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Challenges to a Sustainable Energy Future in a Climate Change Setting

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Abstract

The paper surveys the major challenges to stabilizing the atmospheric CO_2 concentration. Climate change, and policies to deal with it, is viewed as energy problems. The energy problem stems from the fact that no combination of carbon-free energies is currently capable of displacing fossil fuels as the main sources of the world's base load energy requirements. The paper provides rough estimates of the amount of carbon-free energy required to stabilize climate, the potential contribution of "conventional" carbon-free energies, the contribution of renewable energies, and the size of an "advanced energy technology gap". The findings indicate that stabilizing CO_2 concentration will require a long term commitment to research, develop, and eventually deploy new energy technologies and sources including hydrogen. The paper suggests that the role of technology is what makes stabilizing CO_2 concentration economically feasible. In this respect technology tends to "trump" economics, with advances in the former taking precedence over the application of market-based instruments, such as carbon taxes and emission permits. The analysis has implications for the credibility of commitments to target climate change-related factors such as carbon dioxide emissions.

I. Introduction

Our paper addresses the challenges to a sustainable energy future". We do not directly address economic challenges, or anything other than the "low carbon" interpretation of a "sustainable energy future". If we were assessing the challenges to optimally using the world's plentiful conventional and non-conventional fossil fuel resources, economics would be paramount. Most energy economists would emphasize the role of prices in conserving energy use and in bringing forth new supplies. While conventional oil reserves may peak in the next decade or two (even this is not certain, at $50+ a barrel) and its production may begin to fall, there are huge non-conventional oil reserves to tap (e.g., the tarsands in Canada). Economists would acknowledge that at $10-20 barrel oil shortages will appear. At $50 or more, it is not at all clear that looming "shortages" is a good description of our present situation. In any event, long before severe shortages appear, plentiful coal will be liquefied. China is already getting ready to do so, in order to reduce its dependence on oil imports (Aldhous, 2005). What really is threatened by these developments is any hope of stabilizing the atmospheric concentration of CO_2 at levels which would not dangerously interfere with climate.

Here we interpret "sustainable energy future" as a reference to energies capable of meeting the objectives of stabilizing the atmospheric concentration of carbon dioxide at or below 550 ppmv, or double the pre-industrial concentration. The development of sufficient carbon emission-free energies will be, in our view, a very great challenge indeed. But the nature of that challenge, and the relative roles of economics and technology in meeting it, are very much in dispute. One camp evidently believes that the barriers to stabilizing CO_2 concentration are socio-economic and institutional, not technological. Another camp believes that the main barriers to stabilizing CO_2 concentration are technological, and that economic and political barriers can be surmounted by a commitment to finance and sustain, for several decades, research and development into scaleable carbon-free energy technologies and sources.

The paper is organized as follows. Section II briefly describes differing views on what it will take to stabilize CO_2 concentration. In Section III, we present calculations of carbon emission-free energy requirements for stabilization. The calculations illustrate the strong dependence of carbon emission-free energy requirements on two variables: the long term global rate of growth of economic activity and the long term rate at which the energy intensity of the global economy can be reduced. In Section IV, an attempt is made to calculate the potential contribution of "conventional" carbon emission-free energies to stabilization. Section V examines the potential contribution of new renewable energies, solar, wind and biomass. In Section VI we use findings from Sections III, IV and V to calculate an "advanced energy technology gap" (AETG). Section VII comments on the potential contribution of hydrogen to filling the AETG, drawing in particular on recent work by Pacala and Socolow (2004). Section VIII briefly discusses the economics of "getting there": of facilitating a move to a carbon emission-free energy future, in which CO_2 in the atmosphere is eventually stabilized. Section IX concludes.

II. The Energy-Climate Challenge

There is a vibrant debate over what it will take to stabilize CO_2 concentration. The core of the debate is whether or not the means to achieve stabilization are at hand. On the one side are those who believe that a combination of energy efficiency improvements and renewable energies would provide most or all of what is needed to achieve stabilization – and that no major "technological breakthroughs" are needed (Metz, *et al.*, 2001: 8). Moreover, this view holds that stabilization of atmospheric CO_2 is achievable at relatively low costs (0.5 to 3% of global GDP), and that the main barriers to stabilization are socio-economic and institutional in nature. The most prominent examples of this view are members of WG III of the Intergovernmental Panel on Climate Change (IPCC), especially those who were responsible for writing that report's Summary for Policy Makers (SPM) and its third chapter on the technological and economic potential for greenhouse gas reduction (Metz, *et al.*, 2001; O'Neill, *et al.*, 2003; Swart, *et al.*, 2003). In its SPM, WG III said:

> "*Most model results indicate that known technological options could achieve a broad range of CO2 stabilization levels, such as 550 ppmv, 450 ppmv or below over the next 100 years or more, but implementation would require associated socio-economic changes*" (Metz *et al.,* 2001: 8).

A quite different view, one that emphasizes major, long-term, energy technology breakthroughs is found in Hoffert, *et al*. (1998, 2002, 2003), and is mirrored, at least in part, in Battelle (2001), and is implied by Caldeira, *et al*. (2003). The Hoffert, *et al*. papers make clear that stabilization of atmospheric CO_2 concentration will take huge amounts of carbon-free energy, that no current technology or combination of technologies is up to the task, and that stabilization could require an international effort pursued with the urgency of the Manhattan project or Apollo space program (Hoffert *et al.*, 1998:884). Without long-term commitments to finance, research, develop, and eventually deploy energy sources and technologies capable of supplying concentrated carbon-free power on a scale sufficient to meet the world's base load energy requirements by 2100, stabilization of CO_2 at 550 ppmv – or twice the pre-industrial level – will not be possible; and certainly not at any acceptable cost. In concluding their 2002 paper Hoffert *et al.* had this to say:

> "*Stabilizing climate is not easy. At the very least, it requires political will, targeted research and development, and international cooperation. Most of all it requires the recognition that although regulation can play a role, the fossil fuel greenhouse effect is an energy problem that cannot be simply regulated away*" (2002: 986).

