Kefa Cen
Yong Chi
Fei Wang

Challenges of Power Engineering and Environment

Proceedings of the
International Conference on Power Engineering 2007

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CONTENTS

1 Invited Lecture

2 Power Systems

3 Fuel Utilization

4 Boilers

5 Turbines

6 Generators

7 Components, Equipments and Auxiliaries

8 Operation and Maintenance

9 Environmental Protection

10 Heat Transfer, Combustion and Dynamics

11 Fuel Cell

12 Micro, Nano Heat Transfer and Flow

13 Materials for Energy Systems

14 Alternative Energy

15 Economics of Energy System

16 Numerical Simulation

1

Invited Lecture

The Role of Power Generation Technology in Mitigating Global Climate Change

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Abstract: Anthropogenic emissions of greenhouse gases, especially carbon dioxide (CO_2), are primarily responsible for the roughly 0.8 ℃ global temperature increase since the industrial revolution. With industrial activity and population expected to increase for the rest of the century, the projected large increases in greenhouse gas emissions are expected to result in additional, potentially substantial, global warming. Using a powerful, PC-based global climate model, global warming is projected for two business-as-usual cases, as well as simple, yet instructive, scenarios in which major programs are initiated to limit CO_2 emissions. The paper provides a brief overview of 1) the forces driving CO_2 emission increases, 2) how different CO_2 emission trajectories could affect temperature this century, 3) required mitigation technologies with a focus on power generation mitigation options, and 4) R&D priorities. While various aspects of this subject are addressed extensively in the scientific literature,, this paper aims to provide a succinct integration of information about the projected warming of the earth in the decades ahead, the emission reductions that may be needed to constrain this warming to tolerable levels, and the potentially available technologies to help achieve these emission reductions.

Keywords: global warming, carbon dioxide, greenhouse gases, temperature increase, control technologies

1 INTRODUCTION

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

1. "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."
2. "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."
3. "The combined radiative forcing due to increases in carbon dioxide … is very likely to have been unprecedented in more than 10,000 years."
4. "The total temperature increase from 1850 – 1899 to 2001 – 2005 is 0.76 ℃."
5. 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 ℃.

Given these findings, this paper will examine the critical 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 and the anticipated importance of the emissions of key countries. Then, CO_2 emissions will be projected into the future for important contributing sectors. The author will summarize the state of the art of technologies and R&D priorities for power generation, which is the key sector. Finally, the adequacy of research, development, demonstration and deployment will be discussed. (Note that in this paper, all CO_2 concentrations will be in ppm and all warming will be realized or transient warming as opposed to equilibrium or "eventual warming," unless specifically indicated otherwise.)

Although the scope of this paper is limited to the consideration of power generation technologies that can play a significant role in reducing CO_2 emissions, it is important to note that the use of these available technologies alone will not be sufficient to constrain emissions to the extent needed. 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 CO_2 EMISSIONS

The World Resources Institute [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), 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 growth rate. The author has used the Institute's data to generate Fig.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 rates for China and India have both been about 4% per year. For China, increases are driven by economic growth, while increases for India have been driven by economic growth and population growth. 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. However, a recent analysis by Raupach [3] concluded that in the period 2000 to 2004, worldwide emissions of CO_2 have increased at an annual growth rate of 3.2%, which is a more rapid rate than in previous years and a more rapid rate than had been predicted. This is more than twice the growth rate of the 1992 to 2002 time period. Rapidly developing economies in China and other Asian countries are particularly significant in this recent and troubling trend. 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]. Fig.2 summarizes these global emission trends, including the recent 2000 to 2004 data.

