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MARKET PENETRATION OF PRIMARY ENERGY AND ITS ROLE IN THE GREENHOUSE WARMING PROBLEM†

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Abstract—When introduced some 10 years ago, Marchetti's claim for a 50–100 year irreducible penetration time for primary world energy forms legitimized serious consideration of the long-term climatic effect of fossil-fuel released carbon dioxide as a major global environmental concern. Since this time, although the truth or falseness of Marchetti's thesis has not been established, major changes in our perception of the nature of the problem have ensued. We discuss both the effect of the reduction in projected fossil-fuel energy-use rates and the climatic warming effects of trace-gas species in addition to CO_2, and we conclude that, even though most of today's energy projections imply a greatly reduced rate of global warming from future CO_2 emissions, projections of currently observed growth rates in the other greenhouse gases result in a net heating of the earth at a rate and of a magnitude comparable to that estimated in the mid-1970s when serious climatic impacts were thought to be possible within a 50-year period. Redeployment of world energy use from its current fossil-fuel base to renewable forms in order to avoid this environmental problem therefore faces the same critical timing difficulty it did a decade ago.

1. INTRODUCTION

In 1975 Marchetti[1] extended the use of the logistic transition curve from a descriptor for the market growth of an emergent technology to the depiction of the replacement path for one form of the world's primary energy use by another. He applied an empirically based microeconomic property to the global scale, not only to describe past global energy transitions, but also to predict their future. This insight, when applied to the CO_2 climate change issue, was seminal in transforming a scientific curiosity into a significant environmental issue that had policy implications demanding prompt consideration.

Basing his results on careful and extensive analysis of the historical record, Marchetti concluded that the time for takeover of one form of the world's primary energy source by another form was very long, and he cited 50 years as a minimum time for an increase from a 1% to a 50% market share of the replacement technology. Moreover, he claimed that this estimate was applicable to future shifts in energy use. Since, in the mid-1970s, 50 years was the consensus estimate for onset of critical greenhouse warming from the projected increased use of fossil fuels, application of Marchetti's findings implied that immediate steps to replace fossil energy by nonfossil energy would be needed to avert environmental disaster. Without this coincidence in timing of the environmental insult with the response time required to handle it, the CO_2 climate change problem seemed to most at that time to be far too distant and too uncertain to warrant concern, an attitude that is now returning with postponement of timing of a significant CO_2-induced climatic impact, following recent reductions in projected economic and energy growth rates.

The latest reductions in projected energy growth rates considerably delay the most likely date for significant climatic impacts from increasing atmospheric CO_2 levels compared with estimates made as recently as five years ago (about 2070 compared with 2030). The present-day significance of the problem is thereby reduced in a major way, even accepting the irreducibility of the market penetration times that Marchetti claims. However, such a conclusion is not yet warranted for two reasons: First, uncertainty in timing and magnitude of the CO_2-induced warming is so large that the possibility of much more severe or earlier impacts cannot be ignored. Second, projections of recently

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observed trends in growth of other trace greenhouse gases in the atmosphere imply that the total heating effect of these gases plus CO_2 can impact climate within the 50-year minimum-market-penetration-time figure given by Marchetti.

Marchetti's claim for irreducibility of primary-energy market-penetration time was based on the historical record. For application to the greenhouse warming problem, it is necessary to consider its future applicability, and to do so requires more than empirical evidence. In this paper we shall discuss both the consequences of Marchetti's model, if applied to the future, and the socio-economic mechanisms that could be important in developing a causal description of the phenomenon.

2. THE HISTORICAL EVIDENCE

Market-penetration time models as applied to new, and particularly to new technology based products, have been under investigation for more than 20 years. The best known of these that incorporates the logistic-penetration time function that Marchetti also used is due to Fisher and Pry,[2] and these authors chiefly concerned themselves with product replacement for a given end being supplanted by a new technological line. Original consideration of the subject was given by Mansfield 10 years earlier,[3] with applications in the development of major U.S. industries, such as railroads, coal, and steel. Blackman[4] amplified Mansfield's work by the introduction of the same analytic form as used by Fisher–Pry. This logistic functional form is

$$F = [1 + \exp - \alpha(t - t_0)]^{-1}, \tag{1}$$

and it describes the temporal transition of the market share, F, of the new technology from 0 at $t = -\infty$ to 1 at $t = +\infty$. It was originally selected solely because it was a simple, analytic, S-shaped curve that happened to fit the data. There was no claim for deeper significance than this. The empirical evidence for its match to numerous data is now extensive; Marchetti[5] cites 300 tests he made of the formalism.

A rudimentary explanation for the reasonableness of eqn (1) can be noted by writing it in differential form as

$$\mathrm{d}F/\mathrm{d}t = \alpha F(1 - F), \tag{2}$$

meaning that the rate of growth of the fractional share of the new product is proportional both to its degree of penetration and to the residual market size. The above description applies to the case of a single product (an energy source in our case) being supplanted by another. This is usually an oversimplification, and Marchetti[6] developed a modification of the method so that it could be applied to a multicomponent system. In Fig. 1 we show Marchetti's results for past world energy-use transitions, using his multicomponent approach. The solid lines are fits to the historic data, and, in this logarithmic plot, $F/(1 - F)$ versus t follows a straight line when obeying the simple logistic form

$$\ln\left(\frac{F}{1 - F}\right) = \alpha(t - t_0). \tag{3}$$

The market-penetration time, or time constant, t_p, for a given component pair is defined somewhat arbitrarily as the time taken for the new technology share to grow from 1% to 50% of the total market. In Fig. 1 we see that in the emergent world markets for coal, oil, and gas, t_p had values between 90 and 100 years.

The data available to Marchetti on nuclear energy growth at the time Fig. 1 was compiled were too meager to allow an estimate of the time constant for nuclear energy. The latest information on growth of nuclear energy use results in the picture shown in Fig. 2. Here, in addition to the reported annual nuclear power consumption values through 1982, shown as dots in the figure, we have plotted logistic growth curves with 30-, 50-, and 75-year time constants, as well as Marchetti's own (1979) projection of nuclear energy growth and one of the latest projections for nuclear growth based on a

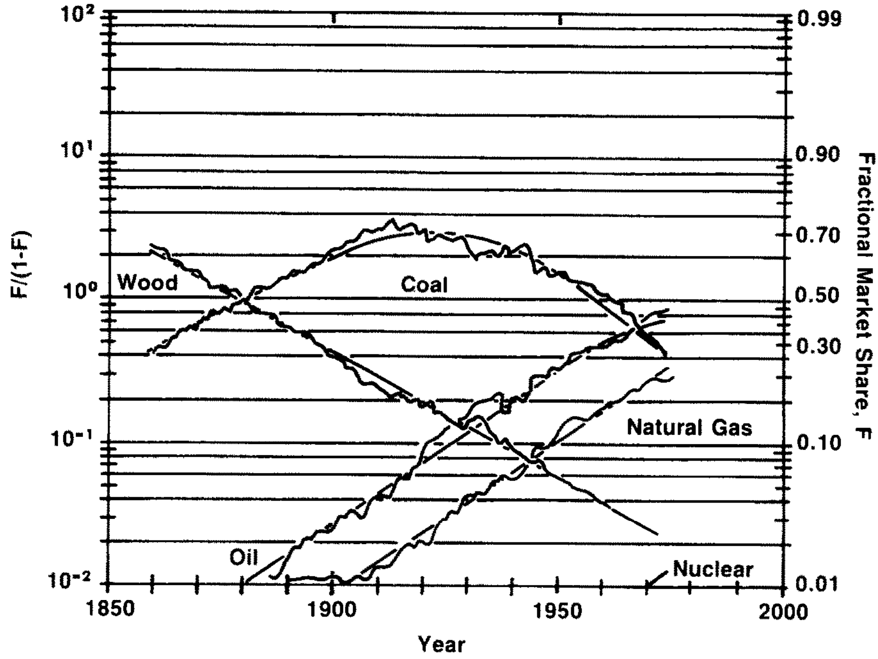

Fig. 1. Past market penetration of the world's primary energy sources (after Marchetti[1]).