III. Carbon-Free Energy Requirements for Climate Stabilization

Two main factors govern the amount of carbon-free energy required to stabilize CO_2 concentration: the long-term rates of (a) GDP growth, and (b) energy intensity decline. (Energy intensity is the ratio of energy to GDP, which on a global scale has been declining in the last half century.) The classic paper demonstrating how carbon free energy requirements depend on a trade-off between the GDP growth rate and the rate of energy intensity decline is Hoffert, *et al.* (1998).

Table 1 uses a variant of the Kaya identity (Kaya, 1989) to calculate the carbon-free energy requirements, in 2100, for several different average annual rates of GDP growth and rates of energy intensity decline, for 2000-2100. Because carbon-free energy requirements, in 2100, also depend on the time profile of carbon emissions during the course of the 21st century, the calculations in Table 1 are for a special case. That case is where the consumption and composition of fossil fuels is maintained constant throughout the 21st century at the levels and composition that existed in 2000. The constancy assumptions yield carbon free energy requirements that are conservative for two reasons: (i) under the best of circumstances global fossil fuel consumption will almost certainly rise substantially before stabilizing and eventually declining; and (ii) the composition of fossil fuel consumption, which for the past half century has been away from coal, the most carbon-intensive fossil fuel per unit of energy, and toward natural gas, the least carbonaceous, is likely to swing back toward coal and carbon-intensive tar-sands and heavy oils as the 21st century progresses. Each of these violations of the special case would tend to raise carbon emission-free energy requirements above those in Table 1, in 2100. Assuming however that carbon energy and its composition, and thereby emissions, could be held *constant* at levels prevailing in 2000, a rough estimate is that atmospheric CO_2 concentration would be approaching stability in 2100 at, or somewhat below, 550 ppmv.

Table 1 demonstrates the important influence that assumptions about GDP growth and energy intensity decline have for estimates of the amount of carbon-free energy required, in 2100, to achieve stabilization of CO_2 concentration. For example, for a 1% average annual rate of energy intensity decline, carbon-free energy requirements increase 8 fold as we move from a 21st century average GDP growth rate of 1.5% to 3%. At a 1.5% rate of energy intensity decline, carbon-free energy requirements, although smaller, rise 25 fold as the GDP growth rate doubles. As Hoffert, *et al.* (1998) found, for a given rate of GDP growth carbon emission-free energy requirements are very sensitive to the rate of energy intensity decline.

Table 1 indicates that for rates of *global* GDP growth of 2.0 – 2.5 %, and for global, long-term average annual rates of energy intensity decline of 0.9 – 1.2%, carbon emission-free energy required in 2100 would be in the range of 500-1600 EJ/yr. In comparison, carbon-free energy contributed apparently 60 EJ/yr in 2000. If the attainable global average annual rate of energy intensity decline could somehow be raised to 1.2 to 1.5 %, from 0.9 to 1.2 %, the range for carbon emission-free energy requirements would be reduced to 300-1100 EJ/yr. However, Baksi and Green (2004a), building on Lightfoot and Green (2001) demonstrate why it will be very difficult to achieve a century-long rate of energy intensity decline of 1.2%, much less raise that rate above 1.2%.

The assumption of stable global CO_2 emissions that underlies the calculations in Table 1, is unrealistic. In reality, global carbon emissions will, at best, increase before they stabilize and begin to decrease. In that case, carbon free energy required to stabilize atmospheric concentration at, or a little below, 550 ppmv will exceed the amounts in Table 1. A rough benchmark is that by 2100, the amount of carbon energy will have to fall to 100 to 150 EJ/yr to offset a rise in carbon energy consumption from 340 EJ/yr to 450 EJ/yr, in the period 2000 – 2050. In such a case, one would have to add roughly 200 EJ/yr to the carbon-free energy requirements in 2100 shown in Table 1. These requirements would be, in 2100, 12 to 20 times the 60 EJ/yr of carbon-free energy produced in 2000.

IV. Contribution of "Conventional" Carbon Free Energies to Stabilization

Where could the carbon (or emission)-free energy come from? To begin with, there are, what is termed here, "conventional" sources of carbon-free energy. We somewhat arbitrarily define "conventional" carbon-free energy to include hydroelectric power; uranium based once through, open cycle, nuclear electric power; solar and wind energy delivered directly to the electric grid; biomass (bio-fuels); and a small amount of geothermal energy. None of these technologies appear to require important technological breakthroughs. Nevertheless, there are limits to the expansion or scale-up of these energy technologies.

Expansion of hydroelectric power is limited by potential sites. Large-scale expansion of conventional nuclear power must overcome a variety of barriers: political, safety, security, and uranium supplies. These are widely understood. But some (*e.g.* IPCC, WG III, 2001) believe that, despite limits to the expansion of hydroelectric and "conventional" nuclear electric supplies, new renewable energies, including solar and wind power and the production and harvesting of "biomass" (especially for bio-fuels), will be sufficient to supply the amounts of carbon-free energy required for stabilization of CO_2 concentration. However, this overlooks the fact that without large scale storage and smart "electric grids" (each likely requiring technological breakthroughs) solar and wind power that is delivered directly to the grid is limited by its intermittency to 5 to 10 percent of electric power demand, except where backed up by large scale hydroelectric energy. Further, land, water availability, and large energy inputs are likely to limit net energy from conventional (non-biotechnological) biomass production.

Tables 2 and 3 indicate the potential contribution of "conventional" carbon-free energy. The potential contribution of hydroelectric, conventional nuclear power, and the "new" renewables (solar, wind) to electric power production are shown in Table 2. The contribution of "conventional" carbon-free energy to other (non-electric) energy uses is shown in Table 3. We begin with electric power.

Currently, the two major "conventional" carbon-free energies are nuclear electric power (row B) and hydropower (row C). Together they currently contribute about 95% of all carbon-free energy. But hydropower is limited by available sites to an approximate doubling of current capacity (although capable of a much improved rate of capacity utilization via adoption of time-of-use pricing). Conventional nuclear energy, once through, open cycle uranium-fueled reactors, is limited by supplies of uranium. In Table 2, we have assumed that economically recoverable reserves can be expanded 10-fold from current levels. (See notes to Table 2.)

