Global climate change – the technology challenge

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Abstract

Anthropogenic emissions of greenhouse gases, such as carbon dioxide, have led to increasing atmospheric concentrations which are at least partly responsible for the roughly 0.7°C global warming earth has experienced since the industrial revolution. With industrial activity and population expected to increase for the rest of the century, large increases in greenhouse gas emissions are projected, with additional and potentially substantial subsequent global warming predicted. The paper provides a brief overview of the factors driving CO_2 emissions for the world and for selected countries, an examination of key technologies that would be required for an aggressive mitigation program, and a concise sector-by-sector summary of mitigation options, along with R&D priorities.

1 Introduction

The Intergovernmental Panel on Climate Change [1] concluded in 2001 that anthropogenic emissions of greenhouse gases, such as carbon dioxide (CO_2), have led to increasing atmospheric concentrations which are to be at least partly responsible for the roughly 0.6°C global warming earth has experienced since the industrial revolution. Since 2001, warming has now increased to an estimated 0.7°C (NCAR [2])

In Figure 1, IPCC [1] has summarized historical and projected trends for atmospheric concentrations of CO_2. In order to make these projections, the Panel evaluated a range of scenarios, including alternative business-as-usual cases and various mitigation scenarios. As Figure 1 shows, the projected concentrations can be as high as 1000 ppm compared to a pre-industrial level of 280 ppm and a

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current level of 382 ppm. This increase in CO_2 concentration and the contributions of other greenhouse gases are the major driving force for global warming.

The author will now discuss the factors that lead to increasing emissions of CO_2 and the anticipated contribution of key countries. Then, CO_2 emissions will be projected into the future for key sectors. Finally, the author will summarize the state of the art of key technologies and R&D priorities for each of four key sectors that can contribute to mitigating such emissions. (Not that in this paper, all CO_2 concentrations will be in ppmv and all warming will be realized or transient warming, as opposed to equilibrium warming.)

Although, the scope of this paper is limited to a consideration of technologies that could play a major role in reducing CO_2 emissions, it is important to note that availability of key technologies will be necessary but not sufficient to constrain emissions. Since many of these technologies have higher costs and/or greater operational uncertainties than currently available carbon intensive technologies, robust policies will need to be in place to encourage their utilization.

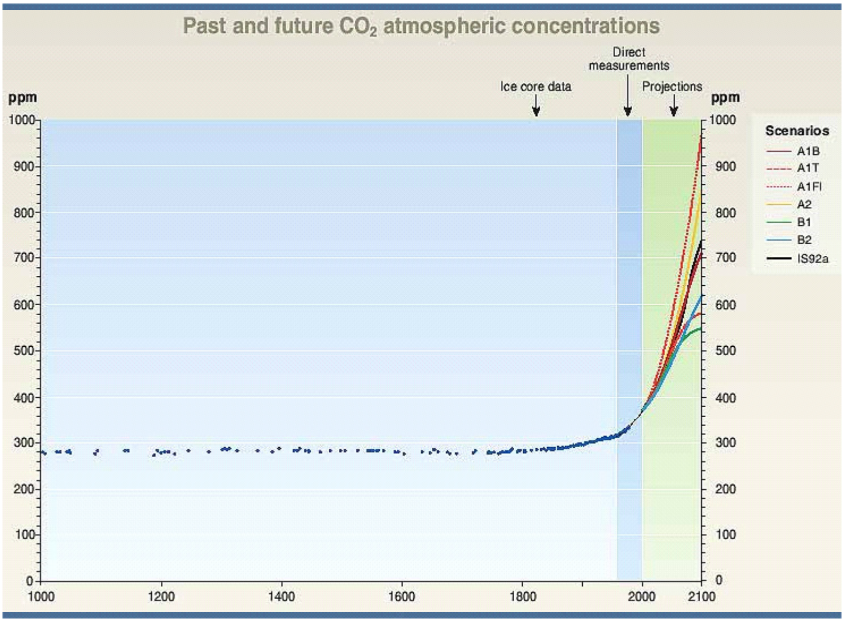

Figure 1: Past and projected atmospheric concentrations of CO_2.

2 Factors that drive emissions of CO_2

The World Resources Institute [3] has examined the factors that have driven CO_2 emissions for key countries in the 1992 to 2002 time period. The factors considered are: Gross Domestic Product (GDP) *((Purchasing Power Parity (Intl $))*, growth per capita, population growth, carbon intensity growth per unit of energy (more coal in the mix increases this factor), and the growth of energy usage per unit of GDP. The sum of these factors approximates the annual CO_2 emission growth rate. The author has used the Institute's data to generate Figure 2, which shows how these factors have influenced the annual growth rate of CO_2 for selected countries during this ten-year period. As can be seen for the *world*, despite *decreases* in the energy use per unit of GDP, the CO_2 growth rate was about 1.5% per year. The rate for the *U.S.* also has been about 1.5%, but the growth rate for *China and India* has been about 4% per year, driven by economic growth, and for India, population growth as well. Note that in the absence of significant decreases in energy use per unit of economic output, CO_2 emission growth rates would have been substantially greater.

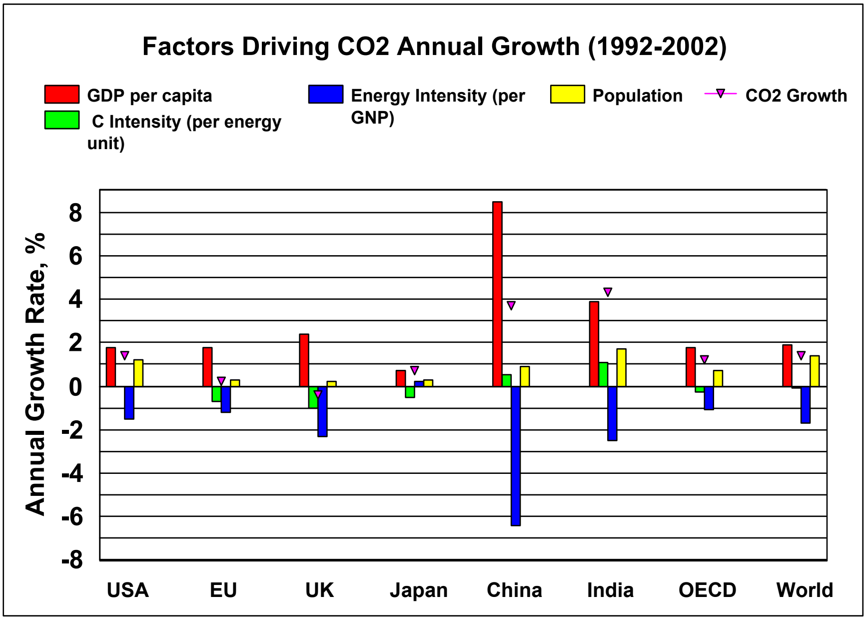

Figure 2: Factors driving CO_2 emissions for selected countries.

