		Consumption, $kBtu/ft^2$-yr (percent of SAMSON Average)	Costs, $\$/ft^2$-yr (percent of SAMSON Average)	Electric Demand, W/ft^2 (percent of SAMSON Average)	Cooling Load, $(Btu/h)/ft^2$ (percent of design size)	Heating Load, $(Btu/h)/ft^2$ (percent of design size)
Denver, Colorado	SAMSON Average	66.1	0.42	4.1	6.1%	-9.2%
	Design Size	--	--	--	16.6	35.8
	TRY	--	--	--	--	--
	TMY	-0.7%	-2.2%	-0.6%	-0.3%	-0.3%
	TMY2	-0.9%	-1.7%	0.4%	7.6%	-9.2%
	WYEC	-1.9%	-2.2%	-0.1%	1.4%	-7.0%
	WYEC2 (TMY)	--	--	--	--	--
	WYEC2 (WYEC)	-1.2%	-1.7%	0.4%	2.9%	-7.5%
Los Angeles, California	SAMSON Average	49.9	1.59	4.1	14.2%	-25.6%
	Design Size	--	--	--	17.1	27.1
	TRY	0.4%	-0.2%	-0.1%	5.9%	-32.9%
	TMY	-0.2%	-0.4%	0.3%	17.0%	-35.6%
	TMY2	-0.8%	-0.5%	-0.3%	7.1%	-32.0%
	WYEC	1.2%	0.1%	2.0%	30.5%	-37.0%
	WYEC2 (TMY)	--	--	--	--	--
	WYEC2 (WYEC)	1.2%	-0.1%	1.3%	22.8%	-35.5%
Miami, Florida	SAMSON Average	50.3	1.11	4.7	11.1%	-43.5%
	Design Size	--	--	--	25.2	27.5
	TRY	-0.2%	0.2%	-0.1%	13.6%	-43.7%
	TMY	-0.8%	-0.9%	-0.3%	7.9%	-22.2%
	TMY2	-0.6%	-0.3%	0.6%	16.3%	-23.7%
	WYEC	-0.8%	-0.7%	-0.5%	8.8%	-37.5%
	WYEC2 (TMY)	-0.6%	-0.6%	0.1%	10.5%	-21.8%
	WYEC2 (WYEC)	-0.8%	-0.7%	-0.4%	6.9%	-38.5%
Minneapolis, Minnesota	SAMSON Average	81.4	0.92	4.4	13.2%	-4.3%
	Design Size	--	--	--	21.2	38.6
	TRY	5.4%	3.3%	0.6%	22.6%	-2.8%
	TMY	2.3%	1.2%	1.4%	20.9%	-0.7%
	TMY2	-0.4%	-0.6%	-2.2%	-1.5%	-7.3%
	WYEC	1.6%	1.4%	-1.0%	2.4%	-5.1%
	WYEC2 (TMY)	--	--	--	--	--
	WYEC2 (WYEC)	1.4%	1.2%	-1.8%	-0.8%	-5.8%
New York, New York	SAMSON Average	67.0	2.12	4.4	12.4%	-3.7%
	Design Size	--	--	--	21.3	33.2
	TRY	-1.4%	-0.9%	-0.8%	8.4%	-11.2%
	TMY	1.1%	-0.9%	-3.1%	-3.3%	-7.0%
	TMY2	0.2%	-0.6%	0.2%	11.7%	3.2%
	WYEC	3.2%	1.2%	-0.7%	9.0%	-1.6%
	WYEC2 (TMY)	1.6%	-1.9%	-6.1%	-11.6%	0.1%
	WYEC2 (WYEC)	3.2%	1.1%	-0.7%	8.5%	-1.6%

TABLE 3 (Continued)
Comparison of Simulated Annual Energy Consumption, Energy Costs, Peak Electric Demand, and Peak Loads for Weather Data Files Types and SAMSON Weather Data