Calculation of the potential contributions of new renewables is much more complex. Some figures for solar and wind electricity are presented in row D of Table 2. These are developed further in Section V. Table 3 presents estimates for non-electric energy from biomass and geothermal sources of energy. Adding rows B, C and D in Table 2 indicates "conventional" sources of carbon-free energy might be able to supply 80-110 EJ/yr electric. Table 3 indicates that 80-110 EJ/yr of "conventional" non-electric energy may also be achievable. In thermal terms (multiply each EJ/yr electric by 3) "conventional" carbon-free energy might supply 315 to 425 EJ/yr compared to about 410 EJ/yr from all energy sources consumed in 2000. As Table 1 indicates, carbon-free energy required to stabilize climate in 2100 is likely to be at least 2 to 3 times total energy consumption in 2000.

V. Potential Contribution of Renewable Energy

There is a widely-held belief that renewables, in combination with energy efficiency improvements, can supply most, if not all, of the carbon-free energy required to stabilize the atmospheric CO_2 concentration. That belief was reinforced by the Third Assessment Report of the IPCC's Working Group III (Metz, *et al.*, 2001, Chapter 3) which indicates amounts of renewable energy ostensibly sufficient for stabilization.

The IPCC calculations cannot be accepted at face value. One problem is that what Metz, *et al.* (2001) report is the "technical potentials" of solar, wind, and biomass. But there is a huge difference between IPCC "technical potentials" (which might better be described as "theoretical potentials") and actual net energy (e.g. in the form of electricity) from these sources, after taking account of energy conversion efficiencies, spacing, and energy required to produce the inputs used in renewable energy production. Some of these defects were the subject of a report by Lightfoot and Green (2002), which systematically calculated attainable energy yields for each of the renewables. They first calculated the average amounts of land (km^2) required to produce an EJ/yr of electric energy (solar, wind) or biomass fuel (both solid and liquid) and then multiplied by the land availabilities assumed by IPCC WGIII.

Table 4 summarizes the findings of Lightfoot and Green (2002). It reports the amount of land (in km^2) needed to produce an EJ/yr of electricity (solar, wind) and biomass fuel. For purposes of comparison, Table 4 also reports estimates from Eliasson

(1998) and the land area per km^2 implied by IPCC WG III's textual discussion (although not its tables). Clearly, renewable energies require large amounts of land. Although the IPCC land availabilities are not necessarily upper limits (the percentages used can be raised for solar and wind energy as others, including Hoogwijk (2004) and Archer and Jacobsen (2005), have observed), the actual production of solar, wind, and biomass energy may face more than land constraints.

It is generally overlooked that the "new" renewable energies, solar, wind, and biomass, are not only highly land using, but they are likely to draw heavily on available water supplies as well. In addition, the production of solar panels and the planting, fertilizing, cultivating and harvesting of biomass energy are highly energy intensive activities; and keeping the solar panels clear of dust, sand, dirt, *etc.* is either energy or labour intensive. Moreover, in the case of the two intermittents, solar and wind, the "attainable potentials" are not remotely approachable without the research, development and deployment of grid (Gellings and Yeager, 2004) and storage-related technologies and capacities that are currently far from reality. Among the specific factors constraining large-scale development of the "new" renewable energies are the following:

- Because solar and wind energy are intermittent as well as dilute, only a small proportion of these energies, when fully developed, can be supplied *directly* to the electric grid (Hirsch, 2003). Furthermore, the best locations for the supply of solar and wind energy are typically far from markets with large electricity demands. An excellent source on the limits to the penetration of utility-scale wind power is Pitt, *et al*., (2005).

- To some extent the development of "smart grids", and also superconductive ones, may reduce the intermittency, diluteness and distance problems, but will not eliminate them. Any further contribution to electricity supply by the intermittents must be backed up by *stored* solar and wind energy and/or by operable *and* highly flexible operating base load energy supply such as pumped or dammed hydro.
- Very large amounts of storage (whether in the form of hydrogen, compressed air energy (CAES), batteries, flywheels or pumped hydro) would be required to back up an electricity system that relies heavily on solar and wind energy. It is estimated that storage systems would have to be the magnitude of several months' consumption for solar/wind based electricity supply (Love, 2003). With the possible exceptions of CAES (Cavallo, 2000) and costly electrolytic hydrogen, the other forms of storage are limited in capacity and/or will require important enabling technology breakthroughs for large-scale storage of solar and wind electricity. In addition, the land-intensive generating capacity required to capture sufficient solar and wind energy would have to be substantially larger than average demand in order to (a) replenish storage and assure that supply is maintained at safe and reliable levels (see Love, 2003 and Love, *et al.*, 2003), and (b) to make up for reduced (by storage in storage out) conversion efficiencies.
- If hydrogen is used to store solar or wind energy, large amounts of fresh water are required. It is estimated that 21 billion U.S. gallons (or approximately 80 billion litres) of freshwater of distilled water quality is required to produce an EJ/yr of hydrogen (Lightfoot and Green, 2002). This is enough water to meet the needs of a city of 500,000 persons.

