SCOPE 27 - Climate Impact Assessment

9 Energy Resources

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9.1 INTRODUCTION

The impacts of climate and weather on energy supply and demand have received increasing attention in recent years, especially since a number of severe winters in the northern hemisphere middle latitudes have highlighted mankind's vulnerability to climatic variability. Cold winters have increased the demand for energy and have also led to disruptions of supply. At the same time, interest has been growing with regard to future energy supply and the possibilities of using renewable sources of energy, especially solar energy, instead of nonrenewable, especially fossil fuel, resources. The renewable energy sources tend to be dependent upon climatic elements such as solar radiation, wind, rainfall and cloudiness.

This chapter is divided into two main parts: one considering the impact of climate on energy demand and one on the impact on supply. Studies on energy demand have concentrated mostly on the demand for energy for space heating and cooling. This emphasis is a reflection of the fact that a considerable proportion of the energy demand in industrialized countries is for space conditioning and this demand tends to be more climate sensitive than, say, the demand for energy for transportation. McKay and Allsopp (1980) state that over one-third of the energy consumed in industrialized North America and about 50 percent of that consumed in Europe (Denmark and Great Britain) is used to overcome the direct or indirect consequences of climate.

McKay and Allsopp point out that although the influence of climate on energy demand is most evident in the case of space heating, significant demands also occur in agriculture, transportation, and in outdoor industries such as construction and forestry. The latter uses, however, are small in comparison to the demand for energy for space conditioning. Pimentel (1981) estimates that America and Europe currently use about 17 percent of their total energy for their food systems. About 6 percent is used directly for agricultural production. In developing countries, Pimentel estimates that the amount of energy used in the food system is 30-60 percent.

There are three basic methods that have been used so far to study the impacts of weather, or climate, on energy demand. These three methods are discussed in Section 9.2. The first method is that of the case study, in which the impacts of particular climatic anomalies are documented. The other two methods involve models. One set of models is referred to as physical models. These models consider the actual heat losses from a building, or a number of buildings, and compute the changes of these heat losses as a function of changes in climatic variables such as outside temperature and windspeed. Physical models are useful for studying the detailed response of individual structures, but the amount of input information that is required makes them inappropriate for studies of the impact of a cold winter on the demand for energy for the space heating of an entire country. In such a case, it is necessary to aggregate data and use statistical samples.

The second set of models is referred to as statistical or empirical models. Usually they involve regression analyses, with some expression of energy demand as the dependent variable and some climatic variable, usually temperature or degree days, as one of the independent variables in the regression equation.

Section 9.3 considers the impact of climate on energy supply, mainly on renewable sources of energy. Basically, there are two methods for studying these impacts. The first method involves data acquisition and analysis. The main aim of such studies is to provide a detailed description of the availability of renewable energy resources such as solar energy, wind energy, and hydropower and to provide information on their likely variability overtime as a result of climatic variability. The second method is the development of computer models to simulate the performance of renewable energy technologies in different climate zones. These models have been useful, for example, in showing the interplay between solar energy availability and heating requirements as a function of climate.

Section 9.4 discusses energy supply and demand in developing countries. Attention must be devoted to traditional, non-commercial sources of energy in the developing countries. Studies have been made of the potential role of renewable energy sources, with some studies suggesting only a limited role in the short term. Increasing pressure on traditional, non-commercial energy sources in developing countries has the end result of deforestation. Studies must consider the multiple uses of land for energy and agriculture, both of which are influenced by climate.

9.2 THE IMPACT OF CLIMATE ON ENERGY DEMAND

9.2.1 Case Studies of Climatic Events

Relatively few studies have been made of the impact of climate on energy demand. A brief description of the impact of the cold winter of 1947 and the more prolonged and severe winter of 1963 on British fuel supply and demand was given by Burroughs (1978).

Living with Climatic Change (Beltzner, 1976) presented a series of illustrative examples, or scenarios, as a guide for concrete investigations of climate sensitivity. The purpose was to present to the planner possible sequences of climatic events which are, in some sense, representative of the type of stress which climatic variations place on the social and economic structure of North America. Two considerations prompted the study to select real periods of past climates as models for the future. First, the situations are inherently credible: what has occurred can occur again. Second, it was felt that only real data contain the complex richness of detail that characterizes the atmosphere and is essential for planning in the real world. Therefore, periods of past weather that placed stress on society were studied. It is pointed out that well-documented instances are necessary for credible scenarios, so that only instrumentally observed events after 1880 were considered.

The scenarios that affected the energy sector were:

variability (1895–1905),
Midwest drought (1933–37),
energy (1935–36),
Mexican drought (1937–44),
variability (1950–58),
eastern urban drought (1961–66),
sea ice (1964-65 and 1971–72),
snowfall (1970–74).

The variability scenario (1895–1905) was characterized by: a cool climate; a wet period in the northwestern Great Plains; sustained drought in the Pacific Northwest; extreme cold in the Gulf States; heat waves in California and the Midwest; and East Coast and Great Lakes storms. Stress on the economy and society was not continuous but varied in type, time and place. The authors point out that a cold winter followed by a scorching summer as in 1899–1900 could today overtax the energy supplies and systems upon which society has become increasingly dependent.

In a brief description of the impacts of the cold winter of 1976–77 in eastern Canada, Won (1980) points out that secondary climatic impact on energy consumption involves the disruption or expenditure of energy resources due to extremes in weather. For example, many communities had expended their yearly budgets for snow removal before midwinter and disruptions in transportation occurred often. Ice storms that resulted in the collapse of transmission towers and lines caused extended power interruptions.

Quirk and Moriarty (1980) discussed the impact of the 1976–77 winter on the United States. The winter brought continued drought to the western United States and cold weather to the eastern United States. Quirk (1981a) indicates that the winter of 1976–77 had 11 percent more population-weighted heating degree days than in the preceding year, which implied an increase in the demand for heating fuel of about the equivalent of 350 million barrels of oil. The drought on the West Coast caused reductions in hydropower, resulting in an additional demand for another 50 million barrels of fuel to produce electricity. These anomalies are illustrated in Figure 9.1 from Quirk (1981a).

An extension of the case study approach is the development of climatic scenarios. The scenarios are based on recurrent patterns of anomaly identified by principal components analysis. These can be used to postulate future situations and their impact (Quirk, 1981b). As Quirk points out, the scenarios must contain information on the geographical pattern, amplitude and timing of typical climate anomalies. Data on climatic anomalies are obtainable for the land areas of the temperate latitudes of the northern hemisphere for the last 80 years, and the use of eigenvector analysis helps to find the minimum number of patterns representing the large part of the variations. Diaz and Fulbright (1981) have used eigenvector analysis to find the empirical orthogonal functions describing temperature deviations from normal in the United States. They found that only three patterns were needed to explain 86 percent of the variance in winter temperature for the period 1894–1978.

