Global Climate Change and the Mitigation Challenge (Upgraded Final 8/18/2008)

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Abstract

Anthropogenic emissions of greenhouse gases, especially carbon dioxide, CO_2, have led to increasing atmospheric concentrations, the primary cause of the 0.8 ^oC warming the 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 potentially substantial global warming predicted. *While much literature exists on various aspects of this subject, this paper aims to provide a succinct integration of the projected warming the earth is likely to experience in the decades ahead, the emission reductions that may be needed to constrain this warming, and the technologies needed to help achieve these emission reductions.* This paper uses available, transparent modeling tools and the most recent existing literature, to draw broad conclusions about the challenge posed by climate change and potential technological remedies. The paper examines forces driving CO_2 emissions, how different CO_2 emission trajectories could affect temperature this century, a concise sector-by-sector summary of mitigation options, and R&D priorities. It is concluded that that it is too late too avoid substantial warming. The best result that appears achievable would be to constrain warming to about 2.4 ^oC (between 1.6 and 3.2 ^oC) above pre-industrial levels by 2100. In order to constrain warming to such a level, the current annual 3% CO_2 emission growth rate needs to transform rapidly to an annual decrease rate of from 1 to 3% for decades. Further, the current generation of energy generation and end use technologies are capable of achieving less than half of the emission reduction needed for such a major mitigation program. New technologies will have to be developed and deployed at a rapid rate, especially for the key power generation and transportation sectors. Current energy technology research, development, demonstration and deployment (RDD,&D) programs fall far short of what is required.

Implications

In order to avoid the potentially catastrophic impacts of global warming, the current 3% CO_2 global emission growth rate must be transformed to a 1 to 3% declining rate, as soon as possible. This will require a rapid and radical transformation of the world's energy system. The current generation of energy technologies are not capable of achieving the mitigation required, given projected economic and population growth, especially in rapidly developing countries. New generations of low carbon emission generation technologies and end use technologies will be needed. It will be necessary to substantially upgrade and accelerate the current worldwide RDD&D effort, in order enhance the likelihood that they such technologies are available in the time frame required.

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1. Introduction

In February, 2007 the Intergovernmental Panel on Climate Change (IPCC) (1) concluded that:

- "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."
- "Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."
- "The combined radiative forcing due to increases in carbon dioxide,… is very likely to have been unprecedented in more than 10,000 years."
- "The total temperature increase from 1850 – 1899 to 2001 – 2005 is 0.76 ^oC."
- Depending on the assumed greenhouse gas emission trajectory, warming in 2095, relative to pre-industrial levels, is projected to be 1.6 to 6.4 ^oC.

Given these findings, this paper will examine the critical global energy sector with the aim of evaluating the ability of technologies to moderate projected warming. The author will discuss the factors that lead to increasing emissions of CO_2, the critical greenhouse gas, and the anticipated importance of key countries. Then, CO_2 emissions will be projected into the future for key sectors. The paper 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 (Note that in this paper, all CO2 concentrations will be in ppmv and all warming will be realized or transient warming, unless specifically identified, as opposed to equilibrium, also known as eventual or ultimate warming.)

Although, the scope of this paper is limited to a consideration of technologies that can play a significant role in reducing CO_2 emissions, it is important to note that availability of such 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.

2. Factors That Drive Emissions of CO_2

The World Resources Institute, WRI, (2) 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) *per capita*, *population*, carbon emissions per unit of energy, aka, *carbon intensity*, and energy usage per unit of GDP, aka, *energy intensity*. The relationship is as follows: Carbon emissions=GDP per capita x population x carbon intensity x energy intensity. The sum of the *rates* of these factors approximates the annual Carbon (and CO_2) emission *growth rate*. The author has used the WRI data (2) to generate Figure 1, 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 has been about 1.4% per year. The rate for the *U.S.* also has been about 1.4%, 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.

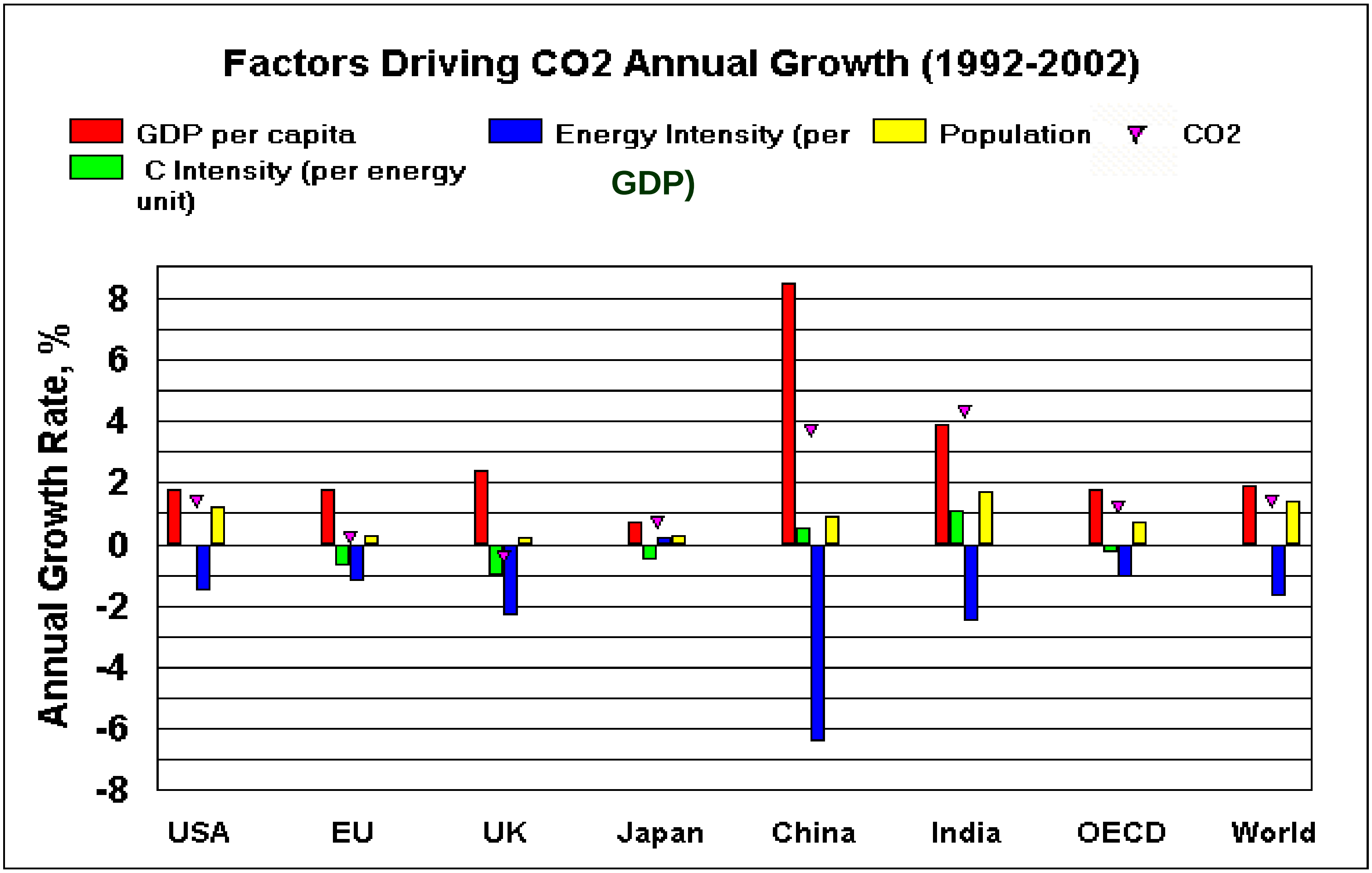

Figure1. Factors driving concentrations of CO_2 for selected countries for the 1992 to 2002 period

However, a recent analysis by Raupach (3) concluded that in the period 2000 to 2004, CO_2 worldwide emissions have increased more rapidly than in previous years and more rapidly than predicted; at an annual growth rate of *3.2%.* This is more than twice the growth rate of the1992 to 2002 period. Rapidly developing economies in China and other Asian countries are particularly significant. China is currently constructing the equivalent of two, 500-megawatt, coal-fired power plants per week and a capacity comparable to the entire United Kingdom power grid, each year (4). Developing economies, together forming 80% of the world's population, accounted for 73% of the global growth in CO_2 emissions in 2004. However, these economies accounted for only 41% of emissions themselves and only 23% of emissions since the start of the Industrial Revolution around 1800. Figure 2, Raupach (3), summarizes these global emission trends, including the recent 2000 to 2004 data. Using country level data from this reference, Figure 3 was derived, indicating the importance of China as the major factor driving this increased growth rate in recent years. In October of 2007, analyzing the most recent data, Canadell (5) concluded that global emissions have grown at 3.3% annually for the 2000 to *2006* period. Therefore, the high growth rate has continued for the last six years that data is available.

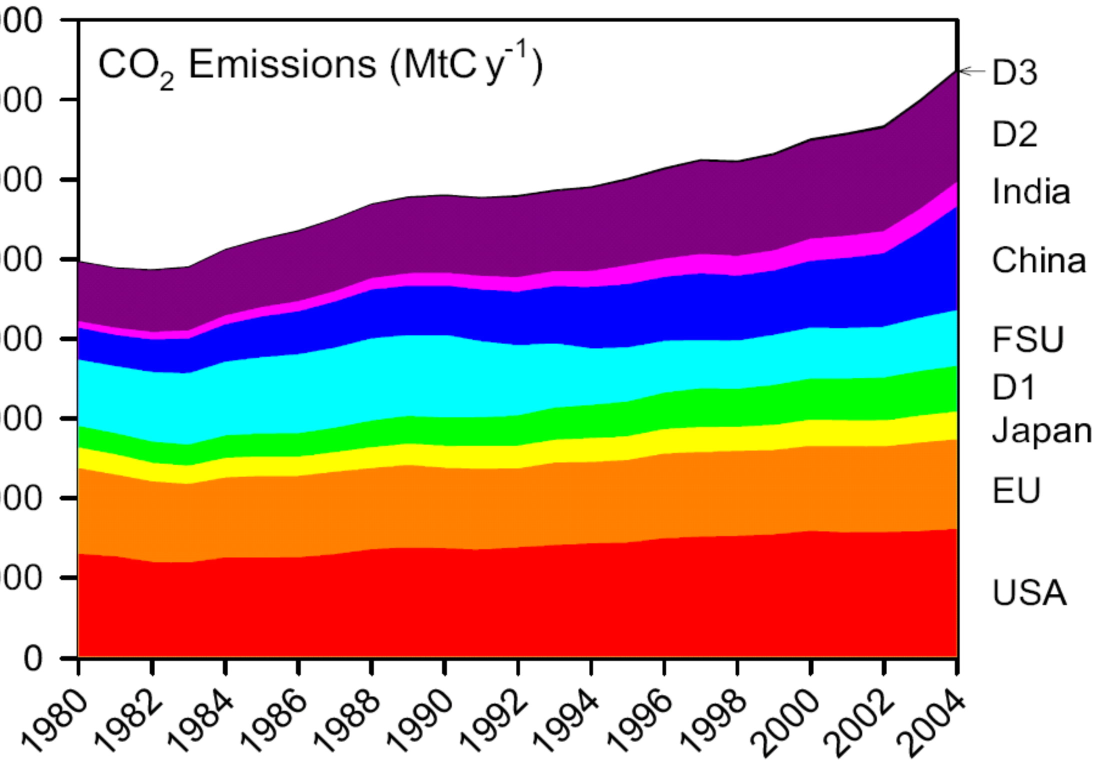

Figure 2. Recent CO_2 Emission Data by Countries and Sectors

(Note the following regional designations: FSU=republics of the former Soviet Union, D1=15 other developed nations, including Australia, Canada, S. Korea and Taiwan, D2=102 actively developing countries, from Albania to Zimbabwe and D3= 52 least developed countries, from Afghanistan to Zambia.)

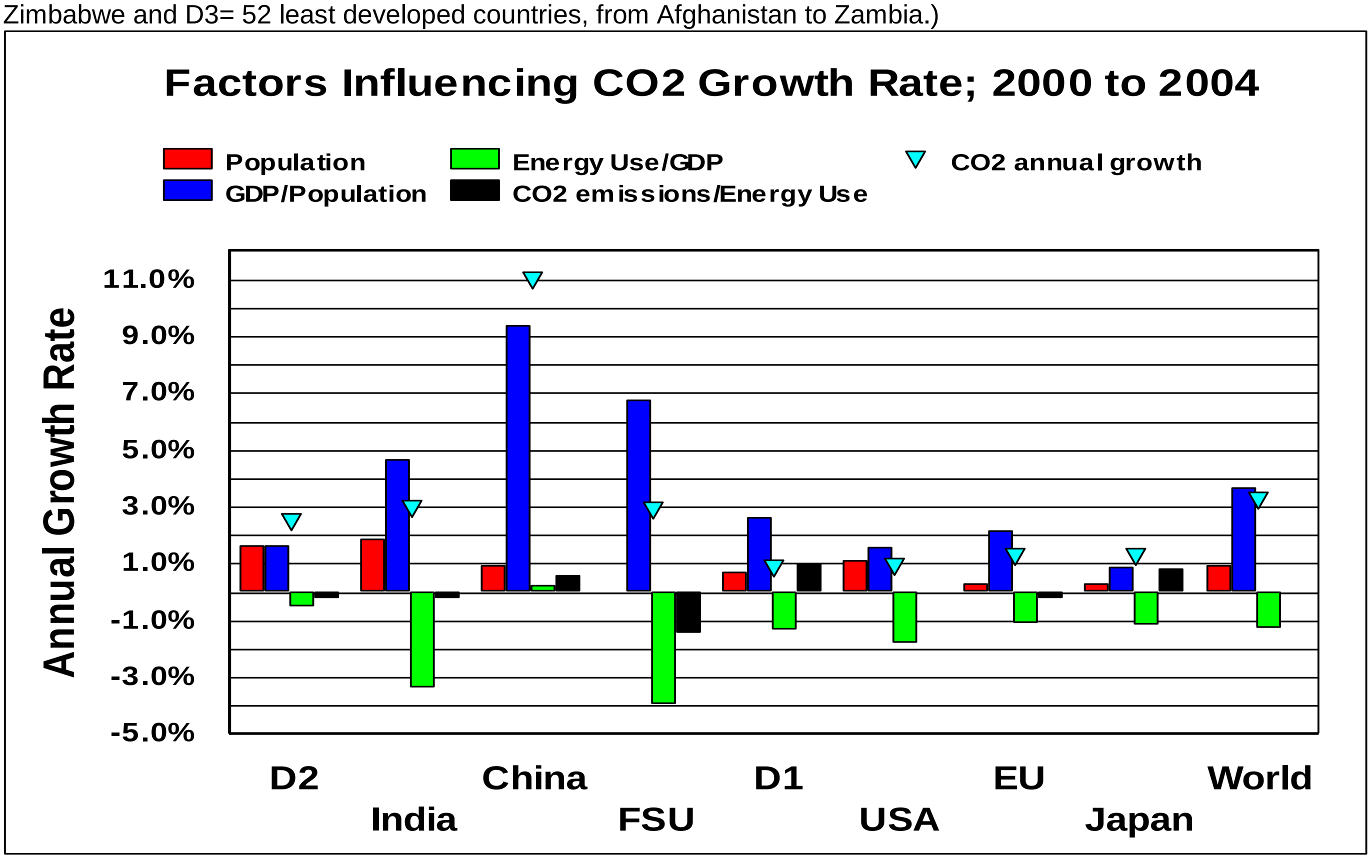

Figure 3. Factors driving concentrations of CO_2 for selected countries for 2000 to 2004 period

3. Emissions and Voluntary Programs in the U.S.

It is noteworthy, that the U.S. in 2002, initiated a strategy to cut greenhouse gas (GHG) intensity by 18% over 10 years, with the aim of moderating CO_2 and other GHG emissions. Greenhouse gas intensity growth rates, although they account for gases in addition to CO_2, can be approximated by the sum of energy and carbon intensity growth rates, delineated in Figure 1; about -1.4% for the U.S for the 1992-2002 period. A recent analysis by WRI (6), Figure 4, suggests that even if this program meets its target, it will have a modest impact on greenhouse gas emissions, since such improvements in energy intensity would likely have occurred in the absence of such a program, based on historical trends driven by the continued economic advantage in decreasing energy expenditures. The dashed line shows U.S. voluntary program target projections, the full line represents a business as usual projection.

It should be noted that although current programs may not have a major impact on constraining emissions as currently designed, constructive collaboration between government and industry from voluntary programs, and the expertise gained in promoting enhanced end use efficiency technologies, could provide a solid foundation for a more aggressive program consistent with the mitigation challenge. Such programs are particularly significant in the power generation and transportation sectors.