- Biomass is even more water-intensive than electrolytic hydrogen. It is estimated by Bernedes (2002), that 150 to 300 EJ/yr of *solid* biomass (75-150 EJ/yr of liquid biomass) could use as much water as does all current agriculture. Since agriculture, particularly that which is irrigated, currently accounts for a very large fraction of world water withdrawals, large scale biomass would add a huge new element to future world water demand, surely straining, if not exceeding, future water supplies.
- Biomass energy requires large energy inputs, especially when converted to liquid form (bio-fuels). In fact, one recent study (Pimentel and Patzek, 2005) finds that it takes more energy inputs to produce ethanol from corn, wood cellulose, or switchgrass, or biodiesel from soybeans or sunflower than the energy contained in the ethanol or biodiesel.
- Harnessing solar energy is also materials and energy intensive. An editorial article in *Nature* (2002), entitled "Materials for Sustainability", uses solar cells as an example of a supposedly "sustainable resource" which is both materials and energy intensive. According to the article:

  > *"… it has been estimated that solar cells take between three and eight years to pay back their energy costs. Significant energy input stems from the aluminium or steel frames in which the cells are placed. Additional costs come from the manufacture of solar cells, the disassembly and recycling of components, and finally from chemicals that might pose occupational health risks to workers and are difficult to dispose of."*

- The energy intensity of the inputs into solar and biomass energy production has implications for the potential long-term shift away from energy intensive activities. A shift to less energy intensive activities is one means of increasing the rate of energy intensity decline and thereby reducing the amount of carbon (or emission)-free energy required for stabilization. A large increase in the share of energy produced from solar and biomass sources could slow the rate of decline in energy intensity. Doing so, could, as Table 1 indicates, increase the amount of carbon-free energy required for stabilization.

In sum, several factors may limit the scope for large-scale production of energy from the "new" renewables, solar, wind, and biomass. There are two major types of limitations. One is "technological" (storage and grid); the other is "resource" (land, water, and energy). If these constraints are not overcome, then it is unlikely that the land availabilities indicated in Table 4 would be binding.

Table 5 attempts to take account of resource and technological limitations. It presents what might be more realistic *maximum* "attainables" from the new renewable energies, along side the amounts of carbon free energy from solar, wind, and biomass energy when there are only land constraints. When only the land constraint binds, renewable energies might supply anywhere from 326-421 EJ/yr, or 20 to 90 % (col. A) of the carbon free energy required for stabilization under the assumptions on which the core estimates in Table 1 are based. (See notes to Table 5). However, in face of more general resource and technological constraints, a more realistic *maximum* energy supplied by the three "new" renewables is likely to be in the neighbourhood of 125-170 EJ/yr in 2100 (col. B).

Realistically, then, unless resource and technological (primarily storage) constraints to large-scale production and utilization of "green" energy are substantially relaxed, the maximum combined contribution of the "new" renewables, solar, wind and biomass, is unlikely to account for much more than a small fraction of the carbon-free energy required for stabilization. If the "new" renewables are to play more than a niche role in future energy supply, two important decisions will be required: (1) a willingness to turn over large and increasing amounts of surface area and other resources to energy production, and (2) a start now to the research and development of electric grid and storage technologies/capacities that would *enable* large-scale production, storage, and consumption on demand of solar and wind energy. Thus even if global society is willing to turn over large amounts of land and water to energy production, it is still necessary to undertake committed, long-term research and development of "enabling" technologies to make possible the prospect of a major contribution from renewable energies.

VI. Advanced Energy Technology Gap

The two preceding sections provide us with rough indicators of (i) the *maximum* contribution of the two chief current non-carbon energies (hydro and conventional nuclear), and (ii) the *maximum* amounts of carbon-free energy from three "new" renewables that can be expected, in the absence of technological breakthroughs in storage. From Table 3, the maximum contribution of hydro and conventional nuclear is about 210 EJ/yr. To that amount is added: (a) 24 to 31 EJ/yr electric (70 to 90 EJ/yr thermal) from solar and wind energy delivered to the grid, and (b) 80 EJ/yr from biomass, geothermal, ocean and tidal energies, for a total of 150-175 EJ/yr (thermal equivalent) from solar, wind, biomass and other non-hydro renewable energies (see Table 5, col. B). Thus, "conventional" carbon-free renewable energies and conventional nuclear could potentially supply anywhere from 360 EJ/yr to 385 EJ/yr. Note that this is a physical estimate and does not address the issue of economic competitiveness.

Hoffert, *et al.* (1998), developed a framework encapsulated in figure 1, indicating the amount of carbon-free energy (EJ/yr)/terawatts of power required to stabilize the atmospheric CO_2 concentration. (A terawatt, 10^{12} W, is equal to 31.5 EJ/yr. Because the Hoffert *et al.* (1998) article employs TWs instead of EJ/yr, and that article is so important to climate policy, the Hoffert diagram is produced here, using TWs, with a notational translation to EJ/yr.) The trade-off curve, ZW, in Figure 1, indicates how the required amounts of carbon-free power vary with the rate of energy intensity decline (similar to what is reflected in Table 1). Hoffert, *et al.* assumed a variable GDP growth rate for (1990-2100), one that averages 24.6%, and a 1.0% average annual rate of energy intensity decline. Estimates (Lightfoot and Green, 2001; and Baksi and Green, 2004a) place the *maximum* attainable average annual rate of energy intensity decline through 2100 in the range of 0.9 to 1.2 percent. As indicated above, a rough estimate of the maximum amount of "conventional" carbon-free energy is 360-385 EJ/yr, or about 12 TW. In Figure 1, line CD is based on the assumption that 12 TW (≈ 380 EJ/yr) "conventional" carbon-free energy is attainable. The area between curve ZW and line CD, indicated by the hatched lines, represents the amount of carbon-free energy that must be met by "advanced" carbon-free energy sources and technologies (including stored solar and wind power).

In other words, the hatched area in Figure 1 brings together the attainable combinations of energy intensity decline, and *conventional* carbon free energy potentials to indicate an "*advanced energy technology gap*" (AETG). If the attainable rate of energy intensity decline is 1.0%, and the attainable amounts of renewable and other "conventional" carbon-free energies are approximately 380 EJ/yr (≈12 TW), the AETG is about 790 EJ/yr (≈25 TW). If, optimistically, the attainable rate of decline is 1.2%, the AETG is almost 15 TW, or about 470 EJ/yr (≈15 EJ/yr). At lower (higher) rates of GDP growth the amounts of carbon-free power (energy) required for stabilization would be commensurately lower (higher) and the AETG lower (higher), given the rate of energy intensity decline, as Table 1 demonstrates. Also note that the calculations above are for stabilization of the atmospheric CO_2 concentration at 550 ppmv. For stabilization at 450 ppmv, the AETG would be much larger.