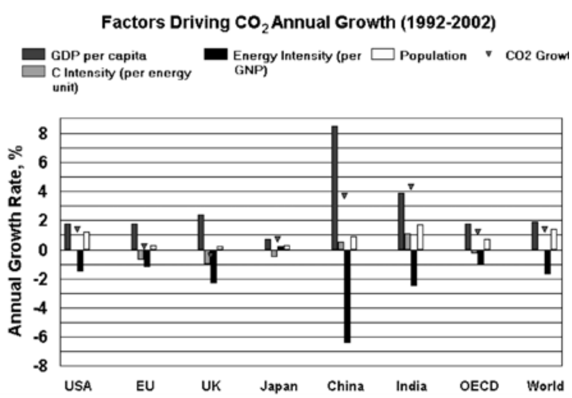

Fig. 1 Factors driving atmospheric concentrations of CO_2 for selected countries

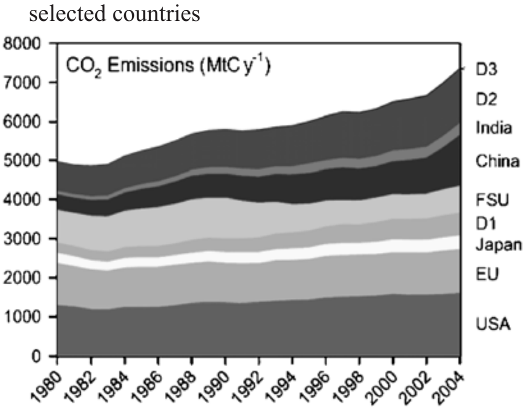

Fig.2 Most Recent CO_2 Emission Data by Countries and Sectors

(Note that 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.)

3 PROJECTED LEVELS OF WARMING AND THE UNCERTAINTIES

A credible base case, or business-as-usual scenario, must be established if we are to estimate warming with any confidence between now and the year 2100. IPCC [1], IEA [5], and Hawksworth [6] have all postulated scenarios that allow such estimates. The IEA base scenario was selected as the basis for this analysis, since it is consistent with current driving forces and does not assume major technology changes over time. Since it was limited to 2050, the author extended it to 2100 by assuming reduced emission growth rates between 2050 and 2100. The modified IEA approach assumes the following CO_2 emissions increases 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 assumption of reduced growth rates during the period from 2050 to 2100 was based on projected declines in population growth rates and relatively stable growth rates of GDP, carbon intensity, and energy intensity. Based on the emission scenario just described, Version 4.1 of MAGICC (Model for Assessment of Greenhouse gas Induced Climate Change) (Wigley [7]) was used to generate predictions of CO_2 concentrations and warming from pre-industrial times to the year 2100. Fig.3 shows predicted concentrations, and Fig.4 shows predicted warming.

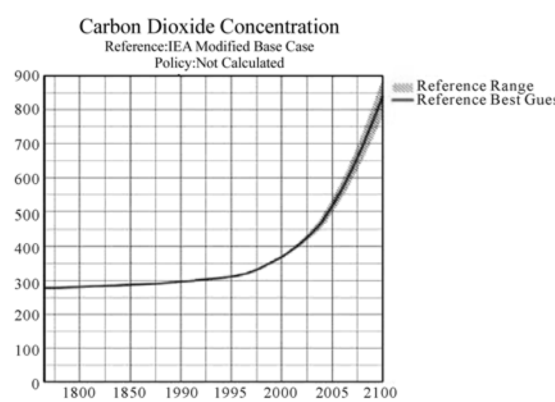

Fig. 3 Projected CO_2 concentrations for Base Case

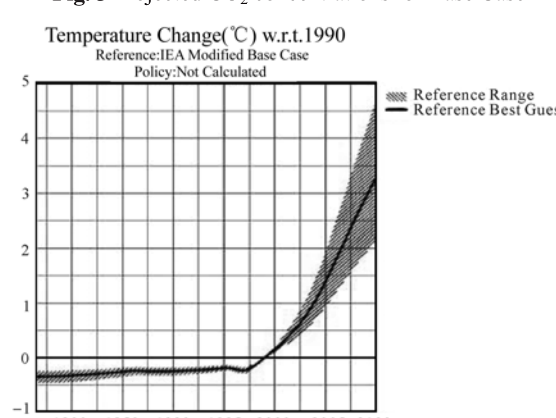

Fig. 4 Projected Warming for Base Case

An earlier version of this PC-based model was used by the IPCC in its Third Assessment Report (TAR) to evaluate the impacts 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 Fig.3 and 4 the uncertainty range generated by the model, is included. As can be seen, projections of warming are much more uncertain than projections for concentration increases. Also note that warming is projected to continue after 2100. When one accounts for the continued warming projected into the next century, the equilibrium or eventual warming is projected to range from 3.0 to 8.1 ℃ with the best guess at 4.8 ℃ above 1990 levels, assuming that the ultimate steady state CO_2 concentration will be 1000 ppm. 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 if CO_2 concentration doubles. IPCC (1), Wigley [7], and others state that the extent of warming is quite uncertain, and their estimates range from 1.5 ℃ to 4.5 ℃.