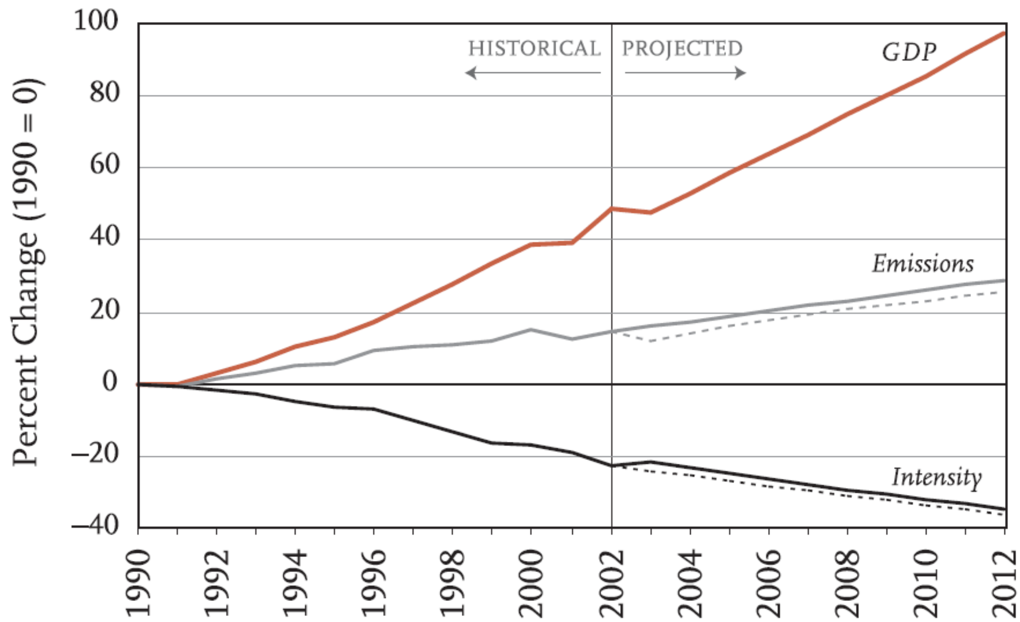

Figure 4. Impact of U.S. voluntary program to reduce energy intensity on GHG emissions
Source: World Resources Institute

4. What Levels of Warming are Projected, What are the Uncertainties?

A credible base case, or business as usual (BAU), scenario must be established if we are to estimate warming with any confidence between now and the year 2100. IPCC (1), IEA (7), and Hawksworth (9) have all postulated such scenarios that allow such estimates. The IEA base scenario was selected as the basis for this analysis, because it does not assume major technology changes over time. Since it was limited to 2050, the projection was extended to 2100 by assuming reduced emission growth rates between 2050 and 2100. This scenario assumes the following CO_2 growth rates in the specified time intervals: 2000 to 2030, 1.6%; 2030 to 2050, 2.2% (from IEA); 2050 to 2075, 1.2%; and 2075 to 2100, 0.7%. Note that the reduced 2050 to 2100 growth rate assumption, was based on projected declines in global population growth rates, but relatively stable GDP, carbon intensity and energy intensity growth rates.

Figures 5 and 6 present model-generated graphics of both CO_2 concentrations and warming from pre-industrial times projected to 2100, assuming this emission scenario. The Model for the Assessment of Greenhouse-Induced Climate Change, MAGICC, (version 4.1) (Wigley (10)) was used to generate these projections. An earlier version of this model was used by the IPCC in its Third Assessment Report (TAR) to evaluate impact of various emission scenarios. MAGICC is a set of coupled gas-cycle, climate, and ice-melt models that allows the determination of the global-mean temperature resulting from user-specified emissions scenarios, which the author generated. Note that in both figures, which were generated directly by the model, the uncertainty range is included, as calculated by the model. As can be seen, warming uncertainties are much higher than for concentration projections. The main uncertainty factor for warming projections, is the extent to which the atmosphere is sensitive to a doubling of CO_2 concentration, i.e., how much does the global equilibrium temperature change with such a doubling. IPCC (1), Wigley (10), and others state that this is quite uncertain, and their estimates range from 1.5 ^{o}C to 4.5 ^{o}C. Note that the model assumes a default value of 2.6 ^{o}C for the *most likely* atmospheric sensitivity. However, recently the IPCC (1) concluded that the most likely value is 3.0 ^{o}C. Therefore, all calculations in this paper assume this value, by overriding the default value and inputting the 3 ^{o}C value. This tends to increase 2100 warming by about 0.2 ^{o}C for mitigation cases and 0.4 ^{o}C for business as usual cases.

Also note, warming is projected to continue after 2100. When one accounts for continued warming projected into the next century, the equilibrium, or eventual warming, is projected to range from 2.3 to 7.6 ^{o}C with the best guess at 4.9 ^{o}C above 1990 levels; this assumes an ultimate steady state 850 ppm CO2 concentration.

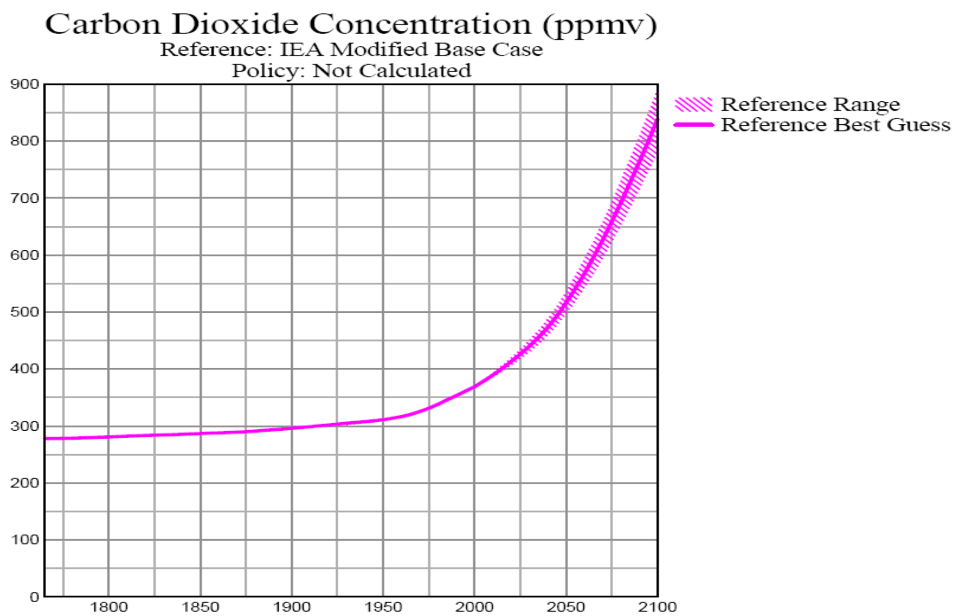

Figure 5. Projected CO_2 concentrations for Base Case

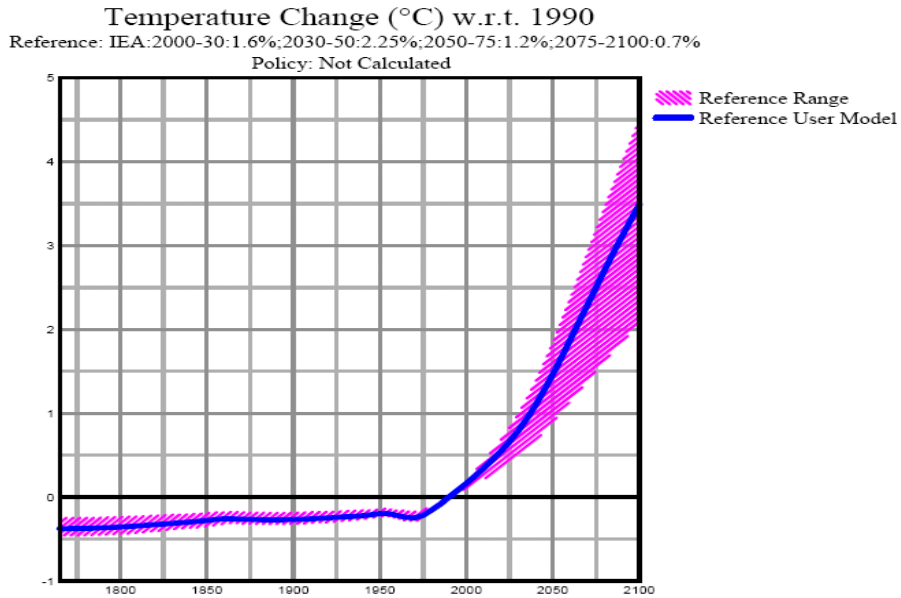

Figure 6. Projected Warming for Base Case

As mentioned earlier, new data indicates that the recent annual global CO_2 growth rate is much higher than expected; 3.3% in the 2000 to 2006 time frame. However, model calculations for Figures 5 and 6, assumed a 2000 to 2030 growth rate of 1.6%, consistent with mainstream projections. Figure 7 illustrates the impact of assuming a 3.0% growth rate in this critical period. As can be seen, it would substantially increase the atmospheric CO_2 concentrations and global warming. Equilibrium warming, which would occur during the next century, would be from 3.1 to 9.5 ^oC, with the best guess 6.3 ^oC above 1990 levels.

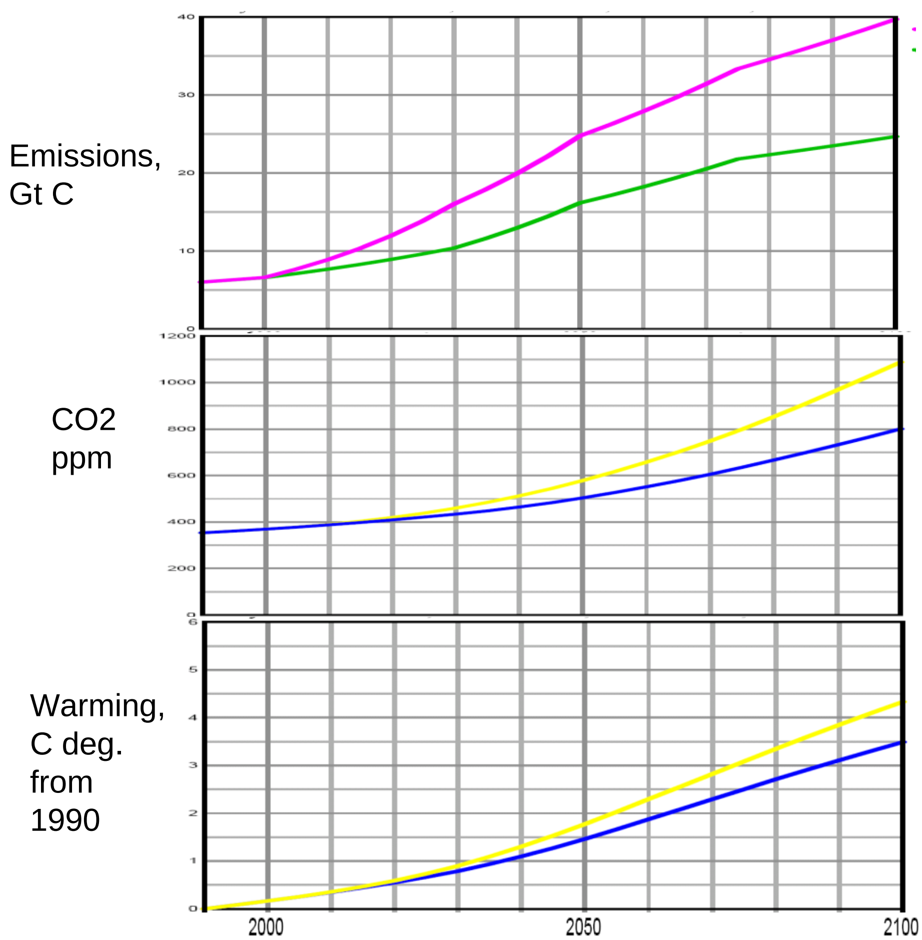

Figure 7. Two Emission Scenarios: Original: IEA base case assumed 1.6 % growth rate from 2000 to 2030; Revised: growth rate of 3.0% from 2000 to 2030

5. Achievable Mitigation Levels

Figure 8 presents the recent IPCC (11) analysis relating projected warming from 1990 to 2100 to the following global impacts: fresh water availability, ecosystem damage, food supplies, seawater rise, extreme weather events, and human health impacts. The author has added projected warming ranges for a credible business-as-usual case and an aggressive global mitigation case. *Note that for both ranges, it was projected that global annual emissions would grow at a 1.6 % rate until 2030 or until mitigation starts, not the most recent (2000 to 2006) 3% growth rate*. Figure 9 is a modified version of Figure 8, and shows the potential impact of a 3% growth rate in emissions until mitigation. The mitigation option in this case assumed 1% annual reductions that would start in 2025. Delayed mitigation amplifies the effect of the high growth rate, because it allows greater quantities of CO_2 to be emitted before mitigation, over a longer time period. It is significant that current (2007) warming (0.3 °C since 1990 and 0.8 °C since 1750) has already had measurable impacts.

For both base cases (Figures 8 and 9) temperature increases in these range would result in potentially severe impacts, especially if the temperature increase is in the middle to upper end of the range. Note that for the 3% growth case both the base and mitigation ranges are substantially greater with potentially more severe impacts. Also note, the upper end of the base case is off the IPCC chart, indicating the potential seriousness if warming is on the high end of the uncertainty range. Particularly troublesome impacts could include the following: water could become scarce for millions of people, wide-scale ecosystem extinctions, lower food production in many areas, loss of wetlands, damage and mortality from storms and floods, and increased health impacts from infectious diseases. Although not included in Figure 7, IPCC also projects declining air quality in cities, due to warmer/more frequent hot days and nights over most land areas.

It is important to note that even for the two mitigation cases, substantial warming is projected, especially if the high emission growth rate continues and serious mitigation is not initiated until 2025. Therefore, limiting warming to about 2.0 ^{o}C (range of 1.2 to 2.8 ^{o}C) from 1990 values is likely the best result achievable even with a major global mitigation program. Figures 8 and 9 indicate global impacts consistent with that warming, will be significant. Note, the warming between the pre-industrial era and 1990 is about 0.4 ^{o}C. It should be recognized that superimposing mitigation warming ranges on the IPCC impact graphic is included for illustrative purposes only. Aggressive mitigation would yield substantial changes to human settlements, whose vulnerability to climate change could be different than the Business as Usual case.

To more carefully explore the factors influencing the ability to constrain warming, emission scenarios were evaluated to see what reduction levels, starting in what year, would limit warming to the 2 to 3 ^{o}C range from the pre-industrial period. Figures 10 to 12 were generated utilizing a large number of MAGICC runs. They allow selection of combinations of emission growth reductions and start years needed to limit warming in 2100 to a given level. Figure 10 illustrates the impact of the faster 3% BAU growth rate, which yields additional warming, relative to the 1.6% BAU case. As can be seen, additional warming increases as the start year for mitigation is delayed. Figures 11 and 12 assume the 3% BAU scenario, and project 2100 warming and CO_2 concentrations, respectively. Note that an annual decrease of 0.00% means emissions are held constant, at the start year until 2100. Also note that in order to simplify the analysis; it is assumed that there is an *immediate* change in growth rate from the base case, to a decreasing emission rate at the control "start year". In reality, there would be a transition period between the positive and negative growth rates. Therefore, from this perspective, Figures 11 and 12 should be considered somewhat optimistic, since emissions would not be avoided at the ultimate rate, during this transition period.

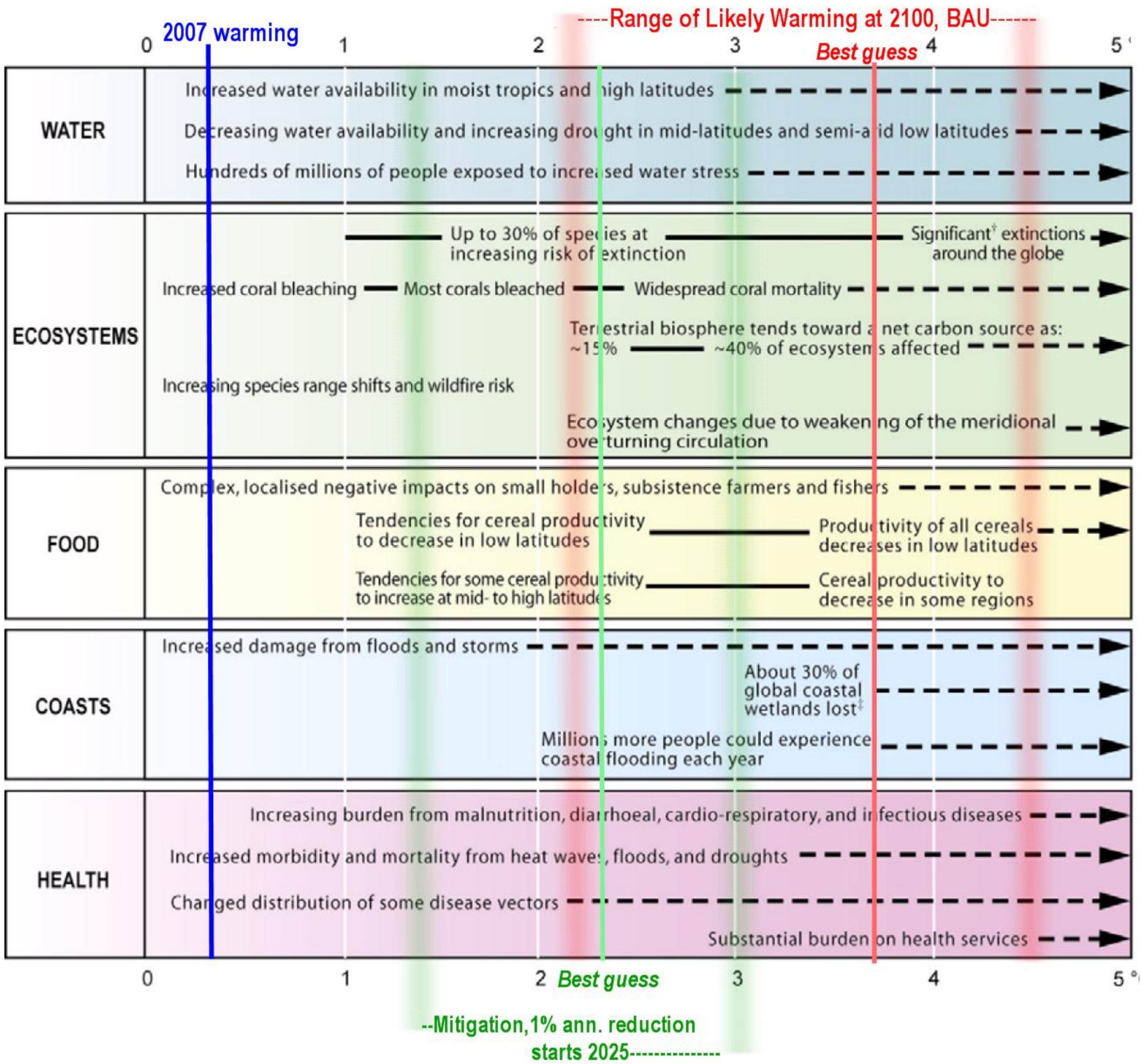

Figure 8. Projected impacts as a function of 2100 warming, ^{o}C, from 1990;1.6% emission growth rate

Note: 1.6% growth rate to 2030. Entries are placed so the left hand side of text indicates approximate onset of impact, black lines link impacts, and dotted arrows indicate impacts increase with increasing warming

