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FOSSIL FUEL RESOURCES AND THEIR IMPACTS ON ENVIRONMENT AND CLIMATE*

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Abstract—This paper reviews the physical impacts of fossil fuel use on the environment and climate system. Such an analysis involves the assessment of the future world fossil fuel resources and their relative share in a future global energy mix. The specific environmental impacts are shown for conventional and unconventional coal, oil and gas production and combustion. The impact on climate is demonstrated for the release of heat, particles and CO_2. The future impact of CO_2 on climate, which may be quite serious and potentionally irreversible, cannot be predicted with confidence at this time. Rough estimates based on a world energy model, a carbon cycle model and a climate model show that for a variety of energy supply scenarios the global average temperature change above the present level around 2030 may fall between 0·5 and 4°C with the most probable value near to 1°C—and this would not be negligible. Autothermal synthetic fuel production may result in significant CO_2 increases, whereas allothermal methods may result in substantial CO_2 reductions. There are no CO_2 emissions if hydrogen is used as a direct energy carrier. In the face of the present uncertainties a flexible low-risk energy–CO_2–climate policy is suggested which would:

(a) encourage the more efficient end use of energy;
(b) promote the expeditious development of energy sources that add little or no CO_2 to the atmosphere, thereby permitting one to keep the global fossil fuel use, and hence CO_2 emission, at the present level.

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 to 1914 coal was the dominant primary energy source with an annual growth rate of about 3% [1]. The two world wars and the world economic crisis reduced the average growth rate of energy consumption to about 1·7% y^{-1}. The former annual growth rate was resumed between 1950 and 1970, when oil and gas became the dominant energy sources supplying more than 70% of the global 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 petrochemical usage is, however, imminent. Based on present global energy planning and development one can expect not only a greater share of the non-fossil fuel energy resources [2], but also a revitalization of coal made possible by innovative extraction and conversion technologies [3], and an intensified search for unconventional fossil fuel resources [4]. It is clear that the future environmental impacts due to fossil fuels will depend on their relative share in a future global energy mix. Therefore, a discussion of the potential future environmental impacts must be preceded by an appraisal of the world fossil fuel resources and by estimates of the magnitudes 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 [5].

The current world coal resources are estimated at about $10{,}000 \times 10^9$ tons of coal equivalent (1×10^9 tce $\approx$ 1 TW-year). It is estimated that from this some 640×10^9 tce are technically and economically recoverable. Based on the planning policy of the major coal-producing countries the present world coal production rate of 2.6×10^9 tce is expected to increase to 3.9×10^9 tce in 1985; 5.8×10^9 tce in 2000; and 8.8×10^9 tce in 2020, respectively. This would require an average annual

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TABLE 1. Two supply scenarios, global primary energy (TW), 1975–2030

	Low scenario			High scenario	
Primary source	1975	2000	2030	2000	2030
Oil	3.61	5.23	4.73	6.77	7.39
Gas	1.51	2.09	2.45	2.80	5.45
Coal	2.26	3.79	9.93	4.68	13.69
Nuclear 1	0.50	2.70	1.63	3.40	4.12
Nuclear 2	0	0.04	5.38	0.04	7.97
Hydro	0.12	0.53	1.04	0.54	1.12
Solar	0	0.17	0.48	0.21	1.14
Other	0.14	0.20	0.55	0.25	0.71
Total	8.14	14.75	26.19	18.69	41.59

Source: Häfele [6].

growth rate of 2.7% during the period 1975–2020 as compared with 2.2% during the period 1950–1975. A three-fold increase in world coal production is a formidable task involving such major obstacles as the construction of an adequate infrastructure with suitable transportation facilities, the long lead times in opening up new mines, the recruitment of qualified miners and engineers, and the availability of capital. The additional environmental problems are discussed in the main body of this paper.

The ultimate recoverable worldwide conventional oil reserves are estimated to be about 260 Gt as compared with the 1977 petroleum consumption of about 3 Gt (0.7 Gt $\approx$ 1 TW-year). The 260 Gt include about 100 Gt of proved reserves already discovered, and 160 Gt of reserves still to be discovered. It is clear conventional oil reserves are running out fast. Unconventional oil reserves have so far been inadequately evaluated because of their low profitability under present economic conditions. The present oil shale reserves are estimated at 400 Gt, of which only 30 Gt are exploitable with current technology. World reserves of tar sands and heavy oils are estimated at about 300 Gt, of which only 5–10% are exploitable on the surface. Overall it may be possible to exploit some 200–300 Gt of unconventional oil (oil shales, tar sands, heavy oils, oil from deep offshore and polar zones, synthetic oils and enhanced oil recovery) around the year 2000 at a price of $20–25 per bbl. at 1976 prices.

The current world conventional natural gas production is about 1.32×10^{12} m^3 (0.8×10^{12} m^3 $\approx$ 1 TW-year). The proven reserves are estimated at about 66×10^{12} m^3, and the remaining undiscovered resources are estimated at about 215×10^{12} m^3. In addition, innovative recovery methods could add enormous amounts of gas from unconventional sources. For the U.S. alone estimates are 8–23 $\times 10^{12}$ m^3 from coal-bed degasification; 14–17 $\times 10^{12}$ m^3 from Devonian shale; 17×10^{12} m^3 from tight formations; and 85–1440 $\times 10^{12}$ m^3 from geopressurized gas.