If these trends continue, first China and then India will surpass the U.S. as the largest CO_2 emitter in the coming decades. The main driver for this accelerating trend for these populous Asian countries is their expected high rate of economic growth as they strive for a standard of living approaching those of the developed countries.

3 The mitigation challenge; which sectors and gases are most important?

In order to identify the most promising mitigation technologies, it is necessary to understand the current and projected sources of CO_2 and the other greenhouse gases. The author has derived the information in Figure 3 from IEA [4]. This graphic projects world CO_2 emissions by sector; it suggests that power generation and transportation sources will be the fastest growing and will be the key to any successful mitigation program. This IEA baseline scenario, assumes a continuation of CO_2 emission growth consistent with Figure 2: for 2000 to 2030, 1.5%; and for 2030 to 2050, a 2.2% CO_2 growth rates. As mentioned earlier, China and India, with a cumulative population of over 2.4 billion, are projected to continue their rapid economic expansion with commensurate pressure on the power generation and transportation sectors. It should also be noted that the energy transformation category in Figure 3 includes petroleum refining, natural gas and coal conversion to liquids and biomass to alcohols, much of which will feed the transportation sector.

For the U.S., The World Resources Institute [5] has generated a very informative graphic. Figure 4 illustrates the relationship between sectors, end use/activities, greenhouse gases, and the resulting driving force for warming for the year 2000.

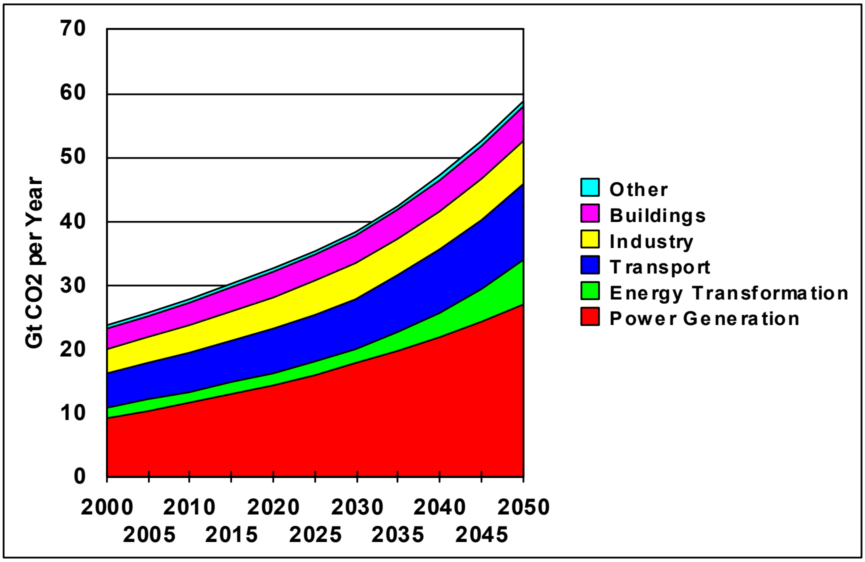

Figure 3: Projected world CO_2 emission growth for key economic sectors.

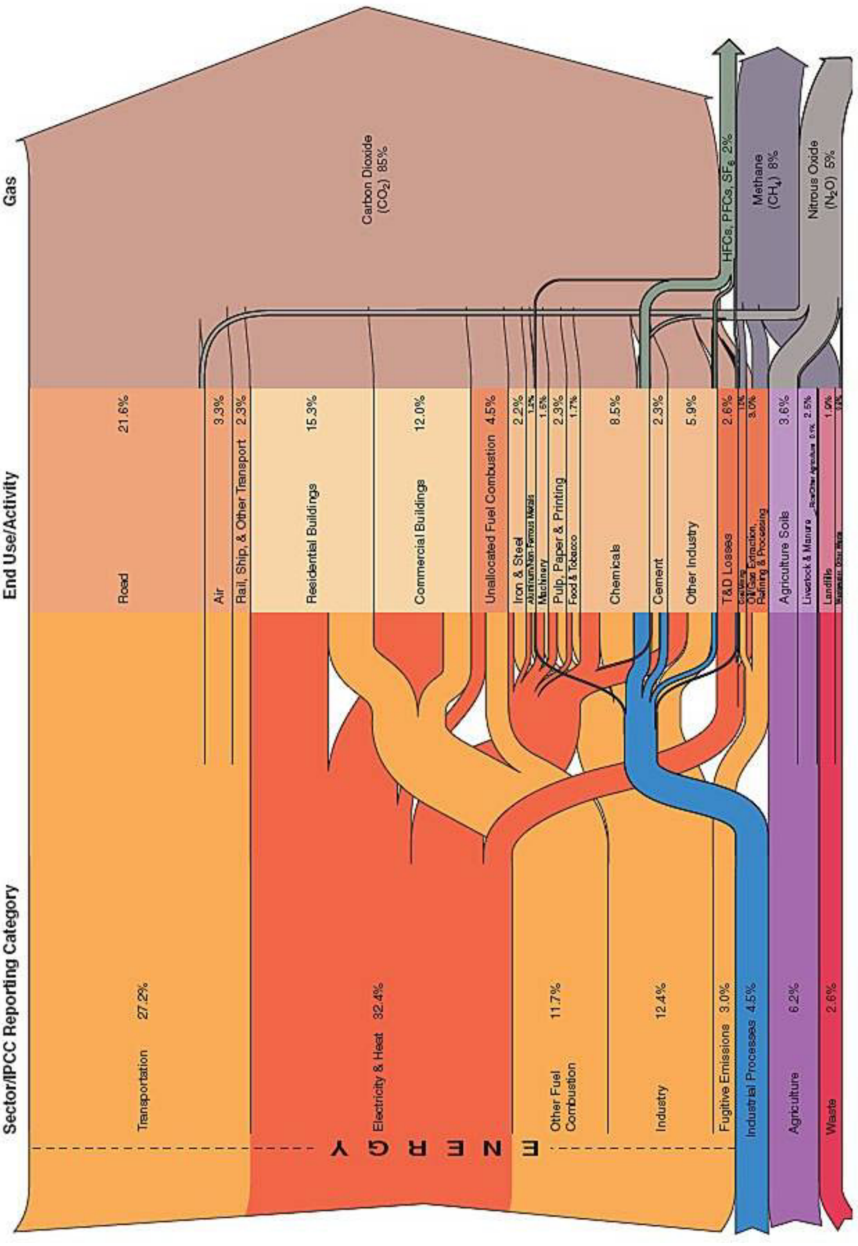

Figure 4: GHG emission flows by sector, end use, and gas in 2000.