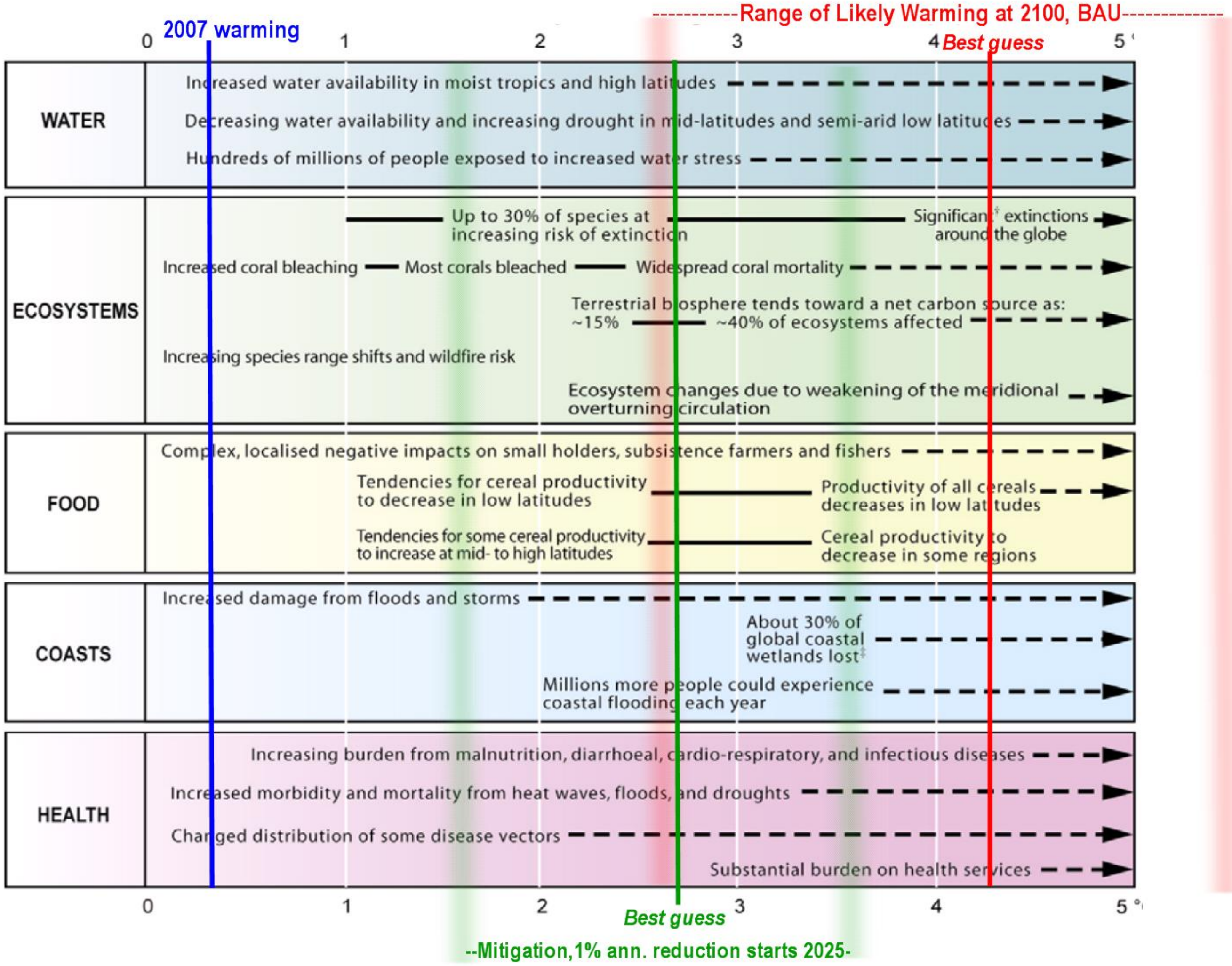

Figure 9. Projected impacts as a function of 2100 warming, ^oC, from 1990,; 3% emission growth rate.
Note: 3.0% growth rate to 2030. Entries are placed so the left hand side of text indicates approximate onset of impact, black lines link impacts, and dotted arrow indicate impacts increase with increasing warming

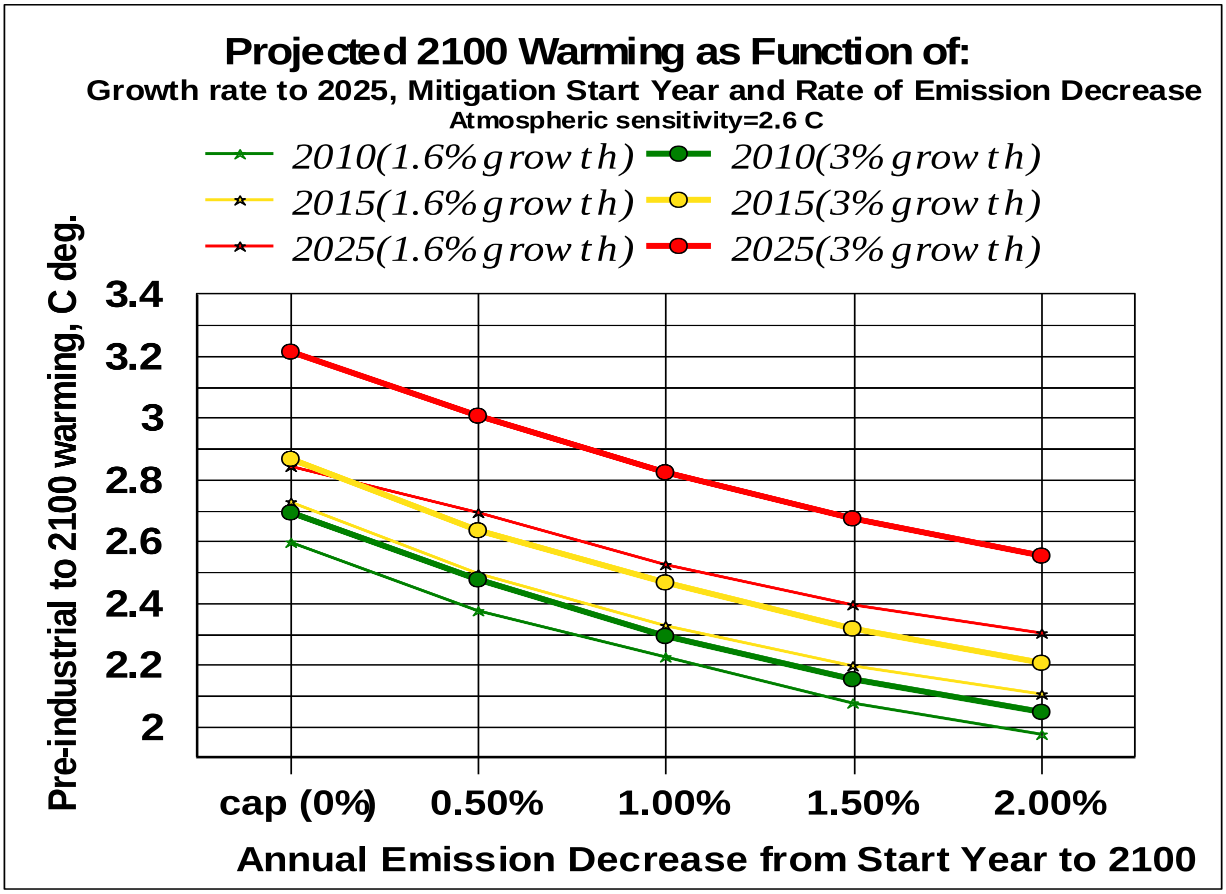

Figure 10. 2100 warming impact of higher emission growth rates as a function of mitigation start year and emission decrease rate

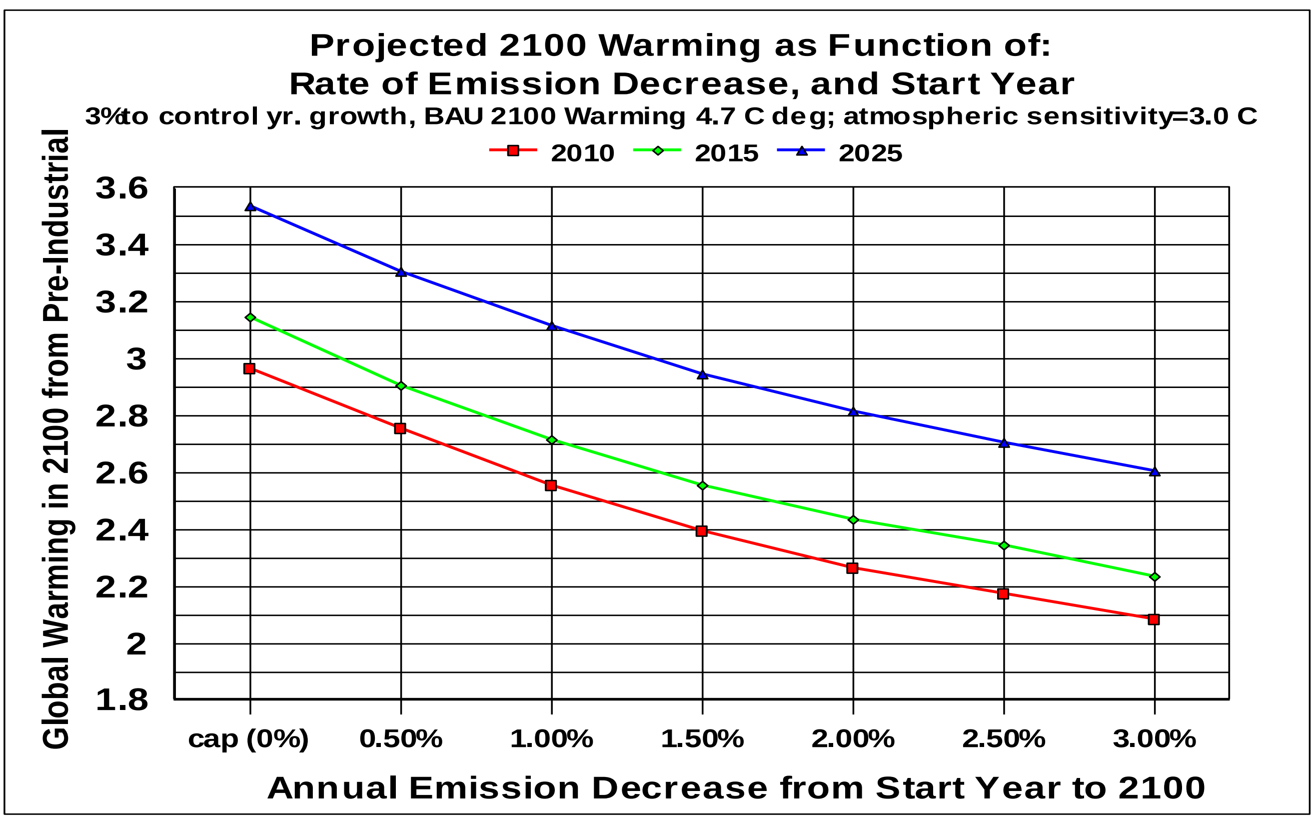

Figure 11. 2100 warming as function of annual emission decrease rate and year reductions start

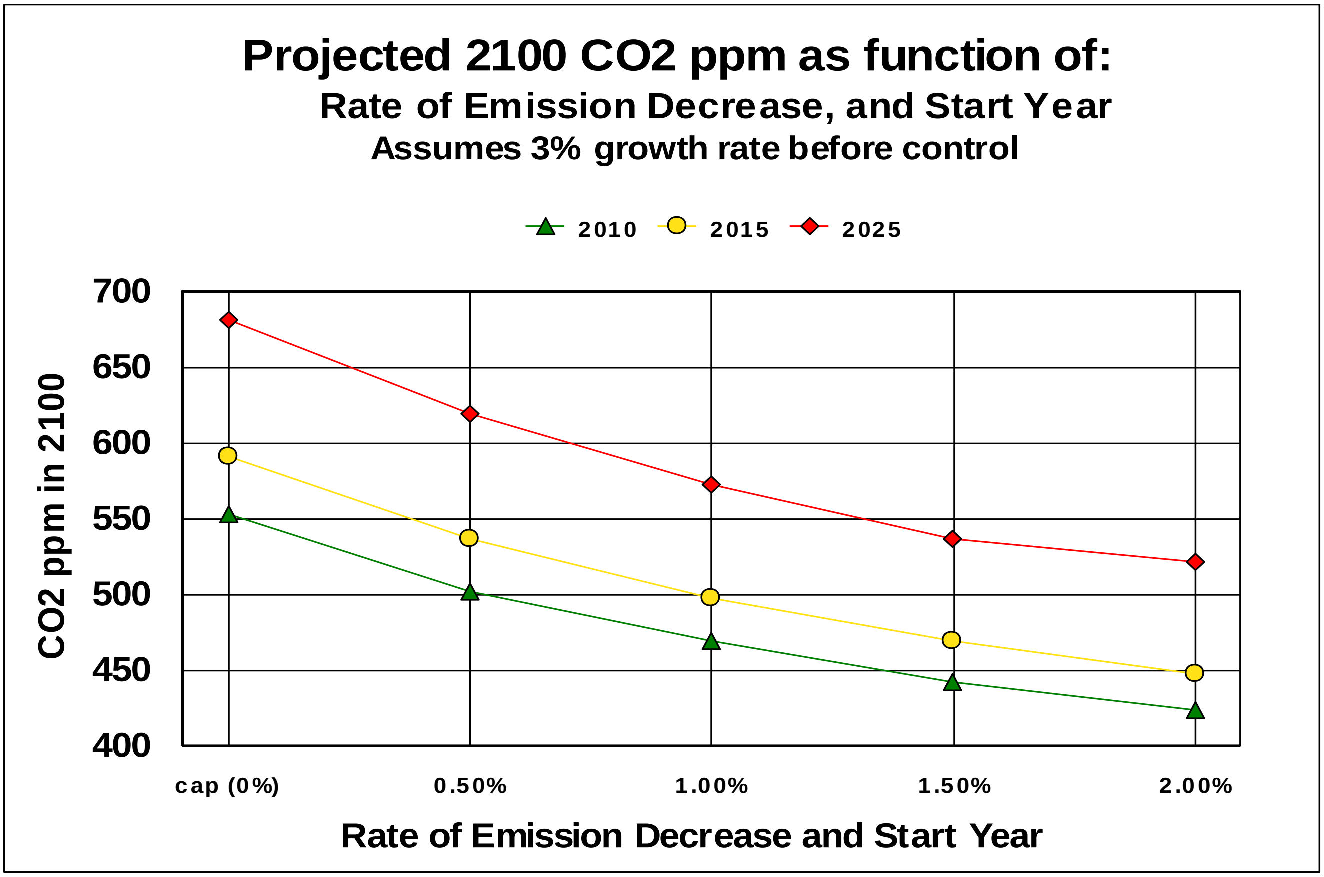

Figure 12. CO_2 ppm in 2100 as a function of annual emissions reduction rate and year reductions start

As can be seen, major *annual decreases* in emissions will be necessary if a warming target below 2.5 ^oC is to be achieved. Note that the earlier this reduction starts, the less the annual reduction rate has to be, to meet a given warming target. For example, if such a program were to start in 2010, reductions would need to be about 1% annually for 90 years to limit warming to about 2.5 ^oC ; whereas if such a program were to start in 2025, annual reductions would need to be in the order of 3% per year for 75 years. Again, it must be noted that there is a large range of uncertainty in the resulting temperature for a given maximum CO_2 concentration. Figure 13 illustrates this, by displaying the range of projected warming, from 1990, for a particular emission scenario, i.e., an annual decrease of 1%, starting in 2010, with a BAU growth of 1.6%, projected to constrain concentrations to the 440 to 480 ppm range. (Note the Figure 13 projects warming from 1990, about 0.4 ^oC must be added to estimate warming from the pre-industrial era, to be consistent with Figures 10 and 11. Also, note an aggressive methane mitigation program would yield additional warming reduction of about 0.2 ^oC in this time frame)

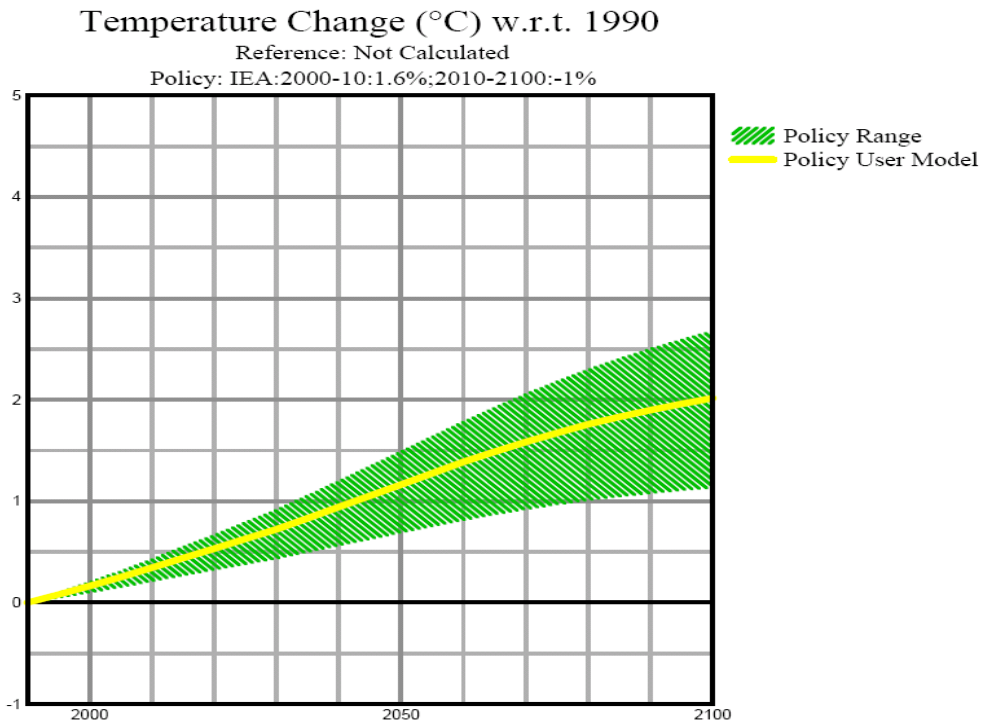

Figure 13. Projected warming range for a 1% annual decrease in CO_2 emissions started in 2010

Figure 14 illustrates the major challenge such reductions represent, relative to the IEA base case (1.6 % growth to 2030) emission trends. The base case emission trajectory is compared to a mitigation scenario where emissions are decreasing at a rate of 1 % per year starting in 2010. This would limit concentration to 460 ppm and warming to 1.9 ^{o}C above 1990 levels.

