```
MACRO  TEHL, TSHL,AVTCP,NCRL=TRPH(VIS,NIR,LWR,AREA)
       ABSRAD=VIS+NIR+LWR
       IF (REGPAR.LT.1) GOTO 600
       EVA   =AMIN1 (EFF*VIS/AMAX,46.)
*      PREVENTS UNDERFLOW
       NCRIL =(AMAX+DPL)*(1.-EXP(-EVA) )-DPL
       SRESL = (68.4*(ECO2C-RCO2I)-RA*1.32*NCRIL)/AMAX1(0.001,NCRIL)/1.66
       IF (SRESL.GT.SRW.OR.SRESL.LT.0.) GO TO 700
   600 CONTINUE
       SRESL = SRW
       TSR=1.66*SRESL+RA*1.32
       GCI=(ECO2C/TSR+CO2C/RMES)/(1./RMES+1./TSR)
       ESTIM=AMIN1(1., (100./SRW)**2)
       CI=IMPL(GCI,ERROR,FCI)
       AM=(CI-CO2C)*68.4/RMES
       EFFE=PROP*CI/(CI+CIEQ)
       EVAE=AMIN1(EFFE*VIS/AM,46.)
       NCRIL=(AM+DPL)*(1.-EXP(-EVAE))-DPL
       FFCI=ECO2C-TSR/68.4*NCRIL
       FCI=CI+(FFCI-CI)*ESTIM
   700 SRES  =AMIN1 (RESCW,SRESL)
       ENP   =0.3*NCRIL
       EHL   =(SLOPE*(ABSRAD-ENP)+DRYP)/(PSCH*(RA*0.93+SRES)/RA+SLOPE)
       SHL   = ABSRAD-EHL-ENP
       TL    =TA+SHL*RR
       TEHL  =TEHL +AREA*EHL
       TSHL  =TSHL +AREA*SHL
       AVTCP =AVTCP+AREA*TL
       NCRL  =NCRL +AREA*NCRIL
ENDMAC
```

Finally the non-regulating situation is defined by the value of the minimum stomatal resistance (70 sec m^{-1} for C4-plants, 125 sec m^{-1} for C3-plants) and that of SRW which assumes a very high value at night and is governed by the crop water status in daytime.

The description presented here implies that the values of the light saturated assimilation rate, AMAX, and the initial light use efficiency, EFF, defined in section 7.1 of the program are obtained from measurements on leaves with regulating stomata. Therefore transpiration rates should be measured concurrently with the determination of the photosynthesis-light response curve, so that the internal CO_2 concentration can be calculated (Goudriaan and van Laar, 1978a). The measured values of AMAX and EFF can then be adapted when conditions other than the assumed ones occur.

The impact of different energy options on atmospheric CO_2 levels

by Friedrich Niehaus

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Even before the recent controversy about nuclear power, it was predicted that future consumption rates of fossil fuels, and especially of coal, would increase rapidly (Voss, 1973). Implementation of fossil-fuel based technology poses similar kinds of problems to those that are already well-known with regard to other modern technology. The inherent risk is of such a magnitude that it is no longer possible to learn from trial and error (Häfele, 1973). Instead theoretical estimates have to be made in advance and decisions have to be taken after considering all uncertainties involved, including discrepancies in expert judgements. The long-term waste-disposal problem of fossil fuels, i.e., the CO_2 problem, represents this kind of risk.

Energy consumption

It is not the intention of this paper to discuss the advantages or disadvantages of several high or low global energy scenarios. Only a few strategies will be discussed which highlight the CO_2 problem and could be used to extrapolate the effects of higher or lower strategies. Avoiding any evaluation, we wish only to summarize some basic global data to determine the correct orders of magnitude (Häfele et al., 1976; Häfele and Sassin, 1977):
- Today the world population of about 4 billion people uses 8 TW of commercial energy. 73% of this population uses less than the average of 2 kW/capita with the majority of countries having a consumption of about 0.2 kW/cap. The European standard is about 5 kW/cap.
- If by the year 2100 the world population has grown to 12 billion people, still using today's average consumption, a total of 24 TW will be needed.
- If by the year 2100 a world population of 12 billion uses today's European standard, a total of 60 TW will be needed.

Consumption rates of fossil fuels, of course, depend both on the total consumption and the energy mix. Both parameters are interrelated mainly by price-consumption elasticities, resources and environmental constraints.

