

CLEAN AIR TASK FORCE



**THE ROLE OF CARBON CAPTURE AND STORAGE TECHNOLOGY
IN ATTAINING GLOBAL CLIMATE STABILITY TARGETS:**

A LITERATURE REVIEW

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1.0 INTRODUCTION

The world is at an energy crossroads. Carbon dioxide (“CO₂”) emissions due to combustion of fossil fuels have already resulted in a roughly 1°C rise in global surface temperatures, and continued emissions threaten the very climate on which human livelihood depends. At the same time population and economic growth in the developed and developing worlds are expected to lead to a doubling of global energy use in the next few decades. Aggressive technological innovation, operating in concert with policy incentives, will be required to meet growing energy demand while stabilizing atmospheric concentrations of CO₂ at safe levels.¹

Energy derived from fossil fuels, when used with carbon capture and storage (“CCS”) technologies, can be a vital bridge to a low-carbon energy future. By removing carbon from fossil fuels and permanently sequestering it deep underground, while using steam or hydrogen to carry energy to electric generators, vehicles, and heating loads, CCS systems can work within existing energy supply paradigms while also working alongside other climate-friendly energy technologies such as efficiency improvements, renewables such as wind, hydro, and solar power, and biomass energy.

The Clean Air Task Force (“CATF”) has reviewed and evaluated numerous expert studies of the potential role of CCS in the world’s future energy systems. In general, most experts agree that without utilization of fossil fuels and CCS, climate change mitigation is likely to be more costly and less effective than if CCS systems are available in a timely manner. In addition, many studies suggest that a world without significant fossil fuel and CCS is a world with significant new nuclear capacity. Informed by these results, and its own analysis, CATF has concluded that CCS is a likely to be key energy technology for mitigating climate change. Rapid deployment of CCS therefore must be a central tenant of any sound global energy policy.

Our review evaluation of several expert studies is outlined below.