Location	Weather File Type	Total Annual Energy		Annual Peak		
		Consumption, kBtu/ft^2-yr (percent of SAMSON Average)	Costs, \$/ft^2-yr (percent of SAMSON Average)	Electric Demand, W/ft^2 (percent of SAMSON Average)	Cooling Load, (Btu/h)/ft^2 (percent of design size)	Heating Load, (Btu/h)/ft^2 (percent of design size)
Phoenix, Arizona	**SAMSON Average**	52.4	1.31	4.7	9.3%	-33.3%
	Design Size	--	--	--	25.7	29.1
	TRY	1.0%	-1.3%	0.7%	15.3%	-15.6%
	TMY	0.2%	-1.0%	-0.4%	4.5%	-26.5%
	TMY2	-0.1%	-0.4%	-0.6%	8.4%	-27.7%
	WYEC	0.2%	-0.6%	-0.2%	8.5%	-46.3%
	WYEC2 (TMY)	0.0%	-1.2%	-0.8%	2.5%	-28.1%
	WYEC2 (WYEC)	0.0%	-0.9%	-0.2%	7.3%	-48.5%
Seattle, Washington	**SAMSON Average**	63.9	0.58	4.0	12.3%	-15.3%
	Design Size	--	--	--	16.1	30.3
	TRY	3.9%	1.9%	1.0%	19.6%	-14.0%
	TMY	2.5%	1.4%	-0.6%	7.6%	-18.5%
	TMY2	-0.2%	-0.1%	-0.3%	5.3%	-20.6%
	WYEC	2.8%	1.5%	-0.9%	5.3%	-14.0%
	WYEC2 (TMY)	2.5%	1.4%	-0.7%	7.3%	-17.8%
	WYEC2 (WYEC)	2.7%	1.5%	-1.4%	2.0%	-16.5%
Washington, D. C.	**SAMSON Average**	63.8	1.23	4.5	9.8%	-7.0%
	Design Size	--	--	--	22.3	32.9
	TRY	-2.3%	-1.3%	-1.4%	0.6%	-9.4%
	TMY	0.2%	-0.3%	-0.7%	2.2%	-5.1%
	TMY2	1.4%	0.7%	1.5%	19.6%	-7.3%
	WYEC	-0.9%	0.1%	0.9%	23.6%	-12.0%
	WYEC2 (TMY)	0.3%	-0.2%	-0.5%	4.4%	-5.0%
	WYEC2 (WYEC)	-0.9%	-0.1%	0.7%	23.8%	-12.2%

SAMSON period of record (1961-1990) differ, TRY data could include years that are either hotter or colder than those in the SAMSON data. For example, the TRY data for Minneapolis (Figure 12) resulted in significantly higher energy consumption and costs; in fact, the energy costs were outside the range of values from the SAMSON data. The TRY data had a winter design condition below that of all the SAMSON data and solar data on the low end of the range as well. Unlike Figures 1 through 8, Figures 9 through 16 exhibit a relatively higher range of variability in energy costs but the range of variation is still small, ranging from –2.2% to 3.3% including the TRY data. With the exception of Washington, D.C., the TMY2 consistent provide a closer match to the average energy consumption of the SAMSON data. With a few exceptions (New York, Seattle, and occasionally WYEC and WYEC2), simulations using the typical weather data sets under-predict the energy consumption and energy costs.

The last set of Figures (17 through 24) presents another aspect of the impact of weather selection on energy performance simulation: annual peak cooling and heating loads. These figures compare the variation in peak annual cooling and heating loads from the simulations using the 30 years of SAMSON data and the weather data file types. The left graph of each figure shows the annual peak-cooling load as a fraction of the average annual peak-cooling load for the 30 years. The right side shows similar information for the annual peak-heating load. The horizontal line shown on each graph is the calculated peak design size based on the design conditions (2-1/2% for cooling and 99% for heating) for the location from the *1993 Fundamentals* (ASHRAE 1993). For the SAMSON simulations (1961-1990), the mean of the annual peak loads is shown as a diamond near the center of the left-hand vertical line on each graph. The vertical line represents the range of annual peak loads for the SAMSON simulations—maximum to minimum. The loads from the weather data sets are shown as a fraction of the mean of the annual peak loads from the SAMSON simulations. The values for the weather data files types are shown as a scatter of diamonds to the right of the SAMSON vertical line.

As would be expected, annual peak cooling and heating load vary more than do either the annual energy consumption (summed hourly energy) or the annual energy costs (monthly peak demand and summed hourly energy consumption). The peaks depend on the how much the building is affected by the hourly temperature fluctuation and incident solar radiation. The range of percentage variation of the peak loads as a function of the design sizing (see above) is shown in the two right-hand columns of Table 3.