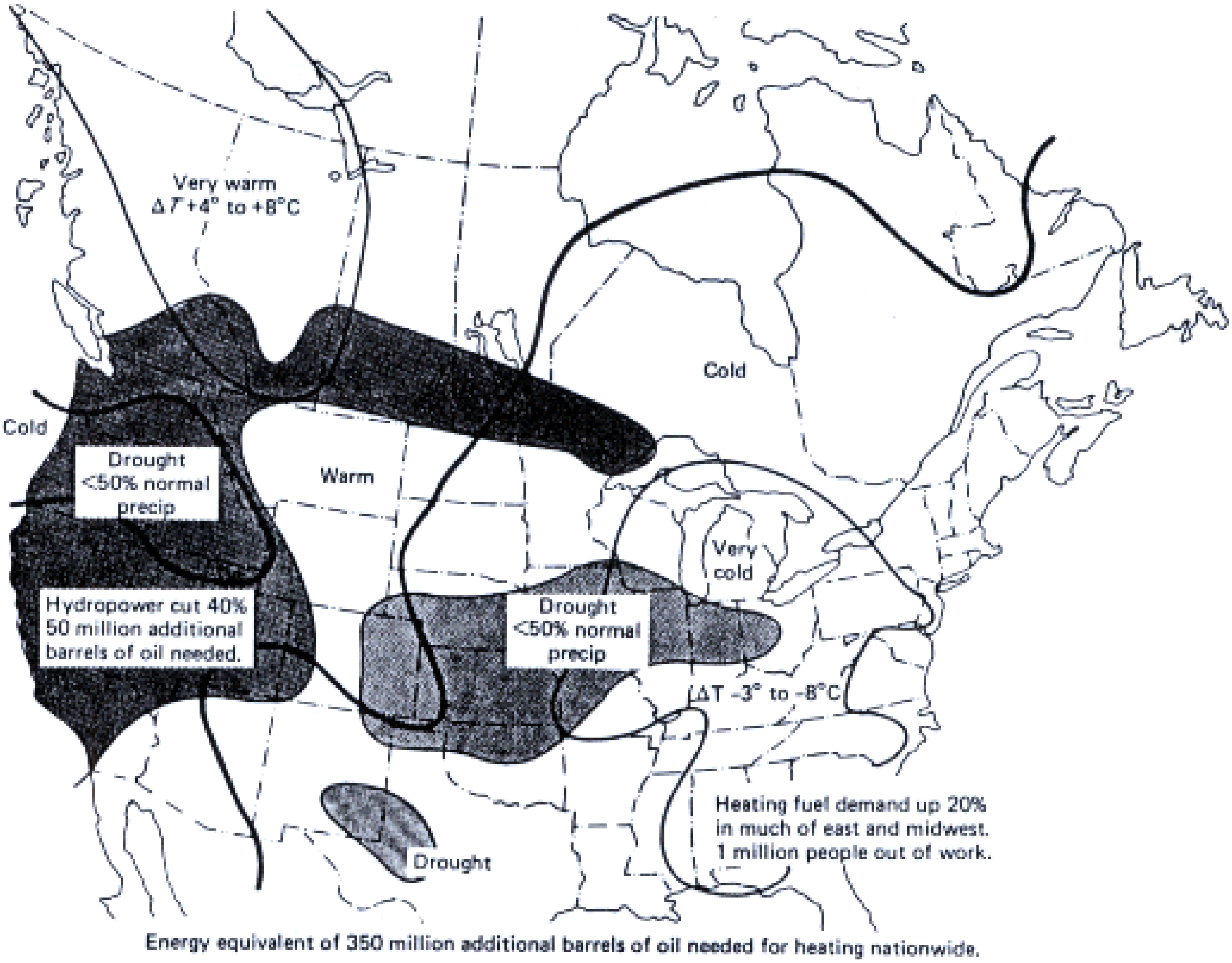

Figure 9.1 Climatic impacts of the winter of 1976–77 in North America. Reproduced by permission of the American Meteorological Society from Quirk, *Bulletin of the AMS*, **62**, 623–631 (1981)

Quirk (1981b) outlines a methodology for deriving climate scenarios. It is necessary first to obtain monthly averaged data for all the heating season months. Statistical analysis (asymptotic singular decomposition) is then required to find the most common patterns. Then data on the variation in amplitude of these patterns for each month of a heating season are used to give information on the timing and amplitude of the climatic anomalies. A scenario thus consists of a month-by-month description of the pattern and amplitude of the temperature anomaly of the heating season. The probability of the occurrence of each scenario could also be given.

Lawford (1981) has documented the climate events in Canada in 1980 that significantly affected the demand for and supply of energy, the exploration for new reserves, and the production of hydroelectricity. He points out that movements of the pack ice in the Beaufort Sea were unusual in the spring and summer of 1980. The pack ice closed in on the Arctic shoreline in September and forced oil drill ships out of the Arctic one or two weeks ahead of average. Lawford estimates that because of weather and ice conditions about two barrels of oil fewer than in 1979 were found for every hundred dollars of capital invested and expended in 1980.

Quirk (1981b) has discussed the impact of climatic variations on international energy supply. He points out that western Europe can have cold winters at the same time as eastern North America. During the winter of 1978–79, the United States, Canada, Sweden, West Germany, Great Britain, France, and northern Italy all had about 8 percent more heating degree days than normal. It is clear, therefore, that those concerned with oil supply shortfalls at the international level could also use climatic scenarios derived from information on past hemispheric climatic variations to determine how best to make energy supply more resilient to climatic variations.

9.2.2 The Computation of Heating Degree Days

Various methods are available for calculating the annual heat and fuel requirements of a building. One guide to the annual fuel consumption is the degree day method. The method requires the use of a base temperature, T_b, that represents the typical indoor mean temperature after taking account of internal heat gains. A base temperature of 18 °C is often chosen. For example, if it is assumed that the heat gains from people and appliances in a house, together with solar energy gains through windows, would raise the temperature by 2 °C, heating is required in order to keep the temperature of the house at 20 °C (a typical value) if the outside temperature falls below 18 °C (T_b). For a well-insulated house the base temperature should be lower, say 12 °C, because the internal heat gains would contribute a proportionately large part of the daily heating load. For a day on which heating is required, the number of heating degree days (DD) equals the difference between the average temperature on that day and the base temperature (T_b). For example, a day during which the average temperature is 13 °C has five degree days, if T_b is 18 °C. The number of heating degree days for the whole heating season can be added and used as a guide to the annual heating requirement. In a similar manner it is possible to calculate the number of cooling degree days required by assuming a base temperature above which cooling is necessary to maintain a particular temperature level in a house.

There are several reasons why degree day figures are useful. First, they are cumulative so that the degree day total for a period is proportional to the total heating load for that period. Second, the relationship between degree days and fuel consumption is usually assumed to be linear. That is, it is assumed that if the heating degree day total is doubled, the fuel consumption is doubled. It has, however, been pointed out (Jäger, 1981) that this assumption is an approximation because fuel consumption also depends on the efficiency of the heating system, which depends on the operation frequency of the system. Fuel consumption also depends on insulation, construction, building exposure, life styles, and so forth.

If the seasonal degree day totals in different locations are compared, the relative amounts of fuel consumption can be estimated. Table 9.1 shows the degree day totals for base temperatures of 18 °C and 12 °C for a number of European locations. It can be estimated that the annual fuel consumption in a building in Lerwick (Shetland Islands, United Kingdom, 3940 degree days, T_b =18 °C) would be about 1.8 times as much as the fuel consumption in a similar building in Toulouse (southern France, 2210 degree days, T_b =18 °C).

Mitchell *et al.* (1973) used the degree day concept in a study of the extent to which the United States national total demand for heating fuels is dependent on the weather. A probability analysis was made of the nationwide variability of seasonal total heating degree days, based on a long series of temperature data and information on the geographical distribution of heating fuel demand. The authors first calculated the seasonal total heating degree days for each of the 48 conterminous states of the United States and for each of the 42 heating seasons from 1931–32 to 1972–73. The heating degree day totals were then averaged together into a nationally averaged heating degree day total for each of the 42 heating seasons. Five different weighting procedures were used, based on the contribution of each state to the national total demand for fuel in each of five categories: all fuels, gas, oil, electricity, and liquefied petroleum gas (chiefly propane). The series of 42 nationally averaged heating degree day totals for each of the five fuel categories was then treated as a direct measure of the relative variations of total national heating fuel demand in that fuel category, for the assumption of a constant economy. Each series was examined for evidence of systematic trends. Lastly, the 42 values in each series were treated as random samples from populations of such data. This provided the basis for constructing appropriate statistical models for the assessment of probabilities of extreme fuel demand in an arbitrarily chosen heating season. Using this approach, Mitchell *et al.* (1973) were able to determine the influence of weather on heating fuel demand in terms that were independent of the long-term growth of demand attributable to economic, demographic and technological trends.

Table 9.1 Degree days to base temperatures of 18 °C, 12 °C, 17 °C and 19 °C for different locations in Europe

Latitude			Degree days base		
band °N	Place	18 °C	12 °C	17 °C	19 °C
59–61	Lerwick Shetlands	3940	1880		
55–57	Glasgow Scotland	3370	1520		
53–55	Dublin Ireland	3156	1317		
	Hamburg FR Germany				3350
51–53	Kew (London)	2780	1200		
	Valentia Ireland	2786	961		
49–51	Uccle (Brussels)	2580			
	Lille France	3062	1378		
	Reims France	3010	1396		
	Nürnberg FR Germany				3370

47–49	Brest France2653	899			
	Strasbourg France3061	1900			
	Freiburg FR Germany				3050
	Munich FR Germany				3730
45–47	Limoges France2820	1231			
	Milan Italy2350		2120		
43–45	Montélimar France2233	938			
	Toulouse France2210	842			
	Montpellier France1875	665			
	Genoa Italy1494		1270		
41–43	Ajaccio Corsica1866	405			
	Rome Italy1570		1350		
39–41	Naples Italy1355		1142		
37–39	Messina Italy806			623	

Values are not given for all countries because calculation methods are not entirely consistent and sometimes correction factors are added.
After Jäger,1981, 47.