An assessment of the impacts from present and future fossil fuel use involves estimates of the present and future world energy demands. Energy models and energy scenarios based on technological, economic, demographic, social, political and environmental factors are used to make demand projections for individual primary energy sources. Table 1 shows the share of the primary energy sources in 1975, and the low and high energy supply scenarios developed at the International Institute for Applied Systems Analysis for the years 2000 and 2030, respectively [6]. The total global energy supply is projected to reach, in 2030, 42 TW for the high scenario and 26 TW for the low scenario. These values have recently been scaled down to 36 and 22 TW for the high and low scenarios, respectively [7]. The fossil fuel share in 1975 was 90% of the total primary energy supply and it is projected to be reduced to about 80% in the year 2000, and to about 68% in the year 2030 for both scenarios. The range of 17–26 TW from fossil fuel use in 2030 as compared with the present value of ~7 TW can be used as a yardstick for the potential environmental impact in the future. Thus, in all likelihood, the problems connected with fossil fuel use will continue to challenge mankind, and, therefore, warrant intensified research.

There is no question that the uncontrolled use of fossil fuels has a severe impact on the environment in general. Additionally, there is a strong suspicion that enhanced fossil fuel use through the emission of CO_2 may change the regional and global climate. The following discussion will deal with these aspects of fossil fuel use.

IMPACTS OF FOSSIL FUEL USE ON THE ENVIRONMENT

Impact of coal

The utilization of coal will require mining, transportation and processing operations. The processed coal is used to fuel electric power plants, blast furnaces, and residential heating and cooling appliances. When the coal is burned it releases appreciable quantities of practically all of the elements in the periodic table [8].

TABLE 2. Annual emission of air pollutants from a 1000 MWe fossil fuel power plant operating at a 75% load factor

	Fossil fuels		
	Coal	Oil	Gas
Fuel consumption	2.3×10^6 tons	460×10^6 gal	6800×10^6 ft^3
Emission of air pollutants ($\times 10^3$ tons)			
Particulates	4.17	0.83	0.31
SO_2	118.77	52.37	0.02
NO_2	18.75	21.88	21.56
HC	0.31	0.42	0.03
CO	1.04	0.63	0.51
CO_2	6356	6088	401
Aldehydes	0.004	0.21	
Emission of nuclides ($\times 10^{-4}$ Ci)			
Ra-226	172	1.5	
Ra-228	108	3.5	

Source: Bach [9].

Table 2, for example, gives a comparison of the air pollutant and radionuclide emissions for three types of 1000 MWe fossil fuel power plants in the absence of a control. Clearly, the coal-burning system emits by far the most pollutants except for aldehydes, NO_2 and HC. Noteworthy from a health point of view are the high values for SO_2, particulates and, especially, radium; while the high CO_2 emission levels are of concern to questions of climatic change.

There are, of course, many other systems effects beside air pollution. Table 3 gives a composite picture with a severity rating that can facilitate decision making when considering the different trade-offs [10]. Take, for example, the question whether surface-mined coal is preferable to deep-mined coal, or vice versa. Table 3 shows that, on the one hand, surface mining disturbs more land, and discharges more water than underground mining. On the other hand, however, deep-mining is much more hazardous than surface-mining as is indicated by the higher rates of fatalities and disabilities. On the whole, coal comes out last also in comparison with the other fossil fuels, oil and gas.

TABLE 3. Environmental impact of 1000 MWe fossil fuel power plants operating at a 75% load factor with low levels of environmental controls

	Air emissions		Water discharges		Solid waste		Land use		Occupational health			
	Tons ($\times 10^3$)	Severity	Tons ($\times 10^3$)	Severity	Tons ($\times 10^3$)	Severity	km^2	Severity	Deaths	Disabilities	Work-days lost ($\times 10^3$)	Other impacts
Coal Deep-mined	383	5	7.33	5	602	3	117	3	4.00	240 (Coal, deep-mined and surface-mined)	8.77	Subsidence, accidents, chronic diseases, waste heat
Surface-mined	383	5	40.5	5	3267	5	137	5	2.64		3.09	Landslides, dust blowing, waste heat, chronic diseases
Oil Onshore	158.4	3	5.99	3	NA	1	83	2	0.35		3.61	Spills on land, waste heat, chronic diseases
Offshore	158.4	3	6.07	4	NA	1	71	1	0.35	144 (Oil, onshore, offshore and imports)	3.61	Spills on water, waste heat, chronic diseases
Imports	70.6	2	2.52	4	NA	1	70	1	0.06		0.69	Spills from tanker accidents
Natural gas	24.1	1	0.81	2		0	83	2	0.20	12.5	1.99	Pipeline explosion, subsidence, waste heat, chronic diseases

NA = not available.
Severity rating key: 5 = serious; 4 = significant; 3 = moderate; 2 = small; 1 = negligible; 0 = none.
Compiled from the 5th Annual Report of the Council on Environmental Quality [9]; Newkirk [10].