detailed world energy/macroeconomic model.[7] Figure 2 is notable in two regards. First, there is a major difference between the current trend of nuclear energy growth (approximating the t_p = 30 years logistic curve) and the Edmonds–Reilly projection. The latter, we should emphasize, is typical of other current projections. The explanation for the

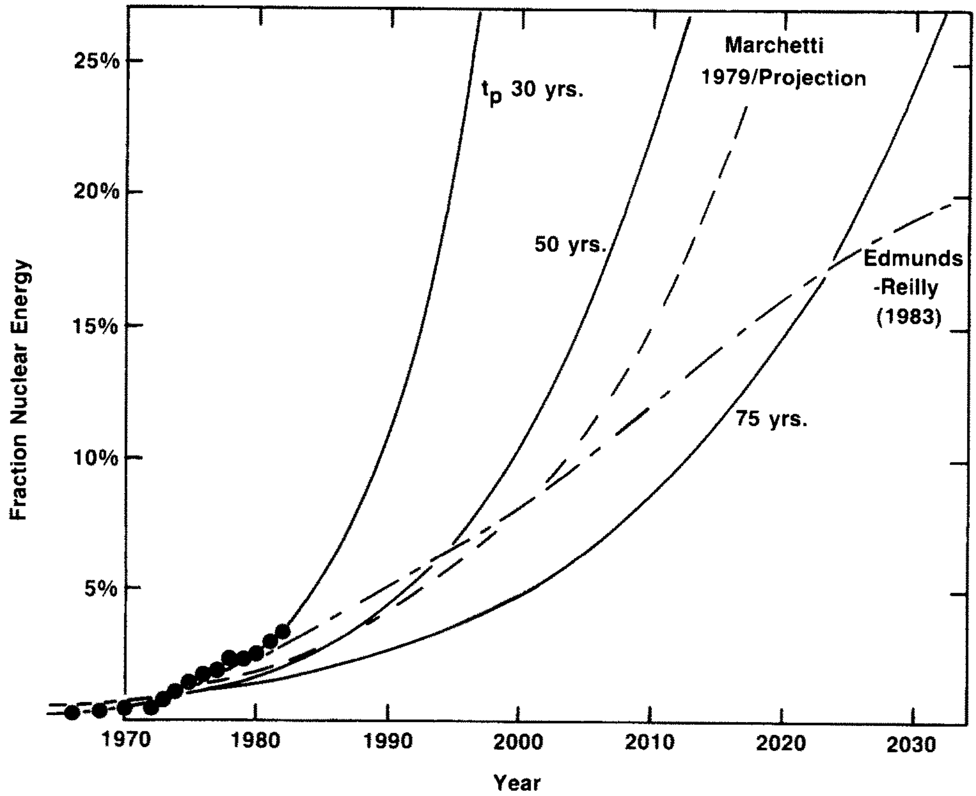

Fig. 2. Past and projected world nuclear energy production as a function of total energy use. Logistic growth curves assume a 1% market share by 1975; t_p is the time for increase from 1% to 50% of market share. Nuclear data are from EIA.[8]

discrepancy probably lies in the fact that nuclear plants currently coming on line reflect plans made 10–20 years ago—before the advent of reduced energy demand struck the developed world and prior to the time of increasing public hostility to their installation. Presumably, nuclear growth in the future will show a fall below the logistic extrapolation. The second significant feature of the data is that they appear to contradict Marchetti's claim for a 50- to 100-year market-penetration time. However, there are reasons why the latter conclusion need not apply. Thus one may argue that early initial penetration rate could be extremely high if actively promoted and capitalized through national programs. Later on, when the new industry starts to compete with the old in a major way, penetration may be forced to slow down. In addition, most of the growth of nuclear energy depicted in Fig. 2 has occurred in developed countries; the results should therefore not be considered as typical for world conditions, and Marchetti,[9] himself, has pointed out that historic time constants for primary energy penetration have been shorter for smaller scales and regions. For example, he suggests that a time constant as short as 30 years would be applicable to Western Europe, with recent evidence for increased use of natural gas confirming this observation. Marchetti's empirical conclusions on the effects of scale and of degree of development of the socio-economic system being considered are important features of market penetration that are pertinent to the issue of moving out of the fossil-fuel area. The changing proportion of energy use between the developed and developing countries (see Ref. 10 for the latest data) is thus an ingredient that has to be taken into account when trying to predict future energy-penetration rates.

3. APPLICATION OF THE LOGISTIC MARKET-PENETRATION-TIME FORMULATION TO THE CO_2 PROBLEM

It is an easy exercise to assume a two-component primary energy system for the world (fossil and nonfossil) and apply the simple logistic formula (1) to see what the effect of alternative fossil/nonfossil energy futures on atmospheric CO_2 levels could be. Figures 3–5 show the results of doing this, assuming 56% of CO_2 emissions are retained in the

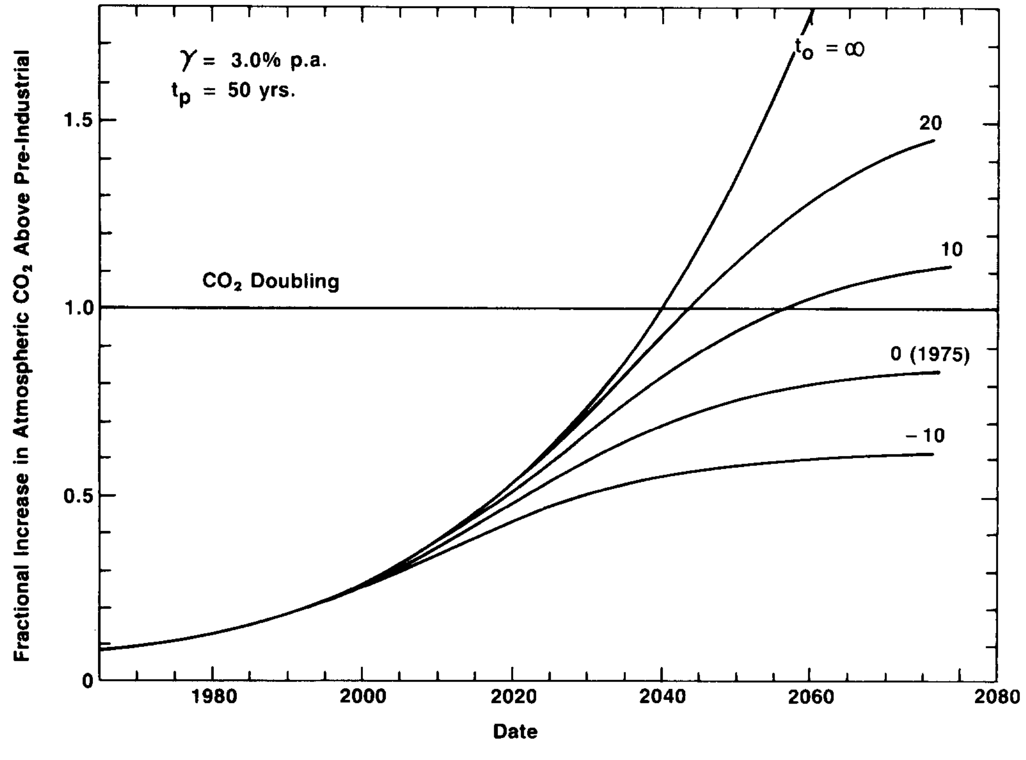

Fig. 3. Growth of CO_2 concentration for logistic nonfossil replacement of fossil fuels. Total energy growth is assumed to be exponential at an annual rate, γ, of 3%. Market-penetration time constant, t_p, is 50 years; various nonfossil entry dates, t_0, for a 1% penetration (relative to 1975) are shown.