The results of the analysis made by Mitchell *et al.* showed, for example, that in only one year out of one hundred years should one expect the national total demand for heating oil to exceed the long-term average demand (for constant economy) by as much as 10.6 percent. Similarly, it was found that the demand for heating oil can be expected to exceed its average demand (for constant economy) by at least 3 percent on an average of one heating season in five.

Mitchell *et al.* noted that in a situation where the national total heating fuel demand is higher than average, it is quite likely that excess demand would be found to center on one section of the nation where the problem is severe, while near-average or even below-average demands would be found in other areas. Therefore, the fuel demand and degree day series were computed for nine regions. As expected, the probable extreme deviations (when expressed as percentage deviations from average regional demands) were found to be somewhat larger than those for the nation as a whole, especially in the southern and Pacific states.

Figure 9.2 shows the heating degree days (base temperature 65 °F) accumulated for each heating season (defined as October–March) for the United States and weighted by population (Diaz and Quayle, 1980). The anomalously cold winter of 1976–77 is quite distinct, as is the decline in the heating degree day total between 1900 and about 1940 and the subsequent increase.

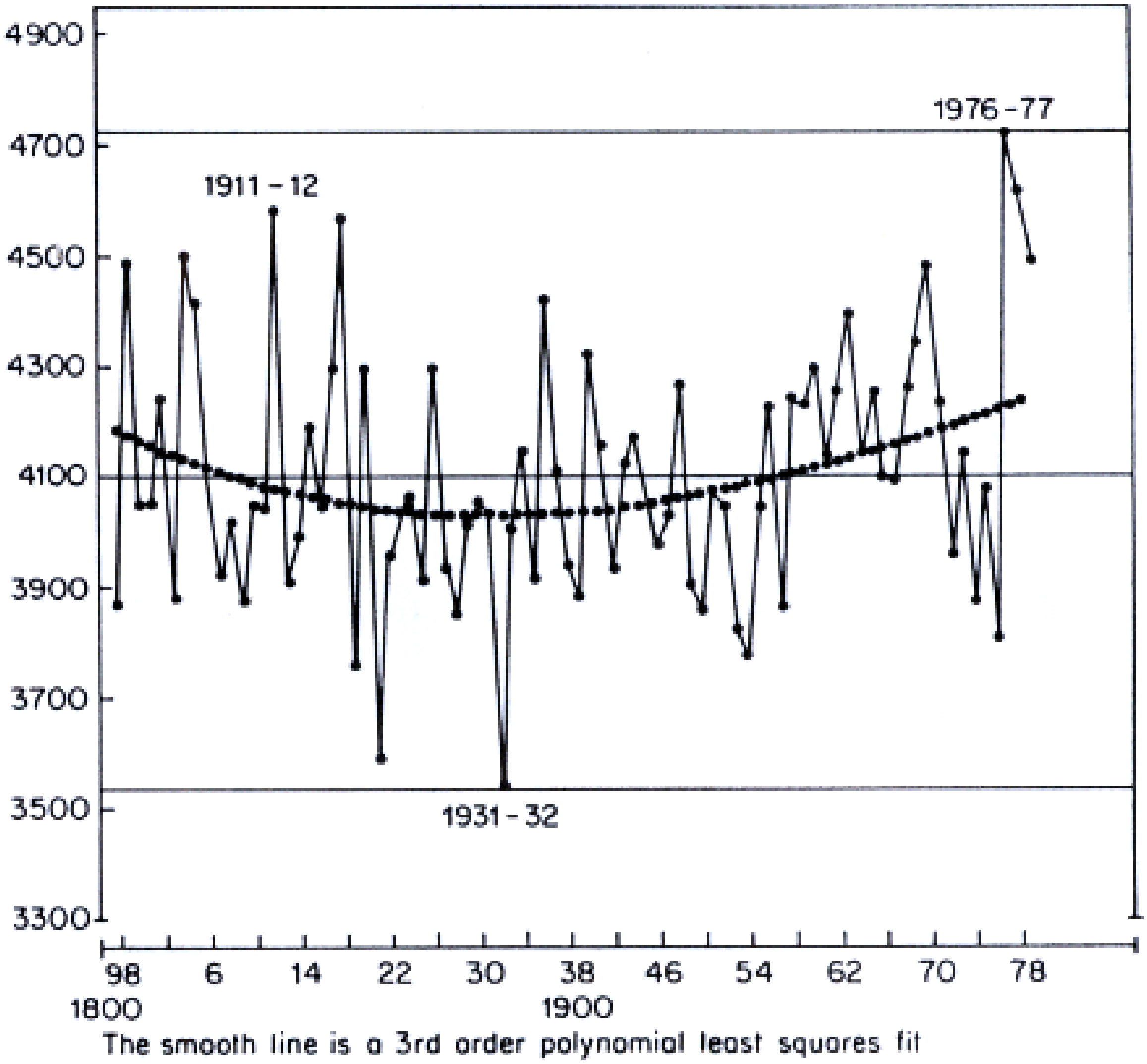

Figure 9.2 Total October-March heating degree days (65 °F base) for the United States weighted by population for 1898-1978. Reproduced by permission of the American Meteorological Society from Diaz and Quayle, *Monthly Weather Review*, **108**, 687-699 (1980)

Ahti (1975) cites Robinson (1974) in pointing out that the degree day method is not appropriate for estimating energy consumption by air conditioning for the following reasons:

– the system energy demand does not necessarily increase linearly with a temperature increase,
– the system energy demand is affected by relative humidity,
– the system energy demand is affected by solar radiation.

McKay and Allsopp (1980) showed the relationship between heating degree days and mean temperature presented in Figure 9.3. On the basis of the known relationship between mean annual air temperature and population distribution, and assuming that the heating requirement approaches zero at 18 °C and 35 percent of the total energy use at 0 °C (based on US and Canadian rates), McKay and Allsopp calculated that the greatest energy use occurs in the regions where the annual air temperature is between 5 °C and 15 °C with a maximum at 10 °C. They conclude that a one-degree change in annual temperature would alter space heating energy demand for people living in the present intensive energy use area by roughly 10 percent. National cumulative abnormal heating and cooling costs for the United States are published, along with information on heating and cooling degree days, by the US Department of Commerce (National Oceanic and Atmospheric Administration, ongoing).