Another major problem is acid mine drainage characterized by surface water or ground water of high acidity or alkalinity flowing from mine sites. Underground mines represent 58% of all sources and produce 71% of all acid mine drainage [11]. The ecological and aesthetic impacts from surface mining can be quite severe resulting in soil erosion, pollution of streams with suspended solids, and in flooding, unless serious efforts at land reclamation are made. Most coal is moved to power plants by rail, and the produced electricity is then carried by transmission lines to the consumer. Thus, large amounts of land have to be devoted to rights-of-way for railroads

TABLE 4. New source performance standards (NSPS) and emissions from baseline coal plant with current technology, advanced control technology, and fuel conversion technologies (based on Illinois No. 6 coal)

		Pollutant emissions and NSPS ($lb/10^6$ Btu)		
		SO_2 NSPS	NO_x NSPS	TSP NSPS
		SF* 1.2 / LF† 0.8	SF 0.7 / LF 0.5 / GF‡‡ 0.2	SF 0.1
Technologies				
Baseline control technology		0.9	1.1	0.07
Advanced control technology	AFB*	1.0	0.3	0.1
	MHD†	0.5	0.3	0.1
Fuel conversion technologies	LBG‡ E‖	0.9	0.3	Not available
	LBG‡ W¶	0.3	0.3	
	HCL§ E	0.7	0.5	
	HCL§ W	0.5	0.5	

* AFB = atmospheric fluidized bed.
† MHD = magnetohydrodynamic.
‡ LBG = low-Btu gasification.
§ HCL = H–coal liquefaction.
‖ E = eastern coal
¶ W = western coal.
** SF = solid fuels.
†† LF = liquid fuels.
‡‡ GS = gaseous fuels.
Compiled from data given by Heitner [16].

and transmission lines. Finally, at a 40% conversion efficiency fossil fuel power plants discharge large amounts of waste heat either to water bodies or directly to the atmosphere.

In this context it is important to assess whether the development of advanced coal conversion processes will reduce the impacts in the future. A number of new measures and processes have been discussed in the literature [12–15]. As an example, I shall compare the effects of three groups of control technologies on air quality [16].

Baseline technology. This is the current technology whereby pulverized coal is burned followed by a flue gas clean-up system that removes most of the suspended particulates and SO_2 from the stack gases. Reduction of NO_x occurs through the careful control of temperatures in the combustion process. The improved air pollution control results in increased plant capital costs and reduced overall efficiency. For example, to increase the SO_2 removal level from 85 to 95% by adding more stages of flue gas desulfurization would increase the capital costs of the power plant by 20%, the maintenance costs by 10%, and reduce the efficiency by 6%. The net impact of this change would be a 15% increase in the electricity costs at the busbar.

Advanced direct combustion technology. Some of the methods involve direct coal combustion and some fuel conversion. The technologies falling into this category include atmospheric fluidized bed boilers (AFB); pressurized fluidized bed boilers; integrated low Btu gasifiers with open-cycle gas turbine combined-cycle power plants; magnetohydrodynamic (MHD) combined-cycle plants; metal vapor topping cycles; closed-cycle gas turbine cycle plants; and integrated coal gasifier with molten carbonate fuel cell combined-cycle plants.

Fuel conversion technology. This involves preprocessing the coal and converting it to an alternate solid, liquid or gaseous fuel, which is then burned in the power plant. To this category belong hygas high-Btu gasification; H–coal liquefaction (HCL); Bureau of Mines low-Btu gasification (LBG); solvent-refined coal liquefaction; and solvent-refined coal solid product production.

TABLE 5. Sources of oil in the oceans

Source	Estimated contribution (barrels y^{-1})	(%)
Production and transport	16,000,000	34.9
Tankers		
Dry docking		
Terminal operations		
Bilges		
Accidents		
Direct sources	6,500,000	14.3
Coastal refineries		
Municipal waste		
Industrial waste		
Offshore oil production		
Indirect sources		
River and urban runoff	14,000,000	31.2
Atmospheric fallout	4,500,000	9.8
Natural sources seepage	4,500,000	9.8
Total	45,000,000	100.0

Source: U.S. EPA [17].

In order to demonstrate the effectiveness of the new control strategies in reducing air pollutants a selection of these technologies has been tested for Illinois No. 6 coal and compared with the U.S. New Source Performance Standards (NSPS). The results in Table 4 show basically that all control technologies will be able to meet the NSPS for SO_2 and total suspended particulates (TSP), but that there will be difficulties in meeting the NSPS for NO_x from gaseous fuels. It is concluded that in all likelihood the baseline technologies with advanced environmental controls will be used for the next 15–20 y, since they can offer advantages in cost and environmental performance.

Finally, I should emphasize that all these technologies look promising with respect to the removal of the "traditional pollutants". However, all of these large-scale coal conversion processes result also in the emission of carcinogenic polycyclic aromatic hydrocarbons, aromatic amines, toxic metals, and organometallic compounds that have barely begun to be investigated [7]. Moreover, practically no information is available on the removal of the climate-affecting CO_2 emissions using these new technologies.

Impact of petroleum

Petroleum production involves drilling through overburden to the oil-bearing strata and removal of the oil [10]. Onshore production is subject to oil spillage especially during the test drillings, and it affects the land through the disposal of large quantities of brine brought up with the oil. Offshore extraction may result in blowouts and cause large oil spills in the oceans. Table 5 summarizes the various sources that contribute to oil pollution of the oceans [17]. Most oil pollution, namely 35%, originates from tanker accidents, bilges and terminal operations including the flushing of the oil tanks. The large share with 31% from river and urban runoff is somewhat surprising. Some 12,000 oil spills occur annually [18]. While one model estimation has shown no effects of oil spills on the reflectivity and evaporation characteristics of ocean surfaces [19], another investigation points to the potentially severe impact of oil spills especially in the sensitive Arctic Sea ice areas [20].