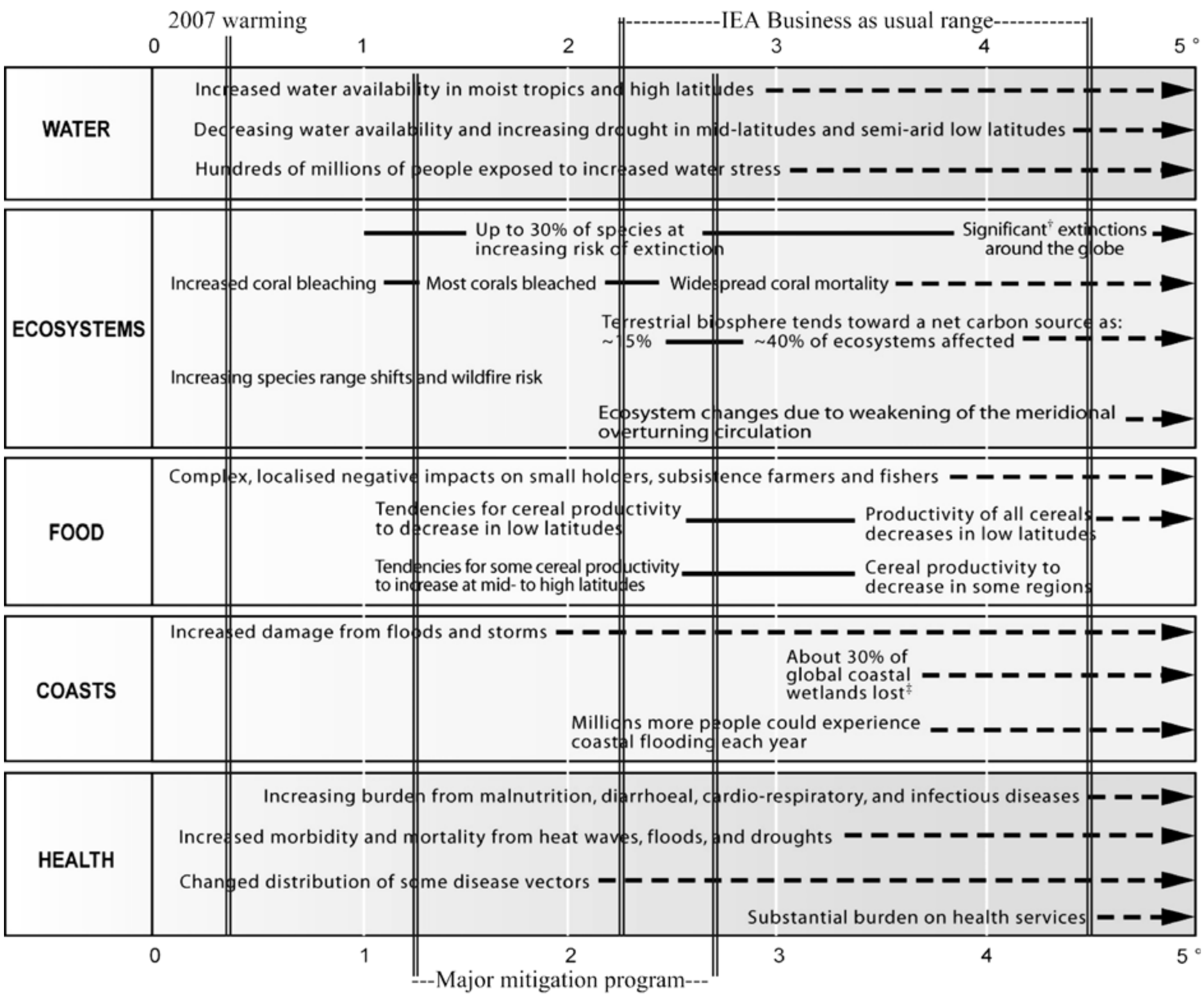

Fig. 5 Projected global warming impacts as a function of 2100 warming from 1990, ℃. and dotted arrows indicate impacts increase with increased warming

4 ACHIEVABLE MITIGATION LEVELS

Fig.5 presents the recent (April 2007) IPCC [8] 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. It is significant that current (2007) warming (0.3 ℃ since 1990 and 0.8 ℃ since 1750) has already had measurable impacts.

Base case warming from 1990 to 2100 is projected to be in the range of 2.2 to 4.7 ℃, with 3.2 ℃ as the best guess. A temperature increase in this range would result in potentially severe impacts, especially if the temperature increase is in the middle to upper end of the 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.