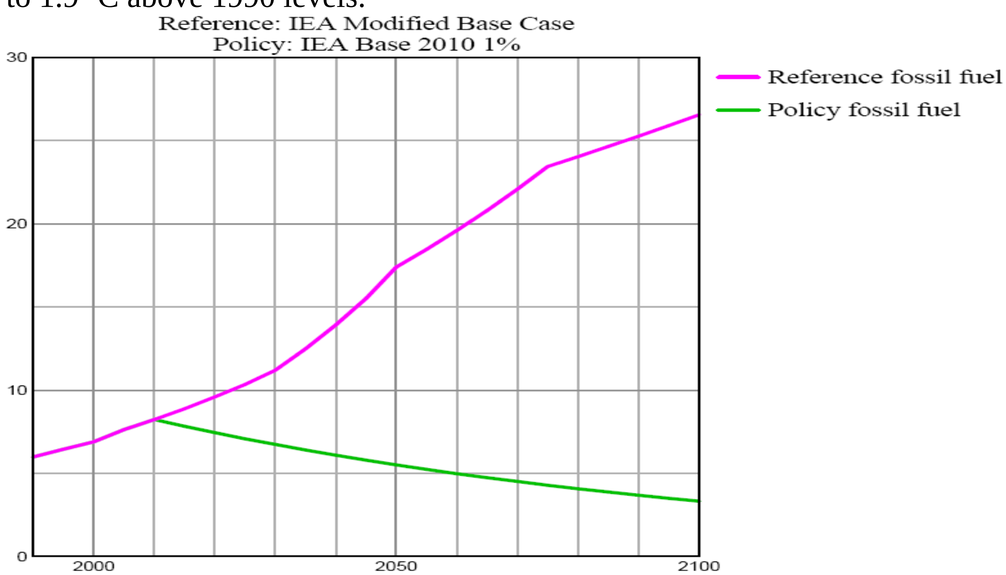

Figure 14. Base case & scenario to limit CO_2 to <2 C in 2100; units: Gt Carbon (note: 3.67 Gt CO_2 per Gt C)

Note that the area between the curves represents the amount of carbon avoidance needed to achieve the target temperature versus the base case: *over one trillion tons of carbon or over 3.7 trillion tons of CO_2 over the 90-year period*.

It should be again noted, that if the world community continues to increase CO_2 emissions at the rate of 3% per year over the next two decades, warming mitigation will be made more difficult. Figure 15 illustrates the consequences of a higher emission growth rate prior to the start of a mitigation program in 2025. Mitigation is less successful in moderating warming when the program is initiated after 25 years of a 3% growth rate, compared to the 1.6% growth rate of the IEA base case. As Figure 10 indicated, this penalty becomes less severe the earlier the mitigation program is initiated.

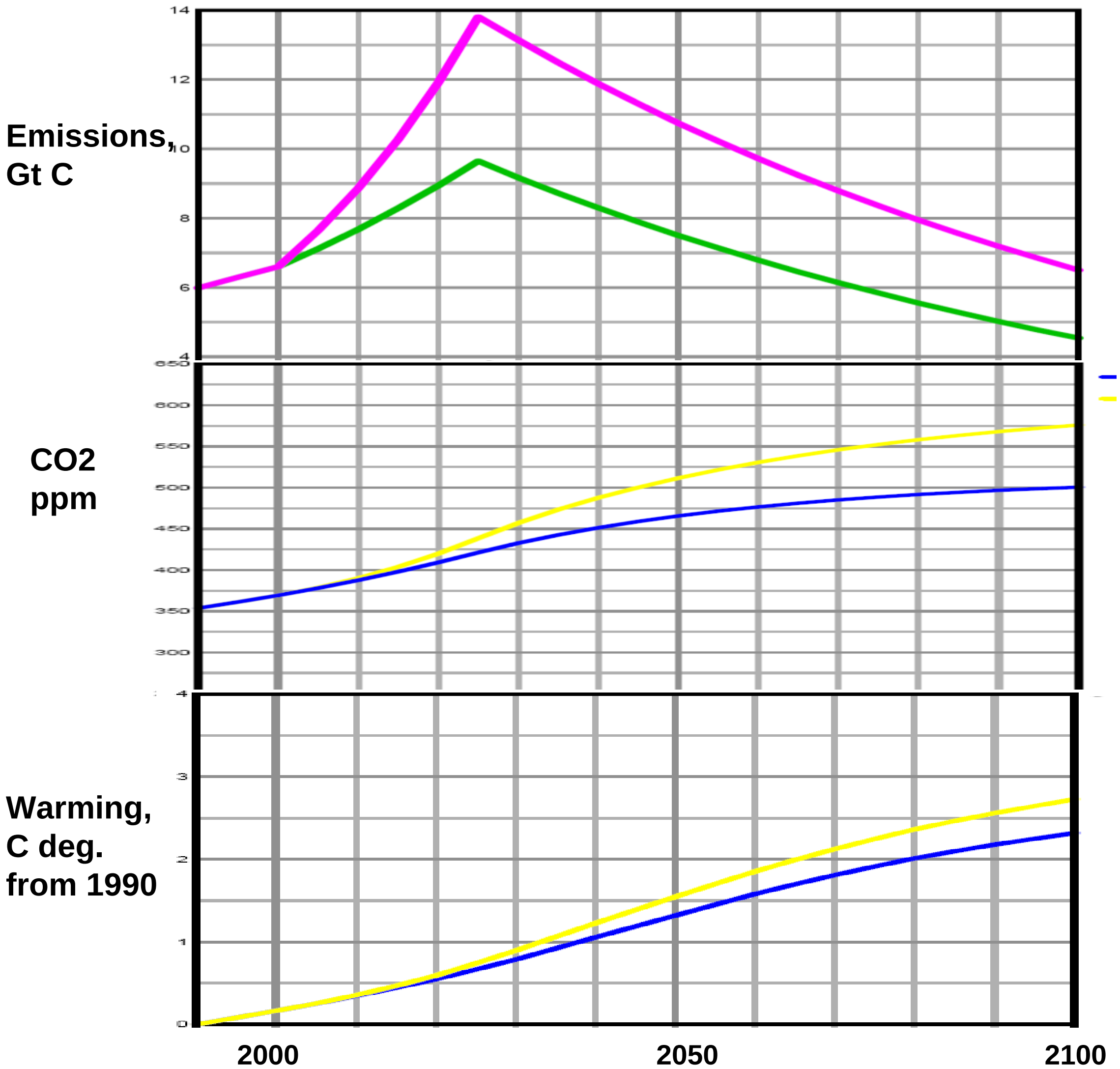

Figure 15. Two Mitigation Scenarios starting in 2025: Original assumed 1.6% emission growth rate from 2000 to 2025, followed by an annual 1% reduction; Revised assumed a 3.0% growth rate from 2000 to 2025, followed by an annual 1% reduction

6. The Mitigation Challenge: Which Sectors and Gases are Most Important?

In order to identify the most productive mitigation strategies, 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 16 from IEA (7). This graphic projects world CO_2 emissions by sector. The emission growth rates are consistent with the business as usual base case, discussed previously: 1.6 % from 2000 to 2030, and 2.2% from 2030 to 2050. It suggests that power generation and transportation sources are the fastest growing sectors and controlling these sources will be the key to any successful mitigation strategy. There is historical evidence that as a country develops economically, it uses greater quantities of electrical power and experiences a sharp growth in the number and use of motor vehicles and other transportation sources. 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 16, includes petroleum refining, natural gas, and coal conversion to liquids and biomass to alcohols, much of which will feed the transportation sector.

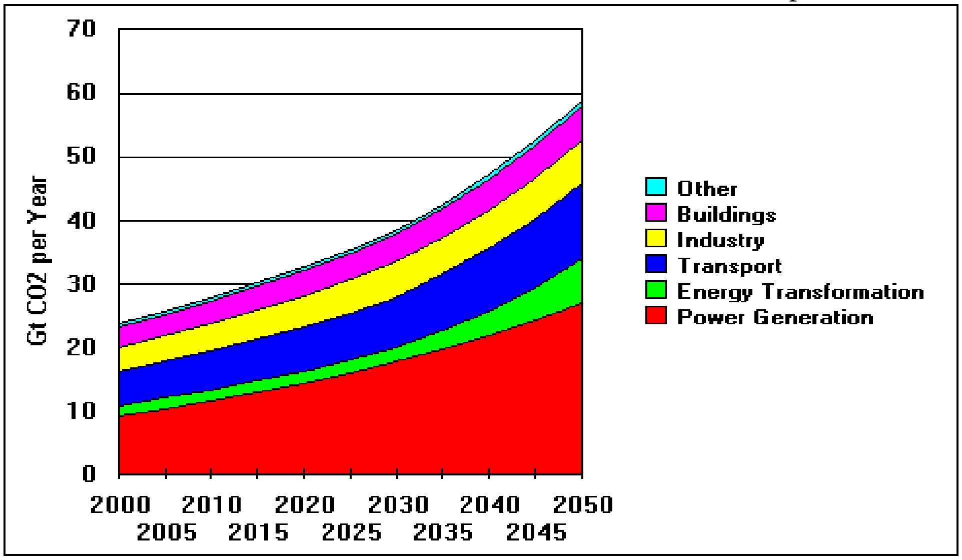

Figure 16. Projected Global CO_2 emission growth for key economic sectors, Gt per year

For the U.S., the WRI (12) has generated a very informative graphic, Figure 17, illustrating the relationship between sectors, end use/activities, greenhouse gas emissions, including methane and nitrous oxide sources in CO_2 equivalents, for the year 2003. This graphic illustrates the relative importance and relationship of the power generation (electricity and associated waste heat in the figure), transportation and industrial production, and the end use of energy in residential, commercial buildings, and industrial operations.

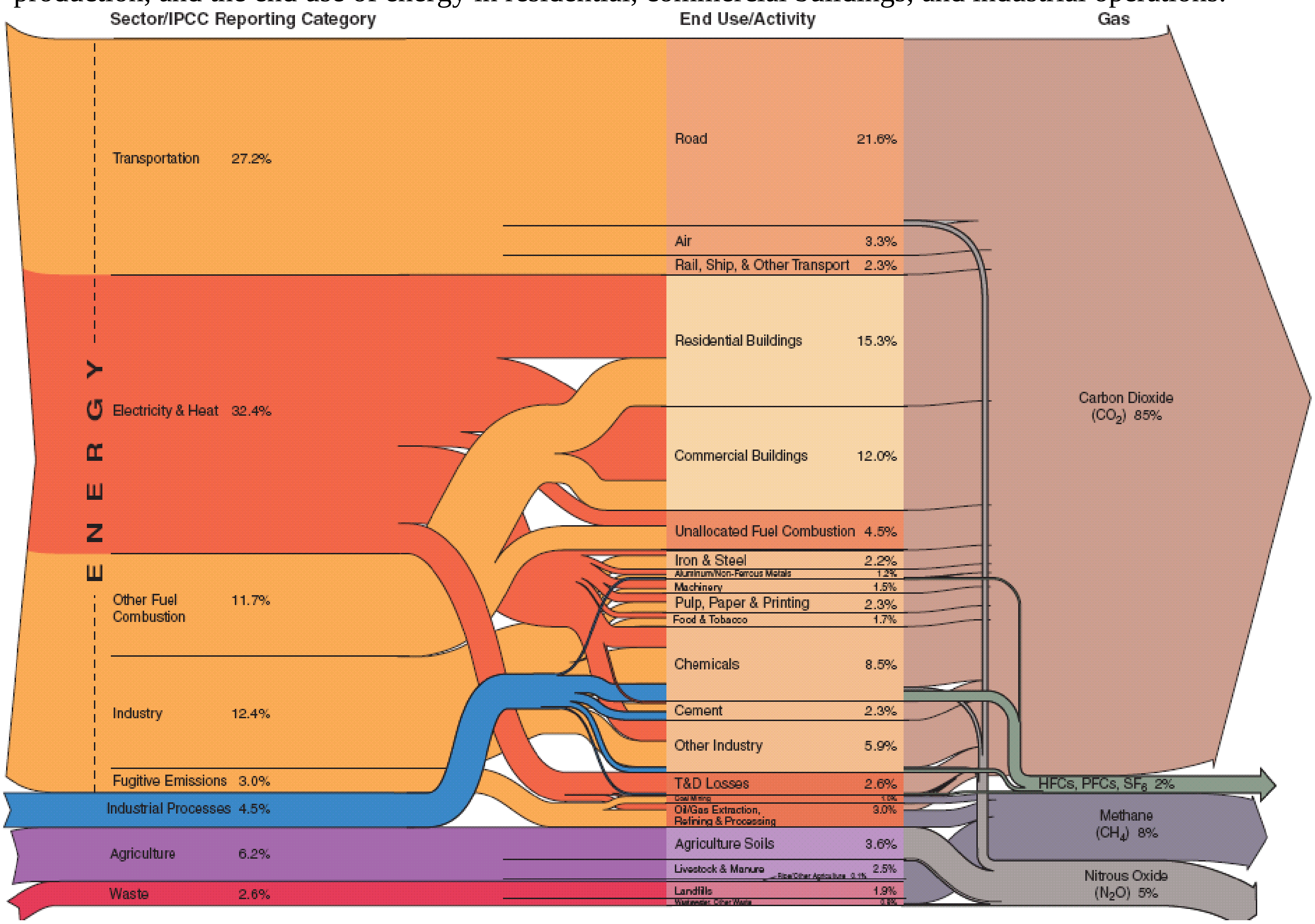

Figure 17. U.S. Energy and GHG emission flows by sector, end use, and gas in 2003

Gases other than CO_2 contribute significantly to warming. Figure 18 illustrates this for the U.S. Although CO_2 is the dominant driver, methane and nitrous oxide are significant, together contributing 13% of the warming driving force. For the global view of the relative significance of the key greenhouse gases, Figure 15 was generated using the MAGICC model. This figure illustrates the relative driving force of the key greenhouse gases for 2020, 2050, and 2100 assuming emissions per the modified IEA base case for CO_2 and IPCC (1) Scenario WRE750 for the other greenhouse gases. For this scenario, methane emissions are projected to grow at 0.5% per year until 2050, and remain constant for the next 50 years. For N_2O, emissions are assumed to grow at 0.4% per year until 2050 and the slow to a 0.1% growth rate until 2100. Also note for the forestry sector CO_2 emissions are projected to decrease at about 2% per year to zero by 2075. Note that mitigating emissions of methane, a short-lived gas, allows for more near-term warming moderation, in contrast to a long-lived gas such as CO_2. Also note Figure 18 projects that fine particles contribute a cooling effect in 2020 that 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 controls to mitigate that health and ecological impact of SO_2 and acidic sulfates. With such emission control, concentrations of sulfate particles, which form from SO_2 in the atmosphere and reflect incoming solar radiation, will consequently be reduced, and their cooling effect reduced, yielding warming relative to 1990.

As mentioned earlier, this paper focuses on energy technologies, and only CO_2 will be discussed, since it is the critical greenhouse gas. However, as noted earlier an aggressive methane mitigation program, in conjunction with aggressive energy technology retooling, could add about 0.2 C warming mitigation, to that achieved via CO_2 mitigation.

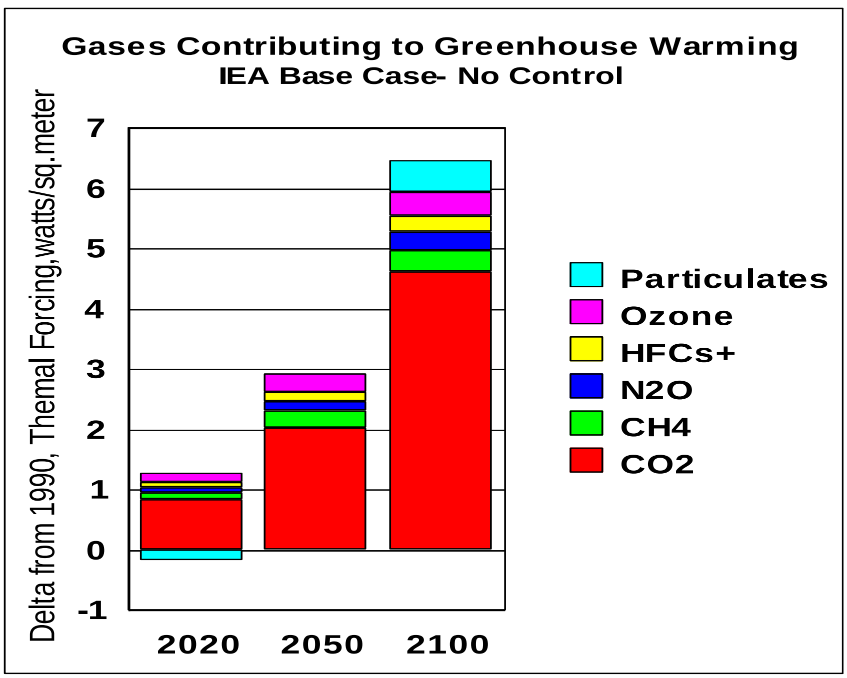

Figure 18. Delta thermal driving force (watts per square meter) of major greenhouse gases

7. The Mitigation Challenge: What can be done and what role can energy technology play?

One key question is, do we need new technology or can we provide deep emission reductions with currently available generation and end use technologies. Three mitigation studies were analyzed to attempt to answer this important question. Enkvist (13) argues that the least expensive way to mitigate emissions in the short term will be to provide incentives to utilize existing technology, both on the end use efficiency side, buildings and mobile sources, and for low emission generation technologies, such as nuclear and wind. He also suggests that state of the art mitigation of non-CO_2 sources could be significant as well. The sum of the mitigation achievable with these state of the art technologies yields an annual savings of about 7.5 Gt CO_2 by 2030. However, assuming that the 3% global growth rate will continue until 2030 in the absence of such a mitigation program, and that we wish to constrain warming to below about 2.5 C, plus/minus 0.7 C, it will be necessary to reduce emissions by about 30 Gt CO_2 in 2030. In the absence of fundamental cultural and lifestyle changes that dramatically reduce our energy usage, *new* energy technology will need to be developed and utilized if potentially catastrophic climate change is to be avoided. Based on the Enkvist analysis, such technology would need to be utilized to yield 74% of the required reduction in 2030. Less dependence on new technology could result if CO_2 emission growth rate would rapidly decelerate to about 1.6% annually, a typical growth rate in the 1990's. Barring an extended worldwide economic slowdown, this appears unlikely. In this case, available technologies could provide about 56 % of the required mitigation.