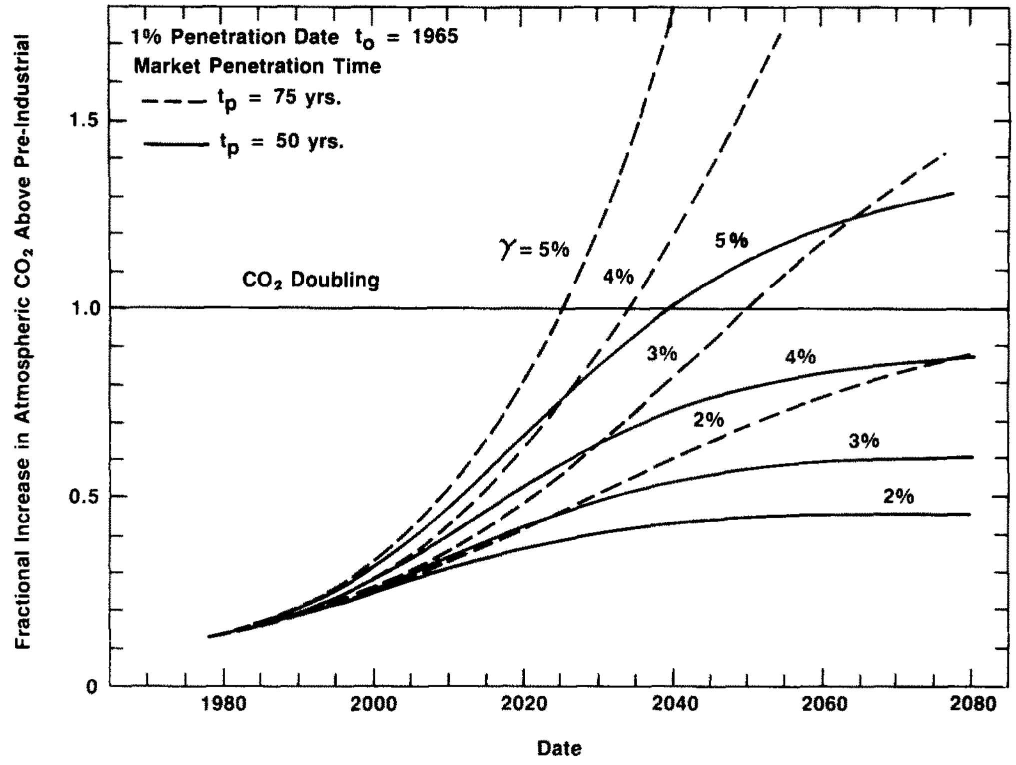

Fig. 4. Atmospheric CO_2 increase for various total exponential energy growth rates, γ. The nonfossil fuel is assumed to be 1% of the market in 1965.

atmosphere.[11] They are plotted for a variety of market-penetration time constants, t_p, and initiation times, t_0, for the introduction of the nonfossil fuel that we are taking as a replacement for the world's currently fossil-fuel-dominated energy production. The latter we identify by specifying values for the time at which nonfossil energy rises to occupy 1% of the market, referenced to a base date of 1975.

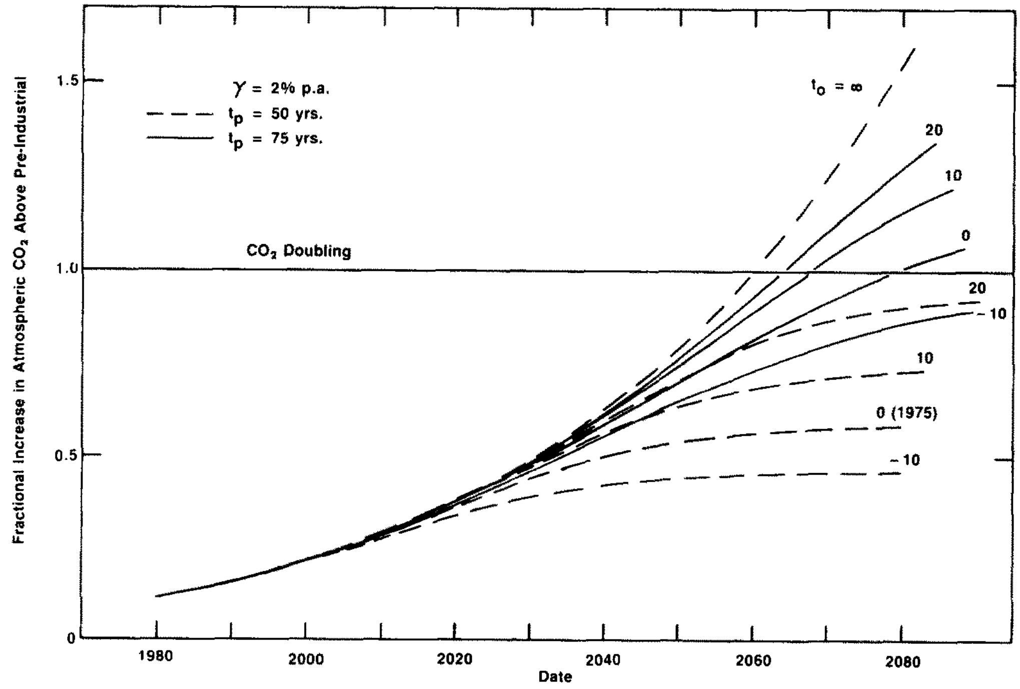

Fig. 5. Atmospheric CO_2 increase for a total exponential energy growth rate of 2% per annum.

The purpose of these illustrative calculations is to demonstrate under what conditions and under which assumptions concerning energy growth and market-penetration time do characteristic atmospheric CO_2 concentrations approach threatening levels, and the CO_2 doubling state (indicated by horizontal lines), we may assume, represents such a condition. For several reasons these should not be taken as faithful projections of possible futures, but rather as indications of what values of t_p and t_0 could give problems if a move to nonfossil energy use is dictated. The restriction to a two-component system is a simplification that is not important for long-term CO_2 abatement policy, though it is clearly in error with today's energy-use mix. It would be possible to amend the calculations to improve the simulation in this regard, but it is hardly merited in view of our objective of presenting only the overall nature of the difficulties in the energy transition process. Excessive detail tends to promote unwarranted belief in accuracy that is not there.

Figures 3 through 5 are also idealized in assuming continued fixed exponential growth of total energy use, γ, with values varying between 2% and 5% per annum. Projections of energy use made prior to the energy crises of the 1970s were typically at constant exponential rates, varying from the 5% figure at the beginning of the decade to 3% towards its end. Exceptions (as in the IIASA projections[9]) were for a few, very long-term projections that took into account population stabilization. By contrast, most current projections have decreasing rates of energy growth starting sometimes early in the next century, as, for example, in the Edmonds–Reilly projection shown in Fig. 2. We feel, however, that broad conclusions regarding the importance of market-penetration time lags should not be affected by omission of departures from exponentiality, at least for consideration of medium time-scale phenomena that are contained within a 50-year market-penetration time. The latter we consider a reasonable lower limit according to the historical results collected by Marchetti. Of greater significance is the very large uncertainty in any of the long-term energy projections, an aspect we discuss further in Section 6.

The curves in Fig. 3 were calculated for an overall energy growth rate of 3% per annum, an acceptable figure in the late 1970s, but an overestimate according to most of today's forecasts, which lie in the 2% per annum range. At the 3% p.a. growth rate, assuming all of this to be contributed from fossil-fuel combustion, atmospheric CO_2 doubling would occur[12] in about 2040, at which time global temperatures would have risen by about 2.5°C.[12,13] The latter figure is highly uncertain and is likely biased upward because of the delaying effect on ocean thermal inertia, which is not included in the equilibrium calculations of climate change that yield the 2.5°C value.