It is important to note that when one accounts for current emission trends, the current unavailability of low-emitting technologies, and the likelihood of inaction in the near term, limiting warming to 2.0 ℃ (range of 1.3 to 2.8 ℃) is likely the best result achievable even with a major global mitigation program (e.g., decreasing CO_2 emissions 1% per year starting in 2010). Fig.6 indicates that global impacts will be significant, even assuming such an aggressive mitigation case.

Therefore, for this analysis, emission scenarios were evaluated to see what reduction levels, starting in what year, would limit warming below about 2.0 ℃. Fig.6 and 7 depict results of a large number of MAGICC cases, indicating annual emission reductions required to meet this warming goal, along with corresponding CO_2 concentration estimates. Note that an annual decrease of 0.00% means emissions are held constant, at the start year. As can be seen, major annual decreases in emissions will be necessary if a warming target below 2.0 ℃ 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 2015, reductions would need to be about 1% annually to limit warming to about 2.0 ℃ above the 1990 level, whereas if such a program were to start in 2025, annual reductions would need to be about 1.8 %.

Again, it must be noted that there is a large range of uncertainty in the resulting temperature for a given maximum CO_2 concentration. Fig.8 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, projected to constrain concentrations to the 440 to 480 ppm range. Note that the high end of this range is higher than the low end of the business-as-usual case (Fig.4). This highlights the magnitude of the uncertainties in current models, of which MAGICC is representative.

Fig.9 illustrates the major challenge associated with such reductions, relative to our base-case 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 CO_2 concentration to about 460 ppm and warming to a 1.9 ℃ increase over 1990 levels.

Note that the area between the curves represents the amount of emission reduction needed to achieve the target temperature versus the base case, which amounts to over one trillion tons of carbon or over 3.7 trillion tons of CO_2 over the 90-year period. This represents what can only be described as a monumental political, social, and technological challenge.

5 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 other greenhouse gases. The author has derived the information in Fig.10 from IEA [6]. The upper graphic projects world CO_2 emissions by sector. It suggests that power generation and transportation sources are the fastest growing sectors and 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 types of transportation. China and India, with a cumulative population of over 2.4 billion people, are projected to continue their rapid economic expansion with commensurate pressure on the power generation and transportation sectors.

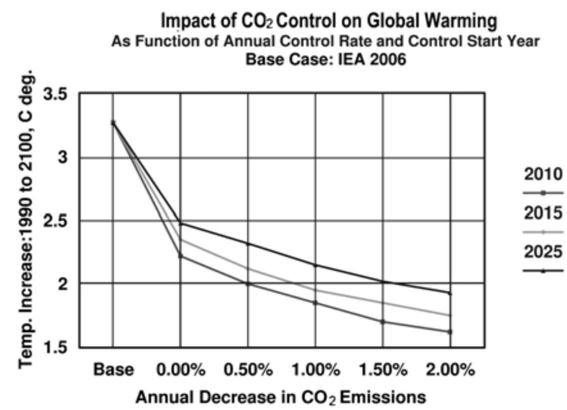

Fig.6 Best guess 2100 warming as function of annual emission decrease rate and year reductions start

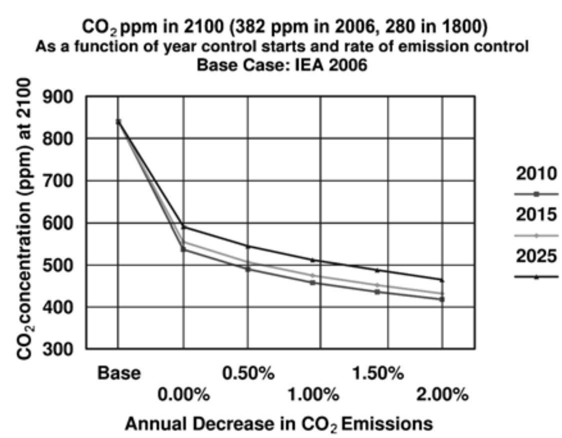

Fig.7 CO_2 ppm in 2100 as a function of annual emissions decrease rate and year reductions start

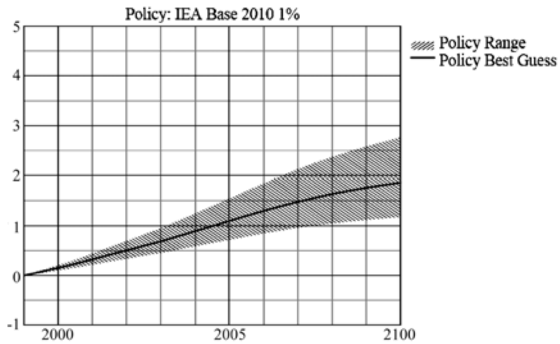

Fig.8 Projected warming range for a 1% annual decrease in CO_2 emissions started in 2010