In reviewing Figures 17 through 24, several observations about the peak cooling and heating loads become apparent. First, the heating design size values are generally higher than the peak heating loads of both the 30-year data set and the typical weather data sets. On the other hand, cooling design size is generally close to or less than the peak cooling loads. This seems to be related to the use of the more conservative 99% design conditions for heating and the more generous sizing allowed for heating by the commercial building energy standards (ASHRAE 1989). The energy standards allow heating equipment to be sized up to 40% larger than the annual peak-heating load calculated based on the design conditions. On the other hand, the energy standards only allow cooling equipment to be sized up to 20% larger than the calculated annual peak-cooling load. For cooling, the combination of less conservative 2-1/2% design conditions and the lower over sizing allowance means that for a few hours every year, the cooling equipment may not be able to meet the load.

Overall the variation in annual peak cooling load ranged from 11.5% below the design size to 30.5% above. Note that in all the locations, the range of cooling loads from the SAMSON simulations was greater than that of the weather data sets. For annual peak heating loads, the variation among the weather data sets ranges from 48.5% below the design size to 3.2% above. The locations with the greatest heating over sizing were those with relatively low heating loads: Los Angeles, Miami, and Phoenix.

SUMMARY

As described above, the range of annual energy consumption and costs and peak cooling and heating loads due to actual weather variation over a 30-year period can be significant; in this case, the SAMSON data set. For the eight locations in this study,

- annual energy consumption varied as much as –11.0%% to 7.0%,
- annual energy cost varied from –4.6% to 3.6%,
- annual peak electrical demand varied from –4.7% to 4.9%,
- annual peak cooling loads ranged from 11.5% below the design size to 30.5% above, and
- annual peak heating loads ranged from 48.5% below the design size to 3.2% above.

The variation in energy consumption is similar to that reported by Haberl (1995) for measured and TMY weather data. Haberl showed DOE-2 predicted energy consumption values that were consistently 5% to 10 % higher than the measured energy consumption.

Before beginning to discuss the weather data types results, it is important to note again that the design conditions in the *1993 Fundamentals* (ASHRAE 1993) and the TRY, TMY, WYEC, and WYEC2 data sets have roughly the same period of record—~1945-1973. The design conditions in the *1997 Fundamentals* (ASHRAE 1997b), SAMSON 30-year and TMY2 have the same period of record, 1961-1990, and data source. Thus, these three should exhibit similar results.

Of the six weather data types studied in this work [TRY, TMY, TMY2, WYEC, and WYEC2 (TMY and WYEC)], TRY showed the most variation, higher and lower (except in mild Los Angeles and hot Miami). This is demonstrated in the annual energy costs for Minneapolis (Figure 12) where the TRY values exceed the maximum from the SAMSON simulations. The TRY is a year outside the SAMSON period of record with more severe winter design conditions (-25 F) than the lowest of the 30-year period for SAMSON (-24 F). The TRY also had higher than average (SAMSON) heating and cooling degree-days, and the annual average solar radiation was toward the low end of the range for SAMSON. Another example is Washington, D.C. where both the annual energy consumption and energy costs are lower than all the other weather types even though it is still within the 30-year range shown for SAMSON. It has lower than average (SAMSON) heating degree-days and higher than even the SAMSON maximum cooling degree-days—another example of the year selected for the TRY being outside the SAMSON 30-year period.

For the six weather data types, the range of variation from the SAMSON average and the design size, as shown in Table 3, is as follows.

- TRY, annual energy consumption from –2.3% to 5.4%; annual energy costs from –1.3% to 3.3%; annual peak electric demand from –1.4% to 1%; annual peak cooling load from 0.6% to 22.6%; and annual peak heating load from –43.7% to –2.8%.

- TMY, annual energy consumption from –0.8% to 2.5%; annual energy costs from –1.7% to 1.4%; annual peak electric demand from –3.1% to 0.6%; annual peak cooling load from –3.3% to 20.9%; and annual peak heating load from –35.6% to –0.3%.
- TMY2, annual energy consumption from –0.9% to 1.4%; annual energy costs from –1.7% to 0.7%; annual peak electric demand from –2.2% to 1.5%; annual peak cooling load from –1.5% to 19.6%; and annual peak heating load from –32.0% to 3.2%.
- WYEC, annual energy consumption from –1.9% to 3.2%; annual energy costs from –2.2% to 1.5%; annual peak electric demand from –1.0% to 2.0%; annual peak cooling load from 1.4% to 30.5; and annual peak heating load from –46.3% to –1.6%.
- WYEC2 (TMY), annual energy consumption from –0.6% to 2.5%; annual energy costs from –1.9% to 1.4%; annual peak electric demand from –6.1% to 0.1%; annual peak cooling load from –11.6% to 10.5%; and annual peak heating load from –28.1% to 0.1%.
- WYEC2 (WYEC), annual energy consumption from –1.2% to 3.2%; annual energy costs from –1.7% to 1.5%; annual peak electric demand from –1.8% to 1.3%; annual peak cooling load from -0.8% to 23.8%; and annual peak heating load from –48.5% to –1.6%.

