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ENERGY AND CLIMATE

A REVIEW WITH EMPHASIS ON GLOBAL INTERACTIONS

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1. Introduction

This paper considers the interaction between energy and climate; an interaction which operates in both directions. The byproducts of the conversion of energy can influence climate, while, in the other direction, climate can influence the demand for and supply of energy. The former aspect has recently received increasing attention /1/ - /3/ as awareness of man's potential to alter the Earth's climate has developed and as observations of the changes already being made on a local scale have been reported /4/.

The impact on climate of the production and use of energy can be on a local, regional or global scale. At the present time, no observed global climatic changes can be attributed to energy conversion but possible changes on this scale in the future are of concern. This paper describes scenarios for the future development of energy systems, based on considerations of energy demand and the sources of supply. These scenarios provide a background against which the potential impact of energy on climate can be discussed. The paper therefore emphasizes the impact on the global climate of three main energy sources (solar, nuclear and fossil fuels), which could undergo further development on a large scale during the next fifty years.

Though the major part of the paper discusses the potential impact on climate of energy systems and the implications of our present state of knowledge for energy policy decision-making, the impacts of climate on the supply of and demand for energy are also discussed. Lastly, the requirements for climate information, in order that the interactions between energy and climate may be more effectively assessed, are outlined.

2. Energy Systems

World primary energy consumption in 1975 was at an average rate of about 8 tera watts (TW) (1 TW = 10^{12}W). The share of oil and gas in this total was about

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5.3 TW, with oil from the Middle East amounting to nearly 1.4 TW. The existence, at present, of this essentially point source of energy supply is of significance when future energy systems are considered.

Growth in energy demand is stimulated by many factors. Predominant among these are the world population growth, the development of less advanced countries and continued industrialization in developed countries. The most important stimulus for energy growth in the future will probably result from efforts to reduce the differences between developed and developing countries. The present unequal distribution of energy consumption is illustrated in Figure 1.

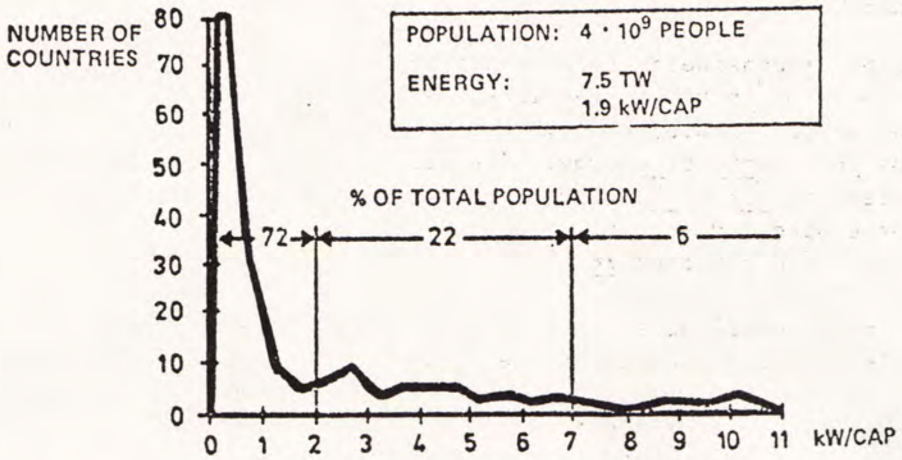


Figure 1: Energy consumption for the world in 1971 (Source: J.-P. Charpentier, IIASA).

IIASA is preparing for publication a detailed description of the scenarios for future energy demand that have been considered in its Energy Systems Programme. The scenarios are defined in terms of population, aggregate economic growth and primary and final energy demand for seven regions of the world. Population projections for these regions were taken from Keyfitz /5/, who assumes a mere replacement level of fertility in the developing regions by 2015. The scenarios are based to a large degree on two recent energy studies: The Workshop on Alternative Energy Strategies /6/ and the tenth World Energy Conference /7/. Two scenarios have been derived: a high economic growth (and energy demand) case and a low economic growth case. For the year 2030 the high and low scenarios give primary energy requirements of 40 TW and 25 TW respectively. That is, the order of magnitude of energy demand fifty years from the present is projected to be 25-40 TW, compared with about 8 TW now.

In addition to demand, it is necessary to consider supply of energy. Most of the present supply is from fossil fuels (coal, oil and gas) and in the future, in addition to these sources of energy, non-conventional fossil fuels such as secondary and tertiary oil recovery, high-cost low-grade coal, tar sands and oil shales must be taken into account. A second supply source is nuclear energy conversion, which at present largely comes from the light water reactor but fission and fusion breeder reactors are potential future sources. Hydropower and localized renewable energy sources (biogas, wind, soft solar and tides, for example) represent supply options which, although important on local and regional scales, have been considered to make only small contributions to a global energy supply of 25-40 TW /8/. A further energy supply source to be developed during the next fifty years is hard solar energy conversion, where the solar energy is converted to electricity, methanol, hydrogen or some other secondary energy carrier. (Note: Soft solar refers to decentralized solar systems such as roof collectors. Hard solar refers to large-scale centralized systems such as solar thermal electric conversion systems.)

Realistically one has to expect global energy supply systems that for almost any conceivable situation would consist of a mix of the above described sources. Indicative numbers are: 15 TW of fossil fuel supply, up to 8 TW of nuclear supply (for electricity or other secondary energy forms), 3 TW for wind, biomass and soft solar, up to 1 TW for hydropower and, possibly, up to a few TW from hard solar.

3. The impact of energy systems on climate

In a discussion of the interaction between energy systems and the climate system, with reference to a projected demand in the year 2030 of 25-40 TW, the impact on climate of the large-scale deployment of three energy supply sources (nuclear, fossil fuel and solar) must be considered. These energy systems influence climate through the ejection of waste heat, by changing concentrations of atmospheric constituents or by large-scale changes in the characteristics of the Earth's surface /9/.

Climate is a complex system with many feedback mechanisms between the components. It is the potential of energy systems to interfere with natural climatic processes so as to produce global climatic changes that has received increasing attention. It should be emphasized, however, that it is not the possibility of a globally-averaged climatic change that is the central issue but rather the inevitable regional shifts in climatic patterns that would result from a perturbation of the climatic system.

4. The impact of waste heat on climate

Power stations (nuclear, fossil fuel and some solar) eject waste heat into the climate system. The heat is added as latent or sensible heat to the atmosphere or as sensible heat to a water body, from which it can enter the atmosphere. On a local scale it has already been observed that releases of waste heat influence climate through the formation of the urban heat island /4/. Although, as pointed out earlier, the problem of regional shifts of climate patterns deserves emphasis, global averages are usually considered in discussions of the impact of waste heat. On a global basis the total amount of heat currently released by mankind's activities is only slightly more than one ten-thousandth of the solar energy absorbed at the surface /10/. An extreme projection of 20 billion people with a *per capita* energy demand of 20 kW, would lead to a total heat release of about 0.5 per cent of the solar energy absorbed and could give rise to a surface temperature increase of 1 deg C, if one considers the energy balance of the global system. However, energy consumption is not and will not be distributed evenly over the surface of the earth, and it is the concentration of waste heat in certain areas that has the potential to alter global climate patterns. This potential could be realized with a total waste heat release less than that in the extreme projection above. Flohn /11/ estimates that natural climatogenic processes producing global-scale climatic changes involve an energy loss or gain of the order of 100-300 TW. It is feasible that man-made perturbations of this magnitude could produce global-scale climatic changes.

