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Energy Implications of CO₂ Stabilization

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Analysis of carbon emissions paths stabilizing atmospheric CO₂ in the 350 - 750 ppmv range reveals that implementing the UN Climate Convention will become increasingly difficult as the stabilization target decreases because of increasing dependence on carbon-free energy sources. Even the central Intergovernmental Panel on Climate Change scenario (IS92a) requires carbon-free primary power by 2050 equal to the humankind's present fossil-fuel-based primary power consumption ~ 10 TW (1 TW = 10¹² W). We describe and critique the assumptions on which this projection is based, and extend the analysis to scenarios in which atmospheric CO₂ stabilizes. For continued economic growth with CO₂ stabilization, new, cost-effective, carbon-free technologies that can provide primary power of order 10 TW will be needed in the coming decades, and certainly by mid-century, in addition to improved economic productivity of primary energy.

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The United Nations Framework Convention on Climate Change (FCCC) agreed to in Rio de Janeiro in 1992 calls for (1) "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system..." Implementing the "Rio Treaty" is fostered by quantitative understanding of the links between the concentration of atmospheric carbon dioxide (the most important greenhouse gas) and policies controlling carbon emissions from fossil fuel burning. Since the thermal energy of fossil fuels is the prime power source of industrial civilization, any serious attempt to control emissions must address the issue of energy supply.

To facilitate Rio Treaty negotiations working groups of the Intergovernmental Panel on Climate Change (IPCC) developed six scenarios for greenhouse gas emissions based on socioeconomic projections (2,3). The central scenario (known as IS92a) incorporated widely accepted mid-range projections and the current consensus on population, economic development and energy technology (4) to generate widely accepted mid-range projections of greenhouse gas emissions for the 21st century assuming "no new climate change policies". While this appears to be a Business as Usual (BaU) scenario, we show here that it does not reflect a "Business as Usual" approach, and in fact requires intensive investment in the development of carbon-free energy sources and improvements in energy efficiency, even assuming marked improvement in the economic and engineering efficiency of using primary energy.

An alternative to deriving emission scenarios from population projections, economic goals and primary energy-to-carbon ratios is to specify concentration paths by which atmospheric CO₂ levels off at some concentration target regardless of costs or benefits; for example: 350, 450, ..., 750 ppmv (3, 5). Emission paths as a function of time can then be computed from an inverse carbon cycle model (6).

Still another approach, which accounts, in principle, for the "damage costs" of climatic change, determines optimal carbon emission paths by maximizing an objective function that is the discounted sum of utilities of per capita consumption — the Nordhaus DICE (Dynamic-Integrated-Climate-Economy) model exemplifying this class of model (7). In practice, optimized CO₂ emission paths are only as good as the climatic damage cost functions

input to the models. Although the DICE-optimized emission trajectory for the UN medium population projection is close to that of IPCC IS92a, the most cost-effective carbon emissions could be much lower if loss of biodiversity and ecosystem services damage costs were included (8).

In general, a given atmospheric CO₂ concentration goal depends roughly on cumulative carbon emissions, and can be approached by an infinite number of paths. Some constrain emissions early, some later. Wigley, Richels and Edmonds (5) showed that delayed stabilization paths which follow BaU emissions early on, with large rollbacks later (hereafter, WRE 350, 450,..., 750 scenarios), could buy time to attain CO₂ stabilization goals. The authors did not consider whether their WRE paths were a realistic transition from the present fossil fuel system; but emphasized that their "results should not be interpreted as a 'do nothing' or 'wait and see' policy." Wigley *et al.* (5) call for prompt and sustained commitment to research, development and demonstration to insure that low-carbon and carbon-free energy alternatives are available when needed. It is also well-understood that since most of the projected increase in fossil fuel carbon emissions comes from rapidly-growing developing nations, the nature and timing of energy technology available to these areas is critical (9,10). Schneider and Goulder (35), while agreeing with WRE that delayed stabilization may well be more cost-effective, demonstrate via economic reasoning that the most efficient ways to obtain cost-effective abatement are to deal directly with the climate damage "externality" (via carbon tax, e.g.) or via a combination of carbon taxes and direct subsidies to R&D developers, especially when there are pre-existing inefficiencies (i.e., market failures) in the R&D sector.