Similar calculations have been made based on mitigation analyses conducted by Pacala and Socolow (14) for the years 2004 to 2054 and IEA (7) for the years 2030 to 2050. For both references, when one calculates the role that existing technologies could play, within the time frame of their assumed mitigation programs, it is estimated that such an aggressive utilization of existing technology could provide only about 25% of the required mitigation if the current 3% growth rate continues and about 45% of the needed mitigation if global emission growth decreases to a 1.6 % CO_2 growth rate in the near term.

Therefore, it does not appear possible to mitigate the roughly 4 trillion tons of CO_2 that may be required to constrain warming below 2.5 ^oC this century, without the extensive 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. Also as suggested by Figure 18, methane, tropospheric ozone and nitrous oxide mitigation approaches could be significant for the roughly 20% of the thermal forcing associated with them.

In order to understand the potential of various energy technologies to prevent CO_2 emissions, IEA (8) evaluated two key mitigation scenarios: the Accelerated Technology (ACT) scenario, which was formulated in their original Energy Technology Perspectives report in 2006 (7) and the new Blue Scenario formulated in the updated version of their analysis (8). The recent scenario analysis was done at the request of G-8 Leaders & Energy Ministers in 2007. Of these, the Blue *Map* scenario is the most optimistic. The scenario *assumes an aggressive and successful research, development and demonstration program (RD&D) to develop and improve technologies and a comprehensive technology demonstration and deployment program. 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 with costs up to $200/metric ton CO_2 . The incentives could take the form of regulation, pricing, tax breaks, voluntary programs, subsidies, or trading schemes.

Figure 19 illustrates the emission projections assumed for the two mitigation scenarios compared with the assumed baseline emission projection. The fundamental difference between the scenarios is that the Act option aims at decreasing CO_2 emissions in 2050 to 1995 levels, while the more aggressive Blue scenario aims to reduce 2005 emissions in half by 2050. Also shown is the projected CO2 concentrations in 2100 and the author's calculated values of 2100 and ultimate (equilibrium) warming for both scenarios. Included, is a plot depicting the implications of the current 3% emission growth rate if it would continue until 2030. As depicted on Figure 19 for the ACT Map scenario extended to 2100, MAGICC calculations indicate best-guess CO_2 warming of 2.7 ^oC relative to the pre-industrial era. *For the Blue scenario warming in 2100 is projected to be 2.3 ^oC.* Such significant warming is projected, despite the IEA assumption of an aggressive R,D&D and deployment program, the optimistic assumption of a 1.7% growth rate in the near term compared to the current 3% growth rate, and for the Blue scenario, the assumption that early and deep global reductions are implemented.

Figure 20 illustrates the energy sector implications of the ACT and Blue scenarios compared with projected baseline emissions up to the year 2050. For the less aggressive ACT scenario, major savings are achieved in the power generation sector. However, for the Blue scenario, major reductions are required in every energy sector.

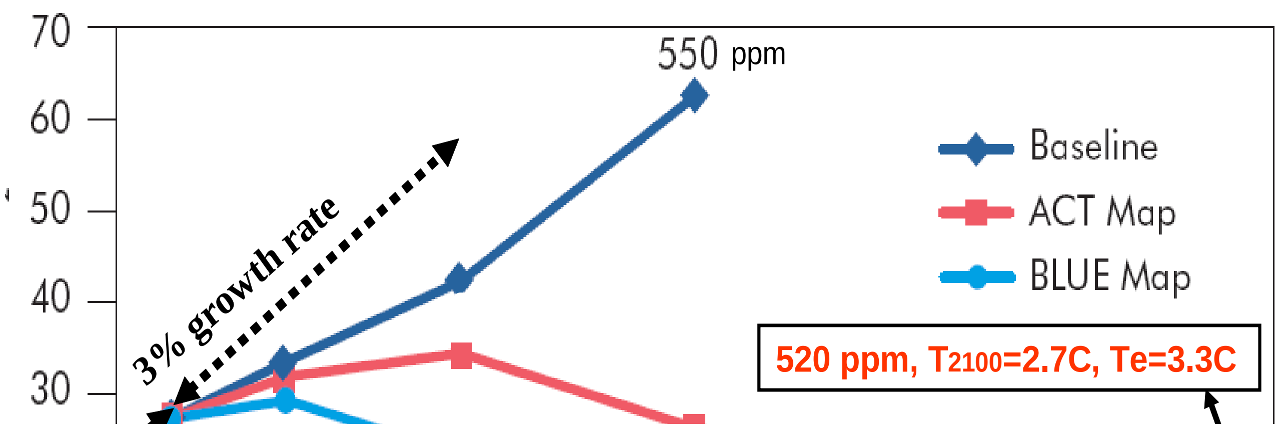

Figure 19. The ACT and Blue IEA emission Scenarios and their projected warming impacts

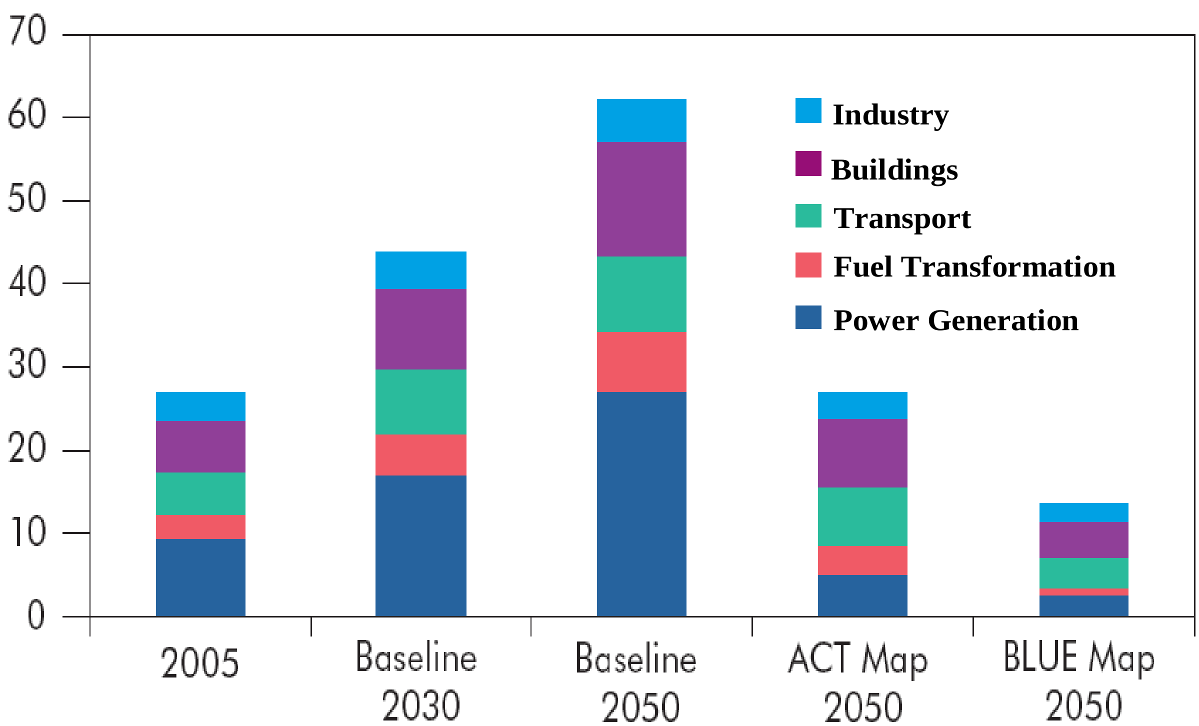

Figure 20. Emissions by sector for Baseline, ACT and Blue Scenarios to 2050 in Gt CO_2

Figure 21 summarizes the results of the IEA analysis by identifying technologies contributing to the CO_2 avoidance of both the ACT and Blue Map scenarios to 2050. The sum of all the bars yields the 35 and 48 Gt avoidance goals for the ACT and Blue scenarios, respectively. The figure illustrates the projected avoidance by technology in the key categories: End Use, Power Generation, CO_2 Storage and Renewables. As can be seen, a diverse array of technologies in all key energy sectors will be needed if these avoidance goals are to be met, especially for the Blue scenario. Of particular importance are end use technologies, in the building, transport and power generation sectors; and carbon storage technologies, in the power generation and industrial sectors. It is important to note that the IEA (8) has characterized the technological changes that would be necessary to achieve carbon reductions consistent with these scenarios: as "A global revolution …. in ways that energy is supplied and used". For the more aggressive Blue scenario they concluded: "The Blue scenarios require urgent implementation of unprecedented and far reaching new policies in the energy sector"

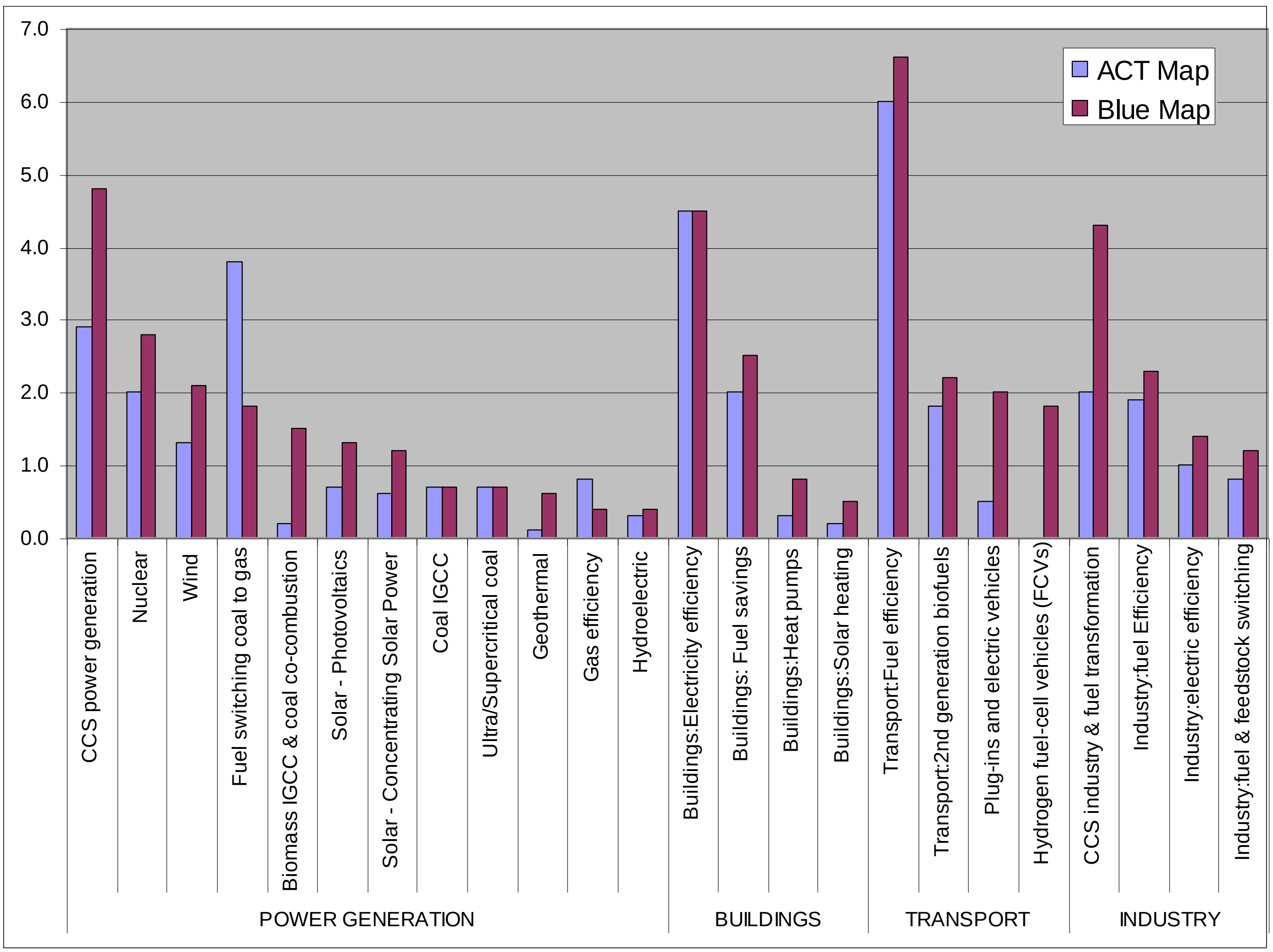

Figure 21. Technologies needed to meet ACT and Blue Map Scenarios Avoidance Goal of 35 and 48 Gt CO_2 in 2050, respectively

<u>8.What are the challenges of an early and deep CO_2 reductions in the energy sector?</u>

It is instructive to examine the implications of an aggressive energy technology mitigation program. The Blue scenario is an ideal option to examine, since it involves early and deep carbon reductions across all the energy sectors, and since the in depth IEA analysis of this option offers us valuable insights regarding the research, development, demonstration and deployment needs, the role that new technology must play, investment requirements and the warming mitigation that is achievable. Figure 22 illustrates the role that new technology will have to play in order to control emissions consistent with both the Blue and ACT scenarios. The author has used engineering judgment to divide the technologies into *existing* and *new* categories. Also, best guess equilibrium (eventual) warming using the MAGICC model is included as a function of the Gt of CO2 mitigated in 2050. As can be seen, new technology will be needed for both scenarios, especially for the Blue option. Also note in the absence of new technology it will be difficult to constrain ultimate warming below about 4 ^{o}C!

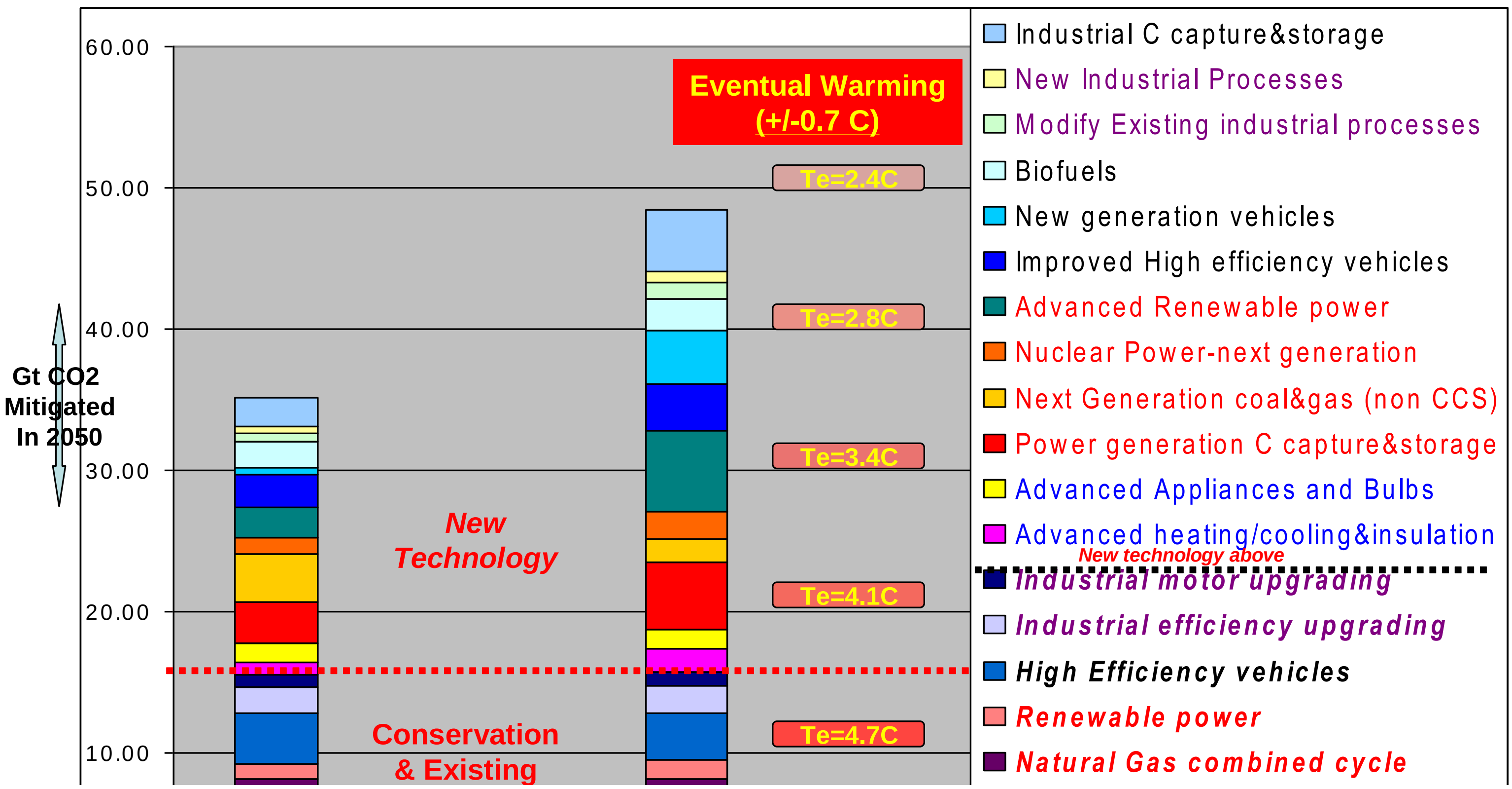

Figure 22. Existing and New technologies needed for the ACT and Blue Scenarios

In order to help quantify the technology requirements, IEA (8) generated Figure 23. It attempts to quantify the ***annual*** need of low carbon power generation facilities in order to reduce emissions consistent with the two scenarios. As can be seen, a fundamental transformation of the power generation sector will be necessary. In addition to unprecedented construction of nuclear facilities and a fundamental shift of coal and gas facilities to incorporate Carbon capture and storage, the Blue scenario will require a massive deployment of solar, wind and geothermal plants.