2.0 SCENARIOS OF FUTURE EMISSIONS

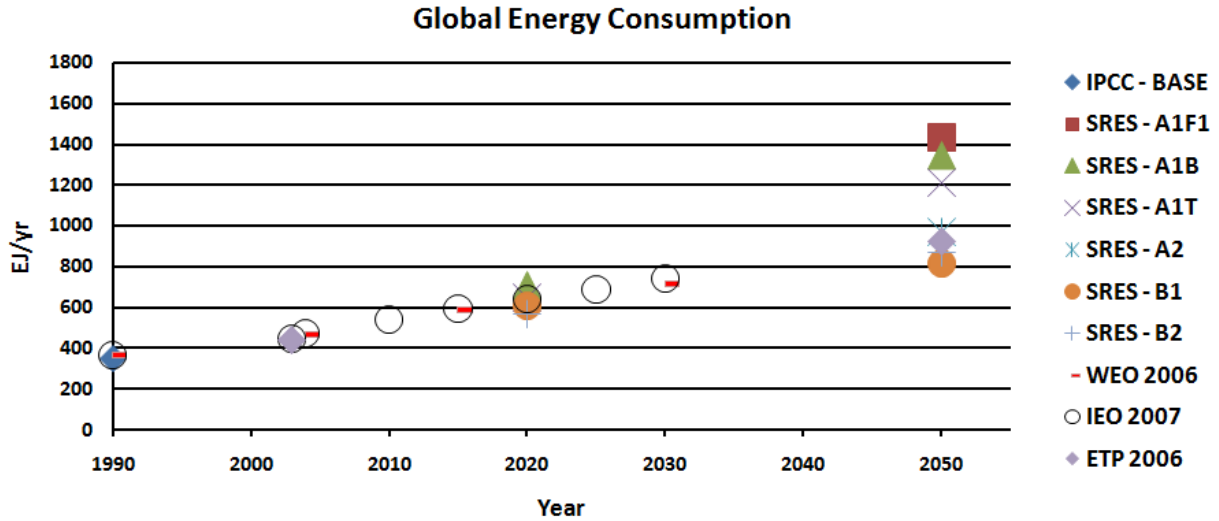
2.1 Business As Usual Scenarios

Organizations such as the International Energy Agency (“IEA”), an autonomous agency linked with the Organization for Economic Cooperation and Development (“OECD”), the Intergovernmental Panel on Climate Change (“IPCC”), a joint program of the World Meteorological Organization and the United Nations Environment Programme, and the U.S. Department of Energy (“US DOE”) have developed global scenarios of future energy use and greenhouse gas emissions based on historical trends without considering any specific feedbacks from climate change and without inclusion of explicit policy efforts to curb greenhouse gas emissions. These scenarios are often referred to as “reference”, “baseline” or “business as usual” (“BAU”) scenarios.

Results from a selection of BAU energy scenarios out to the year 2050 are summarized in Figure 2.1.1 below. In the figure “IPCC” and “SRES” refer to results of IPCC (2000a), “WEO 2006” and “ETP 2006” refer to results of IEA (2006b) and IEA (2006a), and “IEO 2007” refers to

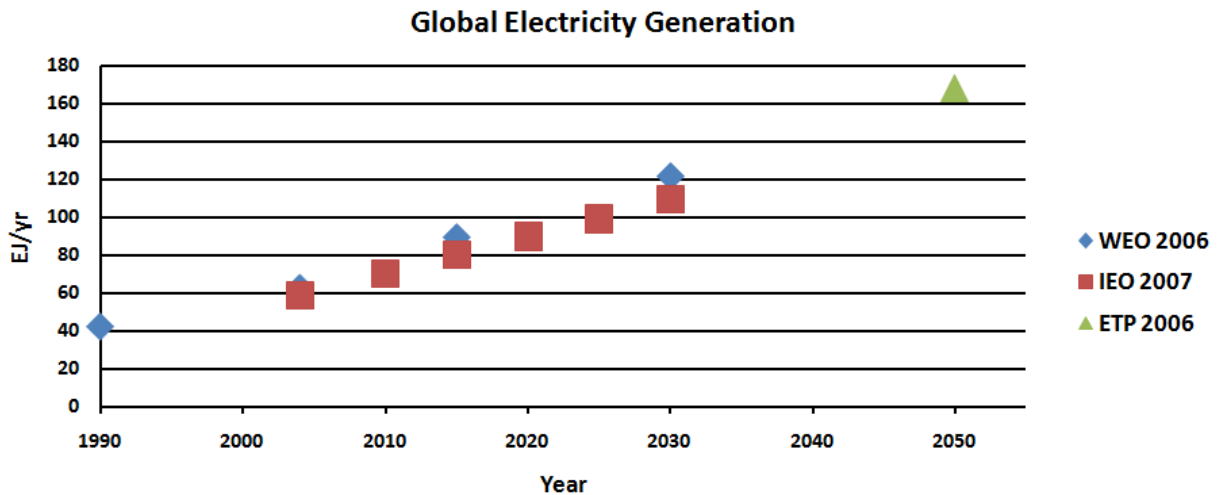
results of US DOE (2007b). In general, despite significant differences in methodology, studies indicate that under BAU conditions global energy use could increase by 100% or more between 1990 and 2050.²

Figure 2.1.1 – Selected Energy Scenarios, 1990 - 2050



Global electricity use is likely to grow even faster than total energy consumption, as Figure 2.1.2 below indicates.

Figure 2.1.2 – Selected Electricity Scenarios, 1990 – 2050



2.2 Climate Stabilization Scenarios

Eight climate stabilization studies produced by organizations as diverse as WWF, Friends of the Earth, and the International Energy Agency are reviewed here. A summary of these studies is included in Table 2.2 below. Details of the studies, and CATF’s review, are provided in the sections that follow.