Model assumptions

a) The energy scenarios used here are based on the world energy model developed by Voss (1973, 1977; Voss and Niehaus, 1977) which simulates the interactions of 6 sectors describing population growth, industrial production, capital stock, resources, environmental constraints and energy production, including substitution processes.

b) The loop structure of the model used to simulate the dynamics of the global carbon cycle is given in figure 1. The model equations and parameters and sensitivity analyses to model assumptions have been described elsewhere. The model has been tested against the historical data on the following parameters (Niehaus, 1976, 1977, 1978; Niehaus and Williams, 1978):
- increase of global atmospheric CO_2 concentration,
- Suess-effect,
- C-14 decrease after the stop of atmospheric bomb testing.

The model does not calculate C-13 flows and is therefore unable to address the problems recently put forward in this connection (Freyer, 1978).

c) The CO_2 concentration/temperature relationship has been taken from Augustsson and Ramanathan (1977) considering a saturation effect in the 15-μm bands. According to these calculations the average global temperature of the lower troposphere would increase by 1.9 °C for a doubling of the CO_2 concentration and by 4.5 °C for a quadrupling of the CO_2 concentration.

Analysis of energy options

a) The nuclear option. Optimistic assumptions about population growth, increase in the standard of living (quantitative), recycling of raw materials, environmental planning, and availability of advanced nuclear technology (high temperature gas cooled reactors and fast breeder reactors) lead to the base case scenario

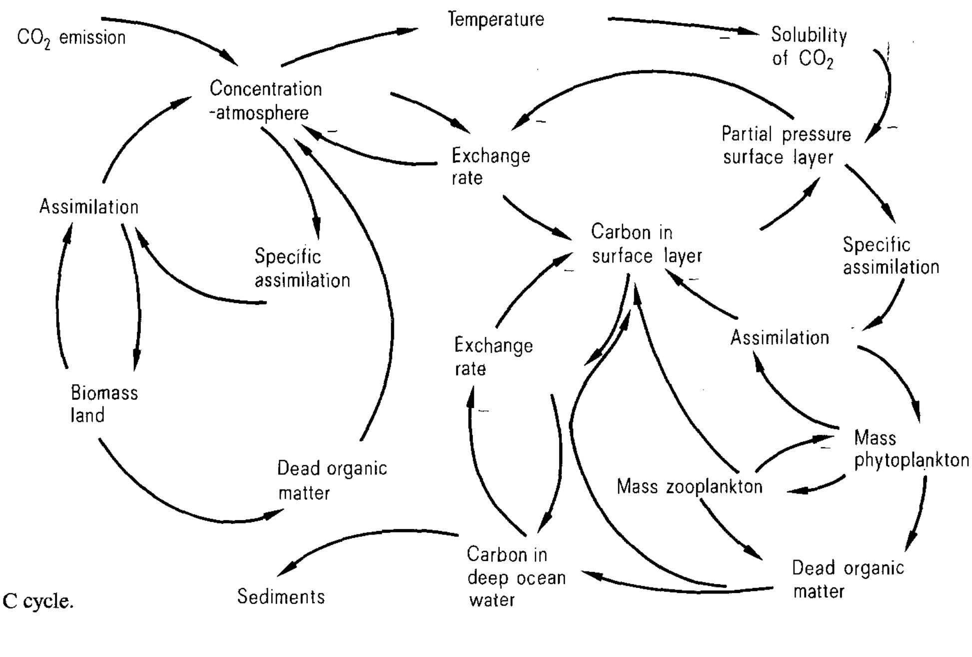

Fig. 1. The loop structure of the C cycle.

shown in figure 2, which has already been described in detail (Voss and Niehaus, 1977). The main characteristics of this scenario are that:

- growth rates of total energy consumption would slow down reaching a maximum value of 65 TW in the second half of the next century,
- the world would run out of conventional oil and gas between 2020 and 2040,
- this energy gap would be compensated for in the first place by coal and then by nuclear energy with advanced nuclear technology supplying most of the energy needs in the long run.