Figure 6 shows projections of average global temperature increase for a fixed 3% p.a. exponential energy growth rate and for an approximately 2% p.a. rate projection made by Rotty in 1980.[14] These are plotted as dashed curves; we have also indicated on the abscissa the revision in timing of the climate change due to a 20-year lag from ocean thermal-inertia effects. Our objective in presenting Fig. 6 is to bring in another important feature of the greenhouse warming problem that results from a growing realization of importance of infrared absorbing trace gases in addition to CO_2. The solid lines in the figure show the effect of these additional greenhouse gases on temperature change. They demonstrate that the effect of reduction in fossil-fuel use growth from 3% to about 2% per annum on climate change is essentially eliminated if we accept Ramanathan's[15] estimate of the effect of the OGGs (other greenhouse gases). Overall, the effect is a return to the mid-1970s viewpoint on timing and criticality of anthropogenetically produced climatic changes. Ramanathan's estimate of the additional warming (as shown in the figure) was for a 70% temperature elevation above the CO_2-alone response, a value thought to be too low today;[16] an increase by 100% or even more is believed possible.†

In studying the significance of the nonfossil market penetration results presented in Figs. 3–5, we thus believe it wise to consider the $\gamma = 3\%$ input as more representative of a likely future than a lower rate, as long as we take the CO_2 doubling levels shown on the figures as indicative of serious climatic impact and assume growth in the other greenhouse gas concentrations continue their present trend. Alternatively, we could use

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† But it would be difficult to account for the current absence of a clear climatic change signal if the supplement is too large.[13] An analysis of this implication of OGG growth has yet to be undertaken.

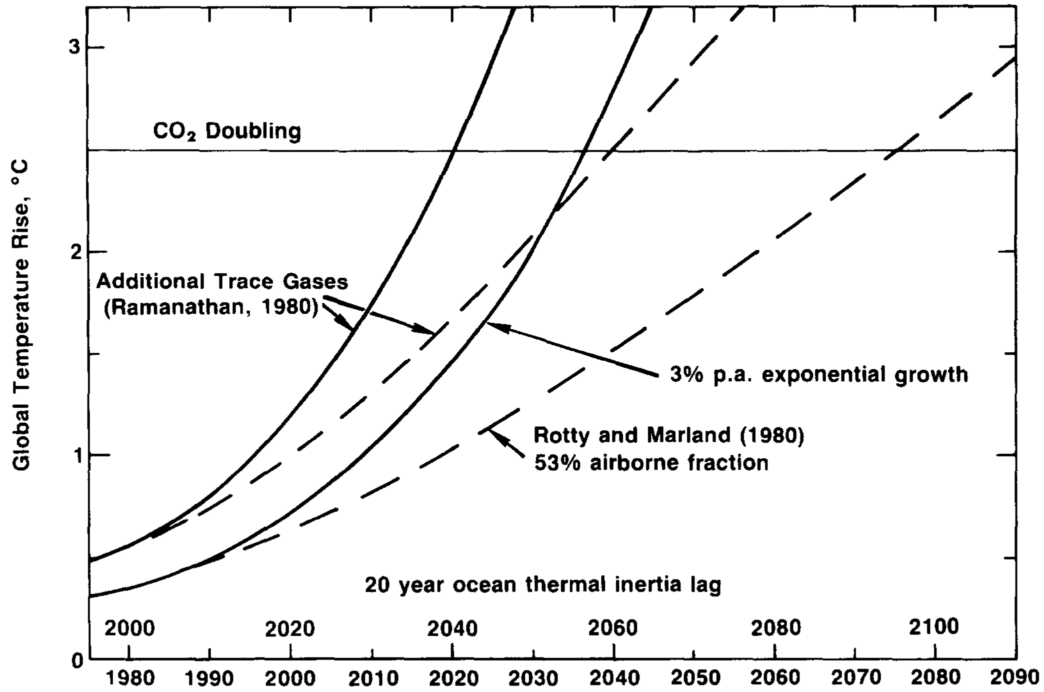

Fig. 6. Climatic change with and without the presence of other trace greenhouse gases.

the lower 2% growth rate, and take a lower CO_2 concentration as indicative of significant impact. If we follow the latter argument, the range of CO_2 levels that need to be considered critical (defined as producing a temperature rise of 2.5°C when combined with the OGGs) corresponds to increases between 50% and 100% above the pre-industrial level: the upper limit allows for no effect from the additional trace gases; the lower, for a doubling of the CO_2 response alone.

Figure 3 is plotted for a 50-year market-penetration time constant and a variety of initiation dates, t_0, for the introduction of nonfossil fuel-energy sources. These indicate that a 3% per annum total energy growth rate, with a 50-year time constant, requires immediate movement away from fossil-fuel use to avoid the CO_2 doubling state. However, reduction of energy growth to 2% per annum, retaining the 50-year t_p value, would eliminate the problem for several decades to come, as can be seen from the calculated results shown in Figs. 4 and 5. Increasing the market-penetration time to 75 years would reintroduce the difficulty (Fig. 5). These general conclusions apply to the climatic impacts of CO_2 emissions. Adding the other greenhouse gases and assuming their effect is to double the warming from CO_2 alone completely changes the picture. With a 50-year penetration time, both for reduction of CO_2 and the other greenhouse gases, and a 2% per annum energy growth rate, Figs. 4 and 5 indicate that it is too late to avoid a serious climatic effect, unless this is achieved by replacing fossil fuels with nuclear energy, which already has a sizable market share (see Fig. 2). This pessimistic conclusion can be relieved if an allowance is made for the lag effect of ocean thermal inertia, as discussed above. A 20-year delay from this effect would put us currently on the $t_0 = -10$ year curves that are plotted in Fig. 4, and then the 50% CO_2 increase level would be asymptomatically avoided at a 2% per annum energy growth rate and a 50-year penetration time. However, with $t_p = 50$, as we can see from Fig. 5, the respite would be short, with action being called for in under 20 years from now if the 50% increase is to be avoided.

These conclusions are based on an assumption that use of resources contributing to release of the OGGs can be reduced at the same rate as CO_2 from fossil fuels. Since it is currently believed (but is by no means sure) that the additional trace gases come from nonenergy sources, this scenario requires multiple decisions applied to different societal sectors for its implementation. The problems of following such a course have yet to be looked into. We only note here that, if the contribution of the OGGs to climate warming is as large as the latest estimates indicate, reduction of atmospheric CO_2 emissions alone will do little to relieve the anticipated climatic change.†

Before leaving the perspective on the market-penetration time issue yielded by these calculations, we should point out two reservations to the general conclusions that they give. First, the reduction in temperature rise from ocean thermal inertia is not a permanent effect; eventually, assuming that atmospheric CO_2 levels stabilize, the climate change will approach the steady-state estimate, so it is possible that the eventual climatic impacts will be merely delayed rather than avoided. The implications of this possibility for decision-making, particularly in its irreversibility, and for the role of the market-penetration time problem have not yet been studied. Secondly, we have accepted in our discussion that an overall temperature rise corresponding to a doubling of atmospheric CO_2 levels is a condition to be avoided. However, the curves of CO_2 growth that are marginally close to this state are nearly horizontal (see any of Figs. 3–5), so that a fixed criterion based on avoiding the doubling condition yields unduly high sensitivity of conclusions to, for example, the precise value of t_0. Such behavior is an artifact arising from imposition of sharply defined critical criterion (i.e. CO_2 doubling), and it would be more appropriate to apply a more gradually imposed condition, such as arrived at by consideration of the increasing economic costs of growing climatic impacts (see Laurmann[18] for an illustration of such an approach applied to the CO_2 impact problem, though not to market penetration).