Table 2.2 – Key Features and Results of the Stabilization Studies

Study	Approach and Assumptions	Timeframe	Regions	Key Results
WWF (2007)	Industrial feasibility with Monte Carlo simulation of technology deployment	To 2050	Global	Fossil fuels with CCS provide 26% of global energy supply under stabilization constraints
Friends of the Earth (2007)	Backcasting; 2.5% per year economic growth and large intensity reductions	To 2050	UK only	Fossil fuels with CCS provide 40% of UK primary energy under stabilization constraints
UK DTI (2007)	MARKAL model with 60% GHG emission reduction constraint	To 2050	UK only	Fossil fuels with CCS provide 50% of UK electricity, if no nuclear build is allowed
IEA (2006a)	MARKAL model with “TECH Plus” assumptions	To 2050	Global	CCS provides large, cost-effective, emission reductions; efficiency measures are also key
IPCC (2000b) and (2005)	Various scenarios and modeling approaches	To 2100	Global	Large potential contribution from CCS; technological innovation is key
Krewitt et al. (2007)	Backcasting; extremely ambitious intensity assumptions	To 2050	Global	No CCS; massive biofuels, wind, PV deployment
CCSP (2007)	IGSM, Merge, and MiniCAM models; various assumptions	To 2050	US & Global	450 ppmv stabilization implies 1500+ GW global electricity with CCS by 2050
McKinsey (2007)	Technical-engineering abatement potential cost curve	To 2030	US	CCS provides largest abatement potential; also identifies large ‘negative cost’ options

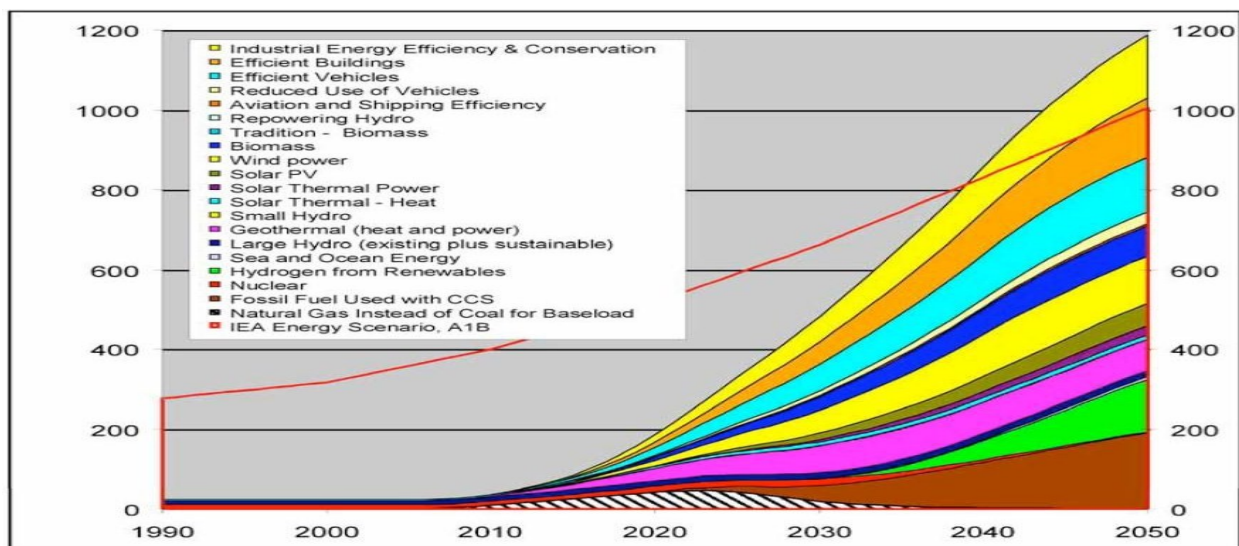
2.2.1 World Wildlife Fund, 2007

WWF (2007) examined the global technical and economic feasibility of a variety of greenhouse gas emissions mitigation technologies, premised on a trajectory with maximum permissible CO₂ emissions between 2004 and 2200 of 400 GtC – 500 GtC.³ WWF used literature review, expert consultation, and review by independent panels to assess a number of current state-of-the-art or expected energy system mitigation measures including nuclear power, biomass fuels, fossil fuels with CCS, renewable energy including wind, solar, and hydroelectricity, renewable hydrogen, and energy efficiency and conservation (and including behavior-based mitigation measures such as forest management practices and reduced use of vehicles). Probability distributions were generated for expected values of key parameters for each technology (e.g., growth rate of the

amount of energy use avoided by efficient vehicles; growth rate of new wind turbine capacity) based on the compilation of expert estimates. A Monte Carlo simulation was used to estimate the probability of various configurations of the world energy system in 2050, subject to WWF's stated CO₂ emissions constraint.