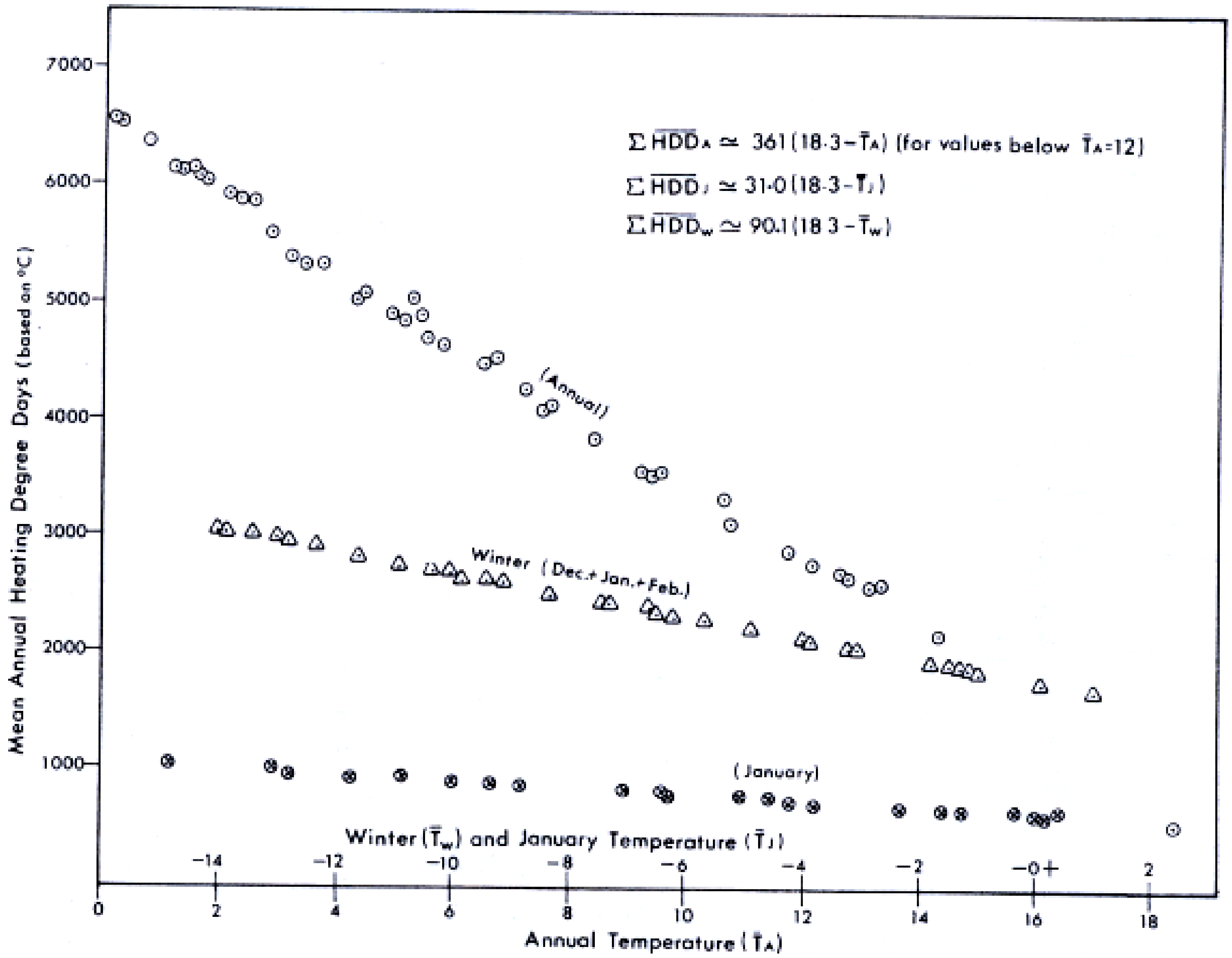

Figure 9.3 Relationships between heating degree days and mean temperature. Reproduced by permission of D. Reidel Publishing Company from McKay and Allsopp (1980)

Cohen (1981) has designed what he believes to be a more realistic climatic index of long-term residential energy consumption and shows how this index is better than heating degree days. The index includes non-temperature elements and provides a more complete representation of climate for use in multivariate energy demand models. A statistical approach was used to relate seasonal frequencies of daily upper air circulation patterns to energy consumption. Principal component analysis was used to identify the significant upper air (500 mb) flow types. Simple linear regression analysis and Pearson product-moment correlation analysis were used to examine separately the statistical relationship between seasonal energy consumption and the two variables: seasonal frequencies of upper air circulation types and seasonal heating degree day totals for each state in the United States. The energy data base consisted of annual per-household consumption of natural gas for each state from 1960 to 1978. Cohen concluded that the 500 mb circulation type frequencies are a better climatic index of long-term residential natural gas consumption than heating degree days.

9.2.3 Computing the Heating Requirements of a Building

In order to calculate the heat losses of a building a number of factors must be considered:

- the coefficients of heat transmission of all parts of the building through which heat can be lost (walls, windows, doors, etc.);
- the outer surface area of these parts of the building;
- the temperature difference between the interior and exterior of the building;
- the ventilation losses.

The transmission heat loss from a building is dependent on the mean coefficient of transmission of the building, the total exterior surface area, and the temperature difference from the interior to the exterior. The ventilation heat loss depends on the airflow and the specific heat of the air. Not only does the outdoor temperature continually change during the day, but indoor conditions also vary due to changes in ventilation, absorption of solar radiation by the building, solar radiation coming through windows, and heat emissions from people and appliances. The most accurate models for the determination of heating requirements take account of the dynamic effects arising from the thermal storage capacity of the building components and heat transfer in these components as a function of time.

Jäger (1981) has used a detailed computer model for the calculation of heating requirements. The model was based on guidelines set up by the Federal Republic of Germany for the dimensioning of heating systems. The different components of the energy balance of a building (such as transmission and ventilation losses and heat gains from occupants) were calculated for each hour. The model used hourly meteorological data (temperature, direct and diffuse radiation). This method allows a more exact calculation of the annual heating requirements than can be made with the degree day method, which can consider the heat gains from the sun only approximately through a reduction of the base temperature. The model did not, however, take into account the dynamic effects mentioned above. For the calculation of the heating requirements a reference house was considered. Two sets of house insulations were studied. The first set consisted of those required by present regulations in the Federal Republic of Germany. The second set of insulation standards was based on the more stringent present standards in Denmark. The annual heating requirement for the two house types was calculated using meteorological data from two locations, Copenhagen in Denmark and Carpentras in southern France. The computed annual heating requirements are shown in Table 9.2. For both house types the heating requirement in southern France was about 63 percent of that in Denmark. In both locations the heating requirement in the better-insulated house was about 50 percent of that in the house built according to lower standards.

Table 9.2 Computed annual heating requirement for two types of reference houses in two European locations

Annual heating requirement (kWh)	German standard	Danish standard
Copenhagen, Denmark	30 420	15 350
Carpentras, France	19 280	9750

Source: Jäger, 1981, 49.

Hörster (1980) has reviewed the methods of calculation of energy requirements of buildings. He points out that a number of mathematical models exist which are based on first principles. These models calculate the magnitude and distribution of interior temperature and the relative humidity in individual rooms. The models require much computer time; it is therefore necessary to develop simplified models. As Hörster points out, the simplified methods use the most important physical factors that determine the heating requirements.

Hörster distinguishes between dynamic and stationary models. The simplified stationary models do not take into account the energy flows within the building. These flows are especially important when the insulation standard is high.

9.2.4 Climate-Energy Use Models

9.2.4.1 A Buildings Model

In a series of reports, Reiter *et al.* (1976,1978,1979,1980,1981) have discussed the results of a long-term project to study the impact of weather variations on energy demand for space heating. The authors decided that statistical models relating weather variables and energy consumption, especially models based on historical data, have a number of limitations. These are accurate only if physical structures, use patterns, and comfort levels remain constant. Therefore, Reiter *et al.* (1976) decided to base their model on physical features which could be derived from basic heat transfer relationships.

The authors point out that a model cannot be developed for each individual building in a region, but in the United States there is a remarkable degree of thermal similarity among the vast majority of residential, commercial and industrial high- or low-rise buildings constructed within fairly distinct time periods. It was concluded that buildings could be grouped into thermally equivalent classifications and aggregated. The physical model therefore consists of:

1. a generalized computer program for predicting the space-conditioning energy requirements of selected building classifications,

2. a set of modules generated from the above program, with each module representing a particular building type, use and vintage classification.

The generalized computer program computes transmission losses and infiltration losses as outlined in Section 9.2.3.

The meteorological input to the model consists of insolation or percent of cloudiness (amounts, types, thicknesses and altitudes), windspeed, and ambient temperature (air and ground). A second requirement is a census of the buildings that comprise the population region to be studied by types, usages, ages, numbers, sizes, construction characteristics, materials, shading and sheltering from sun and wind, energy sources, heating and cooling systems, internal heat loads and locations. The model also provides for the selection of thermostatic settings, for the introduction of multipliers to characterize infiltration rates, and for the variation of the physical (thermal) characteristics of structures for known or assumed building uses and occupant habit patterns. This latter part of the model is referred to by the authors as the adaptive portion of the model, and it is suggested that the policy-maker could use it to introduce a variety of alternative scenarios into the physical model in order to investigate their relative impacts on energy consumption for space conditioning.

Reiter *et al.* (1976) applied the overall model to predict the daily gas consumption for Greeley, Colorado, during the period 1 December 1975 through 29 February 1976. The model predicted the mean daily energy consumption to within 8 percent, with a standard deviation of 5 percent. The model underpredicted during cold periods and overpredicted during warm periods. The authors investigated several possible causes for this, including the variations in furnace efficiency caused by more frequent switching between on and off-cycles during cold periods, and the converse during warm periods.