The crude oil is pumped to the refinery by pipelines which may rupture, thereby contaminating soil and ground water. Pipeline rights-of-way also claim large land areas. Refining of the crude oil and storage of the refined products lead to air and water pollution. After refining, a major product, namely residual fuel oil, is transported to a power plant either by pipeline or by tanker and barge. Such operations may again result in oil spills.

The combustion of the oil in a power plant results in the emission of air pollutants and waste heat. The rights-of-way for the transmission of the produced electricity again requires large amounts of land. In general, Table 2 shows that, except for NO_x, HC and aldehydes, an oil-burning power plant emits much less air pollutants than a coal-burning power plant of equal size; Table 3 shows that an oil-burning power plant as compared to its coal-burning counterpart comes out best in practically all impact categories.

The extraction of oil from unconventional sources such as shale oil deposits is linked to a large variety of environmental effects [10]. It has been estimated that surface mining of oil shale for a 1000 MW power plant would disrupt some 2000 acres of land over a time period of 15 y. Retorting of the shale oil would also produce large amounts of hydrogen sulfide and solid waste by-products, whose volume before and after compaction is respectively 50 and 15% more than the in-place shale. Retorting, shale oil upgrading, and spent shale disposal require large amounts of water which can subsequently lead to soil and water pollution problems.

Impact of natural gas

The production of natural gas is in many ways similar to oil extraction, since both fuels are often recovered from the same well [10]. Similar to oil recovery, gas extraction on land affects the surrounding soil through brine disposal, and it requires land area for drilling rigs and the rights-of-way for pipelines. Air, water and heat pollution occur at the processing facilities and the power plants. Combustion at high temperatures produces large quantities of NO_x. Handling of gas in liquid form involves the risks of fire and flameless explosions. Of the fossil fuel alternatives natural gas is by far the least damaging to the environment as is clearly demonstrated by Tables 2 and 3.

IMPACTS OF FOSSIL FUEL USE ON CLIMATE

There are three major ways in which man through his activities affects climate [21–23]:

(a) by releasing heat into the atmosphere;
(b) by altering the composition of the atmosphere through the emission of particles and trace gases;
(c) by changing the physical and biological properties of the earth's surface.

In the special case of assessing the impact of fossil fuel use on climate we are mainly concerned with only the first two items.

Impact of heat release on climate

There is ample evidence that combustion processes through the release of waste heat in sensible or latent form to the atmosphere or to a water body can change the local climate [24–26]. Presently such heat emission originates predominantly from the combustion of fossil fuels. Future impacts of heat emission on climate must be evaluated against the continued trend toward urbanization and industrialization plus the clustering of heat sources in energy centers and against the data of general energy growth and energy mix. In fact, a switch to higher conversion technology, nuclear and solar-based energy resources, will result in greater emissions of waste heat due to higher conversion losses.

A number of climate model experiments have been conducted to simulate possible regional and global effects of heat emissions. A few results of such experiments are now presented. Using the three-dimensional general circulation model of the National Center for Atmospheric Research at Boulder, U.S.A., Washington [27] tested the effect of a heat impact of 300×10^{12} W (about 37 times the present global commercial heat production) to the environment system. Although the heat release was distributed realistically according to population density, the model results were inconclusive showing that the thermal effects upon the atmosphere were within the noise level of the model's natural variability.

In subsequent model experiments, testing the regional effects for winter and summer months, it was assumed that the present energy flux density of 90 W m^{-2} for Manhattan existed in the year 2000 from the Atlantic Sea Board to the Great Lakes and Florida [28]. The main conclusion from these experiments was that the temperature may increase by about 12°C in January and only 3°C in July in the vicinity of the anomalous heating, but that the heating effect was restricted to a shallow boundary layer with a depth of about 3 km. The latest results indicate that such a megalopolis over the eastern U.S. could lead to significant temperature changes not only over the region itself but also upstream and downstream from it in both winter and summer [29]. It is also interesting to note that over most of the prescribed change region the soil dried out in January and became wetter in July [30].

The response of temperature, pressure and precipitation patterns to model experiments involving ocean energy centers of 150 and 300×10^{12} W was tested by a group from the International Institute for Applied Systems Analysis and the British Meteorological Office [24]. Although the results show some large changes over a number of regions, it is not yet valid to assume that the climate system would follow the model's predictions because of such model shortcomings as the absence of a coupled atmosphere–ocean system, and the inadequate treatment of clouds, and hydrological and subgrid scale processes. The present results suggest that the release of heat from a possible future energy consumption level of 26–42 TW (see Table 1) may not be a problem on a global scale. However, model and analogue studies and comparisons with natural phenomena suggest that there could be effects from power plants clustered in energy centers of 10–50,000 MWe and that these could produce significant changes in cloudiness and precipitation with an increase in the probability of severe weather.