WWF results for global energy supply potential and a list of the technologies and behaviors available for deployment in their assessment is shown in Figure 2.2.1 below. Energy supply potential is plotted relative to the energy demand of the IPCC SRES A1B scenario to demonstrate that by the year 2050 sufficient technologies could be available to more than meet energy demand associated with the A1B scenario while also staying below allowable emissions to that point in time (330 GtC – 425GtC per WWF). The brown area of the graph (at the bottom of the figure at year 2050) represents fossil fuels used with CCS.

Figure 2.2.1 – WWF's Feasible Energy Technology Mix to the Year 2050 (in EJ/yr)⁴



Results from WWF indicate that fossil fuels used with CCS could account for as much as 26% of global energy supply by 2050, with resulting avoided emissions of 3.8 GtC per year, and suggest that fossil fuels with CCS are necessary in order to meet energy needs in the year 2050 while staying within a strict carbon emissions budget. This conclusion holds even after considering drastic improvements in energy efficiency and contributions of renewable energy sources.

2.2.2 Friends of the Earth and the Co-operative Bank, 2006

The Tyndall Center for Climate Change Research at the University of Manchester ("TC") studied the potential role of a number of energy system climate mitigation options under contract to Friends of the Earth and The Co-operative Bank ("FOE"). The resulting report, TC/FOE (2006) addresses technologies that could lead to economy-wide reductions in CO₂ emissions of 90% for the United Kingdom by 2050, which the authors judge necessary to meet a hypothetical cap on UK emissions to that time of 4.6 GtC.

TC/FOE employ expert judgment and historical experience to determine a plausible configuration for the UK energy system in 2050 that will satisfy the greenhouse gas emission constraint while meeting projected energy demand under assumed socioeconomic patterns and overall annual economic growth of 2.5% per year. Technologies and approaches judged to be potentially applicable during the study time period include renewable sources, fossil fuels with CCS, biomass fuels, nuclear power, hydrogen-powered transportation, and energy efficiency. A “backcasting” scenario development approach was employed to demonstrate that such an energy system is possible, provided that primary energy intensity of the UK economy drops to roughly 20% of its year 2000 value by 2050 and provided that carbon intensity and final energy intensity drop to roughly 25% and 7%, respectively, of their year 2000 values.⁵

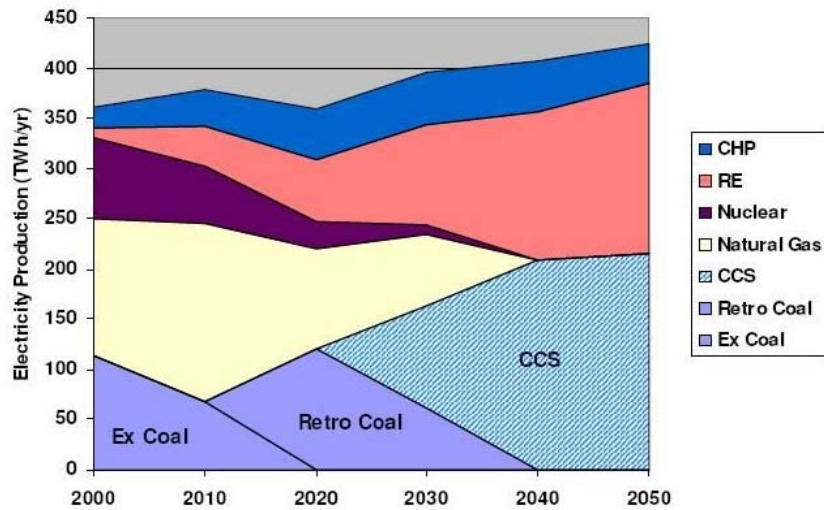
TC/FOE results indicate that fossil fuels with CCS must account for 40% or more of UK primary energy by 2050 in order to simultaneously achieve the required emissions reductions and the desired socioeconomic goals. Renewable sources must also meet 32% of demand and household end-use of energy must be reduced by 58% from present levels.