This graphic also illustrates the relationship of power generation (electricity and waste heat in the figure), and its end use in the building and industrial sectors.

At this point it should be acknowledged that certain gases other than CO_2 contribute significantly to warming. Figure 4 illustrates this for the U.S. Although CO_2 is the dominant driver, methane and nitrous oxide are significant. For the international view of the relative significance of the key greenhouse gases, the author has generated Figure 5 using the MAGICC model (Wigley and Raper [6]). This figure illustrates the relative thermal forcing of the key greenhouse gases for 2020, 2050, and 2100 using emission projections consistent with the author's modified IEA base case for CO_2 and IPCC [1] Scenario WRE750 for the other greenhouse gases. Note that fine particles show a cooling effect in 2020, which transforms to a warming effect in later years. This is explained since emissions of sulfur dioxide are projected to increase until 2020, whereas the emissions will be reduced later in the century as countries install SO_2 controls. With such emission control, concentrations of sulfate particles, which reflect incoming solar radiation, will consequently be lower, and their cooling effect reduced, yielding warming relative to 1990.

For this paper, *the focus will be on CO_2*, since it is the critical greenhouse gas.

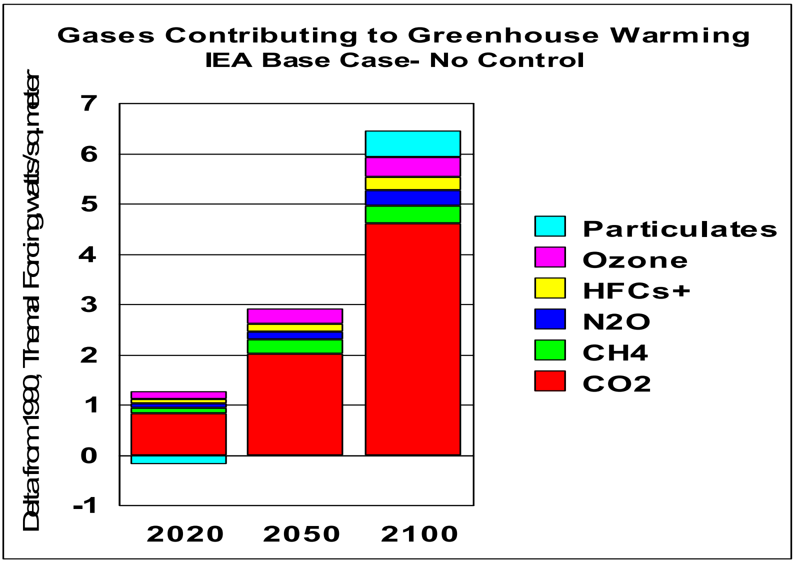

Figure 5: Relative driving force of major greenhouse gases.

4 The mitigation challenge; what role can energy technology play and what are the options:

Although this paper will focus on energy technologies, it should be noted that complimentary approaches could be significant as well. They include life style changes, such as lowering thermostats in the winter and minimizing driving mileage, and more energy efficient urban planning, which could facilitate mass transit rather than car and truck transport. Also, as suggested by Figure 5, methane, ozone and nitrous oxide mitigation approaches could be significant for the roughly 20% of the thermal forcing associated with them. Finally, there have been various geoengineering approaches suggested which could potentially help buy time until new energy technologies are developed and deployed. For example, Wigley [7] suggested simulating volcanoes, which are known to cool the planet after high altitude eruptions, by purposely emitting large quantities of sulfate particles into the stratosphere. The objective would be to reflect incoming solar radiation. Of course such approaches are very early in their design and would have to be carefully evaluated for their economic and environmental impacts.

In order to understand the potential of various energy technologies to mitigate CO_2 emissions, IEA [4] recently evaluated what it called Accelerated Technology (ACT) scenarios. Of these, the ACT *Map* scenario is the most optimistic, assuming an aggressive and successful R, D & D program to improve commercial or near commercial technologies and a comprehensive demonstration and deployment program for key technologies. It also assumes policies in place that would encourage the use of these technologies in an accelerated time frame. These include CO_2 reduction incentives to encourage low-carbon technologies of cost up to \$25/T CO_2 in all countries from 2030 to 2050. The incentives could take the form of regulation, pricing, tax breaks, voluntary programs, subsidies, or trading schemes.

The author has generated Figure 6, which projects CO_2 emissions by sector, for the ACT Map scenario, based on their assumption that major technology implementation starts in 2030. Figure 7 depicts the CO_2 savings projected by sector using the ACT Map scenario. Most of the savings relate to the power generation sector, which includes both production and end use savings. This IEA scenario is projected to result in the mitigation of 32.5 Gt of CO_2 in 2050. As will be discussed subsequently, this level of mitigation, would be impossible without the use of improved and in some cases breakthrough energy technologies. Such technologies are necessary for both energy production, i.e., power generation, and to enhance end use efficiency, i.e., lower emission vehicles.

It is important to note that for the IEA Map scenario extended to 2100, the author's MAGICC (Wigley and Raper [6]) calculations indicate best-guess CO_2 concentrations in 2100 of 500 ppm and a corresponding warming of 2.0°C relative to 1990. This is despite the IEA assumption of an aggressive R,D&D and deployment program and the author optimistically assuming further major (2% per year) emission reductions for 50 years beyond the IEA time frame of 2050. This suggests that even a major mitigation program, globally implemented, based on successful development and deployment of several new technologies, will still allow substantial global warming in 2100.