By limiting the selection method for the WYEC to dry-bulb temperature, the resulting data set is not as representative of the period of record. Note that the solar radiation data for WYEC in Table 1 are often near the high or low end of the range for the SAMSON (recognizing that WYEC and SAMSON have different periods of records).

Simulations using the TMY2 data set more consistently match the simulation results for the SAMSON 30-year period than any other data set. Some of this can be attributed to the TMY2 and SAMSON having the same period of record and data source. This suggests that a data selection method, such as TMY2, that evaluates a composite weighting of each month for multiple variables (solar radiation, dry bulb temperature, dew point temperature, and wind velocity) provides better simulation results, i.e., closer to the mean for the period of record. In several of the locations that are more temperature-dominated than solar-dominated (Los Angeles and Washington, D.C.), the TMY2 appears not to match the long-term temperature averages as well. This suggests that the weights assigned to the weather variables should be adjusted. The TMY2 design temperatures further support this—they occasionally do not match those from the *1997 Fundamentals* (see Table 1)—even though both are derived from the same period of record and data set.

RECOMMENDATIONS

Users of energy simulation programs should avoid using single year, TRY-type weather data. No single year can represent the typical long-term weather patterns. More comprehensive methods that attempt to produce a synthetic year to represent the temperature, solar radiation, and other variables within the period of record are more appropriate and will result in predicted energy consumption and energy costs that are closer to the long-term average. Both TMY2 and WYEC2 use this type of method, are based on improved solar models, and more closely match the long-term average climatic conditions.

We have several recommendations for developers of future weather data sets. The TMY2 method appears to work well in most cases but the resultant files may need to be adjusted to match the long-term average statistics more closely, the mean of the 30-year period of record in this case. A second approach would be to create a typical weather file that has three years: typical (average), cold/cloudy, and hot/sunny. This would capture more than the average or typical conditions and provide simulation results that identify some of the uncertainty and variability inherent in weather.

The method used in this paper needs to be attempted on a broader geographic scale with more typical weather data sets and actual weather data. In a similar study of residential buildings, Huang (1998) evaluated the impact of weather data on heating and cooling loads. The author also believes that a similar approach should be taken to determine if weather data selection methods affect energy and loads in smaller, enveloped-dominated and larger, internal-load dominated commercial buildings (<10,000 ft^2 and >100,000 ft^2).

Which weather data should you use for simulating commercial buildings? From this study, we believe that either the TMY2 or WYEC2 data sets will provide users with energy simulation results that most closely represent typical weather patterns.

REFERENCES

ASHRAE. 1985. *Weather Year for Energy Calculations*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1989. *ANSI/ASHRAE/IESNA Standard 90.1-1989,* "Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings." Atlanta: ASHRAE.

ASHRAE. 1993. *1993 ASHRAE Handbook—Fundamentals*. Atlanta: ASHRAE.

ASHRAE. 1997a. *WYEC2 Weather Year for Energy Calculations 2, Toolkit and Data,* Atlanta: ASHRAE.

ASHRAE. 1997b. *1997 ASHRAE Handbook—Fundamentals*. Atlanta: ASHRAE.

California Energy Commission. 1992. *Climate Zone Weather Data Analysis and Revision Project*, P400-92-004. Sacramento: California Energy Commission.

California Energy Commission. 1994. *The Adjustment of Title 24 Climate Zone Weather Data to Reflect Cities' ASHRAE Design Day Conditions*, Staff Report, 20 July 1994. Sacramento: California Energy Commission.

Commission of the European Community. 1985. *Test Reference Years*, Weather data sets for computer simulations of solar energy systems and energy consumption in buildings, CEC, DG XII. Brussels, Belgium: Commission of the European Community.