The resulting CO_2 emission of such an energy strategy is given in figure 3. Using the model of the global carbon cycle mentioned above it is estimated that this emission would more than double the atmospheric CO_2 concentration. Using the data from Augustsson and Ramanathan this would result in a temperature change of about 2 °C above the present level, at the end of the next century. For a comparison past variations in temperature are also indicated.

b) The fossil option. Resources of coal are large enough to supply the world energy needs for the next century at least. Therefore, the scenario given in figure 4 was designed to analyze the impact on the CO_2 concentration of the atmosphere, if by the end of the next century 50 TW of coal were to be used, with an oil and gas supply equal to that in the base-case scenario. The results are given in figure 5 and indicate that emissions of 40×10^9 t of C per year in the second half of the next century would result in the atmospheric CO_2 concentration increasing to more than 1500 ppm by volume (ppm(v)). Using the relationship described above, an average global temperature increase of more than 5 °C is estimated to occur at the end of the next century.

An analysis of a similarly designed 30 TW fossil strategy (which is not displayed here) indicates that the atmospheric CO_2 concentration would nearly quadruple and result in an average global temperature increase of about 4 °C.

c) A CO_2 strategy. Finally a scenario was designed to keep the temperature change below 1 °C (based on

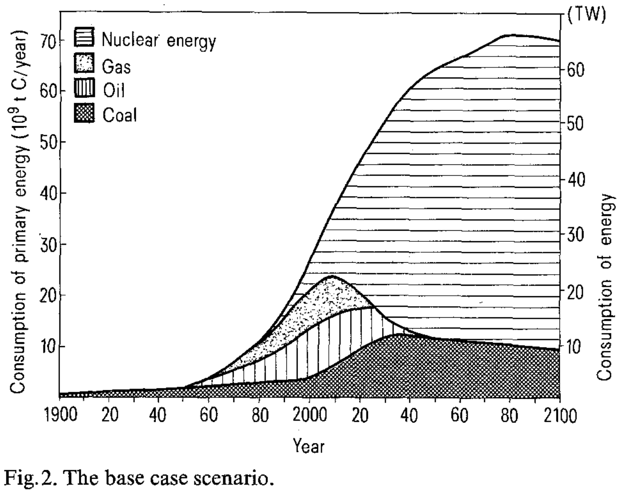

Fig. 2. The base case scenario.

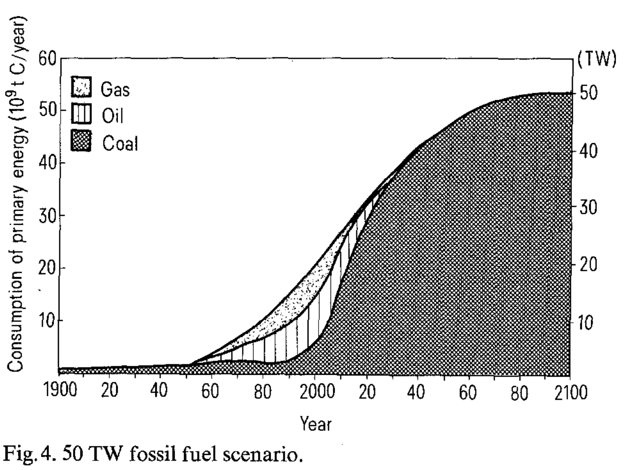

Fig. 4. 50 TW fossil fuel scenario.

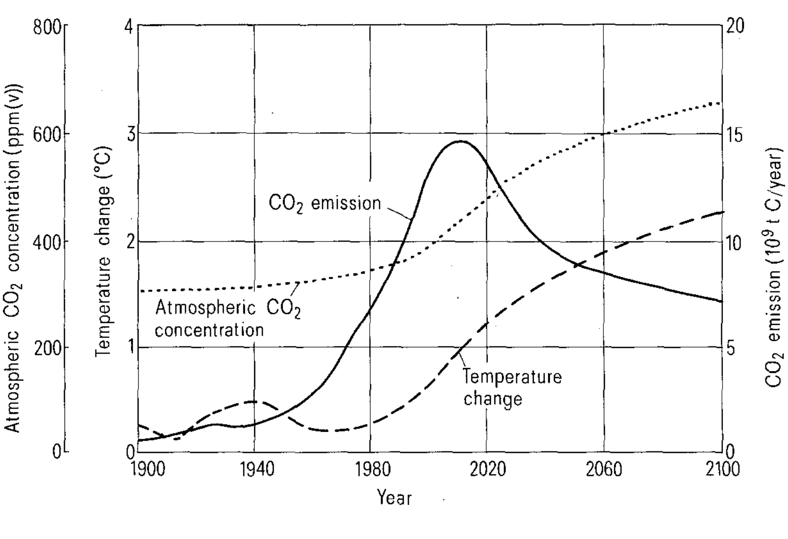

Fig. 3. CO_2 impact of base case scenario.