The maximum amount of electric power generated currently at a single thermal power station is about 3 000 MW and the atmospheric effects of heat dissipation rates are not serious problems /12/. However, concern has been expressed /12/ about proposals to build power parks to generate 10 000-50 000 MW on a land area of 5 to 100 km^2. The meteorological effects of such large releases of heat are not known but can be estimated on the basis of comparable sources of heat and moisture, such as islands heated by solar radiation, urban-industrial complexes, forest fires, volcanic eruptions and others /13/. Man's energy production over areas up to 100 km^2 is sometimes of the order of magnitude or greater than that of natural production. It has been suggested that waste heat release from power parks would increase cloudiness and precipitation in the area and possibly act as a trigger for severe weather /12, 13/. It has been pointed out, however, that the energy transport in tropical cumulonimbus, or hot towers, has an order of magnitude of 100 000 W m^{-2}. Thus the dissipation of large amounts of waste heat in the tropics could have an energy density less than the natural processes. That is, relatively large amounts of anthropogenic heat releases are not necessarily larger than those of natural processes and, when properly managed, should not necessarily have a significant climatic impact. In contrast to the dissipation of waste heat in tropical areas, thermal and pollutant emissions in high-latitude, cold-winter conditions are problematic. In Canada, Alaska, the Soviet Union and Scandinavian countries, strong temperature inversions at the earth's surface in winter create serious problems, which influence decisions on the location of power plants. In Fairbanks, Alaska, for example, mid-winter conditions become extremely unpleasant due to polluted ice fog at temperatures below -35 deg C, with the ice coming mainly from the very small thermal power station, and being trapped by the inversion.

The impact of waste heat on global climate has been studied using numerical models of the atmospheric circulation. The formulation of these models and their application in the study of human impacts on climate are discussed in the overview papers at this Conference by Gates, Mason and Marchuk. General circulation models (GCMs) are recognized as being the best tool available at the present time for investigating the global impacts of perturbations such as waste heat. It should be recognized however that the GCMs do have shortcomings which must be taken into account when the results of experiments are interpreted /14/. In particular the absence of a coupled ocean circulation, poor treatment of clouds, hydrological and other processes, notably on scales smaller than the spatial grid used in the calculations, are seen as shortcomings. The methodological problems of determining the significance of results of experiments have also been extensively discussed /15/.

Washington /16/ used the GCM developed at the U.S. National Center for Atmospheric Research (NCAR) to investigate the response of the model atmosphere to an addition of 24 W m^{-2} over all continental and ice regions. Results showed a 1-2 deg C increase in global average surface temperature with an 8 deg C increase over Siberia and northern Canada. A more realistic input of heat was used in further studies /17/ which assumed a per capita energy usage of 15 kW and a population of 20 billion. The energy was released according to present population density distribution. It was concluded, however, that the thermal pollution effects were no greater than the inherent noise level of the model. In a further experiment with the NCAR GCM, waste heat was added to an area extending from the Atlantic seaboard of the U.S. to the Great Lakes and to Florida /18/. It was assumed that energy consumption in that area was equal to that now consumed in Manhattan Island (90 W m^{-2}). Temperature differences of as much as 12 deg C were observed in the vicinity of the anomalous heating but the authors concluded that the heating had little effect above the surface layer and downwind from the source region.

Within the IIASA Energy Systems Programme and in co-operation with the U.K. Meteorological Office a series of experiments has been carried out, with the GCM developed by the Meteorological Office /19/ in order to investigate the sensitivity of the atmospheric circulation to waste heat release from point sources in ocean areas. The principal reason for considering such point sources was that with a waste heat input of 150-300 TW, a significant response of the simulated atmospheric circulation was only likely if the input was concentrated in a small area. Earlier experiments /17/ had indicated that when 300 TW was input over all of the continental area significant effects could not be detected.

One may or may not give some technological meaning to such point sources. The concept of energy islands was considered by Häfele /20/ in terms of the necessity of "embedding" energy systems within the atmosphere, hydrosphere, ecosphere and sociosphere. As mentioned above, when large amounts of waste heat are released into the atmosphere a point can be reached where the man-made power density equals the natural power density and the atmospheric conditions could therefore constrain the development of energy systems. Häfele /20/ considered the embedding of energy systems into the hydrosphere in terms, among other things, of the amount of water available in continental runoff for the disposal of waste heat. A value of $35 \times 10^3 km^3 y^{-1}$ is quoted for total runoff. If all the runoff were heated by 5 deg C, 0.25 W m^{-2} of waste heat could be dumped, which, given the total continental area, means that about 27 TW of waste heat could be disposed of. These numbers merely illustrate the order of magnitude of the constraint of the hydrosphere. The embedding of energy systems in the ecosphere and sociosphere involves consideration of pollution and the concept of risk respectively.

Five experiments have been made with the Meteorological Office GCM in order to examine the impacts of point sources of waste heat input /21/ - /23/. Figure 2 shows the locations of the heat input that have been considered. The Table below shows the combinations of point sources and heat input used in each experiment.

The impact of 150 TW or 300 TW of waste heat was investigated. These high values for energy input were used since the earlier experiments of Washington /17/ had also used 300 TW and a basis for intercomparison was therefore available. It is also acknowledged that the input into models of large perturbations is required if a significant response is to be seen in the simulated global circulation. The realistic simulation of such heat input would involve the use of a coupled atmosphere-ocean model so that the heat would be added to the ocean, some would be transported by ocean currents and heat would be added to the atmosphere as both sensible and latent heat. In four of the GCM experiments, heat was added only as sensible heat to the lowest layer of the atmosphere, while in the fifth experiment the heat was added to a 10 m deep ocean box simulated beneath each area of waste heat input.

Table

The Combination of Areas and Amounts of Heat Input in Five GCM Sensitivity Experiments (Locations A, B and C shown in Figure 2)

EX	Area	Heat Input	Remarks
01	A & C	1.5×10^{14}W at each	Total heat input 3×10^{14}W
02	B & C	1.5×10^{14}W at each	Total heat input 3×10^{14}W
03	A only	1.5×10^{14}W	Total heat input 1.5×10^{14}W
04	A & C	$.75 \times 10^{14}$W at each	Total heat input 1.5×10^{14}W
05	A & C	1.5×10^{14}W at each	Heat added to 'ocean box' below each area rather than directly to atmosphere

The results of the experiments have been described in detail elsewhere /21/ - /24/. Figure 3 shows the differences in sea-level pressure between the first experiment and the average of three control cases (January cases, averages of days 41-80). There are large coherent areas of sea-level pressure change not just over the areas of heat input but elsewhere in the hemisphere. It is found, for example, that the response in the vicinity of the Atlantic heat input is similar in other experiments and this gives confidence in interpretation of the response as significant.