Crow, Loren W. 1970. "Summary Description of Typical Year Weather Data, Chicago Midway Airport," ASHRAE *Research Project RP-100*. Atlanta: ASHRAE.

Crow, L.W. 1980. "Development of Hourly Data for Weather Year for Energy Calculations (WYEC), Including Solar Data, at 21 Weather Stations throughout the United States," *ASHRAE Transactions* 87 (1). Atlanta: ASHRAE.

Crow, L.W. 1983. "Development of Hourly Data for Weather Year for Energy Calculations (WYEC), Including Solar Data, at 29 Stations throughout the United States and 5 Stations in Canada," *ASHRAE Research Project RP-364 Final Report*, November 1983. Atlanta: ASHRAE.

Haberl, Jeff S., Doug J. Bronson, and Dennis L. O'Neal. 1995. "Impact of Using Measured Weather Data vs. TMY Weather Data in a DOE-2 Simulation," in *ASHRAE Transactions* 101 (2). Atlanta: ASHRAE.

Huang, Y. Joe. 1998. "The Impact of Different Weather Data on Simulated Residential Heating and Cooling Loads," in *ASHRAE Transactions* 104 (2). Atlanta: ASHRAE.

Maxwell, E. 1990. "Producing a 1961-1990 Solar Radiation Data Base for the United States," in *Solar '90 Technical Papers: Proceedings of the 1990 Annual Conference*, American Solar Energy Society. Boulder: American Solar Energy Society.

NCDC. 1976. *Test Reference Year (TRY)*, Tape Reference Manual, TD-9706, September 1976. Asheville, North Carolina: National Climatic Data Center, U.S. Department of Commerce.

NCDC. 1981. Typical Meteorological Year User's Manual, TD-9734, Hourly Solar Radiation—Surface Meteorological Observations, May 1981. Asheville, North Carolina: National Climatic Data Center, U.S. Department of Commerce.

NCDC. 1993. *Solar and Meteorological Surface Observation Network, 1961-1990, Version 1.0*, September 1993. Asheville, North Carolina: National Climatic Data Center, U.S. Department of Commerce.

National Renewable Energy Laboratory (NREL). 1995. User's Manual for TMY2s (Typical Meteorological Years), NREL/SP-463-7668, and TMY2s, Typical Meteorological Years Derived from the 1961-1990 National Solar Radiation Data Base, June 1995, CD-ROM. Golden, Colorado: National Renewable Energy Laboratory.

Perez, R., P. Ineichen, R. Seals, J. Michalsky and R. Stewart. 1990. "Modeling Daylight Availability and Irradiance Components from Direct and Global Irradiance," in *Solar Energy*, Vol. 44, pp. 271-289.

Perez, R. R., P. Ineichen, E. Maxwell, F. Seals and A. Zelenda. 1991. "Dynamic Models for Hourly Global-to-direct Irradiance Conversion," in *1991 Solar World Congress: Proceedings of the Biennial Congress of the International Solar Energy Society*, Vol. 1 (II): pp. 951-956.

Petrakis, M. 1995. "Test Meteorological Years: Procedures for Generation of TMY from Observed Data Sets," in *Natural Cooling Techniques, Research Final Report, PASCOOL*, Alvarez et al., ed. Brussels, Belgium: Commission of the European Commission.

Stoffel, T.L., and M. Rymes. 1997. *Production of the Weather Year for Energy Calculations Version 2 (WYEC2)*, NREL TP-463-20819. Golden, Colorado: National Renewable Energy Laboratory.

Stoffel, Thomas L., and Martin D. Rymes. 1998. "Production of the Weather Year for Energy Calculations version 2 (WYEC2) Data Files," in *ASHRAE Transactions* 104 (2). Atlanta: ASHRAE.

WATSUN Simulation Laboratory. 1992. Engineering Data Sets of Hourly Weather Observations in WYEC2 Format (WYEC2 Files) and Canadian Weather for Energy Calculations (CWEC Files), User's Manual, 15 September 1992, prepared for Environment Canada Atmospheric Environment Service and National Research Council Canada. Waterloo, Ontario: WATSUN Simulation Laboratory, University of Waterloo.

Winkelmann, F.C., W.F. Buhl, B. Birdsall, A. E. Erdem, and K. Ellington. 1994. *DOE-2.1E Supplement*, DE-940-11218. Lawrence Berkeley Laboratory, Berkeley, California. Springfield, Virginia: National Technical Information Service.