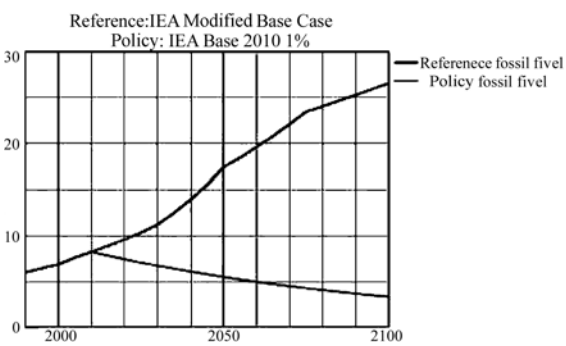

Fig.9 Base case & scenario to limit CO_2 to < 2 ℃ in 2100; units: Gt Carbon (note: 3.67 Gt CO_2 per Gt C)

6 THE MITIGATION CHALLENGE: WHAT ROLE CAN ENERGY TECHNOLOGY PLAY AND WHAT ARE THE OPTIONS?

At the request of G-8 Leaders & Energy Ministers in 2005 and in order to understand the potential of various energy technologies to avoid CO_2 emissions, IEA [5] 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 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 $25/metric ton 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 middle graphic of Fig.10 projects CO_2 emissions by sector, for the ACT Map scenario, based on IEA's assumption that major technology implementation is to start in 2030. The bottom graphic 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. Note that savings attributed to the transportation sector include the savings associated with transforming less coal, petroleum, and natural gas to liquid fuels and their associated CO_2 emissions. 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, e.g., lower-emission vehicles.

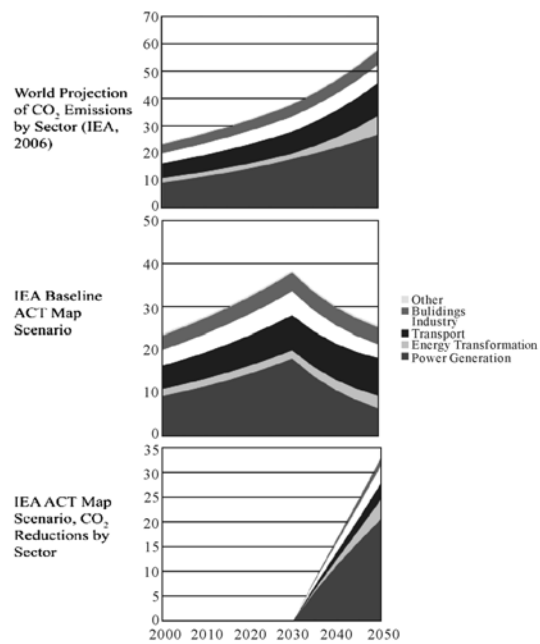

Fig.10 Base case , ACT MAP Control Scenario and CO_2 Emissions Avoided per IEA [5]

It is important to note that for the IEA Map scenario extended to 2100, MAGICC calculations indicate best-guess CO_2 concentrations in 2100 of 500 ppm and corresponding warming of 2.1 ℃ relative to 1990. This is despite the IEA assumption of aggressive R,D,&D and deployment programs, and the author's 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 global mitigation program, based on successful development and deployment of several new technologies, will still allow substantial global warming by 2100. Let us now focus on the critical power sector and examine the technology options available, their current state of development, and the required R,D,&D required for them to meet their potential to reduce CO_2 emissions.

7 POWER GENERATION SECTOR

Of all the sectors, the power generation sector, which is projected to grow at an annual rate of 2%, provides the greatest opportunity for reduction of 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 it 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 retrofit technology for CO_2 removal, which is now in the early development stages.

Major reductions can result from lower emissions during generation and as a result of lower usage due to enhanced end-use efficiency. presents a summary of major generation options that offer significant opportunities for CO_2 mitigation. The options 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, to achieve the mitigation depicted in Fig.9, total required savings in 2050 is about 40 Gt of CO_2 (10.9 Gt C) and for the less aggressive IEA Map scenario, 32 Gt of mitigation would be accomplished .