Impact of particle emission on climate

Atmospheric particles may either originate from anthropogenic combustion processes, from agricultural burning and soil management, from natural particle production, or from particle formation by gas reactions such as converted sulfates, nitrates and hydrocarbons [31]. The total global particle production has been estimated at about 3000×10^6 tons y^{-1}, of which about 300×10^6 tons y^{-1} are of anthropogenic origin, while roughly 100×10^6 tons y^{-1} can be attributed to fossil fuel combustion. The relatively short mean residence time of 9 d for tropospheric particles is responsible for the high regional concentrations near urban and industrial agglomerations. During the past 10–15 y particles measured at the urban stations of the U.S. National Air Sampling Network have shown a downward trend [32]. Considering the control measures which are in existence in most industrialized countries under their national air pollution control acts, there should be no increase in the future particle loading of the atmosphere even with a further increase in fossil fuel use.

The interaction of the particles with the atmospheric radiation balance and hence their effect on climate depends on a number of factors, such as the size distributions and the shapes of the particles, the reflection, absorption and scattering properties of the particles, and the vertical distributions of the particles. Early studies emphasized the fact that particles scatter the solar radiation back to space resulting in a net cooling of the earth–atmosphere system [23]. More recent studies seem to indicate that the heat budget is not so much influenced by the scattering properties of the particles but rather by their absorption coefficients [33]. There may be warming in some regions and cooling in others. The net global effect will probably be one of atmospheric warming [34]. Particles also influence the condensation/precipitation processes, and they cause rather complicated albedo changes under different cloud conditions [35]. The radiative effects of particles require further intensive study.

Impact of carbon dioxide emission on climate

The problem. Man adds CO_2 to the atmosphere through the combustion of fossil fuels, the use of firewood, the practice of gas flaring, the manufacture of cement, and possibly by modifying the biosphere. The rate of fossil fuel use, and hence the CO_2 production, has increased steadily since the industrial revolution. There is clear evidence of increasing CO_2 levels in the atmosphere. It is believed that much of this is due to man's increased use of fossil fuels and deforestation, and to the fact that the major sink, the world's oceans, cannot absorb the excess CO_2 quickly enough. Because of the relatively long residence times of 28 y CO_2 shows a global distribution throughout the troposphere. The radiative effect of CO_2, and hence its potential to change the climate, results from the high transmissivity of shortwave incoming solar radiation and subsequent reradiation. This leads to the so-called greenhouse effect, whereby the increasing CO_2 concentration would act to warm the lower troposphere, but to cool the stratosphere. All numerical climate models suggest that an increase in atmospheric CO_2 will cause a general warming of the lower troposphere with large amplifications in polar regions. Countervailing measures, should they become necessary, will, however, be hampered by the fact that the long market penetration times of at least 30 to 50 y for introducing alternative energy sources are not conducive to short-time policy action. All of these problems are further compounded by the many uncertainties that still exist, such as the role of the biota in the carbon models, the role of the feedback mechanism in the climate models, or the role of the future use of fossil fuels in the energy models [21, 36].

Carbon dioxide developments. The release of carbon to the atmosphere from the combustion of fossil fuels was 0.1×10^9 tons in 1860, and it is presently a little over 5×10^9 tons [37]. Over the same time period the CO_2 concentration in the atmosphere has increased from about 290 ppm to the present (1980) level of about 335 ppm, an increase of about 15%. Except for the interruptions by the two world wars and the great depression the worldwide production of CO_2 has proceeded at a remarkably steady exponential growth rate of about 4.3% y^{-1}.

Regular measurements taken at the Mauna Loa Observatory on the Island of Hawaii since 1958 indicate annual CO_2 increases of 0.7 ppm y^{-1} during the 1950s and 1960s increasing to more than 1 ppm y^{-1} in more recent years [38]. Similar increases have been recorded for places as far apart as the South Pole, Samoa, Point Barrow in Alsaka, and Scandinavia, indicating that CO_2 is well-mixed throughout the troposphere, and that the increase is a worldwide phenomenon.

If energy consumption will follow current projections it seems probable, based on present knowledge of the carbon cycle, that atmospheric CO_2 will increase to a level of about 380 ppm by 2000 and reach twice the pre-industrial level of 290 ppm around 2050. Still further increases could occur before limitations in fossil fuel resources will force a decline in production, so that peak atmospheric CO_2 levels of 4–8 times the pre-industrial value may occur within 2 or 3 centuries [39]. High levels once reached will only slowly decline so that a level over twice the pre-industrial is likely to persist for over 1000 y [40].

Carbon dioxide and climatic change. The increasing atmospheric CO_2 concentrations will lead to a warming of the lower atmosphere. Present climate world estimates give a most probable global warming for a doubling of CO_2 of 3°C with probable error of ± 1.5°C, and a 3–4-fold amplification in northern polar regions [41]. Table 6 summarizes the major modeling efforts for a hierarchy of models ranging from one (1-D) to three (3-D) dimensions. The results of the different experiments are in good agreement except for the Gates' model [42] whose response is a lower limit because of setting the sea surface temperatures at present values as a function of season. It is important to realise that at present the details of regional climate cannot be accurately reproduced and that therefore the locations and intensities of regional climate changes cannot be predicted with confidence. It is hoped that ongoing research will soon be able to predict accurately the seasonal and regional variations in such climatic elements as temperature, precipitation, evaporation and soil moisture, which are so important in climatic impact assessment. Whether or not future climate modeling will result in a substantial revision of the results shown in Table 6