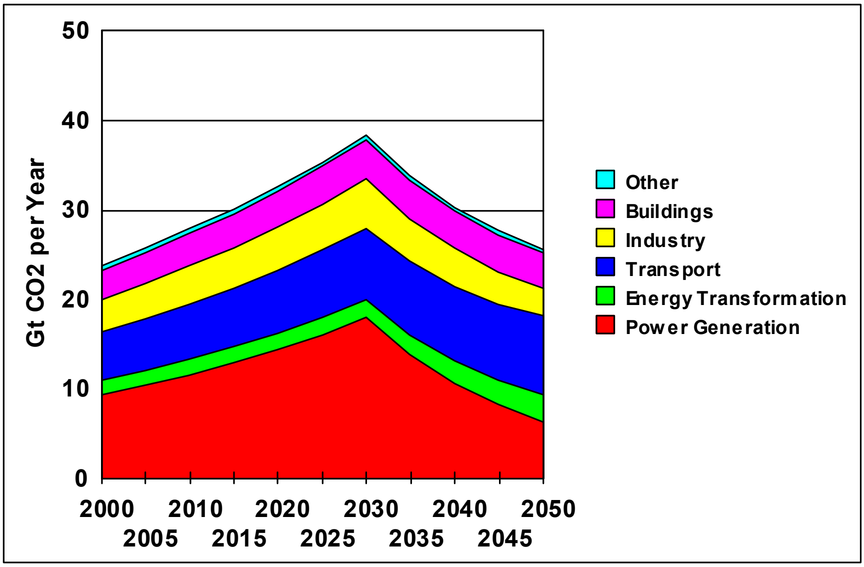

Figure 6: Sector CO_2 emissions for the IEA ACT scenario.

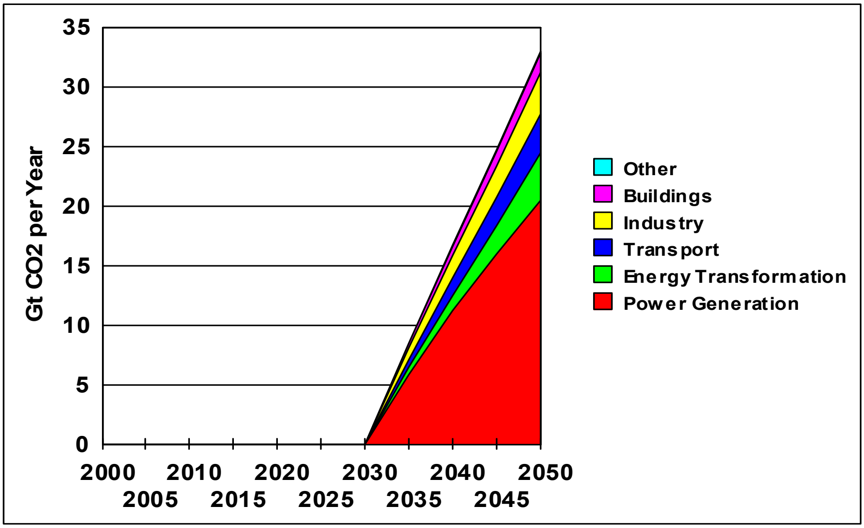

Figure 7: CO_2 emission reductions per sector for the ACT scenario.

The author has generated Tables 1–4 for the key four sectors to summarize the potential and status of key technologies based on the following recent energy technology assessments: IEA [4], Hawksworth [8], Pacala and Socolow [9], Morgan et al. [10]. Two additional references contained useful information relative to hydrogen/fuel cells, USEPA [11], and nuclear technologies, USEPA [12].

Let us now focus on these four critical sectors and examine the technology options available, their current state of the art, and the required R, D&D to allow the technology options to meet their potential to reduce CO_2 emissions.

5 Power generation sector

Of all the sectors, the power generation sector, which is projected to grow at an annual rate of 2%, has the greatest potential to reduce CO_2 emissions in the coming decades. However, it should be noted that there are major capacity expansions underway for coal-fired power generation in China, India, and other countries. Since such plants have no CO_2 mitigation technology planned and can have lifetimes up to 50 years, the sooner technology is ready for implementation and mandated, the sooner new plants can incorporate such technology and control emissions. Carbon dioxide retrofit technology is theoretically possible, but such technology will not be commercially available for some time and will likely be substantially more expensive per unit of power generated than would be the case for new plants.

Major reductions can result from lower emissions on the generation side and as a result of lower usage via enhanced end use efficiency. Table 1 presents a summary of major generation options that offer significant opportunities for CO_2 mitigation. They are presented in the order of highest potential for CO_2 mitigation consistent with the IEA ACT Map scenario. Included in this and the subsequent tables are the IEA projected CO_2 savings for each technology in Gt of CO_2 in 2050. To put these numbers in perspective, full implementation of the IEA Map scenario would mitigate 32.5 Gt of CO_2.

Key generation technologies include nuclear power, natural gas/combined cycle, and three coal combustion technologies (IGCC, pulverized coal/oxygen combustion, and conventional pulverized coal), all with integrated CO_2 capture and underground storage. With the exception of wind power, renewable technologies (green font in Table 1) are not projected to have major mitigation impacts in the 2050 time frame. In the case of solar generation, the technology is projected to be prohibitively expensive unless there is a major research breakthrough. For biomass, major utilization is projected to be limited by its dispersed nature, its low energy density, and competition for the limited resource in the transportation sector.

The author rates R,D&D needs in the power generation sector particularly critical, especially in the area of CO_2 capture and storage (CCS) and for the next generation of nuclear power plants. The CCS area is in the early developmental stage, with extraordinary potential, but with a host of questions that can only be resolved through a major program with a particular focus on demonstrations for the key geological formations, most applicable to the greatest potential capacity. For advanced nuclear power, the technology is quite promising and could start making a major impact by 2030. However, technology needs a number of successful demonstrations to allow for resolution of remaining technical problems and to instill confidence in the utility industry that the technology is affordable and reliable, and in the public, that it is safe.

Table 1: Key technologies for CO_2 avoidance from power generation (projected impact in Gt/Yr of CO_2).