4. OTHER APPROACHES TO THE TRANSITION PROBLEM

The market-penetration time concept was not only the first to be applied to the question of replacement of fossil energy by nonfossil energy, but it remains the only quantitative approach. Several other views of the transition problem have been published, but none have been able to come to grips with evaluating the real impediments to a rapid move away from fossil-fuel use, should this become necessary. The usual approach has been to postulate one or more future energy scenarios, appropriately divided into fossil and nonfossil portions, and ask in what way these would have to be changed to avoid exceeding a preselected atmospheric CO_2 concentration. The resultant required rates of growth of nonfossil energy forms are then studied, and qualitative arguments made as to whether these would be easy or difficult to achieve.

One such analysis[19,20] introduced a new and quantifiable critical variable, the second time derivate of the replacement, nonfossil energy growth rate. This quantity, which is a measure of the required rate of new manufacturing plants that supply hardware to fabricate the new power plant, was found to be extremely large in many energy transition scenarios.

The detailed considerations in Ref. 19, as well as those in similar postulated scenarios, develop only qualitative arguments on the problems of elimination of fossil-fuel use. Clues are provided as to the nature of the potential difficulties, but it is all too easy to present arguments for or against conclusions that might be drawn, depending upon the predilections of the reviewer. Another class of methods that ostensibly would seem to be able to treat the problem more quantitatively and with less chance of controversy, devolve on the use of energy/macroeconomic models for depicting the economic interactions resulting from alternative-energy-use futures. These[21,17,7,13,22,23] typically attempt to evaluate economic impact costs of various levels of CO_2 increase and associate a shadow price with them, from which a taxation rate on fossil-fuel use can be calculated so as to produce the desired reduction in CO_2 emissions and its climatic impact. A variety of differing conclusions has been reached by these authors, though several agree that a taxation system is not an attractive or effective route. We shall not enter into their subject matter, since all the analyses omit the principal problem with which we are concerned, i.e. the constraints of the social or economic system that could prevent a rapid transition to non-fossil-fuel use. Other economic models do exist that have started to incorporate

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† The difficulty reported in a recent EPA analysis[17] in effecting a significant reduction in climatic change through a coal-taxation policy is a direct reflection of this situation. The EPA projections assumed that the other trace gas atmospheric constituent growths would continue unabated.

factors that are important for our subject, such as capitalization constraints and firm profit maximization actions, though we do not yet see any of them to be in a position to derive quantitative values of primary energy market-penetration times, or deal with Marchetti's claim for their irreducibility.

5. THE VALIDITY AND POSSIBLE BASIS OF THE MARKET-PENETRATION TIME CONSTRAINT

The illustrative examples given in Section 3 clearly show that an irreducible market-penetration time for primary energy sources as low as 50 years will give problems in avoiding serious climatic change, unless the nuclear alternative is accepted. Whether 50 years is in fact an irreducible value and, if not, what the economic costs are for making it smaller then become vital questions that need answering in order to draw policy conclusions. Unfortunately, we are not in a position to satisfy this need. We have suggestions as to the nature of the forces that are at work in controlling the speed of transition, but we cannot state whether these imply absolute limits for the transition rate, or whether they involve marginal additional economic costs that can be sustained with relative ease under internationally enforced action. The best we can do in the following is to present a listing of a variety of social and economic factors that we see as playing roles in influencing market-penetration characteristics, though we cannot say that the itemization is complete or even that it includes the most important elements.

Division into three major subdivisions—economic, institutional, and physical—appears to be a reasonable start for developing a taxonomy of factors that could influence market-penetration times. We can further divide these into a number of features that we see as potentially important in constraining the rate of penetration. This listing follows.

Economic

1. Premature replacement of otherwise usable capital equipment—power plants, secondary industry plants, infrastructure needed for delivery of energy from origin to final user, and end-use technologies.

2. Lack of capital for financing new energy systems, including infrastructure and secondary industries. In contrast to item (1), which introduces merely an economic disincentive for use of the new energy source, this feature implies more severe constraint through a need to sacrifice non-energy-sector growth and shift national emphasis to production of the new energy source. A limiting condition is reached when total assets of the nation become insufficient to raise the needed capital resources.

3. Imperfection of the markets. This includes problems of market clearing, specifically absence of adequate trading mechanisms for the new energy product, friction and transaction costs, and market inefficiency of regulatory controls (such as coal taxation), if these are envisaged.

Institutional

1. The commons problem. The international character of the CO_2/climate change issue makes it particularly difficult—and hence time consuming—to achieve a consensus on its importance and on the need for worldwide replacement of fossil fuels. Heterogeneity of national constituencies not only means that self-interests call for differing responses, but varying cultural attitudes make for distinctly different ethical stances on mitigation of the CO_2 threat.

2. It is likely that the move away from fossil-fuel use would involve a reduction of standard of living or at least a slower-than-anticipated rate of increase. Building the required political agreement to act under such circumstances will take time.

3. Even without these major impediments, most nations, whether free-market oriented or centrally controlled, have built-in bureaucratic impediments to rapid major restructuring at a national level. The decision to abandon a primary energy source would constitute such a change.

4. Of less significance to our problem, but a characteristic important for smaller scale substitutions, is consumer acceptance of a new product. In the literature this is often

cited as critical in the initial introduction phase. If the nonfossil energy were to be radically different in form or in end-use efficiency (a decentralized energy system in the United States might be such a case), consumer acceptance could be a relevant issue.

Physical

1. Material constraints. Deployment of a new energy resource base could impose excessive demands on materials and products (in addition to the primary new energy resource itself) in limited supply. Most important in this regard and less obvious is the possibility of shortages in secondary industries and in infrastructural construction needs.

2. Manpower constraints. These could occur in nearly every category—unskilled, blue collar, skilled, and professional. In some instances the shortage may reflect a population deficit; more likely it requires training or retraining to be remedied. Training the professional sector would be the most time-consuming of the latter.

3. Lack of information. The dissemination of "know how" of a new technology is potentially a major retardant to implementation of new ideas. The mechanism for information diffusion has been studied, but is not yet well understood; it clearly includes a social component, which could have been included within the institutional category listed above.

4. Capital resource limitations. This descriptor could also have been put in the economic category, although for the most part it can be ultimately associated with a material deficit. However, a shortage of financing capital could also be reflective of economic considerations of return on investment. To further blur the distinctions between our three main categories, we take note of the fact that the latter problem is also strongly influenced by the very long time nature of the CO_2 problem, so that conventional, high-economically based discount rates serve as deterrents to its remediation. A socially determined discount rate may be lower, and, in this regard, arguments for justifying present-day expenditures to avoid far distant costs hinge on the ethics of intergenerationally suffered impacts and, according to our taxonomy, is thus best listed in the institutional category.

Assuming that we have identified in generic terms the factors needed to be incorporated into an analysis of the market-penetration time phenomenon, we can envisage a research program that addresses them in sufficient detail to ultimately settle our principal question concerning irreducibility of penetration times. Although we strongly advocate that this be undertaken, our needs are urgent, and the research path to satisfy them is very lengthy. A more expeditious route may be found by identifying the potentially most prominent mechanisms. Thus it is easy to understand, and the existing literature already makes it clear, that the substitution process has distinctly different phases. In the analyses of small-scale, innovative technology, the early phase is one of raising venture capital and obtaining customer acceptance. The next phase is often regarded as straightforward economic competition for a fixed-size market. The last, near saturation phase is economically anomalous according to efficient market theory, with 100% share of the emergent technology rarely being obtained. Since the operant factors are of different origins in these three phases, fitting a one-parameter logistic curve cannot allow for independent variations in them, and the simple model is clearly inadequate. Thus in the case of replacement of global fossil-fuel use, one might expect the initial penetration phase to be lengthened because of the need for concerted intergovernmental actions but shortened by non-market-controlled enforcement procedures. In the intermediate phase, maximum nonfossil energy growth would presumably be determined by capital and resource constraints for a mandated transition or otherwise by economic competition.