VII. Additional Sources of Carbon Emission Free Energy: The Contribution of Hydrogen

What are the advanced energy technologies that might be called upon to fill the gap? Some of these may be so futuristic that they are currently unknown. But among the known advanced energy technologies are advanced nuclear fission (Butler, 2004); nuclear fusion; fission-fusion hybrids (Mannheimer, 2004); non-terrestrial solar energy (Hoffert, 2005); deep (below mantle) geothermal; and carbon capture and sequestration (CCS). The process of carbon dioxide capture could produce plentiful hydrogen from plentiful fossil fuels, without emissions to the atmosphere.

Here we will limit discussion to the potential contribution of hydrogen. Hydrogen is not a primary form of energy, but a secondary, or carrier of, energy. Pursuing a "hydrogen economy" will require major breakthroughs not only in the large-scale production of hydrogen, but in its transport, storage, and handling (U.S. Department of

Energy, 2004; NAS, 2004; Crabtree, *et al.,* 2004; Service, 2004; Keith and Farrell, 2003; Eliasson and Bossel, 2003). For a number of reasons, hydrogen's future may depend on CCS, a stand alone means of prolonging the planet's reliance on fossil fuels (Lackner, 2003). The large scale development of CCS depends on cost-effective CO_2 capture and the certification of sufficient safe and secure storage capacity (Herzog, 2001; Lackner, *et al.,* 1998). Pursuit of CCS may therefore hold the keys to large scale use of hydrogen as an energy fuel. In a recent paper, Pacala and Socolow (2004) provide an interesting perspective on hydrogen's potential contribution to stabilizing climate.

In their paper, Pacala and Socolow (PS) suggest that "current technologies" are capable of "solving the climate problem" for the next 50 years. "Solving" according to Pacala and Socolow (PS), is maintaining carbon emissions constant from 2004 to 2054. After 2054, PS agree with Hoffert *et al.*, that new energy technologies will be required. While PS's basic premise, that emissions can be stabilized for the next 50 years with "current technologies", is highly debatable (convincing evidence is lacking that current technologies are sufficiently scaleable to stabilize emissions for the next 50 years), the paper, particularly its supporting on-line material (SOM), contains a wealth of useful information about low or carbon emission-free technologies. Hydrogen and its relationship to other technologies, is one of these.

Hydrogen is currently used chemically, for industrial uses. It is produced chiefly by reforming methane, which in addition to hydrogen yields a stream of CO_2. Although most of the CO_2 is currently vented to the atmosphere, it could be collected and geologically stored. But the larger promise of hydrogen is as an energy fuel. To achieve this promise, a variety of technological problems must be overcome. PS ignore the downstream (post-production) technological problems and ask instead how hydrogen might enter the energy economy.

PS focus on the production of hydrogen, and, once produced, how it is used. Their paper addresses how carbon emission-free energy technologies might each reduce global carbon emission in 2054 by one GtC "wedges". PS analyze and compare (SOM 27-30) different means of producing and using hydrogen. PS find:

1. If carbon-free electricity is available, it "reduces carbon emissions twice as effectively when directed toward the displacement of coal-based electricity than when directed toward the displacement of gasoline fuel *via* electrolytic hydrogen". (SOM: 29)

2. If CCS is available, it is preferable to produce hydrogen as part of a process that uses coal to produce electricity, with CO_2 captured and stored. It is duplicative to produce electrolytic hydrogen, which is later converted back to electricity, for end use. (SOM: 17, 30)

In other words, if nuclear energy is available to produce electricity, and reducing carbon emissions is the objective, then carbon emissions are more effectively reduced, per unit of energy by producing electricity for the grid. To use nuclear energy electrolytically to produce hydrogen for fuel, as for example as a substitute for gasoline, is only half as effective in reducing carbon emissions as using nuclear energy as an alternative to coal-based electricity. Furthermore, using grid electricity instead of carbon-free electricity to power electrolyzers does not currently make sense either. As PS put it, "globally averaged grid electricity at present is too carbon rich to be a source of carbon saving *via* electrolytic hydrogen and fuel cell cars." (SOM: 30)

The apparent inference from the PS analysis is that the most effective way for hydrogen to enter the energy economy is as a byproduct of CCS. In this case the hydrogen can be used as the means of generating electricity, or if technological problems in hydrogen distribution and storage can be overcome, as an alternative to gasoline as a transportation energy fuel. A further inference is that large scale production and use of hydrogen as an energy carrier probably awaits large scale CCS.

PS do not consider the potential role of hydrogen as a means of storing intermittent solar and wind energy. As we saw in Section V, if intermittent renewable energies are to make more than a *niche* contribution to energy supply, large scale means of storage are required. Unfortunately, as we also noted in section V, electrolytic hydrogen is not only costly but requires large amounts of fresh water of a high degree of purity (Lightfoot and Green, 2002, Appendix E). Such quantities of water may not be abundant in areas of high insolation or high average wind speeds. Nonetheless, if there are resource limits or political resistance to the large scale expansion of nuclear energy, and if CCS turns out to be more limited than now seems likely, there will be added pressure on solar and wind energies as alternatives to fossil fuel electricity. That would require their storage, and on a large scale (Love, 2003). Although the process of producing hydrogen electrolytically for eventual electricity-generating purposes, is circuitous, expensive and resource-using, limited storage alternatives may require rethinking of the way in which hydrogen could enter the energy economy.

VIII. Getting There: The Role of Economics Instruments

The preceding three sections make clear that: (1) “conventional” carbon-free energies, in conjunction with energy efficiency improvements, are insufficient to stabilize climate; and (2) hydrogen is one of a number of energy technologies requiring serious research as well as development. As a result, the real economic challenge to a low carbon future consists of: (a) facilitating the R&D of scaleable carbon emission-free energy technologies; and (b) inducing the deployment of successful technologies. These will require different policy approaches and tools.