Technology	Current State of the Art	2050 Impact	Issues	R,D&D Needs	Other Potential Environmental Impacts
Nuclear Power-next generation	Developmental, Generation III+ and IV: e.g. Pebble Bed Modular Reactor and Supercritical Water Cooled Reactor	1.9	Deployment targeted by 2030 with a focus on lower cost, minimal waste,enhanced safety and resistance to proliferation	**High**, Demonstrations of key technologies with complimentary research on important issues	Reduction in emissions of SOx, NOx, Fine PM; small but potent and long-lived waste, could contaminate small area
Nuclear Power-current generation	Commercial, Pressurized Water Reactors and Boiling Water Reactors (Generation III)	1.8	Plant siting, high capital costs, levelized cost 10 to 40% higher than coal or gas plants, potential U shortages, safety, waste disposal and proliferation	**Medium,** Waste disposal research	Reduction in emissions of SOx, NOx, Fine PM; small but potent and long-lived waste, could contaminate small area
Natural Gas Combined Cycle	Commercial, 60% efficiency	1.6	Limited by natural gas availability, which is major constraint; high effiency & low capital costs, extraction R&D coud enhance availability of CH4	**Medium**, higher efficiencies with new materials desirable	Reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts and residues
Wind Power (renewable)	Commercial	1.3	Costs very dependent on strength of wind source, large turbines visually obtrusive, intermittent power source	**Medium**, higher efficiencies, on-shore demonstrations	Reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts and residues
Coal IGCC with CO2 Capture and Underground Storage	*IGCC* : early commercialization , Underground storage *(US)* : early development.	1.3	*IGCC* :High capital costs, questionable for low rank coals,complexity and potential reliability concerns; *US* : Cost, safety, efficacy	**High**, *IGCC* : Demos on a variety of coals, hot gas cleanup research; *US* : major program with long term demos evaluating large number of geological formations to evaluate efficacy, cost and safety	Lower power plant efficiency yields greater emissions of SOx, NOx, Fine PM
Pulverized Coal/Oxy combustion with CO2 Capture and Storage	Developmental	1.3	Oxygen combustion allows lower cost CO2 scrubbing, but oxygen production cost is high; *US* : Cost, safety and permanency	**High**, large pilot followed by full scale demos needed, low cost O_2 production needed, *US* requires major program (see write-up above)	Lower power plant efficiency yields greater emissions of SOx, NOx, Fine PM
Pulverized Coal with CO2 Capture and Storage	Underground storage developmental; CO2 scrubbing with MEA near commercial but too expensive	1.3	*US* : Cost, safety and efficacy issues, CO_2 scrubbing energy intensive: yielding unacceptable costs	**High,** *US* requires major program (see write-up above); affordable CO_2 removal technologies need to be developed and demonstrated	Lower power plant efficieny yields greater emissions of SOx, NOx, Fine PM
Solar-Photovoltaic and concentrating (renewable)	First generation commercial, but very high costs	0.5	Costs unacceptably high, solar resource intermittent in many locations	**High**, breakthrough R,D&D needed to develop & demo cells with higher efficiency and lower capital costs	Reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts and residues
Biomass as fuel and co-fired with coal (renewable)	Commercial, steam cycles	0.5	Biomass dispersed source, limited to 20% when co-fired with coal	**Medium,** biomass/IGCC would enhance efficiency and CO_2 benefit; also genetic engineering to enhance biomass plantations	Reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts and Residues for disposal or use; however potential eco impacts from biomass plantations
Hydroelectric (renewable)	Commercial	0.5	Capital costs high, potential ecological disruption, siting challenges	**Medium**, minimize environmental footprint	Ecosystem Impacts
More Efficient Coal Fired Power Plants	Early commercialization of supercritical and ultra supercritical	0.2	Currently maximum efficiency of 45%, yielding 36% less CO_2 than current fleet	**High,** new affordable materials needed to enhance efficiency to 50 to 55%	Small reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts and residues
Coal IGCC with no CO2 Capture and Storage	IGCC: early commercialization	0.2	IGCC: High capital costs, complexity and reliability concerns, only modest CO2 savings without CCS	**High**, Demos on a variety of coals, hot gas cleanup research	Small reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts and residues

6 Building sector

The building sector utilizes large quantities of electricity and fossil fuels and is expected to increase CO_2 emissions for the next several decades at about 1.1% per year. Figure 4 illustrates the importance of this sector in the US, with commercial and residential buildings contributing 27.3% to national greenhouse gas emissions via use of electricity and direct use of fossil fuels, mostly natural gas and oil. Table 2 summarizes major technologies capable of achieving significant reductions in CO_2 generation in the 2050 time frame. The technologies are divided into two categories: (1) heating and cooling and (2) appliances, which include lighting.

Table 2: Key technologies for CO_2 avoidance from buildings (projected impact in Gt/year of CO_2).

	Technology	Current State of the Art	2050 Impact	Issues	R,D&D priority and Needs	Other Potential Environmental Impacts
Heating & Cooling	**High efficiency building envelope: insulation, sealants, windows**	Commercial	1.6	Lack of incentive, high initial costs, long building lifetime	**Low/medium priority**, incremental improvements to lower cost and enhance performance	Reduction in coal & natural gas emissions
	High efficiency building heating and cooling	Commercial	1.1	Lack of incentive, high initial costs	**Low/medium priority**, incremental improvements to lower cost and enhance performance	Reduction in coal & natural gas emissions
	Solar heating and cooling	First generation commercial	0.6	High initial costs, availability of low cost efficient biomass heating systems	**Medium**, focus on development of advanced biomass stoves and solar heating technology in developing countries	Reduction in coal & natural gas emissions
	District Heating and cooling	Commercial	0.5	Intial capital costs high, CO2 benefit variable; limited applicability	**Low/medium**, improve economics for lower population densities and optimize system to include cooling option	Reduction in coal & natural gas emissions
	Building energy management	First generation commercial	0.2	Computer technology not being adequately applied; lack of incentive & knowledge	**Medium**, integration and operation research and tie in with emergency demand response measures	Reduction in coal & natural gas emissions
Appliances	**More efficient Electric appliances**	Commercial	2.1	Higher initial costs and lack of information to the consumer	**Low/medium priority**, incremental improvements to lower cost and enhance performance	Reduction in coal & gas emissions: SOx, NOx and PM and residues
	More efficient lighting systems	Commercial-fluorescent	1.0	Lack of incentive given higher initial costs	**Medium**, LED and OLED technology need further development with aim of lowering initial cost	Reduction in coal & gas emissions: SOx, NOx, PM and residues
	Reduce stand-by losses from appliances, computer peripherals, etc.	Commercial	0.3	Lack of incentive from vendors and lack of knowledge from end-users	**Low**	Reduction in coal emissions: SOx, NOx and PM and residues

For each of the two categories, the technologies are listed in order of their potential impact in 2050 according to IEA. The technologies summarized in blue font are aimed at enhancing end use efficiency, whereas the rest deal with new alternative building heating/cooling technologies. It is important to note, that high-efficiency appliances and heating and cooling technologies are currently commercial. Lack of incentive and higher initial costs are the primary reasons for the slow rate of utilization. This is in contrast to the power generation sector, which is constrained by unavailable or undemonstrated technology.