Reiter *et al.* (1978) also reported on refinements of the energy model. They point out that the model developed in the previous report was a micromodel, in which the system is decomposed as much as possible. The information needed by a micromodel is extensive. Their first study had, by means of an exhaustive survey, obtained detailed information on physical variables as well as the social behavior of the building occupants. A refinement of this procedure, in which a less detailed building census was generated by means of statistical sampling schemes and procedures, was adopted in 1978. The second approach to the development of a model for energy demand was a macromodel. Macromodels use socioeconomic data that are available in census reports and other data available within the community. Reiter *et al.* indicate that micro- and macromodels both have advantages and disadvantages, and the best approach is probably a combination of the two model types. The micromodel was used to compute the energy consumption for the winter of 1976-77 for Greeley, Colorado, and the results were 99.9 percent of the actual consumption. The model was also applied to Cheyenne, Wyoming, and it predicted 97.8 percent of the actual consumption during January, February and March 1977. The slightly larger error was explained as being due to the fact that no detailed building census was taken in Cheyenne, but a statistical sampling technique was employed instead.

Reiter *et al.* (1979) extended the model of space heating demand by adding a set of hypothesis-testing procedures to measure how the model results compare with the actual energy consumption of a community. These testing procedures enable the model to detect changes in habit patterns and also, by updating, to cope with the evolution of a community. To improve the model without increasing the amount of input data required, a time-series description was developed to complement the original physical model. The time-series description was based on the residual (observed minus predicted) energy consumption and its correlation with various meteorological input variables in time sequence. A description of this type was developed for Greeley, Colorado, and it improved the estimation of energy consumption from a root mean square error of 9.1 percent to 5.8 percent for the 1975–76 winter season.

In addition, Reiter *et al.* (1979) described the development of a second model, referred to as a statistical reference model. This model used the same heuristic algorithm that was used in the physical model for identification of the coefficients of the heat transfer equations used to model individual buildings within a certain typical structure category. However, the statistical reference model does not use actual building information. Instead, it uses the meteorological input and the actual response of the community in terms of energy consumption to derive a single high-order equation that can be used to model the response of the entire community. The model was developed for estimating the performance confidence interval, which was used to show which parts of the model output are acceptable, and indicated when the real community was changing in complexion over time in contrast to the earlier identified physical model assumptions. The authors suggest that the statistical reference model has limitations, largely because it is based on coefficients and does not explicitly include the physics of processes involved in the need for energy consumption for space heating. Thus the model cannot be used to answer questions about the effects of behavioral, structural or other changes. On the other hand, the authors indicate that the model could be useful for assessing the energy use of communities with a small amount of data.

Reiter *et al.* (1980) also report on the development of a model for use in studying the effects of optimal utilization of weather and climate information on energy systems design and operation. To test a preliminary model, the authors adopted a scenario in which a solar energy installation backed up by a resistance heat source should be optimized and the requirements of heat storage for various given climatic factors would be studied. The authors point out that in such a scenario various trade-off decisions concerning the number or size of solar panels, the capacity of the heat storage device, and requirements for auxiliary energy under various cost configurations can be made.

9.2.4.2 A Fossil Fuels Model

Nelson (1976) has examined the influence of climate on the demand for fossil fuels in residential and commercial space heating. Climatic variability was considered in terms of heating degree days. The demand for fossil fuels was considered to be the total oil, natural gas, and coal consumed in the residential and commercial sector in a cross-section of the states of the United States of America in 1971.

It is pointed out by Nelson (1976) that studies of the demand for energy in the residential and commercial sectors can be divided into short-run models and long-run models. The short-run demand for a particular fuel refers to the demand for fuel when the stock of heating appliances is held constant. Nelson suggests that the short-run per-customer demand can best be studied by using time-series data that control for the prices of substitute fuels and heating appliances. In contrast, long-run demand for particular fuels involves variations in both the stock of appliances and the usage of that stock. Studies of the long-run per capita demand require cross-sectional data including the prices of substitute fuels and heating appliances.

Nelson assumes that for each state the total residential and commercial demand for fossil fuel energy is a function of:

- the number of customers,
- the price of fossil fuel energy,
- income,
- and several non-economic variables including climate.

The number of customers per state using a particular heating appliance is assumed to be a function of:

- population size,
- the price of fossil fuel energy,
- prices of substitute fuels,
- income,
- and several economic variables including climate.

Nelson found that

1. Population has a significant and positive effect on energy demand.
2. Income has a significant and positive effect on energy demand when it is added to the regression equation, but when the urbanization variable is added, the income variable is no longer significant. Nelson suggests that this may be due to the high correlation between these two variables.
3. The price of fossil fuels has no effect on the total fuel demand.
4. The electricity price variable has a positive and significant effect on the total fuel demand.
5. Degree days have a positive and significant effect on total fuel demand. A 10 percent increase in degree days would increase total fuel demand by about 5 percent.
6. The two most important variables in explaining changes in total fuel demand were found to be population and degree days.

Because population was found to have a significant impact on energy demand, Nelson rederived the model in terms of the per capita demand for fossil fuel. With per capita fuel consumption as the dependent variable, Nelson found that

1. Income was not significant and became negative when the urbanization variable was added.
2. The price of fossil fuels, the electricity price variable, and degree days all retained their significance and relative magnitude.
3. Climate (degree days) and the price of electricity are most important for per capita demand changes.

Nelson has discussed in detail the possible causes of the fact that a 10 percent increase in degree days would increase total fuel demand only by about 5 percent. He points out that the model does not control for interstate differences in housing insulation and construction standards. Because homes in northern climates are better insulated, the degree day variable will be biased downwards if estimated with cross-sectional data. Also, Nelson points out that the dependent variables examined in this study included some non-space heating uses of fossil fuels. It is estimated roughly that space heating accounts for 80 percent of the gas, oil and coal consumed in the residential and commercial sectors. Since non-space heating uses would not always vary with outdoor temperature, the change in degree days would not entirely determine the change in fuel demand.

Nelson describes two applications of the empirical model: an examination of the expected crude petroleum savings due to lower thermostat settings and higher prices for fuel oil, and a prediction of increased energy consumption if supersonic air transportation were to reduce mean annual global surface temperatures. It was calculated that a 6 °F reduction in thermostat settings would reduce per capita demand by 13.65 percent if all else were constant. For a price increase of 10 cents per gallon relative to November-December 1973 prices, the saving was computed to be 8 percent of 1973 demand. It was calculated that an 8.2 percent increase in degree days in the United States would increase the per capita residential and commercial demand for fossil fuels by 4.1 percent.

9.2.4.3 An All-electric Commercial Buildings Model

Crocker (1976) has examined the impact of climatic variations on electricity demand in commercial buildings, using detailed histories of month-by-month electricity consumption and meteorological variables during a period of a year for about 80 all-electric commercial buildings throughout the United States. The estimates made by Crocker are considered to be long-run because it is assumed that building insulation and heating and cooking equipment are selected on the basis of expected climate.

The dependent variable used in the ordinary least-squares cross-sectional regressions was kilowatt-hours consumed in a given month. The variables used in the empirical analysis were: heating degrees, cooling degrees, average electricity price, total connected load, designed heat loss, designed heat gain, apartments, churches, stores and offices, light manufacturing, and motels.

The ordinary least-squares regressions discussed by Crocker are multiplicative, according to a statistical function used to transform combinations of electricity and other inputs into a variety of outputs. The year was partitioned so that only summer and winter months were considered. The results of the March, June, and September regressions indicated that there was substantially less response to variations in heating degree days (March) or cooling degree days (June and September) during these months than for other months for which regression results were reported. Crocker concluded that these relatively low elasticities were consistent with a relatively small absolute change in quantity demanded with respect to a one-unit absolute change in degree days. Over the observed temperature ranges for the months in question, the electricity consumption for heating and cooling purposes was relatively unresponsive to changes in degree days. Crocker suggests that this behavior seems particularly likely during the spring and autumn months in the temperate climates where the buildings used in the study were located. The results also indicated that for the buildings in question there exists for temperatures below 75 °F or 80 °F a uniformity in the responsiveness of electricity consumption to variations in climate.

9.2.4.4 A Real-time Data Model

Warren and LeDuc (1980) discussed the need to assess the impact of weather on the economy, in particular, on energy use and price. The authors point out that models to estimate the impact of weather on energy demand can be classified according to the energy demand or load that they are intended to estimate. At the lower end of the range there are models for estimating the next day's load, using information such as weather effects and the latest load behavior. Most of these models are utility-specific and integrating them into a model at a regional or national level would require the aggregation of data for many separate utilities.

Warren and LeDuc (1980) describe a model used for estimating natural gas consumption in the United States. Two demand functions for residential consumers were formulated: one for customers who do not use gas for space heating, and a second for space heating customers. The relationship for consumers who do use gas for heating is a function of base consumers, price, and heating degree days. A heating degree day index was formulated to account for the spatial distribution of customers in the division and also for a temporal reporting lag. The average rates of consumption of natural gas in nine regions that together covered the contiguous United States were estimated. The authors conclude that weather alone does not explain all the variations in energy consumption. For example, price and seasonal adjustments were necessary in the above model to explain the variations.