2.2.3 United Kingdom Department of Trade and Industry, 2005

The United Kingdom Department of Trade and Industry (“DTI”) studied the potential role of CCS in helping to achieve a UK CO₂ emissions reduction target of 60% by the year 2050 including intermediate goals of 10% by 2010, 20% by 2020, 35% by 2030, and 45% by 2040 (DTI, 2005). DTI performed a bottom-up analysis using a MARKAL (MARKet ALlocation) modeling approach in which population growth, economic growth, and primary fuel prices were assumed exogenously and the lowest-cost mix of energy technologies for the UK was determined based on detailed assumptions of technological improvements over time. DTI used an internal review process, external workshop, and peer review process to develop parameters describing plausible cost and performance of energy technologies which included CCS for application to existing and new fossil fuel sources, coal gasification and hydrogen production for electricity generation and transport fuel, biomass co-firing in existing coal plants, and energy efficiency improvements.⁶

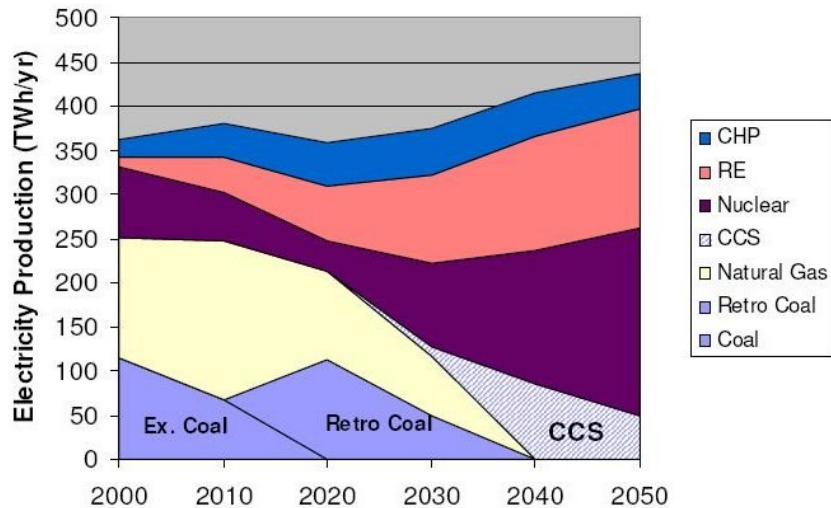
Results of the DTI MARKAL model of the lowest-cost energy system mix from a UK scenario of 60% CO₂ emissions reductions with no new nuclear power build and high energy efficiency are reproduced in Figure 2.2.3.a below. Results indicate that even with end-use energy efficiency improvements sufficient to reduce electricity demand 30% below reference scenario projections for the year 2050, if construction of new nuclear power stations is not allowed then the lowest-cost energy system for the UK that will achieve the 60% CO₂ emissions reductions must include almost 50% electricity production by fossil fuels used with CCS. In the figure “Ex Coal” and “Retro Coal” refer to existing coal plants and coal plants retrofit to comply with UK directives for non-CO₂ emission reduction.

Figure 2.2.3.a – DTI MARKAL Results for UK Scenario of 60% Emissions Reductions⁷



In the UK DTI MARKAL model costs of nuclear power are assumed to be slightly less than fossil fuel power systems that include CCS. As a result, when nuclear build is allowed in the model market penetration of CCS (and renewables) are limited.⁸ See Figure 2.2.3.b below.