Still, the WRE scenarios can be (and have been) misconstrued as "noninterventionist" by those focused only on WRE following BaU near-term emissions. This is wrong for two reasons: First, WRE project very sharp emissions reductions after the initial few decade R&D period; and second, we show below that this facile interpretation is erroneous because even the IPCC BaU which produces atmospheric CO₂ concentrations ~ 710 ppmv by 2100 will require a major ramp-up in carbon-free prime power soon to prevent even higher levels of atmospheric CO₂.

Thus far, energy supply projections by IPCC have mainly assumed present-day energy technologies with more cost-effective economics. For example, the IPCC finding that costs of their "fossil fuel free energy scenario"

will be "small compared to BaU" is based on assumed cost breakthroughs in the 2010-2030 timeframe, not only in solar electricity production, but also in electricity transmission and storage (11), without specifying what physical principles these breakthroughs might be based on. Since funding is limited, more detailed engineering systems analyses of global energy supply systems can help identify innovative and strategic areas likely to foster greenhouse gas stabilization.

A major issue is that technology transitions are typically "nonlinear." Energy technologies of the 21st century are unlikely to be today's technologies with extrapolated costs — we don't, for example, cross oceans today with more cost-effective 19th century sailing ships. There are notorious examples of consensus projections by experts underestimating the way "unconventional" technologies have transformed society; as there are of speculative, but scientifically well-grounded, forecasts that came close to the mark (12, 13). What is needed is not a prediction of the future, but studies that can identify effective CO₂-stabilizing options; particularly those options that can be researched, developed and selected by global markets in time to make a difference.

Business as Usual Implies Active Policies. Earlier we stated that the IS92a BaU "non-interventionist" scenario is implicitly policy intensive. We will now demonstrate this by analyzing the IS92a scenario as a product of four terms, two that deal with social factors and two technological factors. The rate carbon is emitted (as CO₂) by energy production is given by the *Kaya identity* expressing emissions as the product of four factors: (i) population [N], (ii) per capita gross domestic product [GDP/N], (iii) primary energy intensity [$\dot{E}$ /GDP] and (iv) carbon intensity [C/E] (14, 15):

$$\dot{M}_c = N \times (GDP/N) \times (\dot{E}/GDP) \times (C/E). \quad [1]$$

This equation partitions components contributing to carbon emissions into more easily interpreted contributing factors. For example, $\dot{M}_c$ is linked to economic productivity as measured by Gross Domestic Product, GDP; and GDP, in turn, is highly-correlated with the total primary energy production rate (16). The ratio of primary energy to GDP, the *energy intensity*, $I = (\dot{E}/GDP)$, varies somewhat over time and country to country. The primary energy production rate is $\dot{E} = \sum \dot{E}_i$, E_i being the primary energy by type ($i =$

wood, coal, oil, gas, fission, renewable, etc.) and $\dot{E}_i$ the primary energy production rate by type. The carbon intensity, C/E , is the amount of carbon emitted, C , per unit production of primary energy, E ; and depends on the technology used to generate that energy. For example, fossil fuel CO_2 emissions in 1990 computed from these factors by equation [1] were $\dot{M}_c = 5.3 \times 10^9 \text{ persons} \times 4100 \$ \text{ person}^{-1} \times 0.49 \text{ W yr } \$^{-1} \times 0.56 \text{ kgC W}^{-1} \text{ yr}^{-1} \approx 6.0 \text{ GtC yr}^{-1}$ ($1 \text{ GtC} = 10^{12} \text{ kgC}$).

To explore the relative contributions of the factors on the right-hand-side of equation [1] historically and as projected under IPCC BaU we evaluated each of them over the 210-year period from 1890 to 2100; before 1990, from historical data (17); after 1990, from documents defining the IPCC BaU scenario (18-20). The results are illustrated in FIG. 1. Although this information is implicit in IPCC documents, it has not previously been presented in this way.