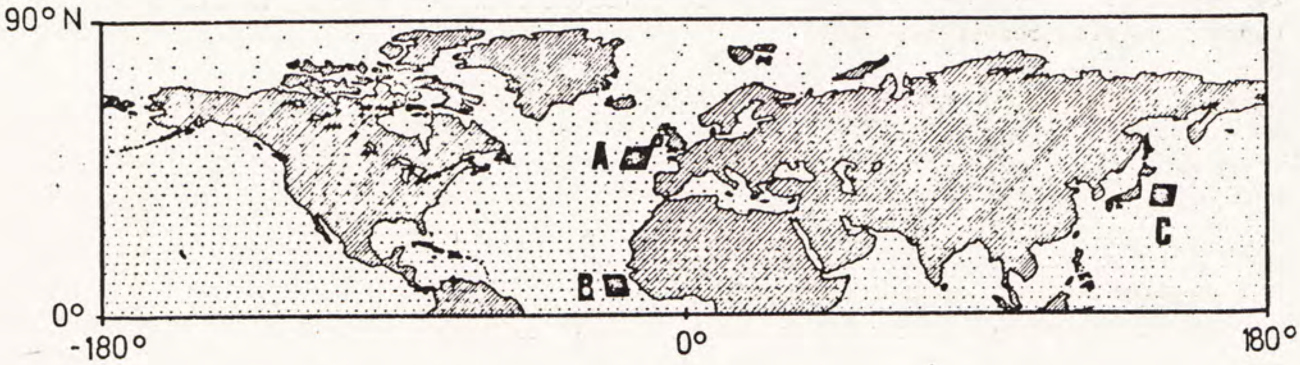


Figure 2: Location of point sources of waste heat input used in GCM experiments /21/ - /23/.

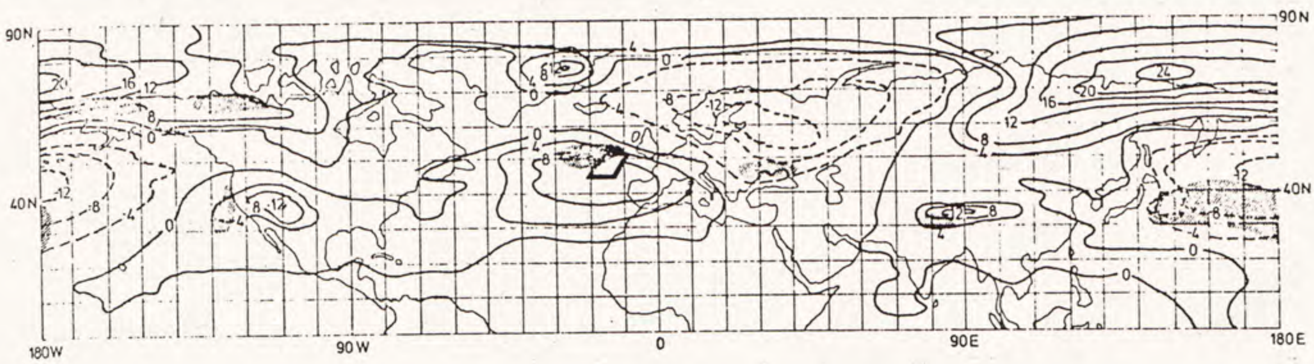


Figure 3: Difference in 40-day mean sea-level pressure in EX01 and the average of the three control integrations. Shaded areas indicate where "signal-to-noise" ratio is greater than 5.0. Units: mb. /21/.

It is found that the response of the simulated atmospheric circulation to the input of large amounts of waste heat at point sources is not just in the area of input. The response varies according to the location, amount and method of heat input. As mentioned above, the results of GCM experiments must be viewed recognizing model shortcomings. It must also be stressed that the amounts of heat used so far in model studies have been unrealistically large in order to ensure a distinct signal. Input of more realistic amounts of waste heat is likely only to impact local or regional climate, as described above, rather than global climate.

Marchetti and Häfele /25/ have suggested that the release of large amounts of waste heat in ocean areas, if done "intelligently" (for example, by making use of deep, cold ocean water), would have no global climatic impact. The release of large amounts of waste heat into the tropical atmosphere, where hot towers are observed to transport energy of the order of several hundred TW, must also be considered. Since such phenomena occur on scales smaller than the grid used in present GCMs, this possibility cannot be investigated with present tools.

Results of GCM experiments suggest that waste heat is a "non problem" on a global scale, in that it is unlikely to perturb the global average climatic state in the foreseeable future. Only when extremely large amounts of heat input (of the order of several hundred TW) were inserted in special modes, such as point sources, could significant changes in the atmospheric circulation be determined. It is notable that these changes were not only directly over the area of heat input. However, with an energy consumption level of 25-40 TW there appears to be little or no ground for world-wide concern regarding the climatic impact of waste heat release.

5. The impact of fossil fuel energy conversion on climate

Fossil fuel energy conversion produces, in addition to waste heat, certain gaseous and particulate substances which can interact significantly with the climate system. The release of carbon dioxide by fossil fuel consumption has received particular attention recently in view of the physical properties of the gas and its observed build-up in the atmosphere. The overview papers by Bolin and by Munn and Machta describe these aspects in more detail. A doubling of the atmospheric concentration of CO_2, according to state-of-the-art climate models, would lead to an increase of 1.5 deg C to 3.0 deg C on the global average surface temperature. Of course these numbers could be high or low because of feedbacks not accounted for or incorrectly incorporated in present models. Also, as discussed above, regional changes in climate (and in particular of precipitation) are of more significance than global average surface temperature changes and model and observational studies have shown that polar areas are more sensitive to a global temperature increase than other latitudes /26, 27/. The release of particulate material has also been considered /28/ and some interest has focussed on releases of sulphur and nitrogen compounds, which will probably not have as large an impact as the above substances /29, 30/.

Particles are both directly produced as smoke or soot and indirectly from gases as in the case of sulphates and hydrocarbons. Observational evidence for changes in particle loading of the atmosphere /31, 32/ show an increase in loading during the past century, but it is not clear whether this increase is a regional or global scale phenomenon /31/. The interaction of particles with radiation and thus their impact on climate depends on complicated absorption and backscatter characteristics of the particles and on surface and cloud conditions. It seems that most anthropogenic particles exist over land where they are formed, and are sufficiently absorbing to cause a warming of the earth-atmosphere system /10/. However, there is no quantitative evaluation of the role of particles at the present time, due to lack of observed data on the nature and distributions of the particles and of appropriate models.