7 Transportation sector

The transportation sector is growing at a fast rate, estimated at 2% per year between 2003 and 2050, driven by developing countries such as China and India, with a combined population of 2.3 billion or 37% of the world's population. It is second only to the power generation sector in importance for the foreseeable future. There are two major technology categories: vehicles and fuels. Technology is currently commercially available for major reductions in CO_2 emissions per mile traveled, especially for light-duty vehicles. Table 3 summarizes the status of major technologies. The first two rows illustrate that major CO_2 reductions could be achieved by incorporating the most efficient internal combustion, chassis, A/C and tire components. Also, hybrid technology, if optimized for efficiency and utilized with high-efficiency chassis components, can have a substantial positive impact. The main impediment to more robust utilization of these commercially available technologies appears to be higher initial costs for hybrids and buyer preferences that, in North America and more recently in Europe, are for larger, heavier, less-efficient vehicles.

IEA [4] projected that increasing and substantial quantities of CO_2 will be emitted by gas and coal to liquid processes, in the energy transformation sector.

The author believes that processes generating liquid fuels from tar sands and oil shale could be major emitters as well. To the extent vehicle efficiency can be improved and renewable fuel options developed, major savings can be realized in the transformation sector.

Of all the biomass processes, thermo-chemical processes that can convert biomass to bio-diesel or other transportation fuels using gasification, pyrolysis, or Fischer-Tropsch technology, appear to have the most potential for CO_2 mitigation and should be considered for an aggressive R, D & D program.

Also, ethanol production by biochemical processing of biomass offers the potential for large-scale displacement of gasoline. However, breakthroughs will be necessary in the ability to chemically break down major biomass components to sugar for fermentation to produce ethanol.

Hydrogen/fuel cell vehicle technology is still in the early development stage, since the fuel cell stack still has limitations in terms of cost and longevity, and hydrogen storage in vehicles remains problematical. Also, EPA [10] and IEA [4] assessments suggest that CO_2 savings would not be substantial unless or until the hydrogen could be generated from low-emission, renewable sources.

Table 3: Candidate technologies for CO_2 avoidance from mobile sources (projected impact in Gt/year of CO_2).

	Technology	Current State of the Art	2050 Impact	Issues	R,D&D Needs	Other Potential Environmental Impacts
Vehicles	**Improvements: Current Internal combustion engine components**	First generation: commercial	2.2	Lack of customer incentive major problem; trend to larger vehicles in US and recently Europe counter-productive	**Medium**; Transmission and drive train improvements	Lower emissions of VOCs and Nox
Vehicles	**Non-engine Improvements:tires , A/C, light materials**	First generation: commercial	1.8	Lack of customer incentive major problem; trend to larger vehicles in US and Recently Europe counter-productive	**Medium**, Lower weight construction, improved tires and more efficient A/Cs	Lower emissions of VOCs and Nox
Vehicles	**Hybrid vehicles**	First generation: commercial	1.4	Higher costs (about $3000),"light" hybrids not as efficient as full hybrids, some newer models yield power over mileage benefits	**Medium/High**,Minimize incremental cost and enhance efficiency	Lower emissions of VOCs and NOx
Vehicles	**Hydrogen fuel cell vehicles**	Developmental	0	Fuel cell costs and fuel cell stack life; also hydrogen storage, safety and lack of infrastructure	**High**, Breakthrough R,D&D needed to develop cost competitive, long lived fuel cells. Vehicle storage R,D&D also needed	On road emissions close to zero, H2 production emissions depends on feedstock & process
Fuels	**Ehanol from sugar**	Commercial	0.7	Limited by land capable of high sugar yields,e.g., sugar cane	**Medium**, develop sugar cane cultivars with higher yield and more frost tolerant	Potential eco impacts from biomass plantations, other impacts unclear, environmental studies would be useful
Fuels	**Biodiesel & other fuels from biomass; thermochemical processes**	Developmental	0.6	Developmental,yet potentially high production and lower cost via gasification/Fischer-Tropsch synthesis	**High,** Breakthrough R,D&D needed to develop and demonstrate viable technology for biomass feedstock	Potential eco impacts from biomass plantations, other impacts unclear, environmental studies would be useful
Fuels	**Biodiesel from vegetable oil**	First generation: commercial	0.2	High costs, low yield from oil crops, limited waste cooking oils, low S a plus	**Low**	Not clear, environmental characterization would be useful
Fuels	**Ethanol from grain/starch,e.g., corn**	Commercial	0.2	Limited by grain supply; high costs, energy intensive production	**Low**	Modest delta impacts compared to base case
Fuels	**Ethanol from biomass; biochemical process**	Early Developmental	0	Inability to convert all biomass components, high production costs, dispersed biomass source	**High**, Breakthrough R,D&D needed to develop lower cost generally applicable process(es)	Not clear, environmental characterization would be useful
Fuels	**Hydrogen**	Commercial from natural gas and electricity	0	Cost via electrolysis high, CO2 benefits if produced via natural gas low	**High;** breakthrough research to generate H2 at low cost from renewable or nuclear sources	Depends upon feedstock source and production process

Despite the serious technical issues, in light of the ultimate potential of fuel cell /hydrogen and biochemical ethanol, the author believes both are also strong candidates for an aggressive R, D, & D focus with the aim of breakthrough technology.

8 Industrial sector

CO_2 emissions from the industrial sector are projected to grow at an annual rate of 0.7% per year over the next several decades. Table 4 summarizes major technologies applicable to this sector. Although CO_2 emission control can be specific to a particular industry, there are a number of technologies that can be

Table 4: Candidate technologies for CO_2 avoidance from industrial sources (impact in Gt/year of CO_2).