The first two factors in the Kaya equation, population and percapita GDP shown in FIG. 1A and 1B, increased over the past hundred years; and are projected under BaU to continue increasing over the twenty-first century. Global population, N , shown after 1990 is the UN midrange projection (21) which begins leveling off at mid-century as human fertility declines, but still reaches 11.3 billion by 2100. Likewise, percapita global mean wealth continues its monotonic rise, even more so than population since it maintains its historical growth rate $\sim 1.6\%/\text{year}$ over the entire 21st century (22). Note that the GDP/N curve in FIG. 1B is inflation-corrected to 1990 US dollars.

A partial compensation for more people, and more wealthy people on average, is that primary energy intensity and mean carbon intensity are projected to decrease under BaU (FIG. 1C and 1D). Although BaU is widely regarded as a noninterventionist scenario, we found from a deeper look at the IS92a energy intensity and carbon curves that carbon emissions could easily grow faster over the next century than specified if assumed improvements in "energy efficiency" (23) and carbon-free energy do not materialize.

Primary energy intensity, $I = \dot{E} / \text{GDP}$, and its reciprocal, the *economic productivity of energy*, $(\text{GDP}/\dot{E})$, are both shown as opposite logarithmic scales in FIG. 1C. "Top down" Integrated Assessment models typically assume that energy intensity will decrease in the future; expressing this aspiration by exogenously specifying some annual compound interest rate, AEEI, the so-called "autonomous energy efficiency index," by which I declines (24). The

logarithmic slope for small annual percentage changes is $d(\ln I)/dt = -\ln(1 + AEEI) \approx -AEEI$. For example, the IPCC IS92a scenario shown in FIG. 1C is equivalent to $AEEI \approx 1.0\%$ per year global mean decline in specific energy over all of the next century.

Note that a primary energy intensity declining "exogenously" at 1%/year over an entire century is equivalent to a 1%/year increase in the economic productivity of energy, P — the ability of energy to create GDP — often treated as synonymous with increasing end-use energy efficiency. The effect on carbon emissions of even more vigorous improvement in the rate P increases (25) were explored in the IPCC LESS (Low Emission Supply System) scenarios, with $AEEI$ increasing to 2% per year by 2050 in one case. A conclusion from these sensitivity experiments was that "disagreement in the outcome of (Integrated Assessment) models, in the very long run, is due less to the modelling structure than to the exogenous hypothesis (11)."

Historical data for individual nations show that I typically *increases* during economic development, reaching a maximum as infrastructure investments peak, and declining only after some lag as investment pays off in greater economic productivity (26). This trend also seen in our globally aggregated data of the past hundred years if one excludes "noncommercial" energy (FIG. 1C) — mostly firewood burning by preindustrial societies. In view of the historical tendency of $\dot{E}/GDP$ to first increase in developing nations like China and India before decreasing, and the fact that most of next century's population increase is expected to occur in developing nations, this assumption ought perhaps to be considered optimistic rather than "Business as Usual." To focus on energy supply issues, we provisionally accept the I projections of BaU, recognizing that they may be difficult to implement in developing nations (10).

Another opportunity for emission reductions is continuation of the "decarbonization" trend of the past hundred years as reflected in decreasing carbon intensity of the global energy mix. The mix of fossil and carbon-free primary energy sources produces CO_2 emissions with some average *carbon intensity*, $(C/E) = \sum f_i E_i / E$, where $f_i = C_i / E_i$ is the carbon emission factor of a component energy source (27). (The values of f_i for coal, oil and gas are shown in FIG. 1D; f_i is zero for carbon-free energy sources.) Primary energy can be produced by tapping renewable solar or geothermal energy fluxes, by

nuclear fission or fusion, or by combustion of fossil fuels of varying carbon/hydrogen ratio.

We emphasize here the importance of carbon-free primary energy sources. Substitution of energy-carriers like hydrogen (H_2) for fossil fuels can only continue the historical decrease in carbon intensity if (i) the H_2 is made from carbon-free feedstocks (28), or if (ii) carbonaceous by-products are sequestered away from the atmosphere; e.g., by pumping CO_2 to the deep sea or depleted natural gas wells, or buried as solid carbon ash; processes requiring substantial additional primary energy (29).