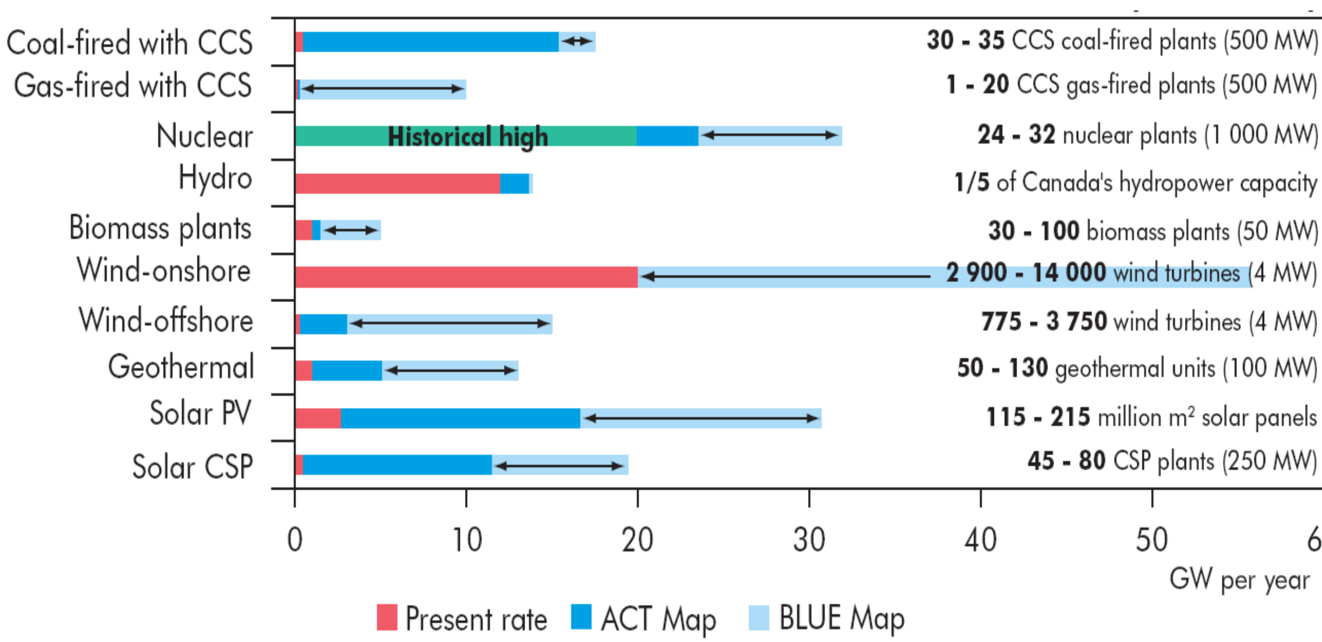

Figure 23. Numbers of plants and their GW per **year** production needed for ACT and Blue scenarios

A key question is: what are the research, development. demonstration and deployment (RDD&D) requirements by technology for each energy sector? Figure 24 has been derived from IEA's Blue scenario (8) to relate RDD&D resource needs compared with the quantity of CO2 projected to be mitigated by technology. Note that the units are Gt per year, and for the costs, ***monthly*** expenditures in $ billions, required over the assumed forty year period. The monthly interval was used to allow the graphic to use the same ordinate values for mitigation and resource requirement quantification.

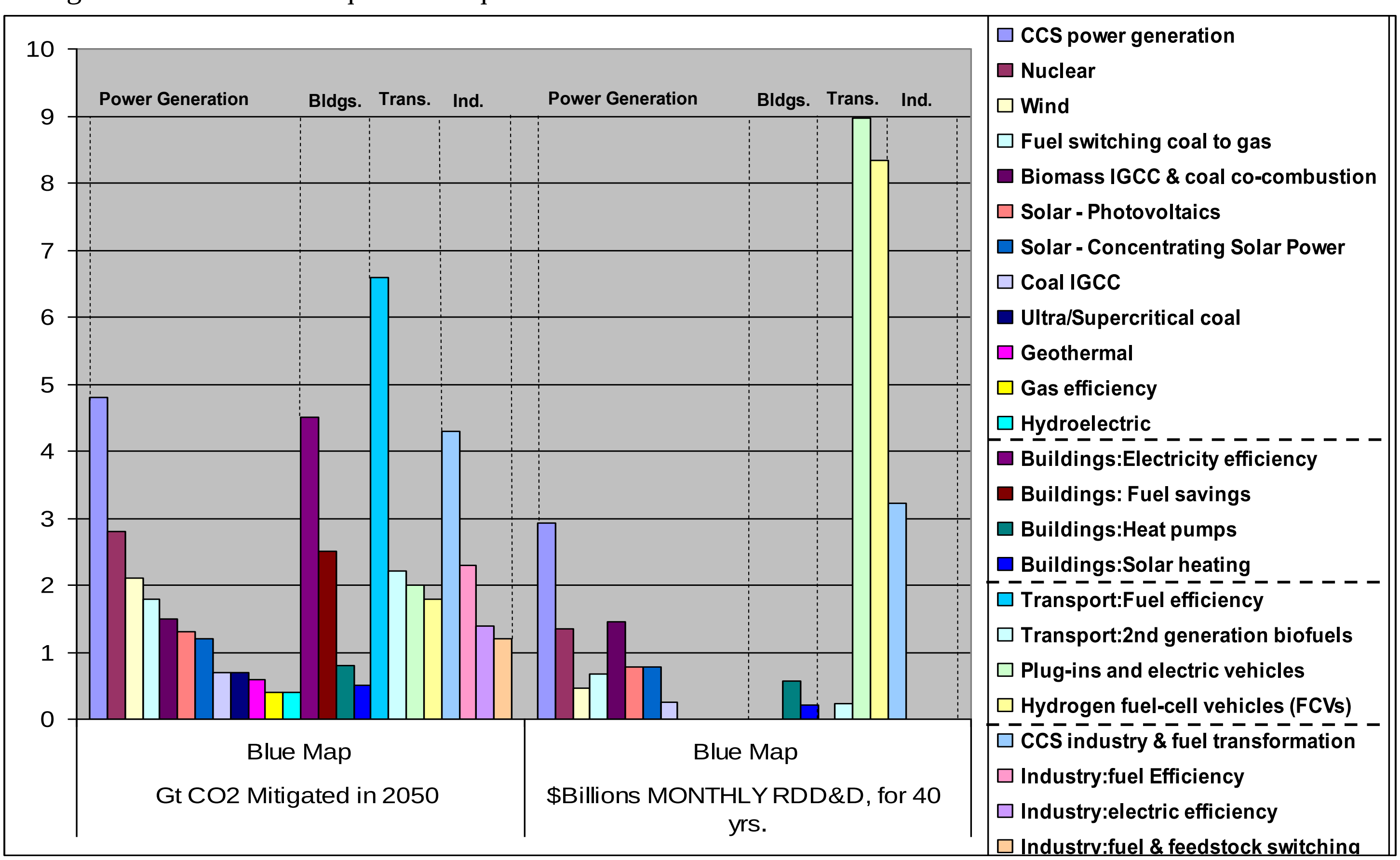

Figure 24. Gt CO2 mitigated with corresponding RDD&D requirements by technology, for Blue scenario

Note that when added together by technology, the annual RDD&D requirements are estimated at $35 billion and total costs over the 40 year period at ***$14 trillion***. As can be seen from the figure, most of the resources are required for mobile source technologies (electric, hybrid and hydrogen/fuel cell vehicles) and for carbon capture and storage (coal generation, energy transformation and industrial facilities). When these technologies are commercial and utilized per the Blue scenario, IEA estimates capital investment requirements of $45 trillion. However, energy savings associated with these new technologies could recover $43 trillion of that investment over time, assuming a 10 % discount rate.

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 for them to meet their potential to avoid CO_2 emissions. Tables 1,2,3 and 4 summarize the potential and status of key technologies based on the following recent energy technology assessments: IEA (7,8), Hawksworth (9), Pacala and Socolow (14), Morgan (16). Two additional references contained useful information relative to hydrogen/fuel cells, USEPA (17), and nuclear technologies, USEPA (18).

9. Power Generation Sector

Of all the sectors, the power generation sector, which has been growing globally, at an annual rate of about 4%, 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. Current retrofit technology is theoretically available, but will likely be substantially more expensive per unit of power generated, than would be the case for new plants with CO_2 capture built in or advanced CO_2 removal retrofit technology now in the early development stages.

Major reductions can result from lower emissions on the generation side and as a result of lower usage via enhanced end use efficiency on the user side. 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 Blue 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 for both the Blue and the less aggressive ACT scenario. Also included is information regarding potential environmental issues assuming wide scale deployment of the given technology, and the relative priority of environmental characterization and risk management research to understand and minimize these problems, Priority judgments were based on the potential magnitude of the environmental impacts and the relative availability of information relative to the magnitude and the mitigation potential of such impacts.

Key generation technologies include nuclear power, natural gas/combined cycle, and three coal combustion/capture technologies (Integrated Gasification Combined Cycle (IGCC), pulverized coal/oxygen combustion, and conventional pulverized coal), all with integrated CO_2 capture and underground storage. Figure 25 illustrates the major components of each technology. IGCC technology is the primary focus of the U.S. R,D&D program, but requires complex chemical processing, pure oxygen for the gasification process and cannot be readily retrofitted to existing plants. Oxy-combustion systems also require pure oxygen for combustion but are less complex and have the potential for retrofitting existing plants. CO_2 removal via scrubbing, adsorption or membrane separation is conceptually simple, is inherently retrofitable, but is at an early development stage; commercial amine scrubbers use large quantities of energy for sorbent regeneration and are expensive. Figure 26 schematically depicts a promising CO_2 capture technology under development by Research Triangle Institute (RTI). The Department of Energy has sponsored pilot testing at EPA's Office of Research and Development 's (ORD) Multi-pollutant Combustion Research facility. Early pilot testing results showed high CO_2 capture and efficient sorbent regeneration.

MIT (5) recently completed an in-depth study of coal in a carbon constrained world and concluded that: "… CO_2 capture and sequestration is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs." They concluded that current research funding is inadequate and "what is needed is to demonstrate an integrated system of capture, transportation and storage of CO_2, at (appropriate) scale."

With the exception of wind power, renewable technologies are not projected by IEA (8) to have major mitigation impacts for the ACT scenario in the 2050 time frame. In the case of solar generation, both photovoltaic and concentrating, technologies are currently prohibitively expensive. However, the Blue scenario assumes major improvements and cost reductions for both solar technologies, allowing them to play a major role in low carbon power generation before 2050. 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 critical, especially in the area of CO_2 capture and storage (CCS) and for the next generation of nuclear power plants. All three capture technologies described above, warrant aggressive R,D&D programs. The author concurs with MIT (5), that there are too many uncertainties with regard to IGCC to limit R,D&D focus to that technology alone. Therefore, more emphasis should be placed on pulverized coal/oxygen (oxy-fuel) combustion, and high efficiency pulverized coal with CO_2 flue gas capture technology. Underground sequestration will be needed for each of these technologies and is in an early developmental stage, with extraordinary potential. However, there are a host of economic, environmental, safety and efficacy 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 storage capacity.

An example of an important sequestration environmental issue, is the potential of such operations to adversely impact drinking water sources. While CO_2 itself is not toxic, it could change subsurface geochemical conditions in such a way that toxic metals, such as arsenic, could be released into the water. Also, impurities in the captured CO_2 stream, could also impact drinking water quality. Because of these potential impacts, and the likely large areas of the subsurface impacted by such sequestration if applied on a wide scale, this issue should be given a high research priority. EPA's ORD has expertise in subsurface geochemistry, gas transport, field measurements, and remediation. Such expertise would be useful in assessing this potential problem and to evaluate potential mitigation approaches.

MIT (5) estimates that 3 full scale CCS projects in the U.S. and ten worldwide are needed, to cover the range of likely accessible geologies for large scale storage. EPA capability in the area of protection of groundwater resources should be productively utilized in planning and implementing such a demonstration program.

For advanced nuclear power, the technology is quite promising and could start making a major impact by 2030. However, the 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 to the public, that it is safe.

Ideal power generation technologies from environmental and sustainability viewpoints, would be based on renewable energy sources. Therefore, major technological development efforts, should be focused on enhancing performance and reducing costs for wind power, both on-shore and off-shore, and both solar generation technologies.

Table 1. Candidate Technologies for CO2 Mitigation From Power Generation (projected impact in Gt/year of CO_2)						
Technology	**Current State of the Art**	**ACT 2050 Impact**	**Blue 2050 Impact**	**Issues**	**Technology R,D&D Needs**	**Potential Environmental Impacts/ *R&D Needs***
Solar-Photovoltaic and concentrating (renewable)	First generation commercial, but very high costs	1.3	**2.5**	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 for disposal or use. Potential upstream emissions/effluents associated with manufacturing cells ***/Medium***
Wind Power (renewable)	Commercial	1.3	**2.1**	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 for disposal or use; possible local impact on bird population/ ***Medium***
Fuel Switching coal to gas	Commercial	3.7	**1.8**	Key issue is availability and affordability of natural gas	**Medium**, higher efficiencies with new materials desirable	Reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts and Residues for disposal or use. Extraction R&D could enhance availability of CH4/ ***Low***
Nuclear Power-next generation	Developmental, Generation III+ and IV: e.g. Pebble Bed Modular Reactor and Supercritical Water Cooled Reactor	1.0	**1.8**	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	Relative to coal, reduction in emissions of SOx, NOx, Fine PM; fewer mining wastes. Small quantities of potent and long-lived waste, could contaminate small area/ ***High***
Coal IGCC with CO2 Capture and Storage	*IGCC*: early commercialization, Underground storage *(US)*: early development.	1.0	**1.6**	*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 environmental impact, efficacy, cost and safety	Lower power plant efficiency yields greater emissions of SOx, NOx, Fine PM and coal mining impacts, including acid mine drainage. Sequestration could impact groundwater quality/ ***High***
Pulverized Coal/Oxygen combustion with CO2 Capture and Storage	Developmental	1.0	**1.6**	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 and coal mining impacts, including acid mine drainage. Sequesrtation could impact groundwater quality/ ***High***
Pulverized Coal with CO2 Capture and Storage	Underground storage developmental; CO2 scrubbing with MEA near commercial but too expensive	0.9	**1.6**	*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 efficiency yields greater emissions of SOx, NOx, Fine PM and coal mining impacts, including acid mine drainage. Sequestration could impact groundwater quality/ ***High***
Biomass as fuel gasified or co-fired with coal (renewable)	Commercial, steam cycles	0.2	**1.5**	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 and excessive water use from biomass plantations***/ Medium***
Nuclear Power-current generation	Commercial, Pressurized Water Reactors and Boiling Water Reactors	1.0	**1.0**	Plant siting, high capital costs, levelized cost 10 to 40% higher than coal or gas plants, potential U shortages, safety, waste	**Medium,** Waste disposal research	Relative to coal, reduction in emissions of SOx, NOx, Fine PM; fewer mining wastes. Small quantities of potent and long-lived waste, could contaminate small area/ ***High***
More Efficient Coal Fired Power Plants no CO2 Capture and Storage	Early commercialization of supercritical and ultra supercritical	0.7	**0.7**	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 for disposal or use ***/Low***
Coal IGCC with no CO2 Capture and Storage	IGCC: early commercialization	0.7	**0.7**	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 for disposal or use ***/Medium***
Geothermal	Early commercialization	0.1	**0.6**	Cost of deep drilling and fracturing, distance from users	**High,** large number of demos in various geological formations	Potential for water and land pollution problems at geothermal site***/Medium***
Natural Gas Combined Cycle (new)	Commercial, 60% efficiency	0.8	**0.4**	Limited by natural gas availability, which is major constraint; high efficiency & low capital costs	**Medium**, higher efficiencies with new materials desirable	Reduction in emissions of SOx, NOx, Fine PM; fewer mining impacts & residues for disposal. Extraction R&D could enhance availability of CH4/ ***Low***
Hydroelectric (renewable)	Commercial	0.3	**0.4**	Capital costs high, potential ecological disruption, siting challenges	**Medium**, minimize environmental footprint	Local ecological impacts ***/Low***