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. The three coal capture technologies are quite important; the IEA scenario projects each of the three to reduce emissions by 1.3 Gt of CO_2 in 2050. Fig.11 illustrates the major components of each technology. IGCC technology is the primary focus of the U.S. R,D,&D program, but this technology 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 by scrubbing, adsorption, or membrane separation is conceptually simple and is inherently retrofitable, but these technologies are in the early stages of development. Commercial amine scrubbers use large quantities of energy for sorbent regeneration and are expensive. MIT [4] 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." The MIT researchers 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 scale."

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.

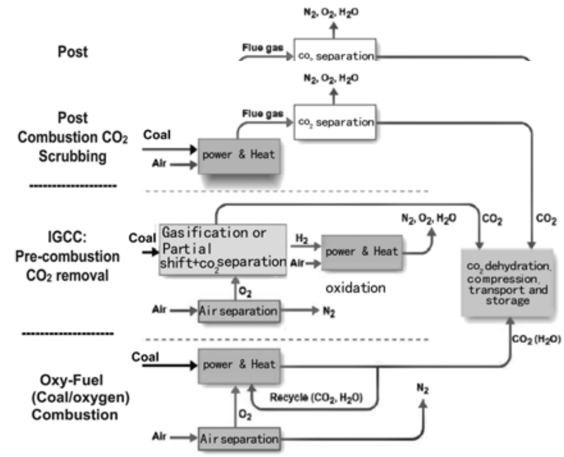

Fig.11 Three key technologies capturing CO_2 from coal-fired power plants

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 [4] that there are too many uncertainties with regard to IGCC to limit R,D,&D focus to that technology alone. Therefore much 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, which will be needed for each of these technologies, is currently in an early developmental stage, but it has extraordinary potential. However, there are 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. MIT [4] 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.

Advanced nuclear power technology is quite promising and could start making a major impact by 2030. However, the technology needs a number of successful demonstrations to allow resolution of remaining technical problems, instill confidence in the utility industry that the technology is affordable and reliable, and assure the public that it is safe.

Fig.12 summarizes the IEA projection for the impact of key technologies in reducing CO_2 emissions in the power generation sector in 2050. As can be seen, assuming an aggressive R,D,&D and incentive programs, end use efficiency improvements, carbon capture and sequestration, and nuclear power are projected to play important roles in that time frame.

Table 1 Candidate Technologies for CO_2 Mitigation From Power Generation (projected impact in Gt/year of CO_2)

Technology	Current State of the Art	2050 Impact per IEA (2006)	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 SO_x, NO_x, 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 SO_x, NO_x, 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 efficiency & low capital costs	**Medium**, higher efficiencies with new materials desirable	Reduction in emissions of SO_x, NO_x, Fine PM; fewer mining impacts and Residues for disposal or use
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 SO_x, NO_x, Fine PM; fewer mining impacts and Residues for disposal or use; extraction R&D could enhance availability of CH_4
Coal IGCC with CO_2 Capture and 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		Lower power plant efficiency yields greater emissions of SO_x, NO_x, Fine PM and coal mining impacts

Technology	Current State of the Art	2050 Impact per IEA (2006)	Issues	R,D&D Needs	Other Potential Environmental Impacts
Pulverized Coal/Oxygen combustion with CO_2 Capture and Storage	Developmental	1.3	Oxygen combustion allows lower cost CO_2 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 SO_x, NO_x, Fine PM and coal mining impacts
Pulverized Coal with CO_2 Capture and Storage	Underground storage developmental; CO_2 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 efficiency yields greater emissions of SO_x, NO_x, Fine PM and coal mining impacts
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 SO_x, NO_x, Fine PM; fewer mining impacts and Residues for disposal or use
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 SO_x, NO_x, 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 SO_x, NO_x, Fine PM; fewer mining impacts and Residues for disposal or use
Coal IGCC with no CO_2 Capture and Storage	IGCC: early commercialization	0.2	IGCC: High capital costs, complexity and reliability concerns, only modest CO_2 savings without CCS	**High**, Demos on a variety of coals, hot gas cleanup research	Small reduction in emissions of SO_x, NO_x, Fine PM; fewer mining impacts and Residues for disposal or use