In the major growth period the potential constraints on rate of substitution are clearly a function of scale, and the literature supports the conclusion that the larger regions and economic entities involved in the replacement process have longer time constants. We have already quoted Marchetti's results on this characteristic for energy transitions on the global, as compared to the national, scale. Other investigations[12] on small-scale innovations support this general thesis. However, there is an additional important factor in delimiting the range of possible energy substitution rates that has apparently been ignored to date and is also related to scale. Thus, elementary consideration argues that the penetration time constant has to be a function of the rate of growth of the total energy market (i.e. world energy use in our case). All small-scale applications to date have been for replacement in a market of fixed size. However, Marchetti's historically based results are for a growing world energy and economy (he estimates a growth of energy use at about the 2% per annum rate over the last 100 years). No method for amending the logistic growth prescription has been devised to account for a changing underlying market size, and it is easy to see that a change in total energy growth could affect penetration rate differently, depending upon which of the above causative factors are at work. For example, a limited capacity to extract a necessary material good could be a time-limiting factor at high-enough demand rates, whereas a high energy-use rate that brings with it high economic growth could help overcome replacement-time limitations that were symptomatic of a low state of economic development and an associated shortage of needed technical skills.

This last possibility brings up an aspect of the CO_2 problem that is of special interest, particularly since it runs contrary to much of conventional thinking. Thus it is widely accepted that slowing down of the world's energy-use rate, together with a reduction in world GNP growth, is bound to ease the environmental problems associated with fossil-fuel CO_2 release. From most points of view this is difficult to argue with. However, it is important to observe that a reduced growth in GNP implies a slower introduction of research results and technology improvement. The importance of technology development in overall economic growth and quality of life has been emphasized in at least two recent research findings using energy/economy models.[23,24] Sensitivity studies by Hamm[23] have cited technological improvement as one of the prime parameters governing an optimal solution to the CO_2 problem. Unfortunately, this model as well as other macroeconomic models has to incorporate technology improvement as an exogenously set parameter, the value of which is at best an educated guess. Such models therefore cannot offer definitive prescriptions for desired rates of growth to achieve the best solution to the CO_2 problem, allowing for the benefits of technological advances that aid in CO_2 reduction. However, they do lead to controversial propositions for solving the CO_2 problem, such as urging maximum energy growth rate *now* (employing fossil fuels), so as to encourage rapid economic expansion and, with it, the achievement of major technological improvement (either in CO_2-abatement methods or in advanced nonfossil energy) in time to halt the rise of atmospheric CO_2 levels to undesirable levels at reduced cost. It is also worth pointing out that reduction of energy cost via technological advances does not necessarily or automatically work in favor of amelioration of the CO_2 emission reduction. For example, if coal liquefaction and gasification costs are reduced, economic forces would encourage additional fossil-fuel-use growth.

6. THE EFFECT OF UNCERTAINTY

Large uncertainty is an important feature of the CO_2/climate change problem that makes assessment of its present-day importance very difficult. The result has been widely differing opinions on the seriousness of the potential threat and its degree of urgency. Formal techniques exist for treating such a situation, based on a decision analytic approach,[18] provided probability distributions can be assigned to the uncertain variables. This subject matter goes beyond the scope of this paper, so rather than enter into its application to market-penetration time problems, we shall restrict our analysis to a less-formalized discussion on the effect of uncertainty by presenting calculations for the cumulative probability of a CO_2 doubling event as a function of time, using probability estimates for future CO_2 emissions recently derived by Nordhaus and Yohe.[25]

Figure 7 is taken from Ref. 25 and presents probabilities of attaining various atmospheric CO_2 concentrations at a number of probability levels. These were obtained from Monte Carlo runs of an optimal economic-growth model, systematically varying the parameters of the model. Figure 8 transcribes these results into an evaluation of the probability of reaching the CO_2 doubling condition by a given date. For a given market-penetration time constant, t_p, each year in Fig. 8 can be associated with a level of

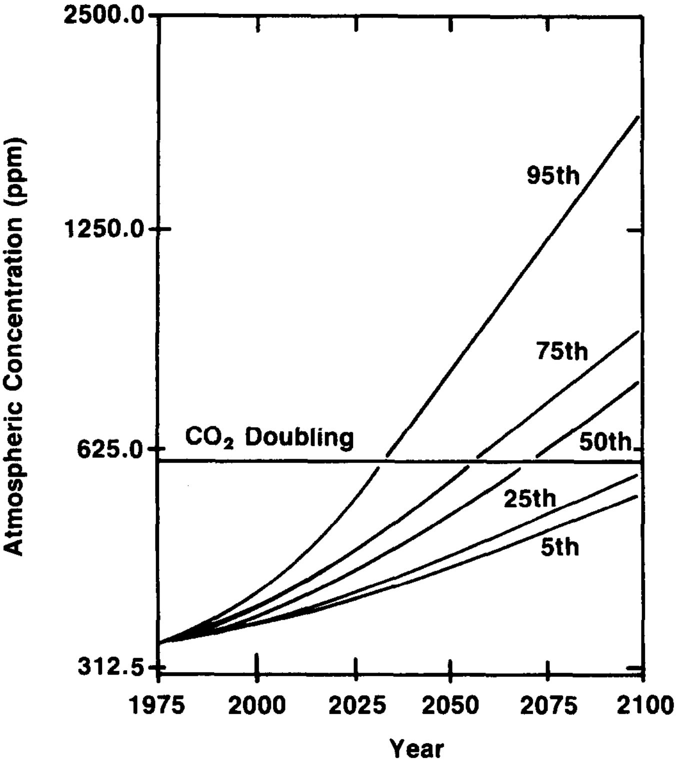

Fig. 7. Probability levels for the occurrence of a given atmospheric CO_2 concentration by a chosen date (after Nordhaus and Yohe[25]).

penetration of nonfossil energy, assuming the logistic form to apply, and using overall energy-growth rates calculated by Nordhaus and Yohe (these are plotted in Fig. 10). Hence, we can calculate cumulative probabilities for avoiding the CO_2 doubling as a function of the entry date of nonfossil fuels. Figure 9 shows the results for a range of market-penetration time constants. We have also plotted cumulative probability curves,

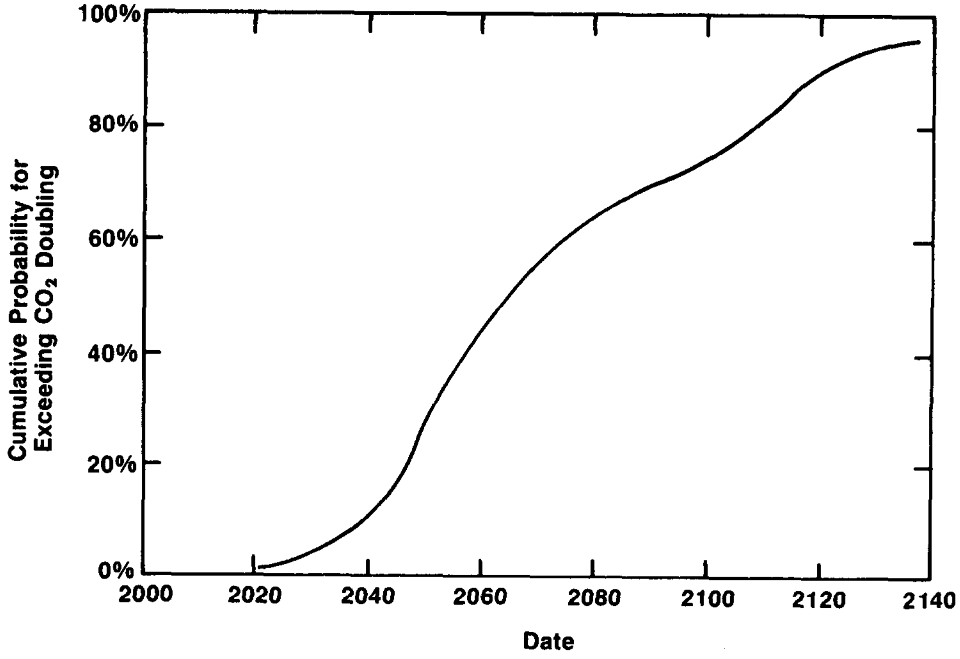

Fig. 8. Cumulative probability of exceeding atmospheric CO_2 doubling for the most probable, future energy growth scenario.