Technology	Current State of the Art	2050 Impact	Issues	R,D&D Needs	Other Potential Environmental Impacts
Motor Systems	Commercial	1.5	For most industries not a major cost; lack of expertise for some industries	**Medium**; lower costs and higher efficiencies desirable	Reduction in coal emissions: SOx, NOx; and PM and residues
CO2 Capture and Storage	Early development	1.5	Applicability limited to large energy-intensive industries; key questions:cost, safety, efficacy	High, major program with long term demos evaluating large number of geological formations to evaluate efficacy, cost and safety	Lower power plant efficieny yields greater emissions of SOx, NOx, Fine PM
Fuel Substitution in Basic Materials Production	Commercial	0.5	Natural gas substiution for oil and coal can be expensive	**Low**	Unclear, environmental studies useful
Enhanced energy efficiency: existing basic material processes	Commercial	0.4	Developing countries can have low energy efficiency due to lack of incentive and/or expertise	**Low**	Unclear, environmental studies useful
Feedstock Substitution in key industries	Commercial	0.4	Biomass and biopastics can substitute for petroleum feedstocks and products; however cost high & availability low	**Medium**, develop affordable substitute feedstocks and products based on biomass	Unclear, environmental studies useful, depends on feedstock & process
Steam systems (required for many industries)	Commercial	0.3	For most industries not a major cost; lack of expertise for some industries	**Low**	Reduction in coal emissions: SOx, NOx and PM and residues
Materials/Product Efficiency	First generation: commercial	0.3	Little incentive to minimize the CO2 "content" of materials and products; life cycle analyses required	**Medium,** conduct life cycle analyses of key materials and products with the aim of minimizing CO2 "content"	Potential reduction in air emissions, water effluents and wastes, depenging on substitute material
Cogeneration (combined heat and power)	Commercial	0.3	Limited by electric grid access that would allow the ability to feed electricity back to grid, also high capital costs	**Low**	Reduction in coal emissions: SOx, NOx and PM and residues
Enhanced energy efficiency: new basic material processes	Developmental to Near-commercial depending on industry	0.2	New, innovative production processes require major R,D&D and would need reasonble payback to replace more C intensive processes	**Medium/High**, Develop and demonstrate less carbon intensive production processes for key industries	Potential reduction in air emissions, water effluents and wastes, depending on new process

applied to a large fraction of the industrial sector (blue font in Table 4). Generally applicable technologies include: more efficient motors and steam generators and enhanced use of cogeneration technology; all are commercially available and offer the potential for major reductions. For the larger, more energy intensive industries such as cement kilns, ammonia production, and blast furnaces, CO_2 capture and storage also offers potential for mitigating large quantities of CO_2. However, as mentioned earlier, CCS is in the early developmental stage with a host of questions that can only be resolved through a major program with a particular focus on demonstrations for key geological formations.

Developing and deploying new or modified industrial production processes can also yield important CO_2 emission mitigation potential. Processes can be modified to utilize more environmentally-friendly feedstocks, or fundamentally new basic material processes can be introduced with inherently less energy

Another approach that has potential is to encourage utilization of products which have lower CO_2 “content,” i.e., require less carbon intensive energy during the their production, use, and disposal. These could be considered “climate-friendly” products. There is currently no incentive to use such products. Also, comprehensive life cycle analyses would be necessary to quantify product CO_2 “content”.

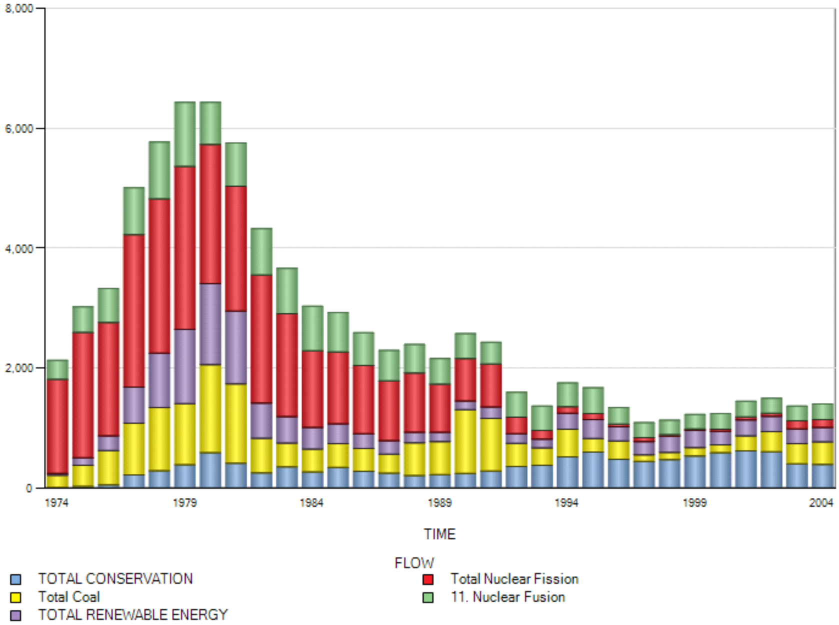

Figure 8: U.S. Federal R, D, &D expenditures for key energy sectors, 2004 $.

9 Adequacy of R, D, &D

IEA [4], Hawksworth [8], Morgan et al. [10], and the author nine years ago (Princiotta [13]) have observed that R, D, & D funding in the energy area will need to be substantially increased in order for key technologies to be ready to reduce carbon dioxide emissions in a time frame consistent with an aggressive mitigation program. Most recently, The Stern Report [14] concluded: "…support for energy R&D should at least double, and support for the deployment of new low-carbon technologies should increase up to five-fold."

Figures 8 and 9, generated from IEA [15], depict U.S. and world research expenditures in critical areas: nuclear power, coal, conservation, and renewables. (Note that world expenditures have only been compiled since 1992.) As can be seen, in the U.S., there has been a major *decrease* in funding since the 1980s, with no major increases in recent years. It is also noteworthy that Europe and Japan have been much more active in the nuclear research area, whereas the U.S. is the key player in coal-related research.