Figure 2.2.3.b – DTI MARKAL Results for UK, with Nuclear Build Allowed

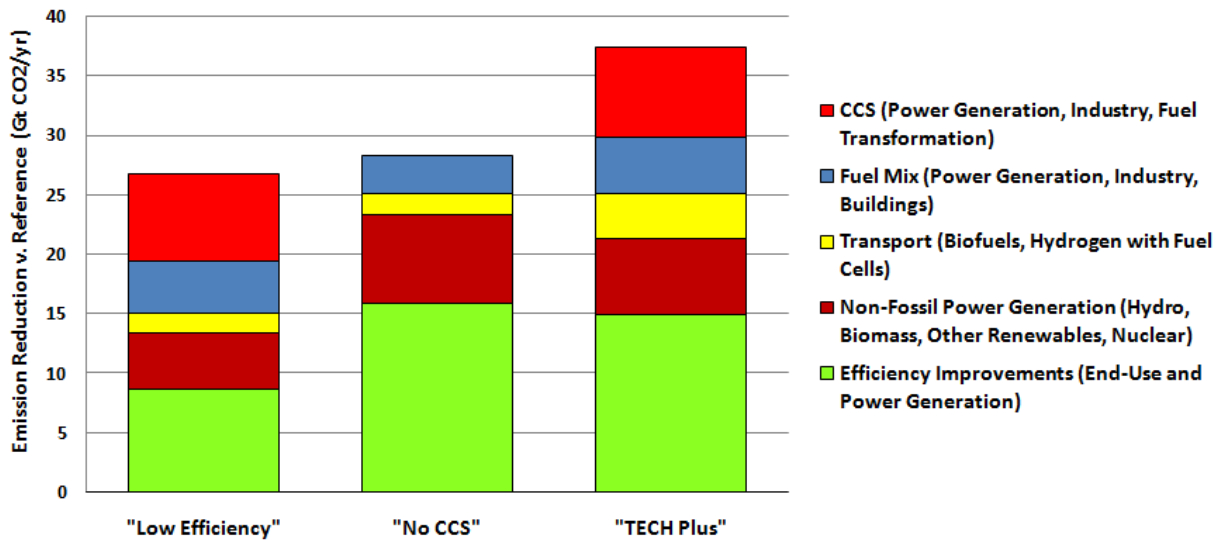


2.2.4 International Energy Agency, 2006

IEA (2006a) employed a multi-region implementation of a global MARKAL cost-optimization energy system model to assess a number of potential future energy scenarios from a standpoint of global CO₂ emissions constraints. Technologies including many forms of energy efficiency, fossil fuel power generation with CCS, nuclear power, electricity generation from renewables, biofuels, and hydrogen and fuel cells for transportation, were evaluated based on exogenous assumptions of potential future cost and performance of the technologies and of global population, economic growth, and fuel prices.

The “TECH Plus” scenario of IEA (2006a) included the most optimistic assumptions about potential technological progress, and resulted in projections of global CO₂ emissions in 2050 that were 16% less than those of 2003 (the base year). These TECH Plus Scenario reductions relative to the IEA Baseline Scenario were achieved by end-use efficiency (39.2%), use of fossil fuels with CCS (20.2%), increased use of renewables (9.9%), nuclear power (7.2%), and fuel switching and biofuels as well as hydrogen use in transport. Key results for the IEA (2006a) “Low Efficiency”, “No CCS”, and “TECH Plus” scenarios are summarized in Figure 2.2.4 below.

Figure 2.2.4 – Emissions Reductions at 2050 in IEA (2006a) and Role of CCS⁹



In addition, IEA (2006a) report that an absence of CCS in their model would increase the marginal emissions abatement cost of CO₂ in Europe by approximately 70% in some scenarios.

2.2.5 Intergovernmental Panel on Climate Change, 2005

Complementing the bottom-up MARKAL modeling approach of IEA and other organizations is a “top-down” approach to modeling the global energy-economic-environment system in which global macroeconomic properties such as GDP and energy price levels evolve in response to exogenously specified population growth, labor productivity growth, and technological progress. Generally speaking energy resources, energy conversion technologies and energy use technologies are specified more coarsely in top-down models than in bottom-up models, but potential impacts of carbon constraints on broad sectors of the economy are more readily assessed.¹⁰ As in the case for bottom-up models, technologies deploy within top-down models only when it is economical to do so.