TABLE 6. Computed surface air temperature changes for a doubling of carbon dioxide to 600 ppm using a hierarchy of climate models

Temperature sensitivity (°C) to a doubling of CO_2	Specification	References
	1-D radiative–convective model (globally averaged)	
2.9	With fixed RH* and clear skies	
2.4	With fixed RH and average cloudiness	
1.4	With fixed AH† and clear skies	
1.3	With fixed AH and average cloudiness	Manabe and Wetherald [43]
	1-D Radiative–convective model with a fixed	
~3.2	cloud-top temperature	
~2.1	With a fixed cloud-top height	Wang *et al.* [44]
	1-D radiative–convective model for CO_2 bands	
1.9	12–18 μm and constant RH and CTA‡	
	For CO_2 bands 12–18 μm plus 10 and	
1.98	7.6 μm and for constant RH and CTA	
3.2	Same but for constant RH and CTT§	Augustsson and Ramanathan [45]
	1-D radiative–convective equilibrium model of the atmosphere with 18 vertical levels up to 37.5 km, coupled with a 1-D mixed layer ocean model with 30 levels extending from surface to a depth of 300 m	
~2.0	Annual average	Hunt and Wells [46]
	2-D annual zonally averaged steady-state hemispherical model with diffuse thin clouds as cloudiness feedback	
1.7	Global annual average	
1.2	0–30° latitude	
1.2–2.0	30–60° latitude	
2.0–6.0	60–90° latitude	Temkin and Snell [47]
	2-D zonally averaged numerical model based on a two-level quasigeostrophic potential vorticity system of equations and a surface heat balance equation	
	Corrected northern hemispheric mean	
~1.6	surface temperature	Ohring and Adler [48]
	2-D atmosphere–ocean statistical–dynamical model, nine levels, zonally averaged, parameterized cloudiness, annually averaged insolation, in oceans prescribed meridianal heat transport, relative share of land and ocean considered in each latitude band	
1.5	Global average	
2.3	Northern hemisphere	
<1	Southern hemisphere	Potter *et al.* [49]

TABLE 6 (cont.)

Temperature sensitivity (°C) to a doubling of CO_2	Specification	References
	3-D atmosphere–ocean GCM, atmosphere with nine levels, fixed cloudiness, annual average insolation, ocean noncirculating and without heat capacity ("swamp model") idealized northern hemisphere, truncated at 81°	
2.9	Global average	
~10	At high latitude	Manabe and Wetherald [50]
	3-D atmosphere–ocean GCM same as [50] except for variable cloudiness and a whole idealized northern hemisphere	
3	Global average	
8	At latitude 80° N	Manabe and Wetherald [51]
	3-D atmosphere–ocean GCM same as [50] except for seasonal insolation, ocean mixed layer (fixed at 68.5 m depth), noncirculating, sea ice submodel, realistic continents and mountains, global	
2	Global average	
5–8	In winter } in high northern latitude	
<2	In summer } in high northern latitude	Manabe and Stouffer [52]
	3-D atmosphere–ocean GCM noncoupled, two atmospheric levels, variable cloudiness, seasonally-varying insolation, ocean surface temperatures fixed at present values as function of season, realistic continents and mountains, global	
0.34	Land } January	
0.10	Ocean } January	
0.48	Land } July	
0.03	Ocean } July	Gates [42]

* RH = relative humidity.
† AH = absolute humidity.
‡ CTA = cloud-top altitude.
§ CTT = cloud-top temperature.

remains to be seen. At any rate in reviewing the major models a study group was unable to find any overlooked or underestimated physical effects that could reduce the presently predicted global warming due to a doubling of atmospheric CO_2 to a negligible amount or reverse it altogether [41].

The potential effect on temperature of a hypothetical future energy strategy is now demonstrated for an all fossil fuel and an alternative fuels case. Such an assessment requires three models [53]:

(a) A world energy model which calculates the future energy consumption rates for the various scenarios [54]. The estimated consumption rates for fossil fuels are used to calculate the CO_2 emission rates to the atmosphere.

(b) A global model of the carbon cycle is used to simulate the exchange of carbon between the different reservoirs and to assess the increase in atmospheric CO_2 concentration [55].

(c) The one-dimensional radiative—convective climate model developed by Augustsson and Ramanathan described in Table 6 is used to estimate the temperature change due to the CO_2 increase [45].

Figure 1 shows the results for an energy scenario that will level out at about 30 TW between 2030 and 2100 and that is based solely on fossil fuels. In this scenario the total cumulative consumption of coal, oil and gas would be about 800, 280 and 170 TW, respectively. This would cause the CO_2 emission to increase from its present value of about 5×10^9 tons of $C\,y^{-1}$ to a maximum rate of about 24×10^9 tons of $C\,y^{-1}$. The present CO_2 concentration of about 335 ppm would increase to well over 1000 ppm in the year 2100, thereby raising the global average temperature by about 4°C.