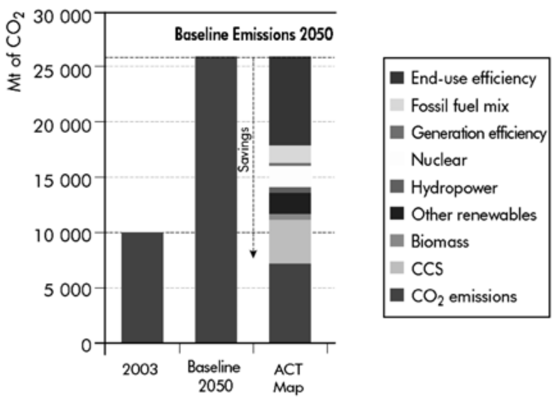

Fig.12 For ACT Map scenario, projected CO_2 savings in power generation sector by technology

8 ADEQUACY OF R,D,&D

IEA [5], Hawksworth [6], Morgan [9], MIT [4], and the author nine years ago, (Princiotta [10], 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 constraining atmospheric concentrations to protective levels. As illustrated earlier, the later a mitigation program is initiated, the more severe emission cuts will need to be if CO_2 concentrations above 450 to 500 ppm are to be avoided. Most recently, The Stern Report [11] 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."

Fig.13, generated from IEA data [12], depicts world research expenditures in critical energy technology areas, showing the same funding trend. 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.

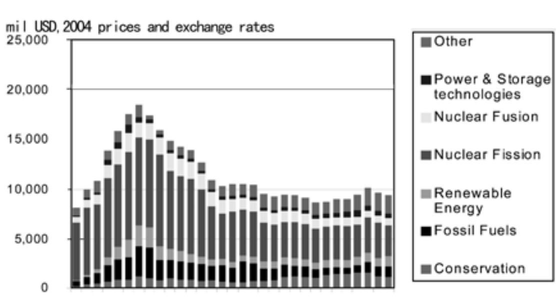

Fig.13 World R,D,&D expenditures for key energy sectors, 2004 $ millions

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 [13]. 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. Also, the USEPA [14] 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 could provide a foundation for an expanded program, consistent with the mitigation challenge.

It is important to note most of the non-coal technologies, offer the potential for lower air emissions, water effluents, and waste generation residues. IGCC also offers the potential for such benefits; however, incorporating CO_2 capture, transport, and storage substantially decreases overall plant efficiency, with the potential for commensurate increases in coal-related pollution per unit of power generated. Also, note that the transportation technologies all 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 huge international market.

9 SUMMARY AND CONCLUSIONS

Summary information and conclusions follow:

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 0.8 ℃ global warming seen since the pre-industrial era is a result of increased concentrations of CO_2 and other greenhouse gases.

- Global emissions of CO_2 have been accelerating at a rate of about 1.4% per year in the 1992 to 2002 time period. However, recent data suggest an acceleration of emission growth in recent years, e.g., 3.2% in the 2000 to 2004 time period. China's major expansion of its coal-fired power generation capacity has been a major factor in this unexpected increase in growth rate.
- Projections of greenhouse warming have been made on a business-as-usual case or base case. 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. This will yield a best-guess average warming, relative to 1990, of 1.4 ℃ in 2050 and 3.2 ℃ 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 4.6 ℃ or as low as 2.1 ℃. This warming would be in addition to the 0.5℃ already experienced from pre-1700 to 1990. Warming would continue into next century and beyond, with

equilibrium temperatures in the 3.0 to 8.1 ℃ range, with the best guess at 4.8 ℃ above 1990 levels; this assumes a steady state CO_2 concentration of 1000 ppm.

- If current worldwide emission trends continue to surprise the prognosticators and grow at 3% per year for the next 25 years, projected warming would be substantially higher. This scenario will yield a best-guess average warming, relative to 1990, of 1.7 ℃ in 2050 and 4.0 ℃ in 2100. The potential warming in 2100 could be as high as 5.5 ℃ or as low as 2.6 ℃. Warming would continue into next century, with equilibrium temperatures in the 3.4 to 9.0 ℃ range, with the best guess at 5.4 ℃.
- 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 would be to constrain warming above the 1990 level to about 2 ℃ (between 1.2 and 2.8 ℃) by 2100. Fig.6 illustrates that global impacts, even for this constrained warming scenario, are potentially serious. This suggests that the world community may have no remaining alternative other than to pursue adaptation approaches aggressively.
- In order to limit warming to the 2 ℃ level, it will be necessary for the world community to decrease annual emissions at a rate of between 1 and 2% 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 1.5% 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. This is a monumental challenge.
- Recent publications were used to relate the implications of a one-trillion-ton mitigation program to the key energy sectors and the technologies within those sectors that can contribute to such a major mitigation challenge. The key energy sectors are power generation, transportation, industrial production, and buildings. The power 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 for 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 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, 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 emission reductions. An accelerated R,D,&D program is particularly important for advanced nuclear reactors, given their high mitigation potential and their serious safety, proliferation, and waste disposal concerns.
- If mitigation of three trillion tons of CO_2 is deemed a serious goal, a major increase in R&D resources will be needed. Technology research, development, and demonstration are of particular importance for coal generation technologies, including 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 at the scale required. Also important are next-generation nuclear power plants.
- Given the monumental challenge and uncertainties associated with a major mitigation program, the author believes it prudent to consider all available and emerging technologies. This suggests that fundamental research on energy technologies, in addition to those in Table 1, be part of the global research portfolio, since breakthroughs on today's embryonic technologies could yield tomorrow's alternatives.
- Finally, the 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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Biomass Utilization as a Clean Energy in Zhejiang University