Historically, carbon intensity (C/E) has decreased in the transition from wood to coal to oil to gas (17). The IPCC assumed that under IS92a the global mean C/E will continue to decrease monotonically over the next century (FIG. 1D). The evolving global energy mix under BaU based on assumed declining costs of nuclear and carbon-free energy backstops relative to fossil fuels has global C/E dropping to that of an entirely natural gas-powered world by 2030; and it declines even more thereafter. Such rapid decarbonization is only possible by the massive introduction of carbon-free power, ~ 10 TW by 2050 (see below). Again, one could hardly call this "Business as Usual," since it requires global-scale carbon-free power fifty years hence equal to that presently provided by fossil fuels. Still, the net effect of the four factors in equation [1] is to more than double 1990 emissions ($\sim 6 \text{ GtC yr}^{-1}$) by 2050, assuming that 10 TW of carbon-free energy can be produced by that date and that 1%/year improvements in the economic productivity of primary energy can be sustained.

Energy Systems Implications of "BaU". FIG. 2 shows (A) carbon emissions, (B) primary power levels and (C) carbon-free primary power required over the twenty-first century for IS92a and the WRE CO_2 stabilization scenarios. Even the optimistic decline of the last two factors in the Kaya identity cannot prevent emissions from increasing from 6 GtC/yr in 1990 to ~ 20 GtC/yr by 2100 under BaU, as shown by the thick black curve labeled IS92a in FIG. 2 (A). Also shown as differently shaded zones are the relative contributions of natural gas, oil and coal to emissions. An interesting feature of IS92a is that the high C/E coal component increases relative to gas and oil after 2025 even though C/E of the energy mix declines, a feature only possible by the massive introduction of carbon-free energy sources. We also know from carbon cycle model (6) runs that IS92a emissions ultimately

produce atmospheric CO₂ ~ 710 ppmv by 2100; much more than doubling the preindustrial 270 ppmv level.

The colored curves in FIG. 2(A) are allowable emission levels over time which ultimate stabilize atmospheric CO₂ at 750, 650, 550, 450 and 350 ppmv according to the WRE paths (5). Recall that WRE scenarios by design follow IS92a CO₂ concentration and emission paths at first to buy time for development and deployment of emission-reducing technology.

The thick black curve in FIG. 2(B) shows the evolution of total primary power required to meet the economic goals of IS92a, with gas, oil, coal, nuclear and renewable components shown as shaded areas. Also shown are allowable primary power levels from fossil fuel sources for WRE stabilization scenarios (30). The difference between allowable fossil fuel power for CO₂ stabilization and the IS92a total power curve must be provided by carbon-free sources if the economic and "efficiency" assumptions of IPCC "business as usual" are maintained; an increasingly challenging goal as the CO₂ concentration targets are lowered. Indeed, stabilization at 350 ppmv via WRE 350 requires a rollback to zero emissions by 2045 and CO₂ *removal* thereafter (for example, by afforestation). For that case, not only is it impermissible to derive energy from atmospheric CO₂-emitting sources by mid-century, but additional carbon-free energy is needed to sequester atmospheric CO₂ previously injected by fossil fuel burning.

FIG. 2(C) shows carbon-free power required for IS92a and for CO₂ stabilization via WRE 350 through 750 paths in a world economy growing as IS92a and with the same improvement rate in the economic productivity of energy (AEEI ≈ 1%). Under these assumptions, the 1990 primary power of the world economy -- 11 TW, of which only 1.3 TW is carbon-free -- is required from carbon-free power sources by 2018 for WRE 350. Even IS92a needs 11 TW carbon-free by 2050. Other CO₂ stabilization scenarios cross the 1990 total power threshold at intermediate times. Although FCCC doesn't stipulate specific greenhouse gas concentrations, a CO₂ level stabilizing at 550 ppmv is often used as a benchmark. Our analysis shows the WRE 550 CO₂ stabilization path requires major increases in carbon-free power relative to the 1990 baseline: ~ 15 carbon-free TW by 2050. This implies a massive transition from our present fossil-fuel-dominated energy infrastructure to stabilize at twice the preindustrial CO₂ level.