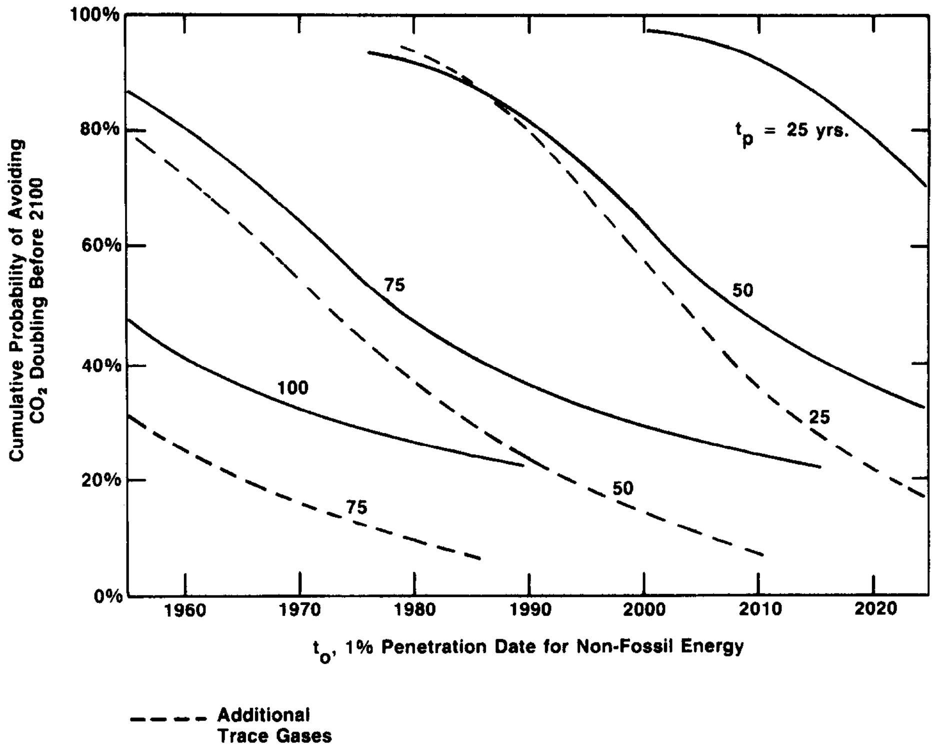

Fig. 9. Cumulative probability for avoiding CO_2 doubling as a function of time of introduction of fossil-fuel replacement energy.

assuming the presence of other greenhouse warming gases at a concentration that doubles the heating due to CO_2 alone. In this case we are dealing with an effective doubling condition, i.e. one that results in a temperature rise equal to that produced by CO_2 in the absence of the other trace species. The best guess for this rise is 2.5°C, but this figure

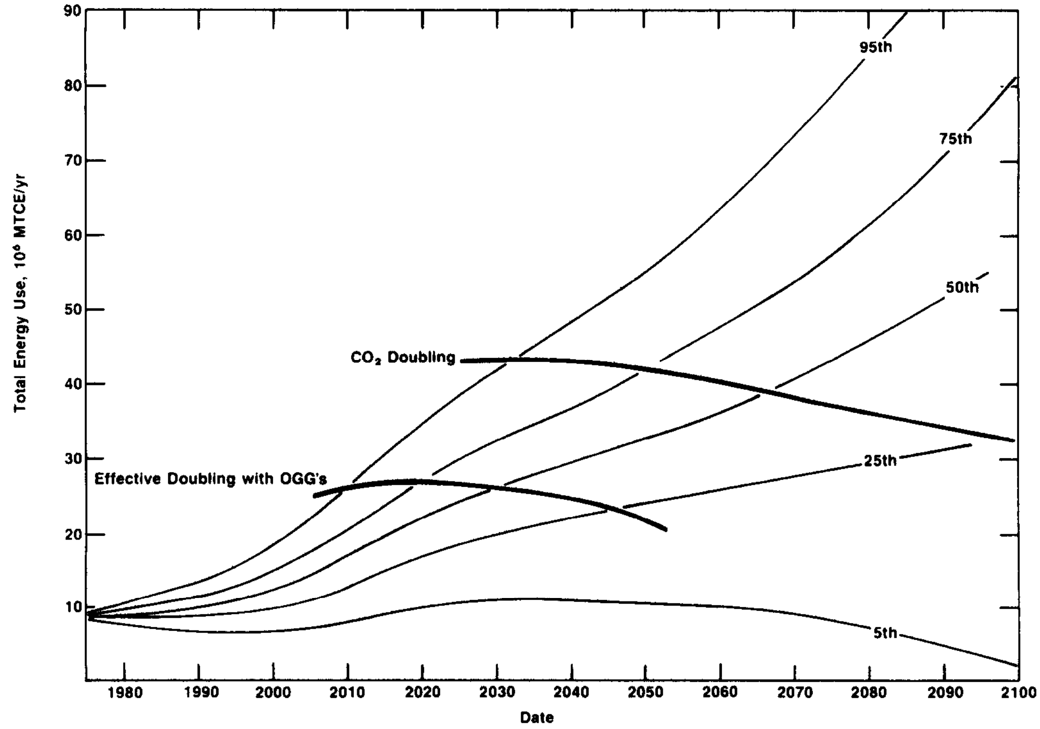

Fig. 10. Probability levels for world energy growth (after Nordhaus and Yohe[25]).

also has a large degree of uncertainty, so that it would be incorrect for us to reinterpret Fig. 9 as cumulative probabilities of avoiding a 2.5°C rise. If this additional source of uncertainty were to be included, it would result in a wider spread of the probability curves and, hence, an even earlier date for any less that 50/50 chance of being able to avoid a 2.5°C temperature increases. Figure 10 has the dates for reaching the doubling condition superimposed on Nordhaus–Yohe's total energy-growth estimates. It also includes a corresponding curve for "effective" doubling of CO_2 when the growth in other greenhouse gases is included (assuming that warming from the latter equals that from CO_2 alone). Both of these doubling date curves were used to produce Fig. 9.

From Fig. 9 we can assess the risk we take in delaying the introduction of nonfossil fuels in the absence of the other greenhouse gases. It shows a chance of 1 in 5 for eventually exceeding CO_2 doubling for a 50-year market-penetration time and entry at a 1% market share in 1992. Entry can be delayed until 2010 if one is willing to take even bets on exceeding the doubling condition (this is the most probable outcome). If one can accept a 1 in 5 chance of being able to avoid doubling, the 1% market share date can be postponed until after the mid-21st century. Inclusion of the other trace gases puts the first of these dates far back to 1955, and even the most probable estimate requires an already-past entry date of 1973. The most optimistic, least-risk-averse 20% probability choice gives 1993 as the date needed for 1% market penetration. As before, we are assuming the other greenhouse gases to be removed at the same logistic rate as CO_2.