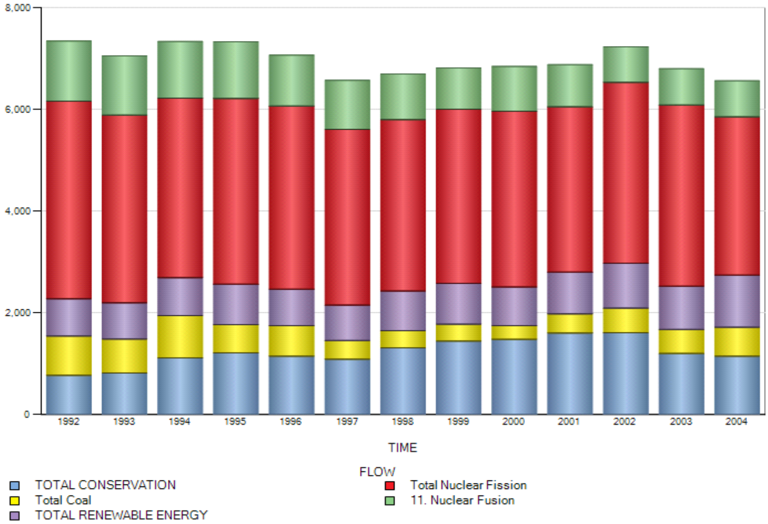

Figure 9: World R, D, & D expenditures for key energy sectors, 2004 $.

It should be recognized that in the last few years, the U.S. has redirected some of its research resources to some key technologies, especially: hydrogen/fuel cells, IGCC, carbon capture and storage, and most recently biomass to ethanol technologies. The U.S. has coordinated its efforts in this area through the Climate Change Technology Program, CCTP [16]. Within the constraint of current budget priorities, the CCTP has coordinated a diversified portfolio of advanced technology R & D, focusing on: energy-efficiency enhancements; low-GHG-emission energy supply technologies; carbon capture, storage, and sequestration methods; and technologies to reduce emissions of non-CO_2 gases.

This could provide a foundation for an expanded program, with funding and schedules consistent with an aggressive mitigation program. Also, the USEPA [17] is implementing a series of voluntary programs which encourage greenhouse gas reduction. They include: Energy Star for the building sector, transportation programs and non-CO_2 emission reduction programs in collaboration with industry.

It is important to note, that IGCC and most of the other non-coal technologies offer the potential for lower air emissions, water effluents and waste generation residues. Also, note that the transportation technologies all offer the potential for reducing our dependency on foreign oil. Further, the country or countries that can bring these technologies to market first, has/have the potential for major revenue streams from what could be a huge international market.

10 Summary and conclusions

The key energy sectors are power generation, transportation, industrial production, and buildings. The power sector and transportation sectors are particularly important, since they are projected to grow at relatively high rates, with China and India being key drivers.

The power generation sector, projected to grow from a large base at 2% annually, offers the greatest opportunity for CO_2 reductions. However, since the key source of emissions is coal combustion, it is critically important to develop affordable CO_2 mitigation technologies for such sources. CCS offer the potential to allow coal use while at the same time mitigating CO_2 emissions. These technologies could be applied to current pulverized coal (PC) boilers, but current CO_2 scrubbing technology is too energy intensive and expensive for PC conditions. Therefore, alternatives to PC boilers are important. The two major candidates are IGCC and oxygen-fed combustors, both of which can remove CO_2 more affordably for ultimate sequestration. However, CCS is an unproven technology with many serious cost, efficacy, and safety issues. Nuclear power plants, natural gas/combined cycle plants, and wind turbines all have the potential to make significant contributions.

The building sector is where much of the electricity generated is utilized and where there are many currently available technologies that can significantly reduce the use of electricity and other energy sources, with a corresponding decrease in CO_2 emissions. The constraints here are less technological and more socioeconomic. However, to the extent R & D can lower cost and raise efficiency of building components, it can help provide extra incentive for building owners to invest in the most efficient heating and cooling systems, lighting, and appliances.

The transportation sector is growing at a rate of 2% per year. The challenge in this sector is two-fold. The first challenge is that current propulsion systems all depend on fossil fuels with their associated CO_2 emissions, suggesting that technologies based on renewable sources such as biomass would be important. The second challenge is that the automobile industry, driven by consumer preferences (especially in North America), have offered heavy, inefficient vehicles such as SUVs. A review of developing technologies suggests that hybrid vehicles and biomass-to-diesel fuel via thermochemical processing are the most promising. However, cellulosic biomass-to-ethanol and hydrogen/fuel cell vehicles offer longer term potential if key technical issues are resolved and, in the case of hydrogen, renewable sources are developed.

Industrial sector emissions are projected to grow at an annual rate of 0.7%. Although CO_2 emission controls can be specific to a particular industry, the following key commercial technologies can be applied to a large fraction of the industrial sector: efficient motors, steam generators, and enhanced use of cogeneration technology. For the larger, more energy-intensive industries, such as blast furnaces, CO_2 capture and storage offer the potential for mitigating large quantities of CO_2. Developing and deploying new or modified industrial production processes can also yield important CO_2 emission mitigation potential. Another attractive approach is to encourage utilization of products that have a lower CO_2 content," i.e., require less carbon intensive energy during product production, use, and disposal.

If mitigation consistent with the IEA scenario is to be accomplished, a major increase in R&D resources will be needed. Technology research, development, and demonstration are of particular importance for coal generation technologies: IGCC, oxygen coal combustion, and CO_2 capture technology for pulverized coal combustors. All of these technologies will have to be integrated with underground storage, a potentially breakthrough technology, but one which is an early stage of development. Also important are next generation nuclear power plants, biomass to diesel fuel processes, cellulosic biomass-to-ethanol production technology, and hydrogen production technology.

Availability of key technologies will be necessary but not sufficient to limit CO_2 emissions. Since many of these technologies have higher costs and/or greater operational uncertainties than currently available carbon intensive technologies, robust policies will be necessary to encourage their utilization.

Finally, given the challenge and uncertainties associated with an aggressive mitigation program based in part on unproven, developmental technologies, it may be prudent to consider all available and emerging technologies. This suggests that fundamental research on energy technologies *in addition* to those in Tables 1 to 4, be part of the global research portfolio, since breakthroughs on today's embryonic technologies could yield tomorrow's alternatives. Also, it may also be prudent to consider geoengineering options, which although radical in concept, could potentially buy the time needed to make the necessary adjustments in our energy and industrial infrastructure consistent with an aggressive mitigation program. For example, it is suggested that the simulated volcano option proposed by Wigley [7] be seriously evaluated.

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