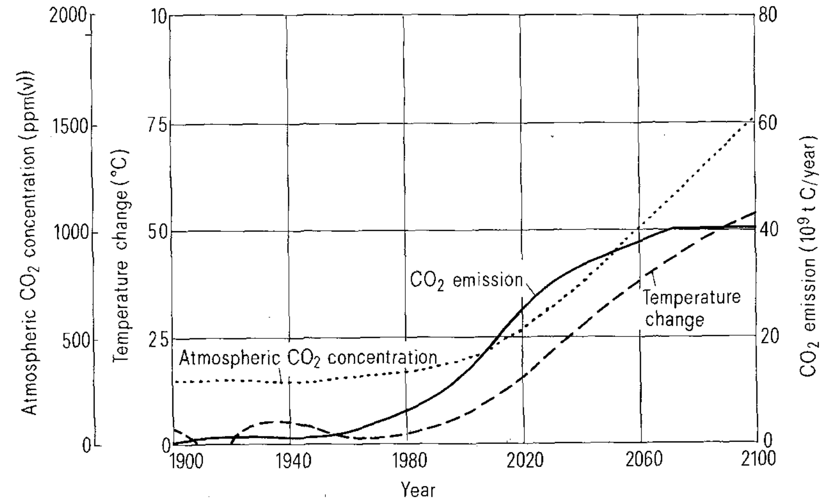

Fig. 5. CO_2 impact of 50 TW fossil fuel scenario.

present estimates). It was assumed that in the year 2000 a 'CO_2 signal' would be detected and a decision would be made to reduce CO_2 emission. Such a strategy is shown in figure 6 for a 50 TW scenario with solar and nuclear energy. Results are shown in figure 7. It should be noted that in spite of such a drastic reduction of CO_2 emission the CO_2 concentration would still increase over the following 40-year period by about 50 ppm(v).

d) Coal gasification. In principle it is possible to reduce CO_2 emission by increasing the specific energy content per C atom through various processes (which of course consume energy). Coal gasification is one of these processes. The energy-specific CO_2 emission of methane (CH_4) is only about 60% of that if the energy were supplied by coal. However, emissions which occur during the gasification process have to be considered:

1. For autothermal gasification the energy needed for the gasification process is supplied by burning part of the coal. Such a gasification produces e.g. 700 m^3 CH_4 and 1030 m^3 CO_2 out of 1 t of coal (awf) containing 93% C. Therefore, the total emission is more than 40% higher than using coal directly.

2. For allothermal gasification the energy needed for the gasification process is supplied by a different source, e.g. high temperature gas-cooled reactors. However, C is still needed to split water to provide

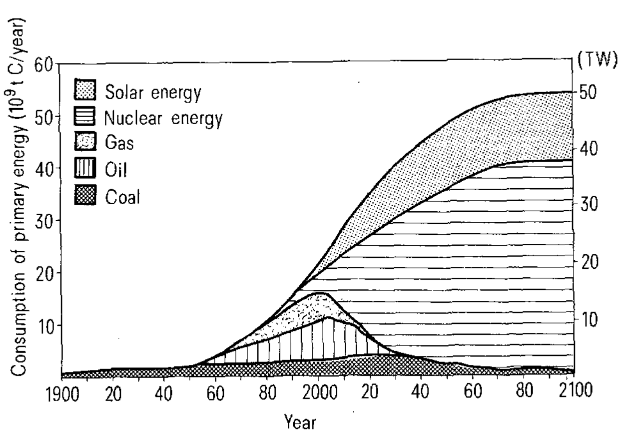

Fig. 6. CO_2 strategy.