7. CONCLUSIONS

A. *Estimated effects of market-penetration time constraints*

The latest projections for global energy demand are much lower than a decade ago, thereby significantly altering perceptions of future fossil-fuel-use growth and the associated climate change problem. Average total energy-growth estimates to the mid-21st century approximate 2% per annum. Accepting such a figure, we can draw the following conclusions on the role of primary energy market-penetration time: (a) If the market-penetration time constant for world energy is 50 years or less, there is no proximate need to consider a move away from the predominant use of fossil energy, as long as the effects of the other greenhouse gases are ignored. (b) However, if current estimates of growth rate and climatic effects of the OGGs are accepted, immediate actions to implement the introduction of nonfossil fuels are needed to avoid significant climatic impact. The latter is defined as a global temperature rise of 2.5% by the mid-21st century, our present best estimate of the climatic effect of a doubling of atmospheric CO_2 levels. (c) If market-penetration time is 75 years or more, it is probably too late to avoid the 2.5°C temperature rise, even in the absence of the OGGs, unless nuclear energy is the replacement for fossil fuels.

B. *Irreducibility of market-penetration times*

The only direct evidence for irreducibility of market-penetration time constants is based on an admittedly lengthy past history of the major shifts in the world's use of primary energy. There is no theoretical basis for the 50-year minimum value that can be abstracted from this history. Furthermore, extrapolation is suspect for a number of reasons, and prime among them are the following: (a) The radically different nature of future, as against past, forces driving the move to new energy forms. The past shifts were economically or technologically preferred, whereas the future is at least presently seen by most as a move away from more desirable to less desirable energy forms because of limited resource availability. (b) The marked past and future anticipated increased rate of technology development, and hence the possibility of new or more efficient means for making the move into nonfossil energy sources. (c) Preliminary evidence indicates that the nuclear-energy-penetration time constant is considerably less than the historically observed minimum of 50 years. If this entry phase property is also characteristic of later phases of nuclear energy growth, the market-penetration time impediment to avoidance of anthropogenetically induced climate change may not exist. It is unknown whether this provisional conclusion can be extended to other advanced renewable energy sources.

The major underlying reasons for belief in large inertial delays in a future wholesale shift out of the use of fossil-fuel forms of energy appear to be ascribable to (a) The possibility that it could entail very large infrastructural and multisector revisions of socioeconomic systems that are overwhelmingly costly. Primary evidence that this could be the case is provided by the fact that the world's investment in all energy-related capital assets is currently about 25% of total developed assets.[9] (b) Cooperation of diverse international cultures and economies is required for enforcement of a mandated move away from the most immediately economically attractive energy alternatives.

C. *The effect of uncertainty*

The very large uncertainty in projecting future world-energy needs implies a high probability of earlier significant climatically induced costs than given by the mean values. This situation has to impact consideration of policy reactions to the threat. For example, allowing for the uncertainty advances by 15 years the date needed to introduce non-fossil-fuel use (as compared with the mean, best-guessed date) in order to avoid a 20% probability of incurring significant climatic impact costs. Such a figure applies for the 50-year market-penetration time constant. This result means that at this probability level, it is already too late to avoid the critical 2.5°C temperature rise, even in the absence of other greenhouse gases, except perhaps if nuclear energy is seen as the replacement energy. The difficulty would be further increased if allowances were to be made for additional uncertainties arising from climate modeling and climatic change impact cost errors.

REFERENCES

1. C. Marchetti, *Chem. Economy & Eng. Rev.* **7**, 9 (1975).
2. J. C. Fisher and R. H. Pry, *Technol. Forecast. Soc. Change* **78**, 427 (1973).
3. E. Mansfield, *Econometrica* **29**, 741 (1961).
4. A. W. Blackman, Jr., *Technol. Forecast. Soc. Change* **5**, 25 (1973).
5. C. Marchetti and N. Nakicenovic, *The Dynamics of Energy Systems and the Logistic Substitution Model.* Report AR-78-1B, Intl. Inst. for Applied Systems Analysis, Laxenburg, A-2361 Austria (1978).
6. C. Marchetti, *Chem Economy & Eng. Rev.* **11**, 7 (1979).
7. J. Edmonds and J. Reilly, *Energy Econ.* **5**, 74 (1983).
8. Energy Information Administration Staff, 0219-82, National Information Center, EIA, Washington, D.C. 20585 (1983).
9. W. Hafele, *Energy in a Finite World: Paths to a Sustainable Future,* Table 9.1C, p. 173. Ballinger, Cambridge, Mass. (1981).
10. R. M. Rotty, G. Marland and N. Treat, Memorandum ORAU/IEA 84-1, Oak Ridge Associated Universities, Oak Ridge, Tenn. (1984).
11. C. D. Keeling and R. Bacastow, Impact of industrial gases on climate, in *Energy and Climate,* p. 72. National Academy Press, Washington, D.C. (1977).
12. J. A. Laurmann, *Environment Intl.* **2**, 4 (1979).
13. Carbon Dioxide Assessment Committee. *Changing Climate.* National Academy Press, Washington, D.C. (1983).
14. R. M. Rotty and G. Marland, Constraints on fossil fuel use, in *Interactions of Energy and Climate* (W. Bach, J. Pankrath and J. Williams, eds.), pp. 269–280. (Kluwer Academic), Hingham, Mass. (1980).
15. V. Ramanathan, Climatic effects of anthropogenic trace gases, in *Interactions of Energy and Climate* (W. Bach, J. Pankrath and J. Williams, eds.), p. 269. Reidel (Kluwer Academic), Hingham, Mass. (1980).
16. J. Firor, The other gas problem, in *Greenhouse Climate Change; Policy Alternatives* (D. Abrahamson and P. Ciborowski, eds.). (Center for Urban and Regional Affairs) University of Minnesota, Minneapolis, Minn. (in press).
17. S. Seidel and D. Keyes, *Can We Delay a Greenhouse Warming?.* Environmental Protection Agency, Office of Policy Analysis, Washington, D.C. (1983).
18. J. A. Laurmann, Assessing the importance of CO_2-induced climatic changes using risk-benefit analysis, in *Interactions of Energy and Climate* (W. Bach, J. Pankrath and J. Williams, eds.), p. 437. Reidel (Kluwer Academic), Hingham, Mass. (1980).
19. A. M. Perry, K. J. Araj, W. Fulkerson, D. J. Rose, M. M. Miller and R. M. Rotty, *Energy* **7**, 991 (1982).
20. J. A. Laurmann, *Energy* **8**, 845 (1983).
21. W. D. Nordhaus, *Thinking About Carbon Dioxide: Theoretical and Empirical Aspects of Optimal Control Strategies.* Cowles Foundation Discussion Paper No. 5, Yale University, New Haven, Conn. (1980).
22. R. F. Kosobud and T. A. Daly, *National* CO_2 *Abatement Policy Inconsistencies and Long Run Energy Technology Choices.* Presented for discussion at the Annual Meeting of the North American Economics and Finance Association, Dec. 18–30, 1983, San Francisco (1983).
23. G. Hamm, *Analysis of Energy Sector Investment Strategies for Flexibility and Risks in Coping with Increasing* CO_2 *Levels in the Atmosphere.* Final Report EPRI TPS 81-820, Engineering-Economic Systems Department, Stanford University, Stanford (1983).
24. H. H. Rogner, *A Long-Term Macroeconomic Equilibrium Model for the European Community.* IIASA Report RR-82-13, Intl. Inst. for Applied Systems Analysis, Laxenburg A-2361, Austria (1982).
25. W. D. Nordhaus and G. Yohe, Future carbon dioxide emissions from fossil fuels, in *Changing Climate,* p. 87. National Academy Press, Washington, D.C. (1983).