Economists who have addressed climate policy tend to emphasize the role of market-based instruments and policies. We think such instruments are, at best, only part of a climate policy story. We suggest that in the absence of scaleable carbon emission-free technologies, there is reason to doubt the efficacy of carbon emission permits or carbon taxes to significantly mitigate carbon emissions (Baksi and Green, 2004b).

Two factors may limit the efficacy of market mechanisms as the primary instruments for stabilizing climate. First, carbon taxes high enough or carbon emission permits scarce enough, to substantially reduce emissions are unlikely to be adopted. If they are adopted they are likely to be rejected at the next election, particularly if it becomes clear that sufficient carbon-free energy is not yet available. Second, there is doubt about the capacity of carbon taxes or emission permits to *induce* the necessary technological change. The first factor is based on a political time inconsistency, elections occur before new technologies are developed much less deployed. The second factor reflects a potential dynamic inconsistency in which a government today is unable to credibly commit future governments to compensate large and risky investments in R&D with sufficiently high future energy prices. (Montgomery and Smith, 2005).

The role of economics in climate policy needs rethinking. We think that, first and foremost, climate change is an energy problem, and stabilizing climate is a difficult energy technology problem. Climate policy should take a cue. While there is a place for policies that can effectively induce greater efficiency in energy use or the efficient adoption of readily available and competitive energy technologies, we should not lose sight of the bigger challenge: the research and development and eventual deployment of scaleable carbon emission-free energies (Hoffert, *et al.*, 2002; Green, 2000).

We suggest dividing the RD&D process into two parts: (a) basic research and development; (b) commercial development and deployment. The first, up-front, part requires a commitment to research and develop a suite of prospective carbon-free energy technologies. Research and development will require not only demonstration *via* pilot plants, but also demonstration of their scaleability. To finance these endeavors requires a commitment to long term public or public/private finance. An appropriate mechanism would be a small, earmarked carbon tax, the revenues from which would be placed in an energy R&D trust fund in a manner similar to the U.S Interstate Highway Trust Fund established by the Eisenhower administration in the 1950's.

When a technology is ready for commercial development and deployment on a wide scale, market mechanisms may then be used to enhance adoption. For example, CCS may be an early candidate for such treatment. Once carbon dioxide storage capacity has been identified and the rights of way for CO_2 pipelines established, carbon taxes or tradable permits could be applied to induce adoption of capture technology. The instruments should be tailored to the carbon emitting entities capable of adopting the carbon capture technologies. At present the main sources would be electric power plants, and some highly energy intensive industries such as petrochemicals, metal production, non-metallic mineral processing, and producers of hydrogen for industrial purposes. In other words, instead of using market mechanisms as means of meeting national emission targets, the mechanisms would be better used to induce the least-cost adoption of newly developed technologies ready for deployment.

IX. Conclusion

The paper addresses same key challenge to a low carbon energy future. The major challenge is the research, development, and eventual deployment of scaleable and affordable carbon emission-free energy technologies and sources. The magnitude of that challenge depends on three main factors: (i) the growth of energy using activities (roughly captured in the GDP growth rate); (ii) the attainable rate of energy intensity decline; and (iii) what the paper terms an *advanced energy technology gap*, the difference between the carbon emission-free energy requirements for climate stabilization and attainable amounts of “conventional” carbon- free energies that can be deployed. The paper shows that a large *advanced energy technology gap* (AETG) exists.

The paper emphasizes that climate change and policy are energy technology problems. As such, in the context of stabilizing CO_2 concentration, technology tends to take precedence over economics. While efficient adoption of carbon emission-free energy technologies will depend on economic factors, the availability of carbon emission-free energies in quantities capable of stabilization is a long term energy technology problem. The paper therefore suggests that a low rate carbon tax be used to finance the necessary long term research and development of scaleable carbon emission-free technologies, with taxes and tradable permits reserved for technologies ready for deployment.

The analysis has implications for climate policy targets and commitments to meet them. While current climate policy focuses on emission targets, the fundamental role of energy technologies suggests an alternative target: the development and deployment of carbon emission-free energy. Without their development and deployment, no commitment to stabilization of CO_2 concentration is credible. For example, many European nations, in particular Germany, France, and the UK, have set emission reduction targets of from 60 to 80 percent from current emission levels, by mid-century (≈ 2050). Kawase, *et al.* (2005), use a Kaya type decomposition analysis to demonstrate that these hugely ambitious targets require improvements in the pace of energy intensity decline and the carbon intensity of energy over the next 50 years that are 2 to 3 times greater than the rapid pace of the last 40 years. Given limits to the rate of decline in energy intensity (Lightfoot and Green, 2001; Baksi and Green, 2004a) most of the weight of emission reduction must fall on the decarbonization of energy. Without technology breakthroughs, the adopted targets are simply not credible.

Technology oriented targets would appear to make more sense than commitments to (a) specified (date and quantity) emission targets, that are neither meaningful nor credible (Schelling, 1992) or (b) atmosphere CO_2 stabilization targets that are not achievable without the required carbon emission-free energy technologies. Despite references that Kyoto emission targets are legally binding; *de facto* they are not easily enforceable.

The Kyoto Protocol does not provide an appropriate procedure for assuring that the convention is respected by its parties (see Birnie and Boyle, 2002). There is a *point of view* which suggests that any international treaty or international arrangement should make its parties responsible for associated domestic legislation. In principle, the legislation would be aimed at achieving required reductions in GHG emissions. But whether any constitutional arrangement by parties to an international climate change-related treaty (convention) can make climate-related commitments credible, is both an important and debatable issue.

We made clear in this paper that without technological breakthroughs, market-based mechanisms/institutional changes alone cannot provide the basis for stabilizing of the atmospheric concentration of CO_2 at levels that do not pose a "dangerous interference" with climate. Establishing a constitutional right to a clean air/healthy environment for every citizen in nations that are parties to the international arrangement may reduce election/lobbying-related time inconsistencies to resolving environmental problems. Of course, one should also pay attention to the costs of enforcing this type of legislation (e.g. social costs of law suits). However, in general, domestic legislation is more easily enforced (more credible) than an international obligation. Therefore in many countries, domestic legislation provides detailed regulations in order to protect the environment (for the framework in France, see Prieur, 2004). But whether similar legal provisions are applicable to the climate change problem is, as we have suggested, debatable.