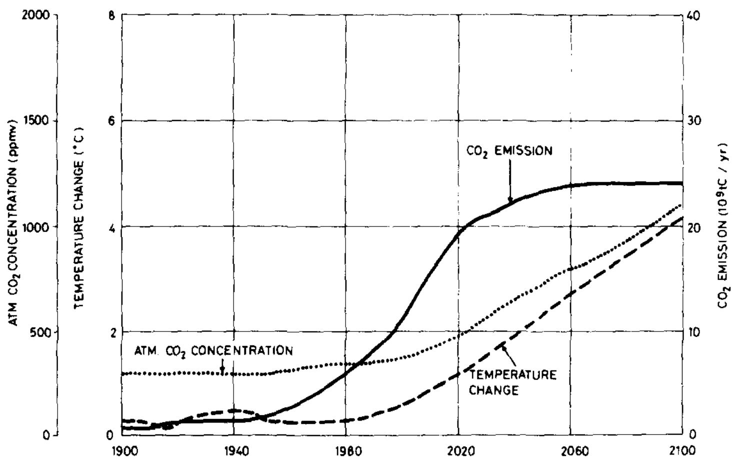

FIG. 1. Simulation of CO_2 impact for a 30 TW fossil fuel strategy. Source: Niehaus [53].

For comparison Fig. 2 shows also a 30 TW scenario, but with a coal consumption that would remain at the present level, while oil and gas consumption would be reduced to about 240 and 150 TW, respectively. The remainder of the energy, a very large share, would be supplied by nuclear and solar energy. In this case the CO_2 emission would peak at about 8×10^9 tons of $C\,y^{-1}$, the atmospheric CO_2 concentration would rise to a maximum of about 400 ppm causing an average global surface temperature change of about 0.45°C above the present level.

While the scenario shown in Fig. 1 is undesirable from a climatic point of view and also unlikely, the scenario shown in Fig. 2 appears to be acceptable from a climatic viewpoint, although the implied rapid and large-scale introduction of nucelar and solar energy may pose problems. Perhaps a more likely energy mix might be that shown in Table 1 somewhat scaled down in its latest version to 14 and 22 TW for the low scenario and 17 and 36 TW for the high scenario. Using these values Niehaus [56] estimated that by 2030 the CO_2 concentration in the atmosphere would increase to about 550 ppm for the high scenario and to about 430 ppm for the low scenario [Fig. 3(a) and (b)]. With all other climatic factors held constant, the global average temperature would increase by about 1.1 and 0.8°C, respectively, above the 1967 reference value.

It must be emphasized again that these model results have many limitations and can therefore not be considered to be reliable predictions. They can, however, serve as rough guidelines that seem to indicate that an all fossil fuel energy economy may not be climatically permissible, while an appropriate energy mix consisting of a large share of non-fossil fuel primary energy sources

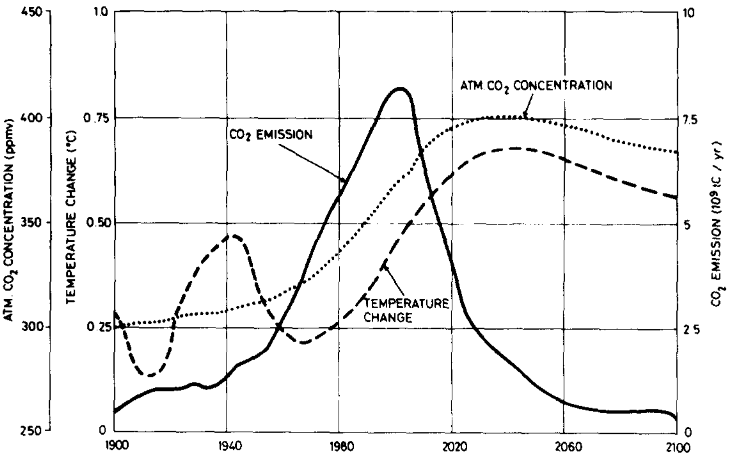

FIG. 2. Simulation of CO_2 impact for a 30 TW fossil fuel, solar and nuclear energy strategy. Source: Niehaus [53].

together with a suitable secondary energy carrier, such as hydrogen, should be environmentally acceptable.

In this context it is of interest what would be the relative CO_2 contribution from a variety of synthetic fuels. Table 7 shows that, depending on the type of fuel used, there is a gradation in the amount of CO_2 released per unit energy. For example, it is seen that the CO_2 emission per unit of energy output for natural gas and hydrogen from natural gas reforming is three times less than

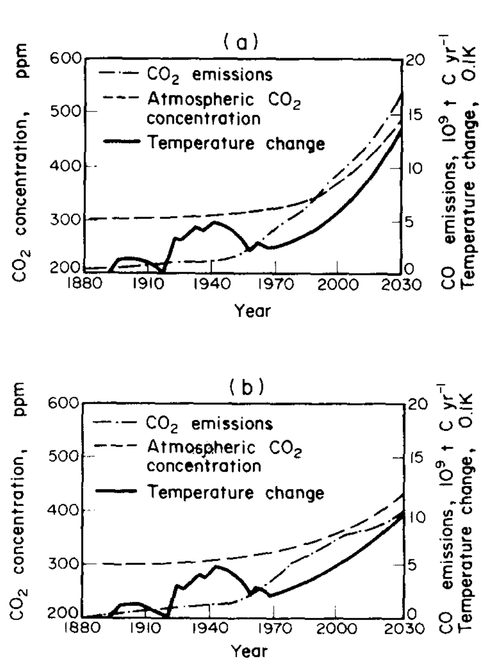

FIG. 3. CO_2 emission, atmospheric CO_2 concentration and temperature change for: (a) the high, and (b) the low IIASA energy supply scenarios. Source: Niehaus [56].