Recent studies by US DoE Labs in support of the Kyoto negotiations to reduce carbon emissions in the 1998-2010 time frame emphasize demand-side reductions from improved energy efficiency in motor vehicles, buildings and electrical appliances (31). Our analysis shows that beyond this time frame carbon-free power technologies will increasingly be needed. It is also possible that fossil fuels could play a productive role in carbon management; either as hydrogen fuel feedstocks (if their carbon can be cost-effectively removed from oxidative contact with the atmosphere), or by promoting global electrification (ultimately powered by carbon-free sources), or if some global-scale "geoengineering scheme" can be cost-effectively employed to compensate for global warming by fossil fuel burning (32).

We do find that carbon-free power will be required in massive amounts even with significant improvements in the ability to convert primary power into GDP. FIG. 3, for example, shows the trade-off between increases in carbon-free power, $\dot{E}_{cf} = \dot{E} - \dot{E}_f$, and energy efficiency improvements parameterized as constant percentage increases per year in energy intensity,

$$I(t) \equiv \text{GDP}/\dot{E} = I_0[1 + \text{AEEI}]^{(t-t_0)}, \quad [2]$$

to achieve a 2 x preindustrial CO₂ goal by the WRE 550 path.

Displayed in FIG. 3 is that AEEI variations of order $\pm 1.0\% \text{ yr}^{-1}$ relative to the base case ($1\% \text{ yr}^{-1}$) create increasingly large differences in carbon-free power required as the twenty-first century progresses. For a $2\% \text{ yr}^{-1}$ compound interest growth of I , the carbon-free power required remains modest even by the year 2100. But $\text{AEEI} = 2\% \text{ yr}^{-1}$ may be almost impossible to sustain over the next century, as that would imply growing the world population and economy significantly at nearly constant primary power. Indeed, recent data from developing nations like China and India suggest near-zero or even negative values of AEEI (26). Were that dismal performance to prevail for the world economy as a whole, some 40 carbon-free terrawatts could be needed by 2050.

The authors of the IPCC central BaU scenario (IS92a) believed that exponential increases in "energy efficiency" at the rate of $\approx 1\% \text{ yr}^{-1}$ were sustainable over the next century by employing only those emission control policies internationally agreed to at the 1992 Rio Climate Treaty negotiations

(19). Achieving either 10-30 TW non-fossil energy supply or pushing AEEI all the way from 1% yr⁻¹ to 2% yr⁻¹ will be very difficult. The need to push hard on both ends is demonstrated by our analysis, as well as the fact that there are real tradeoffs -- more of one can significantly reduce the need for the other.

In any case, stabilizing atmospheric CO₂ at twice the preindustrial level while meeting the other assumptions of business as usual implies a massive transition to carbon-free power, particularly in developing (so-called "non Annex I") nations. There are no energy systems technologically ready at this time to produce the required amounts of carbon-free power (31). Some suggest that the answer is sequestering CO₂ away from the atmosphere or geoengineering compensatory climate change while fossil fuel primary energy continues its historic rise (32). The Kyoto negotiating round of the FCCC just concluded demonstrates that limiting greenhouse gas emissions of only the economically developed ("Annex I") nations to 93% of 1990 levels by 2010 already poses serious problems of energy technology. Our analysis suggests that the Kyoto negotiations are an early warning sign of much greater deficits to come in carbon-free power.

However, there are several renewable, fission and fusion concepts at early research and development stages that could, in principle, provide the needed power (33). But without policy incentives to overcome socioeconomic inertia these could take more than fifty years to penetrate their market potential (34). The year 2050 is closer in the future than Enrico Fermi's 1943 "atomic pile" at the University of Chicago is in the past, and nuclear power today is only a few percent of the global energy mix. Thus far, analyses of carbon emissions targets have quite reasonably emphasized market economics theory (35). It is time now to look hard at the engineering feasibility of transformative technologies that can change the way primary energy itself is produced. Without a massive infusion of such technologies it could be very difficult to stabilize CO₂ at levels preventing "dangerous anthropogenic interference with the climate system."