Length and terms of references preclude pursuing the targets and commitments issue further. It also precludes the important issue of the form that an energy technology race might take. One possibility emphasizes competition, characterized by competing international consortia. But that is a subject for another paper. What is clear is that taking seriously a low carbon energy future, and the eventual "stabilization of climate", requires a reorientation of thinking about climate policy.

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Table 1

Carbon-Free Energy (EJ/yr) in 2100 Required to Stabilize Carbon Fossil Fuel Use at its 2000 of 343 EJ/yr for Constant Growth (Decline) Rates for GDP (Energy Intensity)[a,b]

Average Annual Rates of Global GDP Growth, 2000-2100 (%)	Average Annual Rates of Energy Intensity Decline, 2000-2100 (%)								
	0.7	0.9	1.0	1.1	1.2	1.3	1.5	1.7	2.0
1.5	536	380	309	245	189	141	54	0	0
1.8	838	628	533	447	371	305	190	91	0
2.0	1,094	839	723	619	526	445	306	185	51
2.2	1,405	1,095	954	827	715	616	447	300	136
2.3	1,585	1,243	1,088	948	823	714	528	366	186
2.5	2,001	1,585	1,396	1,226	1,075	942	715	519	300
2.7	2,503	1,998	1,769	1,562	1,378	1,218	942	703	437
3.0	3,470	2,793	2,486	2,209	1,963	1,748	1,379	1,059	703

a) Carbon-free energy in 2000: 57 EJ/yr

b) If carbon emitting energy consumption grows to 500 EJ/yr before mid-century it must decline to between 100 and 150 EJ/yr in 2100 to produce
roughly the same result as maintaining a constant consumption of 343 EJ/yr throughout the 21st century. For non-constant case add about 200+ EJ/yr
to figures in Table.

c) EJ is Exajoules. An EJ is 10^{18} joules (or 1.055 Quads=10^{15} BTU). There are 31.5 EJ/yr to 1 Terrawatt (TW) power (10^{12} W).

Table 2

Potential Contribution of "Conventional" Carbon Emission-Free Energies to Electricity Generation in 2100 (EJ/yr electric)

Electricity Generation and Conventional Carbon Emission-Free Sources	Growth Rate of Electricity Generation/Consumption (2002-2100)			
	1.0%	1.5%	2.0%	2.5%
A. World Electricity Generation in 2100[a] (EJ/yr)	146	237	383	618
B. Potential Contribution of Conventional Nuclear[b]	38	38	38	38
C. Potential Contribution of Hydroelectric[c]	32	32	32	32
D. Potential Contribution of "Direct" (to grid) Solar/Wind Generated Energy (w/o storage)[d]	15	24	38	62
E. Contribution of B+C+D as % of A	58%	40%	28%	22%

a) In 2002, world electricity generation was 1.745 TW_e (equal to 15,290 billion kwh), or 55 EJ/yr electric.
b) Based on 1500 1000 MW_e nuclear generation plants, operating at 80% capacity utilization, and consuming 306,000 tonnes of uranium per year. It is assumed that current proved reserves of 3 to 4 million tonnes can be expanded to 30 million tonnes as uranium prices increase. See *The Future of Nuclear Power*, an interdisciplinary MIT study (MIT, 2003, p. 34).
c) It is assumed that over the course of the 21st century current (2002) hydroelectric capacity of 723.6 million KW can be doubled and that the current worldwide load factor of 40.7% can be raised to 70% by the application of time-of-use (TOU) pricing. By 2100 this would allow the generation of 31.9 EJ_e/yr, or approximately 1.0 TW_e.
d) Rounded to the nearest whole number; it is assumed that intermittency and variability limit the "direct" supply of electricity to 10% electricity generated (Row D is 10% of row A). A further contribution of solar and wind to electricity generation will require large-scale storage of solar and wind generated energy and probably upgrade of grid (smart grids) to cope with increased variability. It is also assumed that the requisite amounts of land, indicated in the Table below, are available:

Table 2 (continued)

Rate of Growth of Electricity Consumption/Generation, 2002-2100 (%)	Contribution of Solar and Wind (row D of Table 2)	Land Requirements (km^2) if		
	EJ_e/yr	All Solar[a]	All Wind[b]	50% Solar, 50% Wind
1	14.5	30,682	290,000	160,000
1.5	23.6	49,938	472,000	260,969
2	38.1	80,620	762,000	421,310
2.5	61.7	130,557	1,234,000	682,279

a) For an average insolation of 200 Wm^2, 2116 km^2 is required per EJ/yr, with 2X spacing.
b) Based on 20,000 km^2 per EJ/yr of wind-generated electric energy (Lightfoot and Green, 2002).

Table 3

Potential "Conventional" Carbon Free Energy: Non Electrical Usage

	EJ/yr
Biomass (Bio-fuel liquid)	**≈60** [a]
Others (mainly geothermal for heating /cooling)	**≈ 20**
Total	**≈80**

a) Net of 50% loss in converting from biomass solid to liquid, and additional losses due to netting the energy used in planting, cultivating, harvesting, and transportation. Note that the estimate assumes the energy output from bio-fuel (ethanol and biodiesel) exceeds the energy inputs in producing the fuels, despite recent evidence to the contrary (Pimentel and Patzek, 2005) implying net energy is actually *negative*. Also assumes that biomass, may be produced on somewhat less than 100% of cropable land not used for crops. (See Table 4., and text.)