9.3 THE IMPACT OF CLIMATE ON ENERGY SUPPLY

The impact of climate on conventional energy supplies has not been studied in detail. The range of impacts is generally known, however. For instance, McKay and Allsopp (1980) state that exploration and transportation phases are climatically sensitive, especially at high latitudes and at sea. Likewise, it is pointed out that climate must be taken into account in the selection of optimum shipping routes, ports and harbors. Strategies, economics, engineering and environmental aspects of offshore drilling, and the development of coastal facilities are also found to be climatically sensitive. McKay and Allsopp (1980) also point out that climatic elements such as air temperature, humidity, solar radiation, wind, and precipitation must be considered in the design and operation of storage systems.

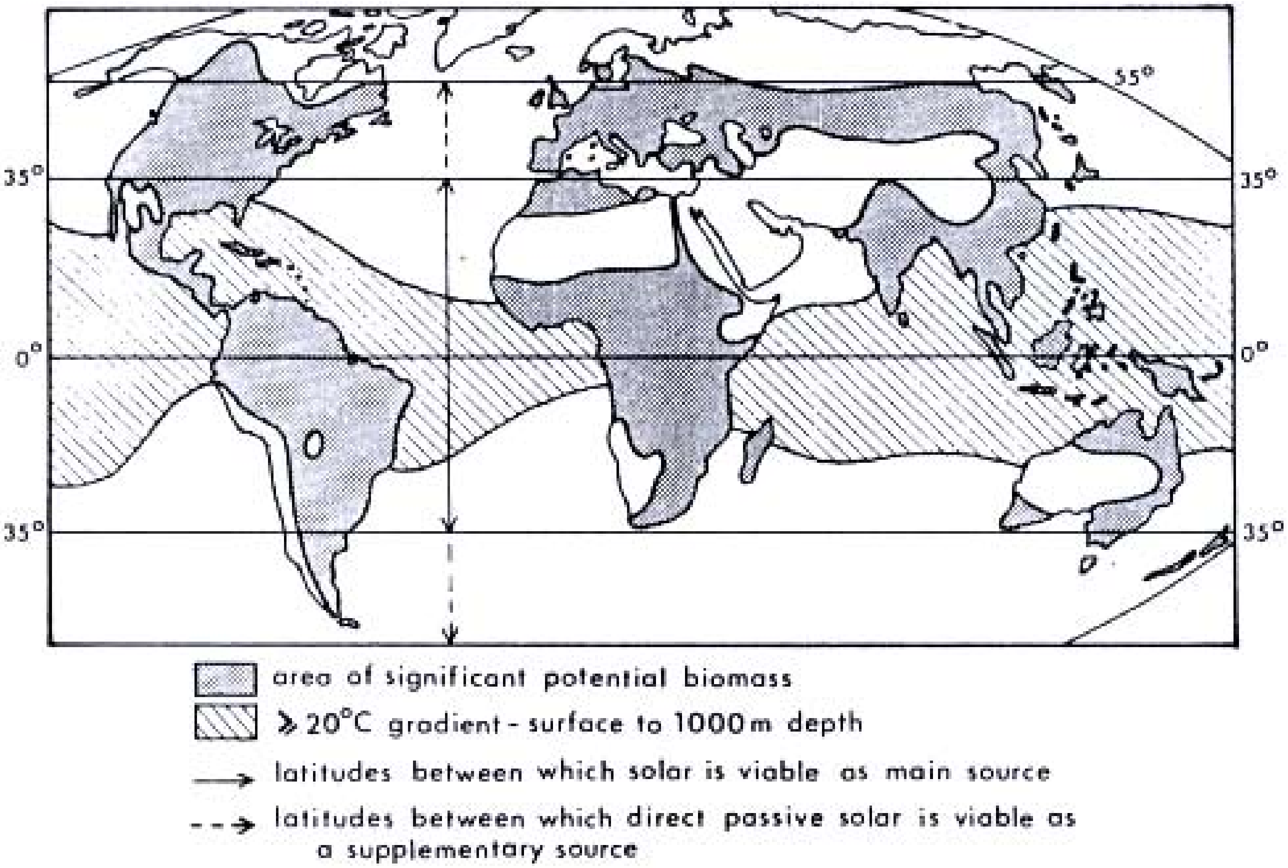

Figure 9.4 Areas favorable for exploitation of solar, biomass and ocean thermal energy. Reproduced by permission of D. Reidel Publishing Company from McKay and Allsopp (1980)

Most impact studies concerning renewable energy sources are at the resource assessment stage with little study, yet, of the variability of the supply due to climatic variability. But as McKay and Allsopp (1980) have indicated, climate dictates the potential supply of renewable energy sources. They provide a general analysis of this supply, showing the influence of geography (Figure 9.4). It is suggested that solar energy systems are most promising between 35 °N and 35 °S. Significant hydropower and biomass production also occur in this zone. Ocean thermal energy is most obtainable in the tropical latitudes, wave energy in ice-free waters, and wind energy is ubiquitous (McKay and Allsopp,1980).

9.3.1 Renewable Energy Supply

9.3.1.1 Hydropower

The impact of climate on hydropower supplies has been discussed by McKay and Allsopp on a quantitative basis. They point out that storage must be provided to overcome climatic variability. The resource potential is greatly diminished in drought and increased in wet periods. The power generation of the Niagara river system in 1964 was reduced 26 percent by drought conditions. The drought in California in 1976-77 (see Figure 9.1) was characterized by 65 percent of normal precipitation in 1976 and only 45 percent in 1977. Hydroelectricity generation (20 percent of total electricity generation on the average) was reduced from about 33 billion to 16 billion kWh in 1976 and 13 billion kWh in 1977 (McKay and Allsopp,1980).

9.3.1.2 Solar Energy

There is a variety of technologies for the conversion of solar energy. These range from solar collectors on house roofs for space and water heating to solar power plants, with large arrays of mirrors concentrating solar energy to heat water and drive turbines to produce electricity. To some extent the type of solar energy conversion system installed in an area depends on the prevailing climate. Solar thermal electric conversion systems based on the `power tower' concept convert only direct solar radiation. Therefore, they are more suited to the dry desert climate regions, where the proportion of direct radiation is high, than to the cloudier middle latitudes, where the proportion of direct radiation is much smaller, especially in the winter months. Insolation resource assessment programs (e.g., Riches and Koomanoff,1978; Commission of the European Communities, 1979) have been established to collect, record and archive solar radiation data. Analyses of temporal and spatial distributions of solar radiations are reported for various countries in the energy journals (e.g. Balling and Vojtesak,1983).

The use of solar energy for domestic space and water heating depends on a number of climatic factors, as has been discussed in detail by Jäger (1981). Not only does the solar energy collection depend on climatic variables, but the heat losses in a house are also climatically sensitive, as described in Section 9.2. The design of a solar house should minimize heat losses in winter, while maximizing the heat gains and also ensuring that the house is acceptably comfortable in summer. Information on microclimatic conditions (shading, sheltering, etc.) as well as on the macroclimate is necessary for the design of a solar-heated house.

Jäger (1981) has emphasized the importance of making a balanced assessment of all factors when making an evaluation of the economic viability of solar heating systems. He points out that if one were to consider only the distribution of incoming solar radiation in Europe, one might draw the conclusion that solar heating would be more economically attractive in the southern locations where the solar radiation availability is high. However, the length of time over which heating is required is relatively short in the south because of the relatively higher temperatures associated with lower cloudiness, more sunshine and less wind. A longer operating season in less climatically favorable regions could give an installed solar space heating system greater economy.

9.3.1.3 Wind Energy

The impact of climate on wind energy resources has also been considered. The distribution of wind energy varies markedly in space and time and a knowledge of these distributions is necessary so that the selection and siting of wind energy conversion systems can be effective. Hardy and Walton (1977) have listed the meteorological properties needed for wind energy conversion system studies as:

- areas of smoothly accelerated or enhanced winds,
- locations of flow separation zones,

- mean hourly wind velocity distributions,
- characteristics of local turbulence and gusts,
- occurrences of extreme winds and calms,
- vertical profiles of wind velocity as a function of atmospheric stability,
- frequency of severe thunderstorms, lightning, hail, icing, tornados, or hurricanes,
- presence of salt spray or blowing dust.