What is needed in the immediate future are studies that can identify effective CO₂-stabilizing options based on currently imaginable technologies; particularly those options that can be researched, developed and selected by global markets in time to make a difference and (b) policies which provide incentives that can both improve the deployment of (a) and encourage R&D into a range of now only dimly imaginable options.

Our results underscore the pitfalls of "wait-and-see." Researching, developing and commercializing carbon-free energy technologies capable of 10-30 TW by mid-century could very well require efforts, perhaps international, pursued with the urgency of a Manhattan project or an Apollo program. If work begins promptly, there is a good chance of success. This past century, accelerated technology development from wartime and postwar research produced commercial aviation, radar, computer chips, lasers and the Internet, among other things. Carbon emission limits to mitigate global warming are presently being portrayed by some as costs to be borne by "industry" for uncertain future benefits. A more historically-based projection is that the prospect of humankind's adverse impact on climate will stimulate entirely new industries in the 21st century; much as World War II and the Cold War did in the 20th, for less environmentally-benign motives.

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22. BaU incorporates the traditional market economics model of unbounded exponential growth for the next 100 years. D.H. Meadows *et al.*, [*The Limits to Growth*, Universe Books, 1972] offered a neo-Malthusian challenge that nonlinearities from finite resources will limit such growth; a controversial idea at the time. Today, many economists recognize that environmental carrying capacity exerts a negative feedback on economic growth [K. Arrow *et al.*, *Science*, **268**, 520 (1995)]. Still, an apparent conflict exists between continued growth of global mean GDP/N (embodied in IS92a) and the need for long-term sustainability. Arguments and supporting data on both sides are given by N. Myers and J. Simon, *Scarcity*

or Abundance? A Debate on the Environment (W.W. Norton & Co., New York, 1994).

23. While it is easier to measure primary energy production than end-use energy for societies as a whole, their ratio in an energy conversion device, or collectivity of devices, is how energy efficiency is normally defined by engineers, $\eta_{\text{eng}} = (\text{end-use energy})/(\text{primary energy})$. Separately, one can define a "\$-efficiency" measuring the effectiveness by which energy end-use generates wealth, $\eta_{\$} = (\text{GDP}/\text{end-use energy})$: hence, $I = P^{-1} = (\eta_{\text{eng}} \eta_{\$})^{-1}$. Increases in η_{eng} can be negated or overwhelmed by high technology costs or investment in other economic sectors which decrease $\eta_{\$}$. Crystalline PV cells, for example, are more efficient than amorphous cells, but low production costs of the latter may make them a better choice for reducing specific energy.
24. A.S. Manne and R.G. Richels, *Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Limits*, MIT Press, Cambridge, MA, 1992).
25. As suggested, for example, by A.B. Lovins *et al.*, *Least-Cost Energy: Solving the CO₂ Problem* (Rocky Mountain Institute, Snowmass, CO, 1982).
26. A.K.N. Reddy and J. Goldemberg, in J. Piel, ed., *Energy for Planet Earth* (W.H. Freeman, New York, 1991), pp. 59-71; R.K. Kaufmann, *Ecol. Econ.*, 6, 35 (1992); H. Dowlatabadi and M. Orvitz, *Understanding Trends in Energy Intensity: A Simple Model of Technical Change*, Center for Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Pittsburgh, PA, 1996).
27. Carbon emission factors are thermochemical properties of carbonaceous fuels. Natural gas (methane) combustion by $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}(\text{g})$ releases $\approx 803 \text{ kJ/mol CH}_4$ [I. Glassman, *Combustion*. Academic Press, New York, 1977]. Since there are $12 \times 10^{-3} \text{ kg C/mol CH}_4$, the carbon emission factor of gas is $f_{\text{gas}} = (12 \times 10^{-3})/(803) = 1.5 \times 10^{-5} \text{ kgC/kJ} = 0.47 \text{ kgC/W-yr}$. Emission factors increase as the C/H ratio of the fossil fuel increases. Carbon emission factors of oil, coal and wood (unsustainably burned) adopted here are [N. Nakićenović, *Global Energy Perspectives to 2050 and Beyond*. World Energy Council, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1995, p. 42, Fig 4-14] $f_{\text{oil}} = 0.60$, $f_{\text{coal}} = 0.77$ and $f_{\text{wood}} = 0.89$ in kgC/W-yr units. Since $1 \text{ kgC/W-yr} = 1 \text{ GtC/TW-yr}$,