Particles can have further impacts on the condensation/precipitation process and on the albedo of clouds /10/ but the climatic consequences of these have not been considered in detail. As Mitchell /31/ has pointed out, if particle loading is non-uniform over the surface of the Earth, geographical inequalities in the radiative effects could induce large-scale atmospheric circulation changes, and the implication of this should be studied with three-dimensional GCMs.

6. The impact of carbon dioxide on climate - implications for energy strategies

In order to assess the future atmospheric CO_2 concentration and its implications, three models are required. An energy model is used to estimate the future use of fossil fuels, and thus the input of fossil fuel CO_2 into the atmosphere. The proportion of CO_2 that remains in the atmosphere is then given by a model of the carbon cycle, as described in the overview paper by Bolin; such models consider the reservoirs of carbon and the transfers between them. Lastly, the effects of the increased atmospheric CO_2 concentration can be assessed using a climate model. At the present time, uncertainties must be attached to the results of each of these models, as discussed in more detail in the overview papers by Munn and Machta, Mason, Gates, Marchuk and Bolin. For example, in the use of carbon models much uncertainty has arisen regarding the role of the biota, i.e., whether it has been and is a source or a sink for atmospheric CO_2. In the use of climate models the role of feedback mechanisms, such as the cloudiness-temperature interaction, have to be included. Because of uncertainties, the future use of fossil fuels and the implications thereof cannot be reliably predicted. Nevertheless the model results can currently be used to assess the magnitude of the problem. An example of the combined use of an energy model, a carbon model and the results of a climate model is given in a study by Niehaus and Williams /33/. The model of the carbon cycle /34, 35/ simulates the exchange of carbon and radiocarbon between eight reservoirs. The global average surface temperature response to the increasing atmospheric CO_2 concentration was assumed from the study of Manabe and Wetherald /36/. Derivation of the energy strategies combined the results of two models of energy demand /37, 38/.

Figure 4 shows two hypothetical energy strategies for the period up to 2050. In Figure 4a the energy consumption reaches a level of 30 TW by the year 2050, the use of fossil fuels peaks at around the year 2000 and energy is largely supplied after that date by solar and nuclear sources. In the second strategy, Figure 4b, the energy consumption reaches 50 TW with the entire demand being satisfied by fossil fuels. Figure 5 illustrates the atmospheric CO_2 concentrations given by the carbon model for these strategies, together with CO_2 emissions resulting from the strategies and estimates of the resulting global average surface temperature change. For the 30 TW nuclear and solar strategy the emissions of CO_2 peak around the year 2000. In this case, the atmospheric CO_2 concentration reaches a maximum of 400 parts per million (ppm) by volume in about 2020 and the resulting change in mean surface temperature is less than 1 deg C. On the other hand, if energy consumption reaches 50 TW by 2050 and only fossil fuels are used to supply this energy then the emissions of CO_2 increase until 2050, giving an atmospheric CO_2 concentration at that time of 800 ppm, implying a mean surface temperature increase of about 4 deg C.

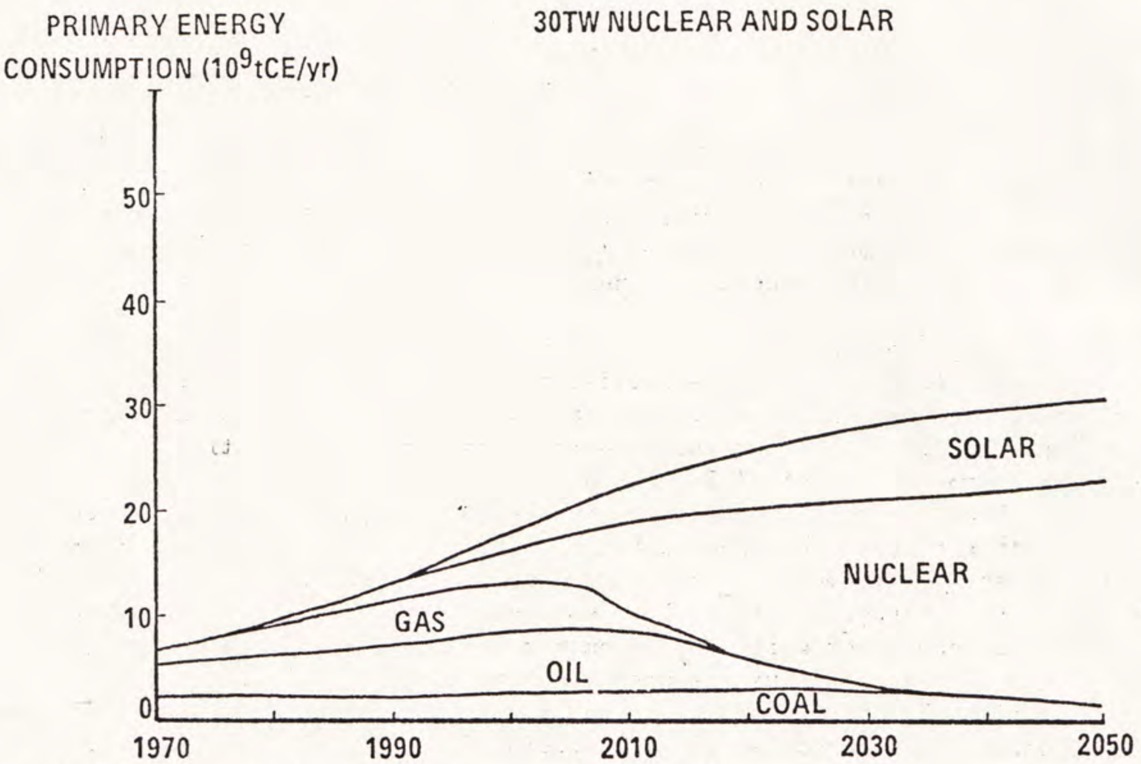


Figure 4a: Energy strategy for the period 1970-2050, maximum consumption of 30 TW with large solar and nuclear contribution /33/.