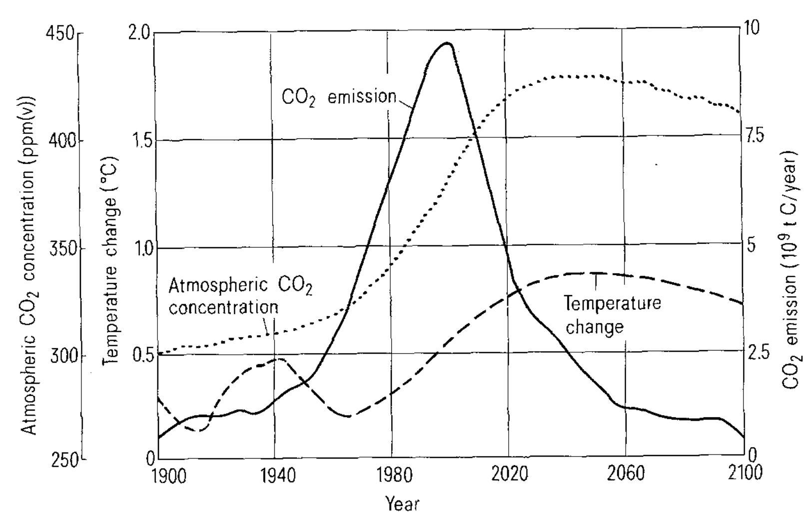

Fig. 7. Effects of CO_2 strategy.

hydrogen; e.g. 880 m^3 CH_4 and 700 m^3 CO_2 are produced out of 1 t of coal (awf) containing 85% C. Therefore, the total CO_2 emission is about 6% higher than burning coal directly.

3. CO_2 emission during the gasification process can be avoided if the hydrogen needed is produced by processes which do not involve C (e.g. electrolysis, thermal water splitting). Therefore, total emission would be reduced by about 40%. Of course, CO_2 emission could be avoided altogether if the hydrogen were used as an energy carrier directly.

e) Coal liquifaction. In principle the same cases apply as given under d). If methanol (CH_3OH) were produced by using hydrogen which is not provided by carbon/water reactions, then the total emission could be reduced by about 30%.

Conclusions

It is found that large differences in future atmospheric CO_2 concentration may be estimated due to different energy supply strategies. At present there seems to be no immediate need to reduce fossil fuel consumption. However, considering the magnitude of possible effects, efforts should be made to keep the increase of fossil fuel consumption as low as possible. Especially with regard to the CO_2 strategy given in figure 6 it should be borne in mind that fossil fuel plants which are planned today are expected to operate beyond the 1st decade of the next century.

Climatic effects of increasing atmospheric CO_2 levels

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Introduction

There is a wide consensus among scientists that the continued use of fossil fuels at about the present rates together with the ongoing deforestation might lead to adverse climatic and environmental effects that could seriously impair the well-being of mankind. Uncertainties in the predictive tools used and the scenarios developed from them have given rise to much speculation. Intensive research can, however, reduce the uncertainties and hence remove the basis for speculation. The following is an account of such research efforts emphasizing the climatic impact of increasing atmospheric CO_2. Specifically, this review starts with an overview of the world's fossil fuel resources, the future world energy demand and energy mix, and the likely effects of different energy scenarios on the CO_2 level. This can give an indication of the potential climatic effects that are due to man's activities in general, and those that are due to the use of fossil fuels in particular. Because the emphasis in this paper is on the climatic effects of increasing CO_2, the potential consequences of a climatic change are also briefly discussed.

1. *World fossil fuel resources*

In the past the world energy market has depended almost completely on fossil energy resources. During the first industrial revolution from 1870–1914 coal was the dominant energy source with an annual consumption growth rate of about 5% (Häfele and Sassin, 1978). The two world wars and the world economic crisis reduced the average growth rate of energy consumption to about 1.78%/year. The former annual growth rate of 5% was resumed between 1950 and 1970, when oil and gas became the dominant energy sources supplying more than 70% of the global primary energy consumption.

While oil and gas can be expected to continue to dominate world energy trade at least until the end of this century, a major shift from their use in combustion processes to petro-chemical usage is, however, imminent. Present global energy planning and development predicts not only a greater share of the non-fossil fuel energy resources (Bach et al., 1979b), but also a revitalization of coal made possible by innovative extraction and conversion technology (Griffith and Clarke, 1979), an intensified search for unconventional fossil fuel resources, and an accelerated development of a synthetic fuels program (Dickson, 1979). It is clear that the future climatic impact of fossil fuel consumption will depend on its relative share in a future global energy mix. Therefore, a discussion of the potential future impact must be preceded by an appraisal of the world fossil fuel resources and by estimates of the magnitude of the individual energy resources and their relative shares in the future global primary energy consumption. The following summary information on coal, oil, and gas has been extracted from a report to the Conservation Commission of the 1977 World Energy Conference (1978).

1.1. *World coal resources*

The current world coal resources are estimated at about $10{,}000 \times 10^9$ tons of coal equivalent (1×10^9 tce $\triangleq$ 1 TW-year). It is estimated that from this some