Data of these types rarely exist in many areas that are considered most appropriate for wind energy systems development. For an evaluation of the continental scale wind energy resource, wind observations from the standard meteorological stations are available, although many of these observations are made at airports, which are generally not located in the more windy areas. Traditional wind data are also difficult to interpret in mountains and hilly and coastal regions.

Wind energy development involves three stages: initial evaluations, site selection and assessment, and machine design and performance. The initial evaluations generally can be made using standard meteorological observations. Data for site selection and assessment are more difficult to obtain because the density of measurements at scales less than 100 km is poor.

Wind variations over long periods of time must also be considered in planning systems. Hardy and Walton (1977) report that long-term (10-year) variations in wind energy conversion system output have been estimated from standard meteorological data from 15 locations in the United States. Power output was estimated by the hour over the 10-year period at each site and averaged. It was found that in addition to expected seasonal variations, significant year-to-year variations also occurred. Interannual variations of about 25 percent of the long-term mean were estimated at most locations. It was also estimated that minimum energy costs could be achieved at all sites with only a modest amount of energy storage to buffer changes in output.

Hardy and Walton (1977) show that in areas without enough observational data, the following steps are needed:

- collection of meteorological observations from multiple sources,
- use of a numerical model to simulate the windfield over terrain,
- statistical analysis of regional wind velocity patterns,
- coordinated application of the field measurement and statistical and numerical modeling effors.

A study incorporating these aspects has been conducted for the island of Oahu, Hawaii, by Hardy (1977a,b).

A methodology to provide accurate estimates of wind power at potential sites from data that are already available has been developed by Bhumralkar *et al.* (1980). The model, which is three-dimensional and based on physical equations, incorporates the effect of underlying terrain and uses available conventional wind data from selected nearby meteorological stations. The program is essentially an objective analysis that interpolates values of wind from observations at irregularly spaced stations.

Another approach to resource assessment is the investigation of joint wind/solar availability (Kahn, 1979; Aspliden, 1981). In this case, one investigates whether the wind blows when the sun does not shine and vice versa. Kahn shows the results of a study on joint wind/solar availability for a single site in Texas. At this location, the wind energy available at two heights was considered. It was found that the larger amount of wind energy available at the higher level produced excess power that was available only in the spring, whereas a smoother aggregate of solar and wind energy was available using wind energy conversion at a lower height. Kahn points out that it is difficult to generalize from such results and it is also necessary to look at smoothing effects, such as geographical dispersion. The relationship between aggregate energy availability and geographical dispersion has been investigated more extensively for wind energy conversion than for solar energy conversion (Kahn, 1979). For example, Kahn cites a study for West Germany which showed that at one site there was no wind energy output for 1500 hours per year. When three sites were considered there was no output for several hundred hours per year, and with 12 sites there was no output for less than 20 hours.

9.3.1.4 Biomass

Biomass is another renewable energy source that is influenced by climate. The overall prospects for the development of the use of biomass as a source of energy in Europe have been evaluated by Palz and Chartier (1980). They point out that the main climatic factors controlling plant growth in Europe are temperature and the length of the growing season, expressed as periods above 5 °C or numbers of frost-free days, and these factors rather than total solar energy received determine the units of productivity. The climate varies sufficiently within the countries of the European Community so that a number of geographic zones can be outlined in which different opportunities exist and different approaches will be necessary if biomass is to be produced specifically for energy. After regional climate, the factors affecting plant productivity are: local climate, soil, topography, and land use. Palz and Chartier (1980) have summarized the characteristics of a number of lowland and upland zones and indicated the most favorable biomass production opportunities arising in them. The main divisions were based on precipitation deficits and winter isotherms. It was concluded that the potentially available source of biomass energy which can be generated without effecting major changes in land use in the European Community represents 15 percent, in gross energy terms, of the projected demand by the Community in 1985.

9.3.2 Model Studies of Solar Energy System Performance

When detailed data assessments or established monitoring of solar heating systems are not practicable, models of solar heating systems and a reference house are useful for assessing the potential for solar energy systems in various climatic zones. The models usually simulate the performance of a solar system over a complete year. There are three major model types for simulating solar systems: finite-element models, component models, and approximative models. Jäger (1981) has used a component model in which the different components of a solar system are presented by individual differential equations and heat transfer between the components is considered. Weather data on an hour-to-hour basis are required in this model type. It has been found that the models are able to make performance evaluations with satisfactory accuracy when all model input data (climate and technical system characteristics) are well known.

Jäger (1981) has computed the performance of solar systems with 40 m^2 of single-glazed, non-selective collectors and 80 liters of store volume per m^2 of collector area. The solar systems were assumed to be built into a house insulated according to high Danish standards. The same house and solar system were considered for each country in the European Community. In this way the influence of climate on performance of the system could be isolated. The disadvantage of this approach is that the chosen reference system may not represent the optimum situation with respect to component dimensions and configuration of the system. Consequently, for some countries, the given results could underestimate the ultimately achievable solar system performance. The performance results were determined by using hour-by-hour simulation in the cases where suitably detailed climatic data were available (Belgium, Denmark, France, the Federal Republic of Germany and Ireland). For those countries in the European Community where such climatic data were not accessible, the reference system performance was extrapolated from information in the literature or from data for adjacent countries with a comparable climate. Except for France, only one reference system was defined for each country. The comparison of the heating requirements in Table 9.3 suggests that the reference locations in Belgium, Ireland, Luxembourg and the United Kingdom have about comparable annual heating requirements. These countries all have a maritime climate with relatively warm and cloudy weather in winter. The contribution which the reference solar system makes to the heating supply (`solar energy share') is also comparable, except for Ireland where more favorable results were obtained from simulation. Jäger suggests that the better performance in Ireland is a result of a better matching of the heating requirement and solar energy supply, since in the maritime climate of Ireland the summers are still cool enough to require some heating that can be supplied by the more available solar energy in that season. Further east, towards a more continental climate, in central France and the Federal Republic of Germany and in the more northern latitude of Denmark, the heating requirements and solar energy share increase. In the Mediterranean areas of France and Italy a higher solar share can be obtained. However, since heating requirements decrease, the amount of fuel that can be substituted by solar energy does not increase in proportion to the solar energy share.

9.4 ENERGY SUPPLY AND DEMAND IN DEVELOPING COUNTRIES

In comparison to the numerous studies described above, relatively little attention has been given to the impact of climate on energy supply and demand in developing countries. The role and potential of renewable sources of energy were discussed, however, at the United Nations Conference on New and Renewable Sources of Energy in Nairobi in 1981. Shakow *et al.* (1981) have pointed out that in eastern and southern Africa, for example, only 5–25 percent of the total energy budget is derived from commercial fuel. They add that if draught animals, human power and passive solar power were included, this figure would be substantially reduced. Commercial fuel, therefore, is not the dominant part of the total energy budgets of oil-importing developing countries. Shakow *et al.* also point out that in eastern and southern Africa 50–60 percent of all commercial energy is used in transport and related activities, 20–30 percent is used in commercial and industrial production, and only 5–10 percent is used in agriculture. Therefore, attention must be devoted to traditional, non-commercial sources of energy in the developing countries. In eastern and southern Africa, for example, household energy consumption is about 75–80 percent of the total energy consumption. Eighty percent of this energy is used mainly for cooking, with firewood, charcoal, dung and crop residues accounting for most of the energy supply in rural areas (Shakow *et al.*, 1981).

Table 9.3 Performance and fuel saving characteristics of reference solar energy systems in countries of the European Community

	Federal Republic of Germany	France	Italy	Nether-lands	Belgium	Luxem-bourg	United Kingdom	Ireland	Denmark
Annual space and water heating requirements, kWh	20 000	17 200	14 000	16 000	16 000	16 500	15 800	15 400	19 600
Solar energy share, %	45	48	75	46	46	45	45	62	49
Annual fuel saving in the auxiliary heating system									
oil, liters	1385	1270	1615	–	1132	1142	–	1469	1478
gas, m^3	–	–	–	1253	–	–	1215	–	–

Source: Jäger, 1981, 133.

Increasing pressure on traditional, non-commercial energy sources in developing countries can have the end result of deforestation. Energy demand and supply balances therefore must be planned within the framework of integrated land management, which involves taking the climate into account. The question of fuelwood supplies will be addressed in more detail below.