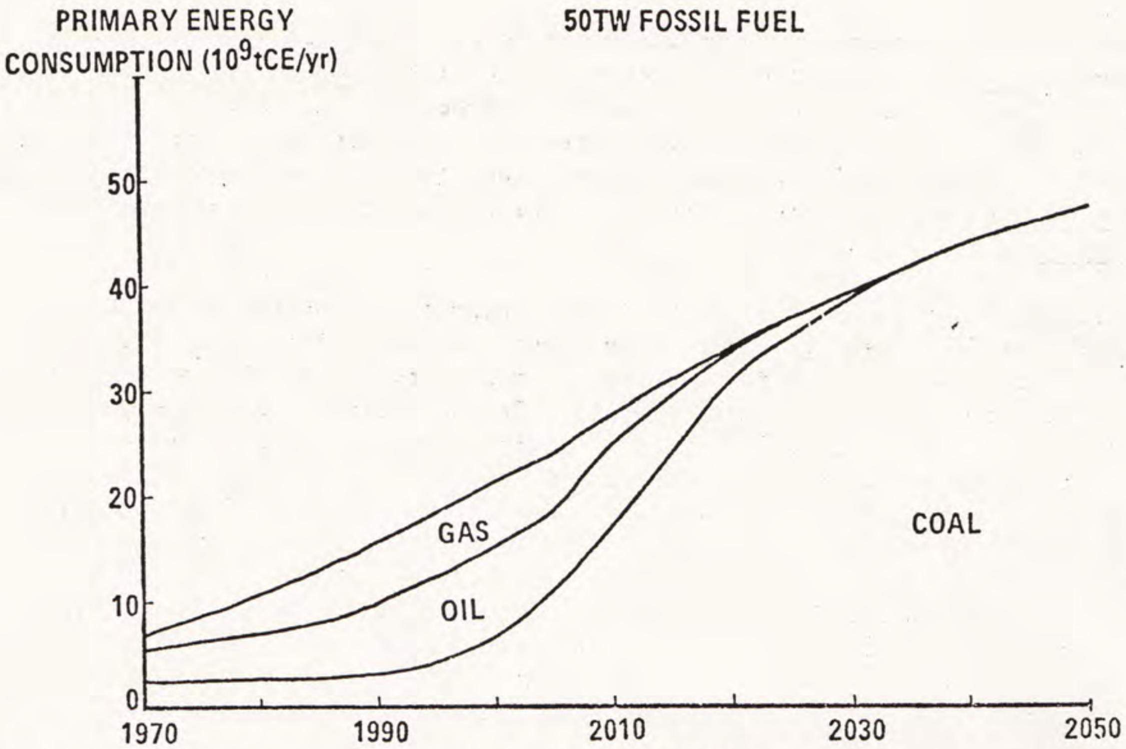


Figure 4b: Energy strategy for the period 1970-2050, maximum consumption of 50 TW with only fossil fuel supply /33/.

As stated above, the results of the models have many limitations and cannot be taken as reliable predictions but they do show that, depending on the energy strategy followed, the climatic impact due to fossil fuel CO_2 would be small (<1 deg C by 2050, as given by a simple climate model) or large (about 4 deg C by 2050). An important point to be considered in this regard is that the dynamics of substitution of primary energy carriers, which depend on economic and technical constraints, has a time scale of decades /39/. That is, it is not easy to change quickly from one energy strategy to another.

In reality the flexibility implied in the two energy strategies illustrated in Figure 4 cannot be assumed. More realistic strategy branching is illustrated in Figure 6, which shows an opportunity tree for energy strategies. In 1978, non-exclusive opportunities exist for three energy branches. If the strategy is towards satisfying an energy demand of 24 TW by the year 2030 it is possible to use conventional fuels. When the conventional sources are not enough to satisfy the demand, the timing of this point is somewhat arbitrary. Either non-conventional fossil fuels can be used or endowments must be created, that is, capital can be used instead of consumptive uses of resources /40/. If non-conventional fossil fuels are used then a point might be reached at which CO_2 becomes a problem, in which case the use of capital instead of resources must be made. In the case of strategy to satisfy an energy demand of 40 TW, the decision to use unconventional fossil fuels or capital in the form of endowments is made earlier and again, if the CO_2 becomes a problem, the switch from unconventional fossil fuels to the use of capital instead of resources must be made. This opportunity tree for energy strategies shows that the 24 TW and 40 TW paths are not so different in terms of the strategy questions that have to be addressed, but rather in their timing. It also illustrates the possibility of

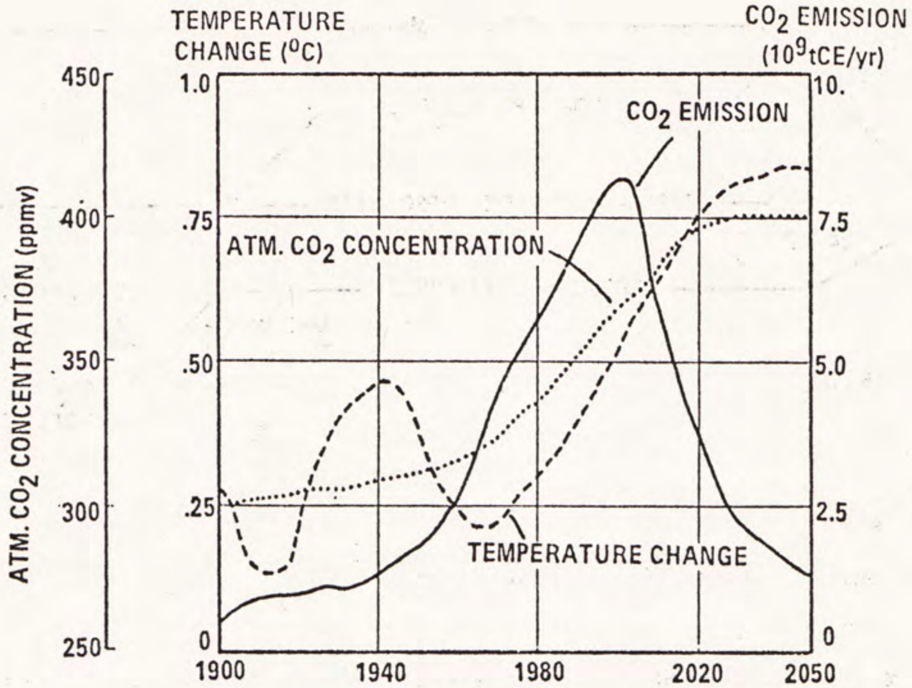


Figure 5a: CO_2 emissions, atmospheric CO_2 concentration and temperature change for strategy in Figure 4a /33/