the same numerical values are used to convert rates of energy production in TW (1 TW = 10^{12} W) to carbon emissions in GtC/yr (1 GtC = 10^{12} kgC).

28. H. Wendt and G.H. Bauer. In C.-J. Winter and J. Nitsch, eds., *Hydrogen as an Energy Carrier*, pp. 166-208, (Springer-Verlag, New York, 1988). Hydrogen is manufactured predominantly by CO_2 -generating steam-reforming of natural gas. The net reaction is $\text{CH}_4 + 2\text{H}_2\text{O}(\text{g}) \rightarrow \text{CO}_2 + 4\text{H}_2$, with a typical an energy transfer to hydrogen of 72%. The net carbon emission factor for a methane-to-hydrogen fuel cycle including hydrogen combustion is $f_{\text{H}_2} = f_{\text{gas}}/0.72 \sim 0.65 \text{ kgC/W-yr}$ — more CO_2 per Joule than burning oil. Hydrogen production by water electrolysis and subsequent combustion is carbon-free but commercially noncompetitive today because low power densities ($\sim 4 \text{ kW/m}^2$) in KOH or solid polymer (SPE) electrolytes require large areas of rare platinum catalysts for stable operation.
29. M.I. Hoffert, Y.-C. Wey, A.J. Callegari and W.S. Broecker. *Climatic Change*, **2**, 53 (1979); H.S. Kheshgi, B.P. Flannery, M.I. Hoffert and A.G. Lapenis, *Energy*, **19**, 967 (1994); M. Steinberg and Y. Dong. In C.V. Mathai and G. Stensland, eds., *Global Climate Change: Science, Policy and Mitigation Strategies*, pp. 858-873. (Air & Waste Management Association, Pittsburgh, PA, 1994).
30. Energy production by fossil fuels for the WRE stabilization scenarios was computed as a function of our inverse-carbon-cycle-derived emission rates, $\dot{M}_c(t)$, from the algorithm:

$$\begin{aligned} \dot{E}_f(\dot{M}_c) &= \alpha \dot{M}_c & \dot{M}_c < 0; \\ &= \dot{M}_c / f_{\text{gas}}, & 0 < \dot{M}_c < \dot{M}_{\text{gas}}; \\ &= \dot{E}_{\text{gas}} + (\dot{M}_c - \dot{M}_{\text{gas}}) / f_{\text{oil}}, & \dot{M}_{\text{gas}} < \dot{M}_c < \dot{M}_{\text{gas}} + \dot{M}_{\text{oil}}; \\ &= \dot{E}_{\text{gas}} + \dot{E}_{\text{oil}} + (\dot{M}_c - \dot{M}_{\text{gas}} - \dot{M}_{\text{oil}}) / f_{\text{coal}}, & \dot{M}_{\text{gas}} + \dot{M}_{\text{oil}} < \dot{M}_c \end{aligned}$$

where α is an energy subsidy per unit mass of carbon to sequester CO_2 from the atmosphere, and $\dot{M}_i = f_i \dot{E}_i$ ($i = \text{gas, oil, coal}$) are fossil fuel carbon emissions of IS92a from the primary energy burn rates $\dot{E}_i$ of Pepper *et al.* (20) and carbon emission factors f_i employed in the present analysis (27).

31. Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies, *Scenarios of U.S. Carbon Reductions: Potential Impacts of*

- Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond.*, 1977.
URL: http://www.ornl.gov/ORNL/Energy_Eff/CON444/
32. B.P. Flannery *et al.*, "Geoengineering Climate," in R.G. Watts, ed., *Engineering Response to Global Climate Change*. pp. 379-427 (Lewis Publishers, Boca Raton, FL, 1997); H.D. Herzog, ed., "Carbon Dioxide Removal," Proceedings of the Third International Conference on Carbon Dioxide Removal," Cambridge, MA, 9 to 11 September 1996; M.J. Fogg, *Terraforming: Engineering Planetary Environments* (SAE International, Warrendale, PA, 1995); E. Teller, "The Planet Needs a Sunscreen," *Wall Street Journal*, October 17, 1997, p. A22.
 33. M.I. Hoffert and S.D. Potter, "Energy Supply," in R.G. Watts, ed., *Engineering Response to Global Climate Change*. pp. 205-260 (Lewis Publishers, Boca Raton, FL, 1997); T.M. Johansson *et al.*, *Renewable Energy* (Island Press, Washington, DC, 1993); P.E. Glaser *et al.*, eds., *Solar Power Satellites: A Space Energy System for Earth* (John Wiley & Sons, New York, 1998); E. Teller, M. Ishikawa, L. Wood, R. Hyde and J. Nuckolls, *Completely Automated Nuclear Reactors for Long-Term Operation II* (UCRL-JC-122708 Pt2, Lawrence Livermore National Laboratory, Livermore, CA, 1996); T.K. Fowler, *The Fusion Quest* (Johns Hopkins, Baltimore, 1997).
 34. M. Ha-Duong, M.J. Grubb and J.-C. Hourcade, *Nature*, **390**, 270-273 (1997).
 35. S.H. Schneider and L.H. Goulder, *Nature*, **389**, 13-14 (1997).

FIGURE CAPTIONS

FIG. 1. Evolution of factors governing the rate of global fossil fuel carbon emissions in the Kaya identity: $\dot{M}_c = N \times (\text{GDP}/N) \times (\dot{E}/\text{GDP}) \times (C/E)$. Historical curves (1890-1990) are from archival data on population, economic growth, energy use by type and carbon emissions (17); Future projections (1990-2100) are for the IPCC "Business as Usual" (BaU, or IS92a) scenario computed from various sources (18)-(20). GDP values are inflation-corrected to 1990 US dollars. All factors are plotted on logarithmic vertical scales to show growth or decay at constant rates of compound interest as lines of constant slope: (A) Global population; (B) Per capita GDP; (C) Primary Energy Intensity ($\dot{E}/\text{GDP}$: left hand scale) and Economic Yield of Energy ($\text{GDP}/\dot{E}$: right hand scale); (D) Carbon Intensity of the energy mix; the horizontal lines are emission factors of individual carbonaceous fuels, as indicated.

FIG. 2. Fossil fuel carbon emissions and primary power in the twenty-first century for IPCC IS92a (BaU) and WRE stabilization scenarios: (A) Carbon emissions; (B) Primary power and (C) Carbon-free primary power. Shaded areas are gas, oil, coal, nuclear and renewable components of IS92a from the EPA energy economics model of Pepper *et al.* (23). Carbon emissions for WRE scenarios are outputs of our inverse carbon cycle model (6). Fossil fuel power for WRE scenarios is based on IS92a burn rates of gas, oil and coal employed sequentially in descending priority and limited by total carbon emission caps as described in footnote (30). Carbon-free primary power is total primary power less fossil fuel carbon power.

FIG. 3. Twenty-first century tradeoffs between carbon-free power required and "energy efficiency" to stabilize at twice the preindustrial CO_2 concentration. Carbon-free primary power is plotted versus an assumed constant autonomous energy efficiency index, AEEL. All cases also assume: (i) WRE 550 CO_2 stabilization paths, (ii) GDP growth of 2.9 % yr^{-1} to 2025 and 2.3 % yr^{-1} thereafter and (iii) fossil fuel power related to allowable carbon emissions as in footnote (30). The rate energy intensity I declines (and economic productivity of energy P increases) in BaU and in our CO_2 stabilization base cases corresponds to $\text{AEEL} \approx 1.0\%/\text{yr}$.

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FIG. 1

FIG. 2

FIG. 3