TABLE 7. CO_2 generation as a function of fuel source

Fuel type	Carbon dioxide generated lb CO_2/lb fuel	lb CO_2/1000 Btu
Synthetic natural gas from coal gasification	8.75	0.34
Methanol (synthesized from coal)	2.75	0.28
Hydrogen (from coal gasification)	16.5	0.27
Coke	3.67	0.26
Bituminous coal	2.75	0.21
Benzene	3.38	0.19
Biomass (wood, cellulose)	1.47	0.18
Gasoline and fuel oil (petrol distillation)	3.14	0.15
Methanol (wood alcohol)	1.38	0.14
Natural gas	2.75	0.11
Hydrogen		
(from natural gas reforming)	7.0	0.11
(from geothermal-electrolytic)	2.44	0.04
(from solar-electrolytic)	0	0
(from nuclear-electrolytic)	0	0

Source: Steinberg and Albanese [57].

that of synthetic natural gas from coal gasification, and there is less than half the CO_2 from burning the coal directly [57]. Specifically, if the energy needed for the gasification process is supplied by burning part of the coal (authothermal gasification) then 1 t of coal containing 93% C produces some 1030 m^3 of CO_2 resulting in a 40% higher CO_2 emission than using coal directly [58]. If, on the other hand, energy is provided by a non-fossil energy source (allothermal gasification), then 1 t of coal containing 85% C produces some 700 m^3 of CO_2 resulting in a 6% higher CO_2 emission than burning coal directly because carbon is still needed to split the water for making hydrogen. Moreover, if the energy is supplied by an external energy source and the hydrogen production does not involve carbon (e.g. using electrolysis, thermal water splitting) the total CO_2 emission could be reduced by about 40%. There is, of course, no CO_2 emission if hydrogen is used as a direct energy carrier.

It should finally be realised that the above model estimates do neither consider those climate-influencing factors that are not directly related to fossil fuel use nor the other IR-absorbing trace substances in the atmosphere. Consideration of all factors might very well result in a greater warming.

Potential consequences of a global warming

At present it is only possible to speculate on some of the potential consequences of a global warming, since actual impacts are not yet discernible. One likely result of a CO_2 and temperature increase is a decrease of the meridional temperature gradient resulting in a drastic change of the atmospheric circulation and precipitation patterns with a shift of the agroclimatic zones, and concomitant disruption of the world food and freshwater supplies. Equally likely are forced readjustments of the world energy supply. The cryosphere also reacts rather sensitively upon a warming. There are plausible arguments to the effect that the Arctic pack ice might play a decisive role in that its removal could come close to an irreversible process—at least on the time scale of human history. Other potential impacts might include changes in regional hydrology, lowered lake levels, and drought increase due to altered precipitation and evaporation regimes; sea level changes, and a disturbance of ocean circulations and upwelling processes resulting in a reduction of fish yield; and finally biological, sociopolitical and moral impacts. A more detailed account of these likely effects is given elsewhere [59–61].

CONCLUDING REMARKS AND OUTLOOK

The present share of fossil fuels in the global primary energy consumption is about 90%, and by the year 2030 it is projected to be still more than one half of the primary energy supply. Without doubt the use of fossil fuels has severe impacts on the environment in general and on the climate in particular. During the next 50 y these impacts are likely to increase with the anticipated 3–4-fold rise in fossil fuel consumption (see Table 1), unless stringent control measures can be implemented. The introduction of new control technology is hampered by the fact that most of it is still in the infant stages of development, thus requiring enormous efforts in R and D, that it is capital-intensive, and that it reduces the overall conversion efficiency. This situation can be alleviated to some extent by introducing co-generation and conservation practices, and perhaps some of the technological fixes that are presently under advicement [22, 61–63]. These measures can be helpful in making the transition from the consumptive energy sources that are mainly based on fossil fuels to the endowment energy resources that are inexhaustable. One promising alternative energy path would be the production of hydrogen splitting the water molecule with energy derived from non-fossil fuel energy sources. However, such production still awaits a breakthrough in thermochemical engineering [64] and the economic feasibility of the new primary energy sources.

Man through his activities has an effect on the local and to some extent also the regional environment and climate. He may also perturb the climate on a global scale, but this may not be detectable in our data before the end of this century. Furthermore, the non-linear highly interactive feedback mechanisms involved are so complex and presently so poorly understood that the effects on global climate, which may be quite serious and potentially irreversible, cannot be predicted with sufficient confidence at this time. In the face of the many uncertainties outlined above, such as those inherent in the use of present state-of-the-art energy, carbon and climate models, prudence dictates a cautious and flexible energy policy. Such a low-risk energy–CO_2–climate–environment policy would:

(a) hlvpromote the more efficient end use of energy;
(b) secure the expeditious development of energy sources that add little or no CO_2 to the atmosphere, thereby permitting one to keep the global fossil fuel use, and hence CO_2 emission, at the present level.

This energy policy, which should be followed anyway—CO_2 risk or not — has the advantage of permitting further energy growth by promoting energy conservation. The major bonus is, however, that in the best case such a policy can avert an impact of man's activities on the global environment and climate altogether, and that in the worst case valuable time is gained to obtain better information to redirect our energy policy.

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