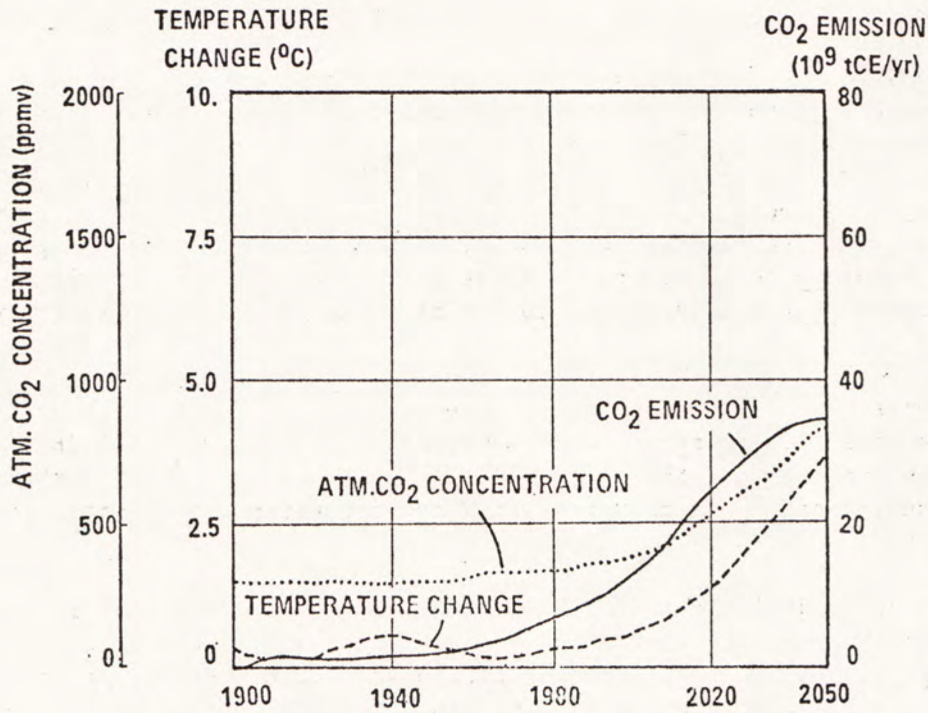


Figure 5b: CO_2 emissions, atmospheric CO_2 concentration and temperature change for strategy in Figure 4b /33/.

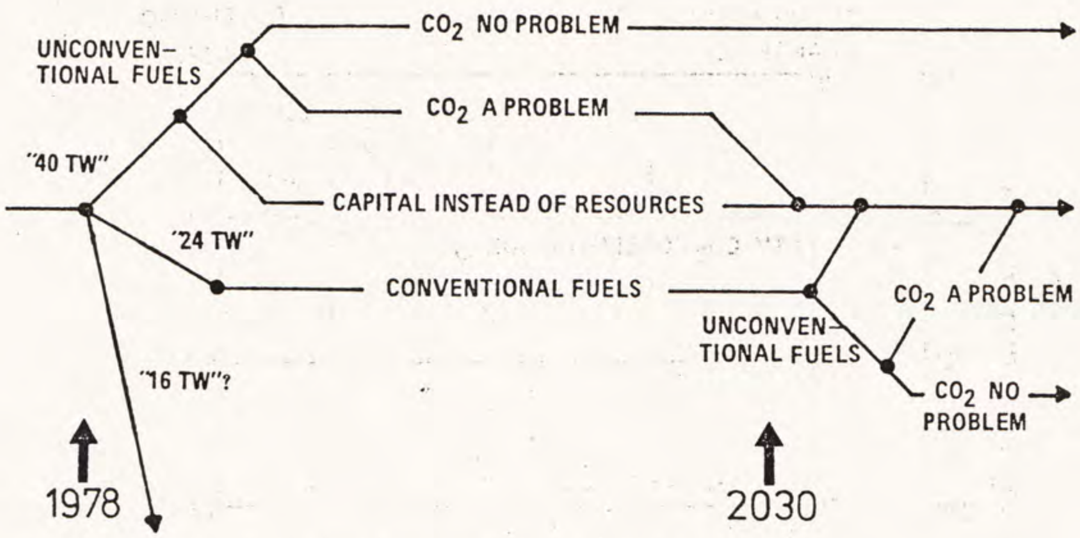


Figure 6: An opportunity tree for energy strategies.

switching from the resource branches to the endowment branches. Such considerations illustrate the large-scale technological and strategic implications of the CO_2 problem.

7. The impact of large-scale conversion of solar energy on climate

If it is assumed that solar energy conversion systems supply the majority of the required energy then it can be considered that the systems that have the potential to supply about 30 TW are solar thermal electric conversion (STEC), photovoltaic (PV), ocean thermal electric conversion (OTEC), and solar satellite power (SSP) systems. The impact on climate of the latter system has not yet been evaluated. Other solar energy conversion systems can locally be used for energy supply (e.g., wind and wave power systems) but are not expected to contribute largely to the global energy requirement /40/ and therefore cannot be expected to have a global climatic impact.

The possible climatic impact of large-scale deployment of solar energy systems has received little attention. A workshop was held at IIASA in 1976 /41/, which discussed the physical characteristics of the systems, assessed their impact on boundary conditions of the climate system and discussed the climatic implications of such impacts.

Large scale deployment of STEC systems would lead to regional changes in the surface heat balance, surface roughness and hydrological characteristics. Jäger et al. /42/, for example, have discussed the surface energy balance changes due to STEC systems. Simple estimates /43/ show that, in the absence of a STEC plant, short-wave radiation, long-wave radiation and sensible plus latent heat leaving the surface are 30 per cent, 35 per cent and 35 per cent respectively, of the total incident radiation. In the presence of a STEC plant with a 40 per cent ground cover ratio, at which 17 per cent of the sunlight reaching the heliostats is converted to electricity, the shortwave radiation leaving the surface is 14-23 per cent, the total of the long-wave radiation and sensible plus latent heat leaving the surface is about the same as in the absence of the STEC plant (i.e., about 70 per cent). However, in the presence of the STEC plant 49-20 per cent of the total incident direct radiation is released as waste heat at cooling towers, the long-wave radiation leaving the surface is 10-25 per cent. The ranges refer to seasonal extremes, the first number is for winter, the second for summer. That is, the STEC systems do not really change the magnitude of the net heat flow from the surface to the atmosphere but the mechanism of transfer is changed; the significantly lower heat release from the surface is compensated by a release of waste heat from cooling towers upon energy conversion. In this respect some impacts of STEC systems on climate can be evaluated in the same way as the potential impact of waste heat from fossil fuel or nuclear power plants.

Since heliostats are several metres tall, the arrays would influence the surface roughness. A few GCM studies have been made of the impact of a change in roughness but no specific studies of the impact of STEC (or PV) systems have been carried out. Similarly, no specific studies of the potential climatic impact of large-scale changes in hydrological characteristics due to these systems have been made, but model and observational studies indicate that large scale changes in surface wetness can significantly influence climate /44, 45, 46/. The potential impact of PV systems is generally considered to be similar to that of STEC systems.

OTEC systems use the vertical temperature gradient in the ocean to generate electricity. Even harvesting a small fraction of 30 TW could cause major impacts which would be due to temperature anomalies caused by reducing the surface temperature and diverting the flow pattern through the discharge of extremely large volumes of cold, deep ocean water required for cooling purposes. Again, both observational and model studies have indicated that sea-surface temperature anomalies can influence climate /47, 48, 49/. Further impacts of OTEC systems could arise because of the upwelling of water, through albedo changes, for example, but these have not been investigated in detail /41, 50/.