A few studies have been made of the potential of renewable energy sources in developing countries. For example, Shakow *et al.* (1981) have discussed the potential in Kenya and conclude that renewable energy technologies do not offer much hope in the short term. They point out that the total hydropower potential in Kenya will not meet the country's needs (500–550 MW) by 1990 and that although extensive exploration for mini-hydropower is underway, much of this potential (750 MW) is distant from the integrated grid system where demand is growing rapidly. The authors also conclude that alcohol production competes directly with food production for land, critically important in countries like Kenya where there is a severe food deficit. They also suggest that although the wind energy resource is poorly evaluated, the potential for economic wind energy utilization is small in both the commercial and rural sectors. Thus, the authors conclude that the renewable technologies have little to offer the developing countries in the near future, although such alternatives are a necessity for the longer term.

Hutchinson (1974) has evaluated the potential of renewable energy sources in Zambia. He concludes that electrical power generation from the wind has little potential because of the difficulties in storage of electrical energy. Most of the energy would be produced in midmorning when the wind reaches its diurnal peak, whereas the heaviest consumption time is in the early evening. The price of required battery storage was considered prohibitive, and mechanical and hydraulic storage also were discounted. Hutchinson points out, however, that windmills are suitable for the pumping of water from wells. The author further suggests that the use of solar energy for domestic water heating appears to hold some promise in Zambia, since the energy available from solar radiation is, in theory, quite considerable.

Revelle (1980) has examined the economic costs and benefits of four renewable energy sources in rural areas of developing countries. He indicates that irrigation demands can, within limits, accommodate the intermittent nature and unpredictability of solar radiation and wind energy. An alternative to the use of windmills for irrigation is direct photovoltaic conversion. In hilly areas where running water is available throughout the year and cultivated areas are closely spaced, locally generated hydroelectric power can be used. Lastly, internal combustion engines for pumping irrigation water can be fueled with biogas.

Revelle (1980) also examines in detail the role of biomass supplies in the future world economy. He estimates that the sustainable yield from the world's forests, if the entire forested area were subjected to intensive silviculture, would be 11.1 billion metric tons of wood per year. If all the harvested wood were devoted to energy production, the total energy available would be near 6 terawatts per year. Revelle estimates that one net terawatt of energy in liquid hydrocarbons could be produced from sugar cane grown on about 10 percent of the presently cultivated arable land. This method of converting biomass energy would be most useful in countries with a warm climate and abundant water and sunshine.

The use of biomass in rural Asia is illustrated by Revelle with examples from Nepal and Bangladesh. In Nepal, for example, a virtually closed farming system has developed over many centuries. Until recent decades, forests, common pasture lands, cultivated fields, domestic animals and human beings existed in stable equilibrium. With rapid growth of the human population, the system has become destabilized. Now the people are destroying the resources upon which their future survival depends. Revelle suggests that a radical alteration of the farming system is needed and would be possible if a relatively small amount of non-biomass energy could be made available. This could be accomplished, according to Revelle, in many villages by the construction of small (15 kW) run-of-the-river hydroelectric plants. The establishment of fast-growing tree plantations is also recommended.

The problems associated with the use of fuelwood and charcoal in Kenya have been discussed by Shakow *et al.* (1981) and O'Keefe *et al.* (1981). Shakow *et al.* describe the problem as follows: woodfuel is the most important energy source in Kenya (75 percent of all requirements). The wood comes mainly from natural woodlands and forests. These are being decimated to make more land available for agricultural production. Kenya cannot continue using woodfuel in the present manner unless adequate arrangements are made to renew this resource. Current annual consumption of woodfuel is estimated to be about 30 million cubic meters per year. The demand in the year 2000 is estimated to be at least 55 million cubic meters. An area of 2 million hectares will have to be planted before the end of the century. Shakow *et al.* suggest that emphasis should be given to urban greenbelts, small-holder high-potential farms, small-holder dry land farms, and settlement schemes. Such a focus would place emphasis on sustained production in the areas of greatest demand.

These examples show that studies of the interaction of climate and energy supply and demand in the developing countries require different emphases than those for the developed countries. In particular, it is necessary to consider the supply of and demand for non-commercial energy. The question of the supply of and demand for fuelwood requires integrated studies considering the multiple uses of land for energy and agriculture, both of which are influenced by climate.

9.5 CONCLUSION

The impacts of climate and weather on energy supply and demand have received increasing attention in recent years. This chapter has examined some of the studies that have been made to determine the impacts of climate on energy supply and demand. Virtually all of the studies reported deal with impacts in the industrialized countries of the northern hemisphere. This is probably a reflection of the fact that most of the global energy consumption is concentrated in these areas, which are both developed and climatologically cold.

There are three basic methods which have been used so far to study the impacts of weather or climate on energy demand: case studies, physical models, and empirical or statistical models.

The case study approach is useful in illustrating the response of energy supply and demand to climatic variability. This approach, however, cannot be used directly for the prediction of future impacts. An extension of the case study method, referred to as scenario development, is more applicable in the policy-making realm. Quirk (1981b) has suggested that energy systems planners could use scenarios of the geographical pattern, amplitude and timing of typical climatic anomalies to determine the optimum way to make energy systems resilient to climatic variations. There is a need, as Quirk has pointed out, to develop scenarios for climatic anomalies not only on a national but also on an international scale, since there is evidence that climate anomalies can occur simultaneously in various regions. For instance, Quirk quotes studies showing that 40 percent of all winters have a pattern in which most of eastern North America and Europe have similar departures of temperature from normal. Lastly, with regard to case studies, Quirk has found that the most important actions that can be taken to prepare for climate anomalies are those that require years of effort, such as improvement of fuel storage and distribution, and weatherization of homes. Thus, Quirk concludes that the improved knowledge of statistics of past climatic variations is far more important than improved seasonal forecasts.

Physical models consider the actual heat losses from one building or a number of buildings and compute the changes of these heat losses, and therefore of energy demand for space heating, as a function of changes in climatic variables such as outside temperature and windspeed. A number of quite detailed physical models have been developed and used to compute the energy demand for the space heating of individual buildings. For studies of energy demand for space heating on a regional or larger scale, statistical sampling and data aggregation are required, although the introduction of statistical techniques is usually at the expense of model accuracy and is compensated by the reduction of the amount of input data.

The main argument usually used against purely statistical models of energy demand is that the models are accurate only if physical structures, use patterns and comfort levels remain constant. The advantage of statistical models is that they can be used for areas where there are only a small amount of data. Two empirical models (Crocker, 1976; Nelson, 1976) have been developed that circumvent the argument against the use of historical data by using cross-sectional data. In each case, the data upon which the empirical model is based are derived, for example, from each of the conterminous states of the USA. It can be assumed that factors such as physical structures, use levels and comfort patterns vary from state to state and that the relationships derived using the cross-sectional data are valid for the long-term analysis of the impact of climate on energy demand.

To date, there has been little or no application of national energy demand models to the study of the impact of climatic variations. Since these models usually take climate into account by means of a degree day variable, it would be relatively easy to make impact assessments on a national and perhaps on a world regional level. An extension of this would be to introduce the climate variable into national or regional models of energy supply. The impact of climatic variations on the balance of energy supply and demand could then be studied.

The impact of climate on energy supply is mainly due to the role that climate plays in renewable energy supply. Renewable energy sources do not yet make a large contribution to the total global energy supply, thus no large studies of the impact of climatic variations have been made. Since it is likely, however, that the developing countries could profit from the further use of renewable energy sources, the study of the impacts of climate is important. On the first level, assessments must be made of the resource potential for such renewable energy sources as the sun, wind and hydropower. Assessments of the average magnitude of the supply and of its variations in time and space are necessary. Computer models are also useful for simulating the performance of renewable energy conversion systems and the dependence of this performance on climate. Since, however, renewable energy sources are diverse, it is likely that large-scale systems could provide more resilience against climatic variability. On the other hand, some climatic anomalies could affect more than one renewable energy source. For instance, Quirk (1981b) points out that India gets 40 percent of its electricity from hydropower and half of its total energy from biomass. Thus, a failure of the monsoon could increase the demand for food and energy imports. It can be concluded that nations using renewable energy systems could reduce their vulnerability somewhat by making use of a variety of geographically dispersed and diversified sources. Nations that depend on renewable energy resources need an awareness of the potential impacts of climatic fluctuations and climatic information for the design of systems that are both resilient and economic.

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