Table 4

LAND INTENSITY AND RENEWABLE ENERGY POTENTIALS

	(1)	(2)	(3)	(4)
Energy Source	**km^2/EJ**	**IPCC WG III (2001)**	**IPCC III Land Availability (km^2)**	**Range of Energy Estimates (EJ/yr)**
Solar **(electricity)**	1,900-2400 [a]	2,100-2,400	393,000	163-206
Wind **(electricity)**	16,700-25,100	16,700	1,200,000 [b]	48-72
Biomass **Solid** **Liquid**	19,000-48,000 50,000-120,000	33,000 60,000-95,000	8,895,000 [c]	234-275 75-179
Total	N/A	N/A	N/A	326-481

Col.

(1) Range of Estimates based on: IPCC WG III (2001); Eliasson (1998); Lightfoot and Green (1992).
(2) Calculated by Lightfoot and Green (2002).
(3) IPCC WG III (2001): solar: 1% of unused land; wind: 4% of all land with average wind speed greater than 5.1 m/s; biomass: 100% of estimated (by Lightfoot and Green (2002)) cropable land not used for crops, in 2100, which is about 25 percent lower than the IPCC estimate for 2050..
(4) Lightfoot and Green (2002). The total assumes that biomass energy is 25% solid and 75% liquid.

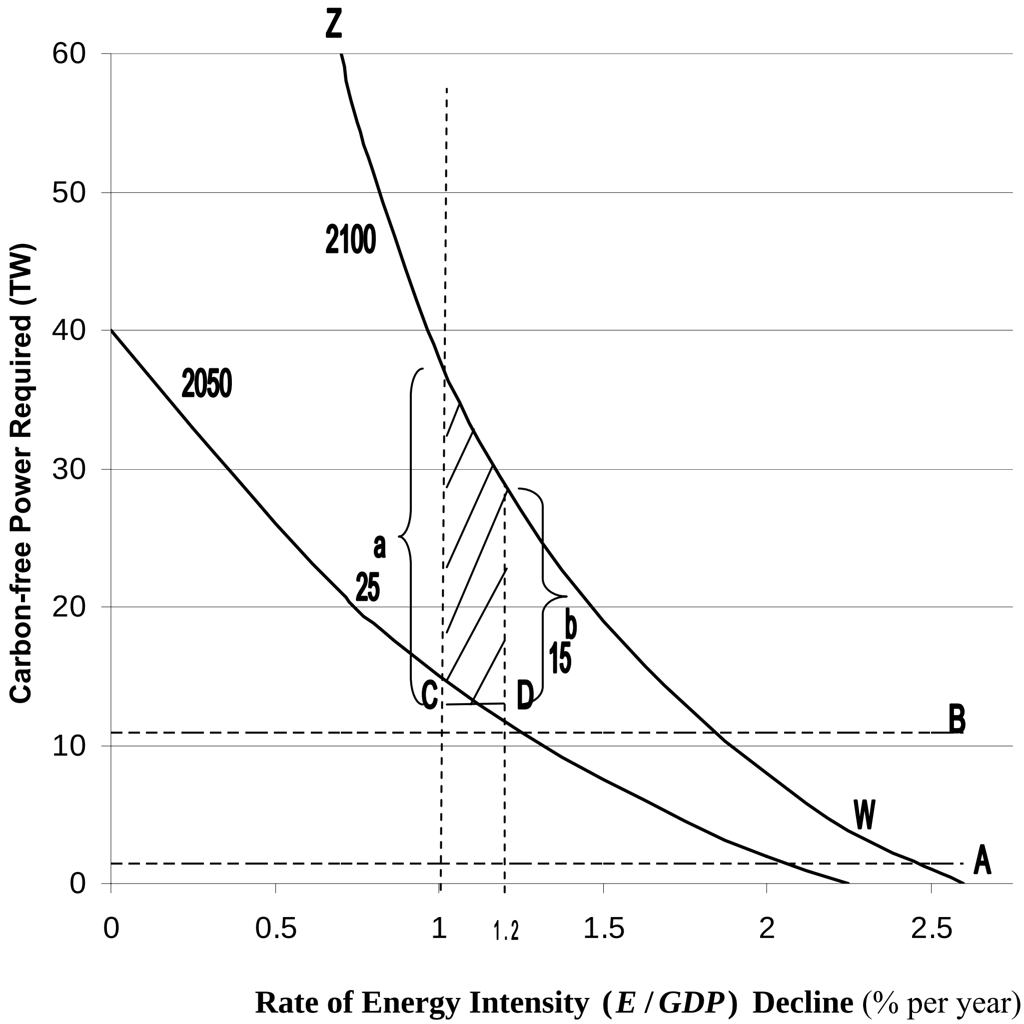
Notes
a) horizontal arrays with spacing which is 2 times area with panels;
b) does not include off shore wind sites;
c) estimate 2100 (see text).

Table 5: Renewable Energies[a] that Could Potentially be Available in 2100, Under Two Different Sets of Assumptions

	A	B
	WG III Land Availability [b]	**A Resource, Storage and Grid Constrained World**[c]
EJ/yr in 2100	326-481 EJ/yr [c]	150-175 EJ/yr[d]
% of carbon free energy needed to stabilize at 550 ppmv IS92a[e]	21-91%[f]	9-33%[f]

Notes:
a) total solar, wind, biomass
b) see Table 4, col. 3.
c) see Table 4, col. 4.
d) from Table 2 row D and Table 3.
e) Carbon-free energy from Table 1 for 100 year GDP growth and energy intensity decline rates of 2.0-2.5% and 0.9-1.2% respectively.
f)Percentages are overstated, if carbon-free energy requirements are higher, in 2100, than indicated in Table 1. (See text, pp. 5-7).

Figure 1: Advanced Energy Technology Gap



Line A ⇒ 1990 Carbon-free Power

Line B ⇒ 1990 Total Primary Energy "Burn Rate"

Estimated magnitude of "Advanced Energy Technology Gap" is indicated by hatched area.
Based on Hoffert, *et al.* (1998) Figure 3. 21st century trade-offs, between carbon-free power required and "energy efficiency", to stabilize atmospheric carbon at twice the pre-industrial CO_2 concentration.

Notes:
a) 25 TW= 787 EJ/yr
b) 15 TW= 472 EJ/yr