8. Implications for energy policy of the climatic constraint

At the present time there are many uncertainties about the specific climate impacts of large scale deployment of any of the major energy supply sources. It seems likely, however, that the global impacts of waste heat and changes in surface conditions will be felt at a more distant point in time than those from changes in concentrations of carbon dioxide and certain other infrared-aborbing gases. In recent years, most concern has been centred on the CO_2 question. The question is, whether present knowledge of the carbon cycle, the climate system and energy strategies justifies changes of energy policy. The IIASA Workshop on Carbon Dioxide, Climate and Society /51/ discussed this question. It was concluded, firstly, that mankind needs and can afford a period of between 5 and 10 years for vigorous research and planning to narrow uncertainties sufficiently to be able to decide whether a major change in energy policy is called for.

With reference to the state of knowledge on the CO_2 problem and all of the uncertainties, participants at the IIASA Workshop formulated a number of policy statements, which will be discussed below and which can, to a large extent, be taken as a general statement on the interaction between energy policy and climate research at the present.

Firstly, it was stated that since quantitative estimates on the rates of increase of CO_2 (and other infrared radiation absorbing molecules) in the atmosphere and resulting global and regional climatic changes are not only uncertain but likely to remain so for most of the next decade, it is premature to implement at this time policy measures requiring the reduction of the use of coal and other fossil fuels. Present knowledge justifies comprehensive study of many alternative energy supply systems but does not yet warrant a policy of curtailment of fossil fuel use.

A second point is, however, that policies that emphasize the use of coal are at present equally unjustified. Such policy decisions can become difficult and very costly to reverse and it is most important to maintain flexibility in energy supply policies at this time. With regard to this call for flexibility, the opportunity tree in Figure 6 demonstrates the strategic importance of the endowment branches, i.e., the opportunity to generate large amounts of secondary clean energy in large capital-intensive central installations.

Thirdly, it is clear that climatological impact assessments of escalating energy use must be performed in greater depth than in the past.

The fourth point discussed the possibilities of energy supply systems that allow ready environmental amelioration. Such systems would have to be either non-polluting (or very nearly so) or lead to environmental effects that can be easily mitigated. There are several possible systems which can satisfy these conditions, e.g., a solar or hydroelectric hydrogen system or an energy supply fuelled largely by synthetic methanol manufactured at energy "islands" using nuclear (breeder) or hard solar energy supply (endowments). Very highly decentralized solar energy supply systems could also be considered to satisfy these conditions but the participants felt that these are unlikely to maintain the global economy at a satisfactory level. Systems employing a short-term recycling of carbon through the atmosphere can also be considered. For example, the use of biomass as a fuel is a possibility. Stripping CO_2 from exhaust stack systems and even from the atmosphere itself /52/ is not in principle infeasible and the manufacture of methane or methanol from the carbon thus obtained would be an effective 'recycling' system. The carbon could also be stored in the living biomass or in the deep ocean /53/.

9. The impact of climate on energy supply and demand

Figure 7, from Critchfield /54/ illustrates the relationship between climate and energy policy considerations, pointing out the role of climate in affecting energy supply and demand in contrast to the impact of energy systems on climate, which has been considered in earlier sections of this paper. In terms of the impact of climate on energy supply, as indicated in Figure 7, climate can influence research and exploration for energy sources. For example, exploratory drilling for oil in the Gulf of Mexico entails climatic problems quite different from those on the North Slope of Alaska /54/. Selection of sites for power stations also requires climatic consideration. The roles of different climatic variables are of particular significance in the case of solar, wind and hydropower sources. For this reason, programmes

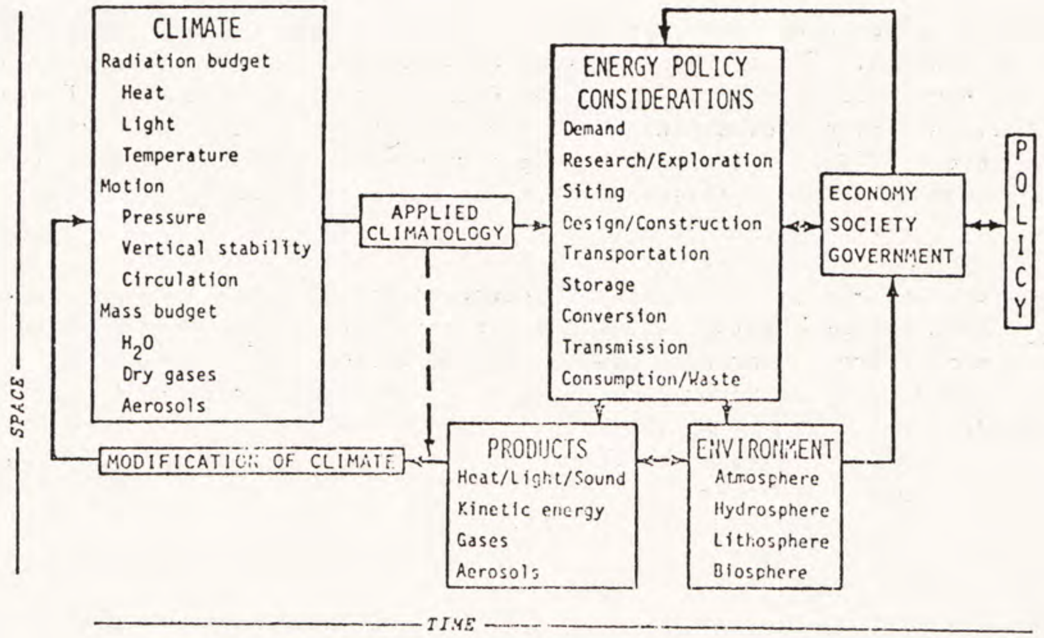


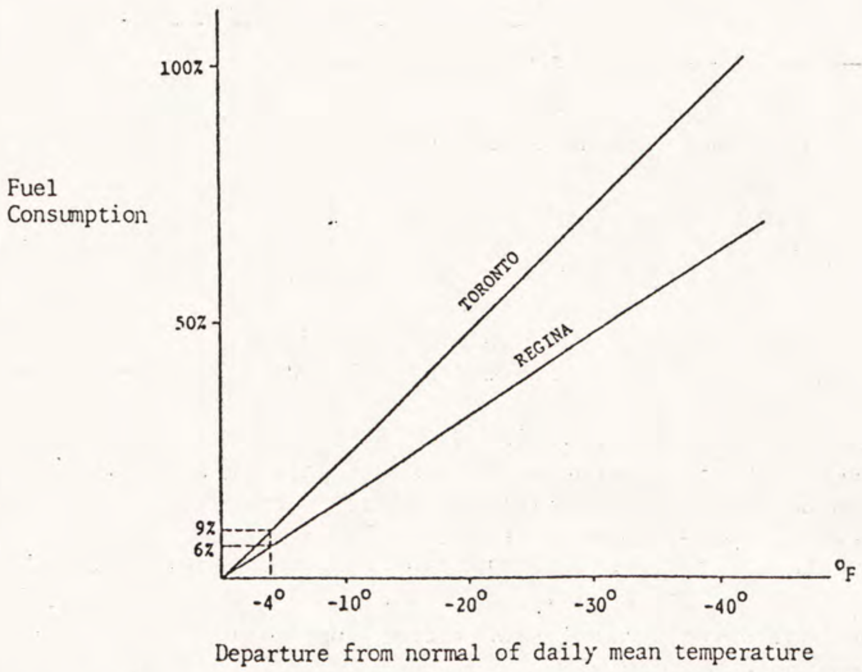
Figure 7: A model of climatology in a comprehensive energy policy /54/.

such as the U.S. National Insolation Resource Assessment Programme are established /55/ in order to collect, record and archive climate data useful to the forecaster and researcher. Local climate also influences the method, materials, timing and costs of construction of energy supply facilities and also the transportation of energy (e.g., routeing of colliers and tankers, highway and railway maintenance).