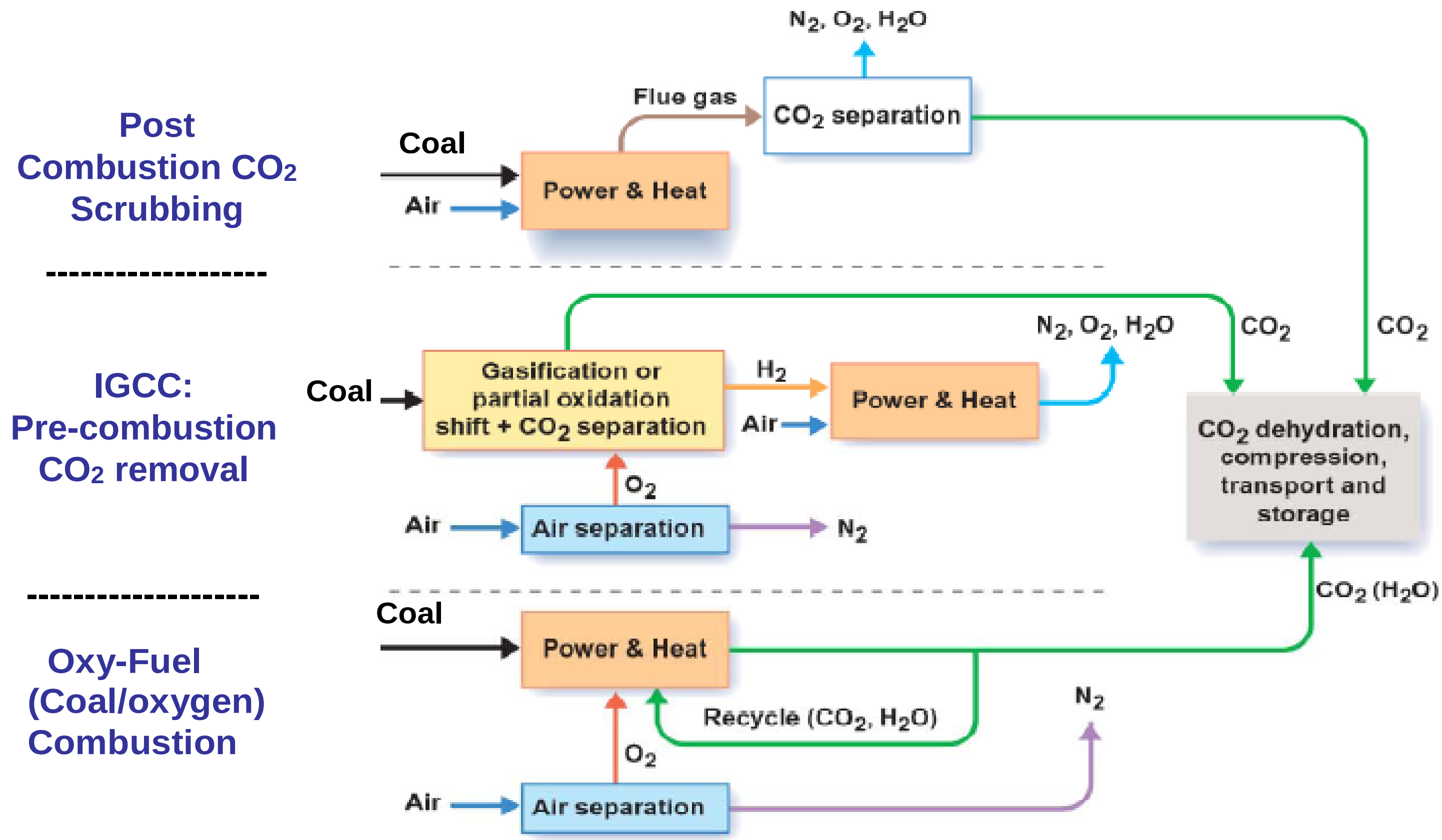

Figure 25. Three key technologies capturing CO_2 from coal-fired power plants

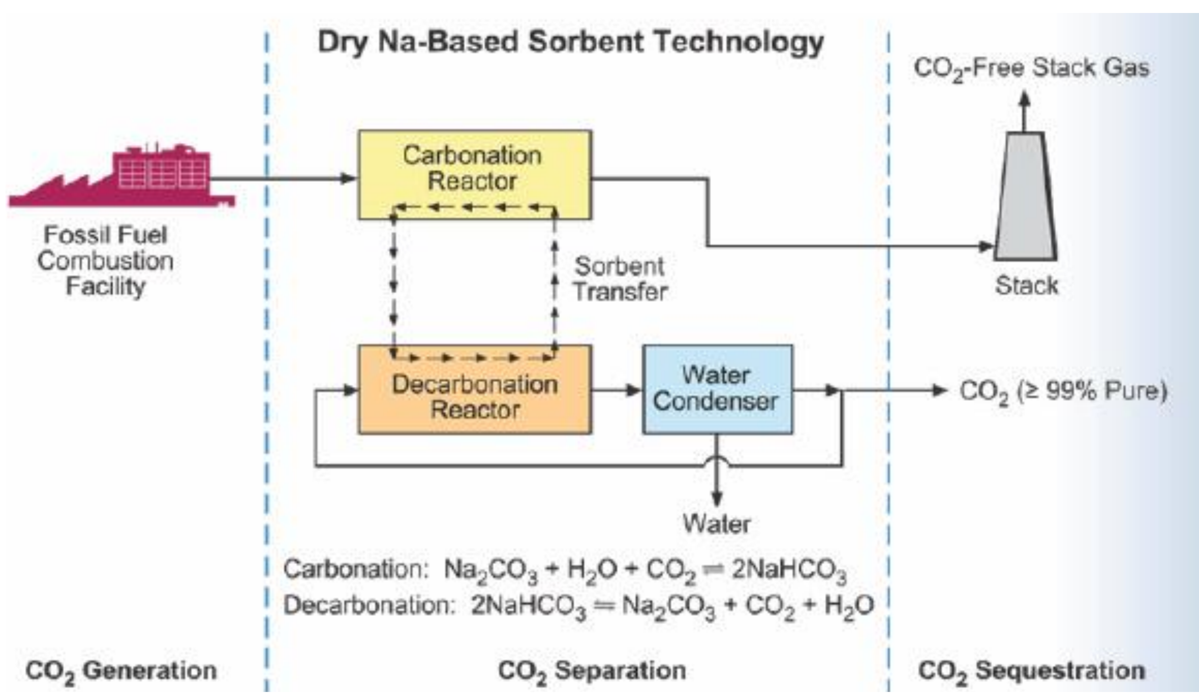

Figure 26. RTI's Dry Carbonate Process for CO_2 capture

10. Building Sector

The building sector utilizes large quantities of electricity and fossil fuels directly and is expected to increase CO_2 emissions for the next several decades at about 2 % per year. Figure 17, illustrates the importance of this sector in the U.S., with commercial and residential buildings contributing 27 % 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 includes lighting.

For each of the two categories, the technologies are listed in the order of their potential impact in 2050 according to IEA for both the ACT and Blue scenarios. The technologies are either aimed at enhancing end use efficiency, or are new alternative building heating/cooling technologies. It is important to note, that high-efficiency appliances and heating and cooling technologies are currently commercial, although there is potential for even higher efficiencies assuming a focused, successful research program. 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.

Table 2. Candidate Technologies for CO_2 Mitigation From Buildings (projected impact in Gt/year of CO_2)

	Technology	Current State of the Art	ACT 2050 Impact	Blue 2050 Impact	Issues	Technology R,D&D priority and Needs	Potential Environmental Impacts/ *R&D Need*
Heating & Cooling	**Enhanced energy mgt. and high efficiency building envelope: insulation, sealants, windows, etc.**	Commercial	2.0	**2.5**	Lack of incentive, high initial costs, long building lifetime	**Low/medium priority**, incremental improvements to lower cost and enhance performance	Less fossil fuel and nuclear power generation, and less on-site fossil fuel combustion, yield reductions in coal & natural gas emissions, and nuclear wastes/ ***Low***
Heating & Cooling	**High efficiency building heating and cooling, including**	Commercial	0.3	**0.8**	Lack of incentive, high initial costs	**Low/medium priority**, incremental improvements to lower cost and enhance performance	Same as above
Heating & Cooling	**Solar heating and cooling**	First generation commercial	0.2	**0.5**	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	Same as above
Appliances	**More efficient Electric appliances**	Commercial			Higher initial costs and lack of information to the consumer	**Low/medium priority**, incremental improvements to lower cost and enhance performance	Less fossil fuel and nuclear power generation, yields reduction in coal & natural gas emissions, and nuclear wastes/ ***Low***
Appliances	**More efficient lighting systems**	Commercial-fluorescent	4.5	**4.5**	Lack of incentive given higher initial costs	**Medium**, LED and OLED technology needs further development with aim of lowering initial cost	Same as above;however, mercury content of fluorescent bulbs could cause health and env. Problems */Med*
Appliances	**Reduce stand-by losses from appliances, computer peripherals, etc.**	Commercial			Lack of incentive from vendors and lack of knowledge from end-users	**Low**	Less fossil fuel and nuclear power generation, yields reduction in coal & natural gas emissions, and nuclear wastes/ ***Low***

11. Transportation Sector

The transportation sector is growing at a fast rate, estimated at 2.5% per year globally, driven by developing countries such as China and India, with a combined population of 2.4 billion. 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 capable of major reductions in CO_2 emissions per mile traveled, especially for light-duty vehicles. Table 3 summarizes the status of major technologies. Again, for each of the two categories, the technologies are listed in the order of their potential impact in 2050 according to IEA's Blue Scenario. 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. To the extent vehicle efficiency can be improved and renewable fuel options developed, major savings can be realized in the transportation sector.

IEA (7,8) projected that substantial quantities of CO_2 will be emitted by gas and coal to liquid processes, in what they refer to as the energy transformation sector as demand for oil exceeds global petroleum and natural gas extraction capability. Such processes would produce fuels primarily for the transportation sector. It is the author's opinion that processes generating liquid fuels from tar sands, and oil shale could be major emitters as well, unless the CO_2 is sequestered. In addition to concerns about large CO_2 emissions, such processes have the potential of generating large quantities of air and water pollutants and hazardous wastes, yielding serious environmental impacts. However, improvements in vehicle and engine technology to enhance conversion efficiency, will lessen the need for such carbon intensive energy transformation processes.

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 (17) and IEA (7) assessments suggest that CO_2 savings would not be substantial, unless or until the hydrogen could be generated from CCS or low-emission, renewable sources.

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.

It should be noted that to displace large quantities of transportation fuels, vast areas of dedicated biomass plantings will be necessary. It will be important to ensure that such plantings are configured and maintained to minimize environmental damage by avoiding depletion of aquifers, pollution of surface and groundwater supplies, and degradation of soil quality. It is also necessary to understand the potential for excessive water utilization, especially in water stressed areas. Finally, there must be some level of confidence that such plantations will maintain their productivity as the climate changes in the decades ahead, and that adverse impact on food production is avoided.

Table 3. Candidate Technologies for CO2 Mitigation From Mobile Sources (projected impact in Gt/year of CO2)

	Technology	Current State of the Art	ACT 2050 Impact	Blue 2050 Impact	Issues	R,D&D Needs	Potential Environmental Impacts/ *R&D Need*
Vehicles	**Improvements: Current Internal combustion engine components**	First generation: commercial			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, CO and NOx, uncertain impact on air toxics ***/Medium***
	Non-engine Improvements: Current Vehicles; tires, A/C, light materials	First generation: commercial	Total of 6.0	Total of 6.6	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, CO and NOx ***/Low***
	Hybrid vehicles	First generation: commercial			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, CO and NOx, uncertain impacts of battery production and disposal ***/Medium***
	Plug-ins and Electric Vehicles	Developmental	0.5	2.0	Battery cost and lifetime key issue. Also requires low C electric generation to maximize Carbon reduction benefits	**High,** intensive R&D necessary to optimize battery performance, lifetime and ability to allow deep cycling and rapid charging	Lower emissions of VOCs, CO and NOx, uncertain impacts of battery production and disposal ***/Medium***
	Hydrogen fuel cell vehicles	Developmental	0.0	1.8	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. Hydrogen storage R,D&D also needed	On road emissions close to zero, H_2 production emissions depends on feedstock & production process ***/High***
Fuels	**Ethanol from sugar**	Commercial			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, soil and water impacts from biomass plantations, environmental studies would be useful /***High***
	Biodiesel & other fuels from biomass; thermo chemical processes	Developmental			Developmental, yet potentially high production and lower cost via gasification/Fischer-Tropsch synthesis	**High,** Major R,D&D needed to develop and demonstrate viable technology for biomass feedstock	Potential eco, soil and water impacts from biomass plantations, production and combustion impacts unclear; environmental studies would be useful/ ***High***
	Biodiesel from vegetable oil	First generation: commercial	Total of 1.8	Total of 2.2	High costs, low yield from oil crops, limited waste cooking oils, low S a positive	**Low**	Not clear, environmental characterization would be useful/ ***High***
	Ethanol from grain/starch, e.g.,corn	Commercial			Limited by grain supply; high costs, energy intensive production	**Low**	Not clear, environmental characterization would be useful / ***High***
	Ethanol from biomass/lignocellulose; biochemical process	Early Developmental			Inability to convert wide range of biomass types, high production costs, dispersed biomass source	**High**, Breakthrough R,D&D needed to develop lower cost generally applicable process(es)	Potential eco, soil and water impacts from biomass plantations, production and combustion impacts unclear; environmental studies would be useful/ ***High***

12. Industrial Sector

CO_2 emissions from the industrial sector are projected to grow at an annual rate of 2 % 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 applied to a large fraction of the industrial sector. Technologies, which are generally applicable, 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, CCS also offers the potential for mitigating large quantities of CO_2. However, as discussed 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 lower energy intensity.

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 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."

Table 4. Candidate Technologies for CO_2 Mitigation From Industrial Sources (impact in Gt/year of CO_2)

Technology	Current State of the Art	ACT 2050 Impact	Blue 2050 Impact	Issues	R,D&D Needs	Potential Environmental Impacts/ *R&D Need*
CO_2 Capture and Storage	Early development	2.0	4.3	Applicability limited to large energy-intensive industries, including fuel transformation processes; 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 process efficiency yields greater air, water and land impacts per product produced, sequestration could impact groundwater quality / ***High***
Motor Systems	Commercial	1.0	1.4	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, PM and residues/ ***Low***
Enhanced energy efficiency: existing basic material processes	Commercial	Enhanced fuel efficiency, total 1.9	Enhanced fuel efficiency, total 2.3	Developing countries can have low energy efficiency due to lack of incentive and/or expertise	**Low**	Potential reduction in air emissions, water effluents and wastes/ ***Low***
Steam systems (required for many industries)	Commercial			For most industries not a major cost; lack of expertise for some industries	**Low**	Reduction in coal emissions: SOx, NOx and PM and residues / ***Low***
Materials/Product Efficiency	First generation: commercial			Little incentive to minimize the CO_2 "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, depending on substitute material / ***Medium***
Cogeneration (combined heat and power)	Commercial			Limited by electric grid access that would allow the ability to feed electricity back to grid' also high	**Low**	Reduction in coal emissions: SOx, NOx and PM and residues / ***Low***
Enhanced energy efficiency: new basic material processes	Developmental to Near-commercial depending on industry			New, innovative production processes require major R,D&D and would need reasonable 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 / ***High***
Fuel Substitution in Basic Materials Production	Commercial	0.8	1.2	Natural gas substitution for oil and coal can be expensive	**Low**	Unclear, environmental studies useful/ ***High***
Feedstock Substitution in key industries	Commercial			Biomass and bioplastics 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/ ***High***

13. Geoengineering Options

Finally, there have been various geoengineering approaches suggested, which could potentially slow warming until new energy technologies are developed and deployed. These options would attempt to change the earth's heat transfer characteristics via interventions at the planetary scale. For example, Wigley (15) 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.

14. R,D,&D

IEA (7,8), Hawksworth (9), Morgan (16), MIT (5), and Princiotta, (19), have observed that R,D,&D funding in the energy area will need to be substantially increased to accelerate deployment and utilization of key technologies. As illustrated earlier, the later a mitigation program is initiated, the more severe emission cuts will need to be if CO_2 concentrations above 500 ppm are to be avoided. The Stern Report (20) 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. IEA (8) reviewed several references and concluded the range of increase for R,D&D required was between 2 and 10 over current levels. As discussed earlier, IEA estimates a total of about $14 trillion of R,D&D *plus deployment* would be required for their Blue scenario. Deployment costs are those costs that would allow construction and operation of near commercial technologies with the aim of improving performance and lowering the cost differential relative to the high carbon emission technology it would displace.

It is important that such R,D&D be conducted at both the federal and private sector levels. Federal funding is particularly relevant for those technologies that require substantial funding due to high capital costs and have a low probability of commercial impact and ultimate profitability in the near term. Examples include carbon capture and storage, and next generation nuclear power technologies. Private sector funding for the lower cost, lower risk technologies could be encouraged by providing incentives, such as regulatory drivers and attractive market prices.

Figure 27, generated from IEA data (21), depicts IEA countries' research expenditures in critical energy technology areas. It illustrates the relatively flat funding in recent years and the major funding reductions since the major funding increases in the 1970's, motivated by the Middle East oil embargo. It should be recognized that, in the last few years, the U.S. has redirected some of its limited 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 (22). Within the constraint of current budget priorities, the CCTP has coordinated a diversified portfolio of advanced technology research, development, demonstration and deployment projects, 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. The key agency responsible for CCTP related research is the Department of Energy, with about 86% of fiscal year 2008 CCTP funding. As part of this program, USEPA (23) is implementing a series of voluntary programs that encourage the reduction of greenhouse gas emissions, including Energy Star for the building sector, transportation programs, and non-CO_2 emission reduction programs in collaboration with industry. These programs, with their focus on conservation and low GHG technologies, could provide a foundation for an expanded program consistent with the mitigation challenge.

Figure 28 depicts the same technologies as Figure 21, with their contribution to CO_2 avoidance in 2050, for the Blue scenario, but characterizes each technology into high, medium and low research priority categories. This is based on the author's judgment regarding the potential contribution to CO_2 avoidance each technology can achieve with an accelerated research, development, demonstration and deployment program. It is noteworthy that for the coal generation sector, these priorities are consistent with MIT (5), which has conducted the most in-depth study of this critical energy source.

As indicated in the last column of Tables 1 through 4, many of these technologies have the potential for significant environmental impacts via ecosystem damage and/or emissions/effluents to the air, water and land. Therefore, a parallel research program to better understand such impacts for key technologies is indicated. Figure 29, which again is based on the IEA Blue technologies, indicates the author's judgment regarding the potential magnitude of environmental impacts, assuming wide scale utilization. As shown, advanced coal and biomass technologies are among those with the potential for major impacts and should be the focus of a comprehensive environmental assessment research program.

EPA's Office of Research and Development has key capabilities that can contribute to the development and assessment of important mitigation technologies. These include a world class coal combustion pilot facility, a large array of dynamometers for vehicle testing, expertise in utilizing the MARKAL "bottom-up" technical-economic model to evaluate the potential of emerging technologies, and expertise in characterizing and controlling emissions and effluents to the air, water, and land. Such capabilities can help ensure the most promising technologies are being developed and that their environmental characteristics are adequately defined.

It should be noted that all the transportation technologies offer the potential for reducing U.S. dependence on foreign oil. Further, the countries that can bring these technologies to market first have the potential for major revenue streams from a multi-billion dollar international market.