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Abstract: Biomass is a possible alternative to the direct use of fossil fuel energy. Especially, Biomass plays an important role in China which has abundant biomass resources. The theories of biomass thermo-chemical conversion were introduced and on the basis of theoretical results utilization technologies of biomass were elaborated in Zhejiang University which included combustion, gasification and liquefaction. Based on lots of work on mechanism of straw combustion and small and bench scale experiments, a new developed technology is specially design for high-alkali biomass combustion in CHP scale. With Developed Biomass Gasification Technology the medium heat value gas (MCV) has supplied to the households in Wenzhou Demo Plant Project. A fluidized bed reactor with 20kg/h throughput operating at an atmospheric pressure with an inert atmosphere at 773 K has been used to produce bio-oils. At optimum pyrolysis conditions maximum bio-oil yield of up to 60% was obtained. The quality of the bio-oil produced remains poor, and a combination of high value products and energy applications were needed for profitability.

Keywords: biomass, combustion, gasification, liquefaction

1 INTRODUCTION

Biomass has been recognized as a major world renewable energy source which is an attractive feedstock for its renewable, zero carbon dioxide, and low sulfur content etc. characteristics. Biomass energy utilization will play an important role in China which has abundant biomass resources contained wood-chip, agricultural residues etc. and large population that farmer takes up nearly 60%. Now Chinese government pays more attention on biomass and its conversion technologies by fund support for researches and some demonstrations.

Some research institutions and universities assumed this responsibility of converting biomass into high-quality fuels. Zhejiang University is one of the main organizations in biomass energy field with overall and in-depth researches. Zhejiang university's works focuses on the development and progress in the research on the biomass thermo-chemical conversion technology, especially in combustion, gasification and liquefaction. The main results will be introduced respectively in this paper.

2 BIOMASS COMBUSTION TECHNOLOGY

Biomass combustion and co-firing are promising ways for biomass utilization. Based on experiences and achievement in this area, lots of work has been done in the field of special fuels combustion in Zhejiang University.

2.1 Mechanism research

Normally straw has high moisture and appears great variety of physics property. All those properties can be handled by adjusting the traditional organization of combustion, but the serious problems caused by high K and Cl from herbaceous straw during combustion have to be considered with new concept, the mechanism of alkali problems is very necessary.

As a very first step, the chemical fractionation was carried out to determine the distribution of alkali materials in straw. The results of the analysis and basic balance of material was shown in Table 1[1].

To study alkali transformation during pyrolysis, samples were taken from the pyrolytic reactors at a series of temperature points from 200 to 1100℃. By analyzing alkali in deferent forms in residue at every pyrolytic stage, the releasing of elements at different pyrolytic temperature was shown in Fig.1. Obviously, the releasing can be roughly divided into two stages, below 400℃, the process of pyrolysis is in progress, the bounded K in sample undergo a rapid escaping, while above 400℃, the primary process is high-heat treatment of char, the K releasing rate almost keeps constant with increasing temperature. The detailed transformation of every forms of K shows the releasing of water soluble K is the main part of overall K reduction. It means active water-soluble K releases is the most important mechanism of alkali pyrolytic liberation. The K in residual form seems to be an inertial factor during the whole process. It's well known that released K have big chance to deposit on heating surface of combustion equipment and can cause heat transfer problem, flue gas blocking and if high metal temperature presence, serious high-temperature corrosion.

During combustion, part of water solvable K can stay in solid residual while part of it releasing at high temperature. This part of K is the main reason why rice straw ash have extremely low melting point comparing with coal ash[2].