The impact of climatic variation on supply is mainly through the impact on renewable resources such as wind and solar systems, although transportation of other energy sources can be affected by anomalous climatic conditions. Droughts have been noted to influence hydropower supply. For example, the drought in the north-east U.S. during the period 1961-66 reduced flow rates of rivers and reservoir levels. New York City reservoir levels were reduced to 40 per cent of their capacity in 1965 /56/. During abnormally wet periods significant surpluses of hydroelectric power may be temporarily available.

As far as the impact of climatic variability on demand is concerned, it has been shown, for the U.S. at least, that the increasing use of air conditioning and electric heating in homes has increased the sensitivity of energy demand to temperate changes. McQuigg /57/ showed that there was a noticeable increase in electricity demand as a function of increasing temperature because of air conditioning. Mitchell et al. /58/ have computed the seasonal total heating degree-days for each state of the U.S. for each of 42 heating seasons from 1931-32 to 1972-73. The study allowed an estimate of climate influences on heating-fuel demand. Results showed that in one year out of 100 years one should expect a national total demand for heating fuel to exceed the long-term average demand (for constant economy) by as much as 10 per cent. Similarly the demand can be expected to exceed its average value by at least 3.6 per cent on an average of one heating season in five. Of course, when one part of the continent is colder than average it is not unusual for other sections to be warmer than average. The probable extreme deviations are larger when regions are considered, especially in the southern and Pacific states of the U.S. For example, for the South Atlantic states, in one year out of 100 years one should expect a total demand for heating fuel to exceed its long-term average demand by 20.4 per cent. To the extent that fuels are not readily distributed from one part of this country to another these inequalities are of great significance.

Examining the record of winter accumulations of heating degree days it was found /56/ that the greatest accumulation occurred over the northern United States and Canada during the winter of 1935-36. Figure 8 shows an estimate of the percentage increase in heating fuel consumption by temperature for Toronto and Regina for the winter season. On the basis of this figure it has been estimated that large areas of the northern United States and Canada would have had an increased fuel consumption of 50 per cent or more in February 1936.



Source: Environment Canada, Atmospheric Environment Service, Toronto - based on heating-degree-day normals.

Figure 8: Estimated percent increase in heating fuel consumption by temperature for Toronto and Regina (for period January, February, March) /56/.

One further interaction between climate, energy demand and supply is in the field of weather and climate forecasting. With regard to the sensitivity of energy use to weather influences, the value of a forecast of an extreme event, based on climatological data has been pointed out /59/. It must also be noted that there is a systematic and deliberate attempt by engineers to design excess capacity into systems to allow for climate-induced problems. This adds to the capital cost, especially in hydropower systems. An example of the interaction between the forecasting of climate events and the setting up of reserve capacity can be cited with reference to natural gas systems, where it has been shown that small temperature forecast errors cause very large reserves of natural gas to be required by moderate-sized cities to protect against optimistic errors during cold weather /60/. There is clearly a need for adequate climatological information for the design of the energy systems, and also for the effective incorporation of this information. The implications of this are far-reaching. Thus for example, if a utility company instals a large amount of hydropower and then has a major surplus of energy production during a period of high runoff, decisions concerning base-load installed capacity (using other sources such as nuclear and fossil fuel power) and export policy to outside purchasers are greatly influenced. There is an obvious link between climate and capital investment, which must be optimized.

As illustrated in Figure 7 there are a large number of interactions between the climate system and energy systems. Many correlations between the two systems have been found but much work is still required. In particular an adequate theory of existing climate and an ability to predict future climatic variability are required. Until these are available much more could be gained from new or revised models for extrapolation, correlation and probability analysis /54/.

10. Concluding remarks

The main points to be drawn from this review of energy and climate interactions are as follows:

(a) Energy and climate interactions are in both directions: the byproducts of the conversion of energy can influence climate, while, in the other direction, climate can influence the demand for and supply of energy.

(b) Detailed considerations of energy demand suggest that of the order of 25-40 TW of energy will be required in the year 2030.

(c) To supply energy to satisfy this magnitude of demand, three large-scale sources are available: solar, nuclear and fossil fuels. Realistically one can expect a combination of these sources to supply the total energy requirement.

(d) Each of the sources can influence the climatic system: by the emission of waste heat, by changing concentrations of atmospheric constituents, or by changing surface conditions.

(e) Model experiments suggest that emissions of waste heat would have to be extremely large (of order 100 TW) to perturb the global average climatic state. However, waste heat can be handled intelligently or non-intelligently as far as the engineering systems are concerned and thus the climatic impact could be diminished or amplified. Likewise, changes in surface characteristics, such as albedo, roughness or wetness, would have to be on a large scale to influence global climate. This is not to say that such perturbations due to energy systems would not influence climate on a local or regional scale.

(f) The impact of increasing atmospheric CO_2 concentrations is perceived as the greatest risk at the present time. However, uncertainties in our knowledge of the carbon cycle and of the climate system are so large that we certainly cannot predict the consequences of increasing use of fossil fuels and a prudent energy policy would maintain flexibility at the present time while a period of 5-10 years is devoted to intensive research. Policies that actively encourage or discourage the use of fossil fuels are not justified at the present.

(g) The impact of climate on energy supply can be considered in terms of the long-term assessment of the solar and hydropower resource. Climate will also influence factors in energy supply such as exploration (for oil in particular), choice of site for power plants, design and construction, transportation and storage. Climatic variability will also influence supply, particularly of the renewable resources.

(h) The impact of climatic variability on demand is mainly through the effect of temperature changes on heating or air-conditioning requirements. The sensitivity is quite large. For the U.S. as a whole a variability of 10 per cent in seasonal requirements has been attributed to climatic variability, but regionally the requirements vary more.

(i) In order to devise energy policies that take into account the climatic constraints, more detailed information on the impacts will be required - in particular, model results showing regional changes to be expected from different perturbations and scenarios of possible future climatic states. In this regard it is clear that major uncertainties still exist regarding the many feedbacks within the climatic system and thus it appears that even basic theoretical research is required in order that prudent energy policies, in which energy-climate interactions are considered, can be devised and used.

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