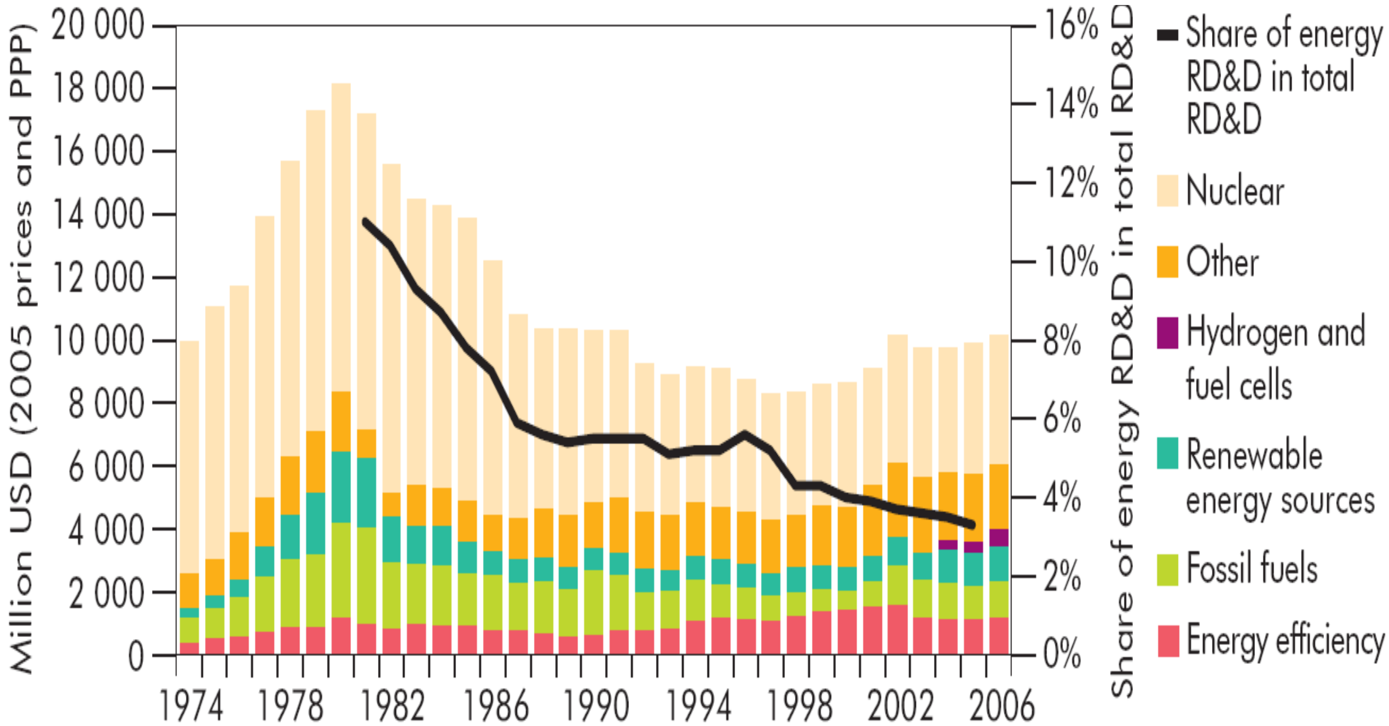

Figure 27. IEA Countries' R,D,&D expenditures for key energy sectors, 2005 US $ (millions)

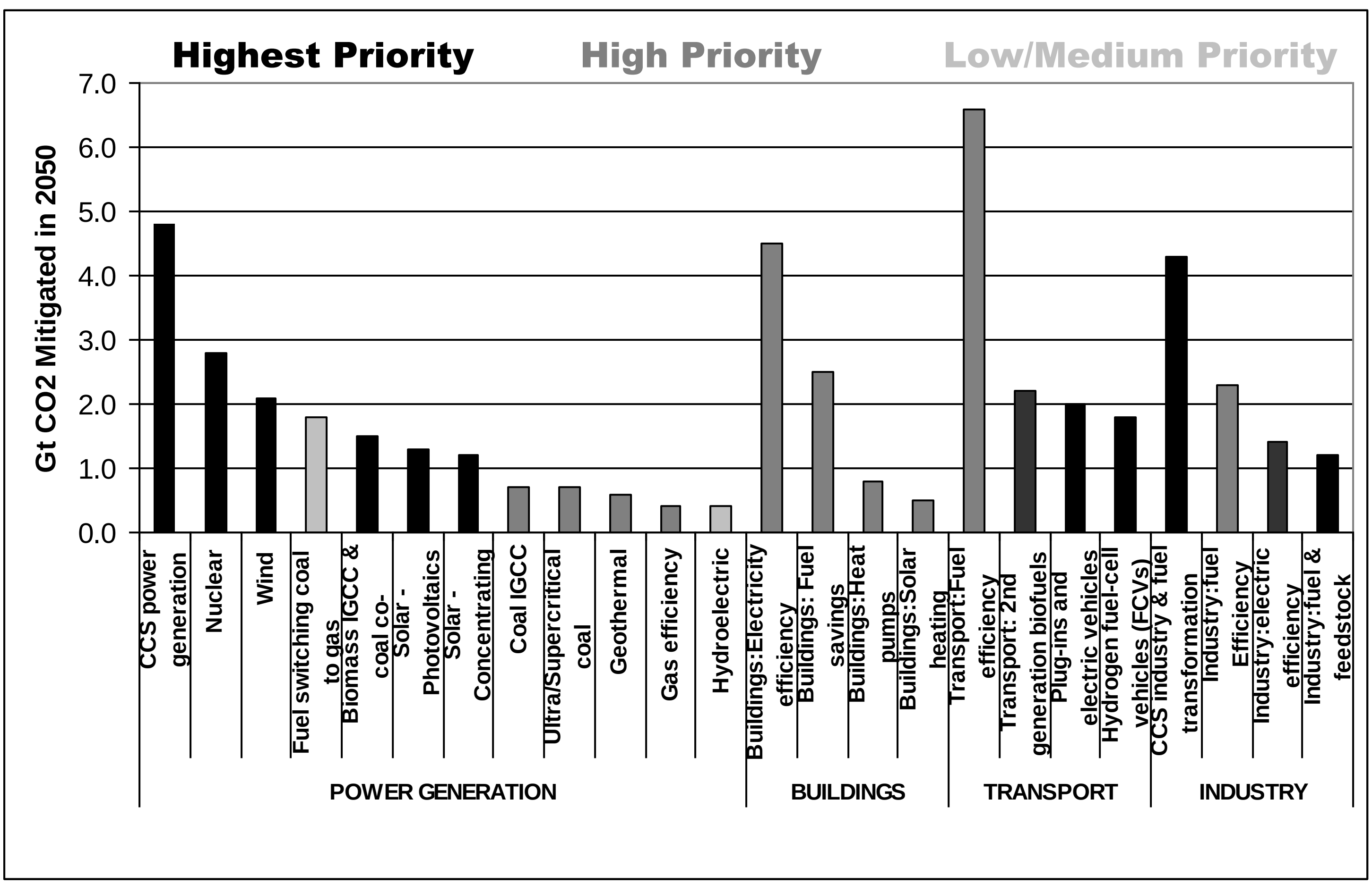

Figure 28. Author's R, D&D priorities to achieve IEA's Blue Scenario CO_2 Avoidance Goal in 2050

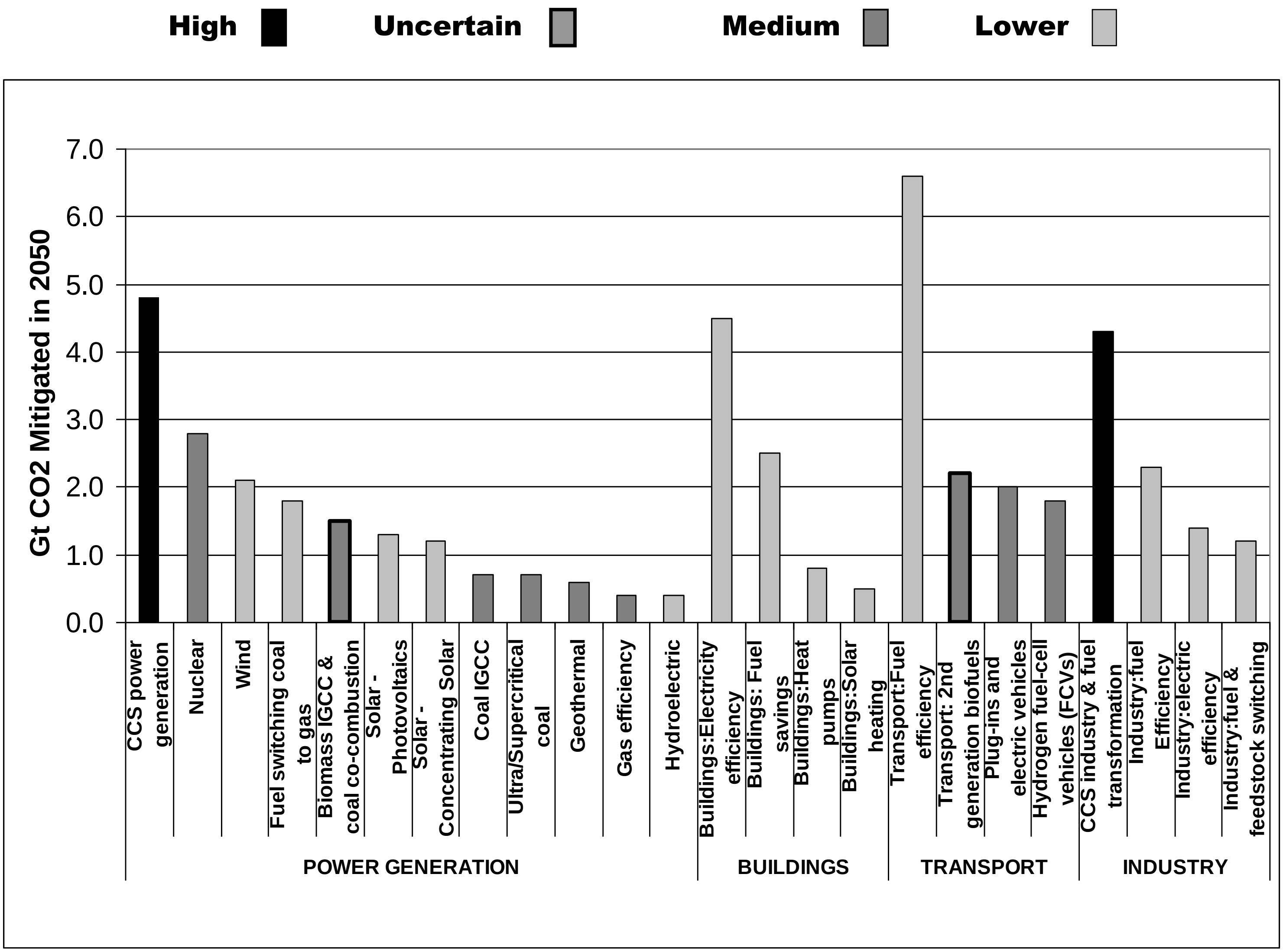

Figure 29. Author's Assessment of the *Potential* Environmental Impacts of Mitigation Technologies for the Blue Scenario

15. Summary and Conclusions

-Concentrations of CO_2 have increased to 383 ppm from a pre-industrial value of 278 ppm. This increase is due to anthropogenic emissions of CO_2 that can remain in the atmosphere more than 100 years. There is close to a scientific consensus that **much if not all of the nearly 0.8 ^oC global warming seen since the pre-industrial era is a result of increased concentrations of CO_2 and other greenhouse gases**. Methane, tropospheric ozone, nitrous oxide, and halocarbons are significant greenhouse gases. Together they are projected to contribute about 20% of projected warming by the end of the century.

-**Global emissions of carbon dioxide have been accelerating at a rate of about 1.4% per year in the 1992 to 2002 time period. However, recent data suggests an acceleration of emission growth in recent years: 3.3% in the 2000 to 2006 period.** China's major expansion of its coal-fired power generation capacity has been the key factor in this unexpected acceleration in growth rate. **It will not be possible to have an effective global mitigation program without a serious commitment by the major emerging economies, e.g., China, India, Brazil**

-A voluntary program such as the U.S. strategy to cut greenhouse gas intensity by 18% over 10 years is **only a starting point toward reducing national emissions. Additional and much more stringent reduction efforts will be needed to moderate warming worldwide.**

- Projections of warming have been made on a credible business-as-usual case based on IEA (7) projections extended to 2100. This base case assumes a global annual growth rate of 1.6% in the next 25 years. Under this assumption, CO_2 concentration is projected to increase to 500 ppm in 2050 and 825 ppm by 2100. **Such concentrations will yield best-guess average warming, relative to 1990, of 1.5 ^oC in 2050 and 3.5 ^oC in 2100**. There is still a large range of uncertainty associated with these warming projections; the potential warming in 2100 could be as high as 4.5 ^oC or as low as 2.1 ^oC. This warming would be in addition to the 0.4 ^oC already experienced from 1700 to1990. Warming would continue into the next century, with equilibrium temperatures in the 2.3 to 7.6 ^oC range, with the best guess at 4.9 ^oC above 1990 levels.

-If current worldwide emission trends continue to surprise the prognosticators, and grow at 3% per year for the next 22 years before moderating, then projected warming, and potential consequences, would be substantially higher. **This scenario will yield a best-guess average warming, relative to 1990, of 1.8 ^oC in 2050 and 4.4 ^oC in 2100**.

-It is too late to prevent substantial additional warming; the most that can be achieved would be to moderate the projected warming. The best result that appears achievable, assuming a major energy technology retooling, would be to constrain warming about 2 ^oC above 1990 levels (between 1.2 and 2.8 ^oC) by 2100. Global impacts for this constrained warming scenario are potentially serious. This suggests that the world community may have no remaining alternative other than to **pursue both mitigation and adaptation approaches aggressively**.

-In order to limit warming to the 2 ^oC level (plus/minus the uncertainties) utilizing CO2 emission mitigation, it will be necessary for the world community to **decrease annual emissions at a rate of between 1 and 3% per year for the rest of the century**. The earlier the mitigation program starts, the less drastic the annual reductions would need to be. Since the base case assumes a roughly 1.6% positive growth rate, approximately one trillion tons of carbon (3.7 trillion tons of CO_2) will have to be mitigated by 2100 relative to the base case. An aggressive methane mitigation program could contribute in the order of an additional 0.2 ^oC of warming avoidance. This would be **an historic challenge**. Never has the world community had to face the prospects of fundamental energy production and utilization transformations to such an extent and at such a pace.

-Recent publications were used to relate the implications of a 4 trillion-ton mitigation program needed to constrain warming to below about 2.5 ^oC to the key energy sectors and the technologies within those sectors that can contribute to the major mitigation challenge. It is concluded that an aggressive mitigation program relying on ***existing*** **technologies is capable of mitigating only between about 25% and 45% of the required CO2**, depending on projected business as usual CO_2 growth rates. Therefore, in the absence of fundamental lifestyle changes, new technologies are required for the key energy-related sectors: power generation, transportation, industrial production, and buildings. **The power-generation sector and transportation sectors are particularly important, since they are projected to grow at relatively high rates, driven especially by China and other actively developing countries.**

-The **power-generation sector,** projected to grow globally, from a large base at 4% annually, offers the greatest opportunity for CO_2 reductions. However, since the key source of emissions from this sector is coal combustion, it is critically important to develop affordable CO_2 mitigation technologies for such sources and to develop economical alternatives to coal-based power generation. CCS offers the potential to allow coal use while at the same time mitigating CO_2 emissions. The three major candidates for affordable CO_2 capture are: PC boilers with advanced CO_2 scrubbing, IGCC with carbon capture, and oxygen-fed (oxy-fuel) combustors. Of the three, only IGCC is being funded at levels approaching those needed. However, all three approaches rely on underground sequestration, an unproven technology at the scale required for coal-fired boilers, with many serious cost, efficacy, environmental, and safety issues. Nuclear power plants, natural gas/combined cycle plants, and wind turbines all have the potential to decrease dependence on coal generation and make significant contributions to CO_2 avoidance. An accelerated RD&D program is particularly important for advanced nuclear reactors, given their high mitigation potential since serious safety, proliferation, and waste-disposal concerns remain.

-The **building sector,** where emissions are projected to grow globally at about 2 % per year**,** is where much of the generated electricity 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&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.

-Emissions from the **transportation sector** are growing at a rate of 2.5% 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 Sport Utility Vehicles. A review of developing technologies suggests that hybrid and plug-in hybrid vehicles and biomass-to-diesel fuel via thermochemical processing are the most promising in the near term. However, cellulosic biomass-to-ethanol and hydrogen/fuel cell vehicles offer longer term potential, if key technical, economic and environmental 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 2%. Although CO_2 emission avoidance approaches 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 life-cycle CO_2 content, i.e., require less carbon intensive energy during product production, use, and disposal.

-If near-term mitigation of four trillion tons of CO_2 is deemed a serious goal, **a major increase in R,D&D resources will be needed.** Current CO_2 mitigation research expenditures in the U.S. and globally have been relatively flat in recent years, and the U.S. federal research expenditures on energy technologies are 70% lower than research expenditures in response to oil shortages in the mid-1970's. U.S. private sector research has fallen even more precipitously in recent years. It is important that such R,D&D be conducted at both the federal and private sector levels. Federal funding is particularly relevant for those technologies that require substantial funding due to high capital costs and/or have a low probability of commercial impact and ultimate profitability in the near term. Examples include carbon capture and storage, and next generation nuclear power technologies. Private sector funding for the lower cost, lower risk technologies could be encouraged by providing incentives, such as regulatory drivers and attractive market prices. 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 at an early stage of development and faces environmental and cost issues. Also important are next generation nuclear power plants, solar technologies, biomass to diesel fuel processes, cellulosic biomass-to-ethanol production technology, and hydrogen production technology. Given their potential for wide scale utilization, all of these emerging technologies must evolve with full consideration of the need to minimize their environmental impacts. Toward this end, concurrent research to assess potential environmental impacts and to identify risk management alternatives is needed.

-Given the monumental challenge and uncertainties associated with a major mitigation program, it may be **prudent to consider all available and emerging technologies. This suggests that fundamental research on energy technologies in addition to those currently in advanced stage of development, be part of the global research portfolio, since breakthroughs on today's leading-edge technologies could yield tomorrow's alternatives.** Also, it is the author's opinion that it is prudent to consider geoengineering options, which although radical in concept, could potentially buy the time we may need to make the necessary adjustments in our energy and industrial infrastructure.

- Finally, **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 regulatory/incentive programs will be necessary to encourage their utilization.

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