Using the MiniCAM top-down model Edmonds et al. (1999) explored marginal CO₂ emissions abatement costs for alternative visions of the world’s future both with and without availability of CCS for fossil fuel energy sources, and determined that availability of CCS held potential to reduce the cost of stabilizing atmospheric CO₂ concentrations at 550 ppmv by 50% or more

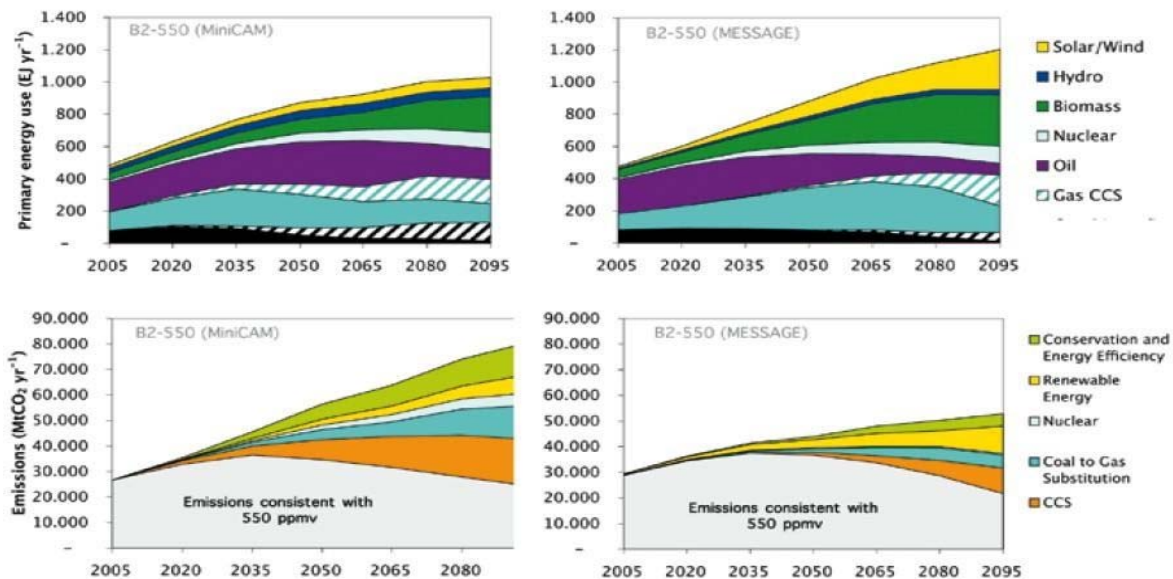
(1999). Edmonds et al. (2001) explored the results of Edmonds et al. (1999) in greater depth and reported results for global carbon stabilization costs reductions of as much as 81% by inclusion of CCS. Summary results from Edmonds et al. (2001) are reproduced in Table 2.2.5 below. In the table, cost reductions are calculated as energy costs in each stabilization scenario versus energy costs in the same scenario but without CCS deployment.

Table 2.2.5 – Reduction in Present Discounted Cost of Limiting Carbon Concentrations in MiniCAM as a Result of CCS Technologies¹¹

Reference case	450 ppmv	550 ppmv	650 ppmv	750 ppmv
Global Reduction in Cost (10 ⁹ US\$)	4700	1100	400	200
Percentage Reduction in Cost	68%	73%	77%	81%

IPCC (2005) explicitly evaluated the technical and economic feasibility of fossil fuel energy and CCS systems as a climate mitigation alternative using a number of different engineering and economic approaches. Mitigation relative to the IPCC B2 marker scenario was compared using harmonized approaches in MiniCAM and the bottom-up MESSAGE model of the International Institute of Applied Systems Analysis (“IIASA”). Results, which are reproduced in Figure 2.2.5 below, indicate that the modeling approaches imply similarly large contributions from CCS in order to achieve CO₂ reductions goals.

Figure 2.2.5 – Energy Use and Emissions for the IPCC B2 Scenario

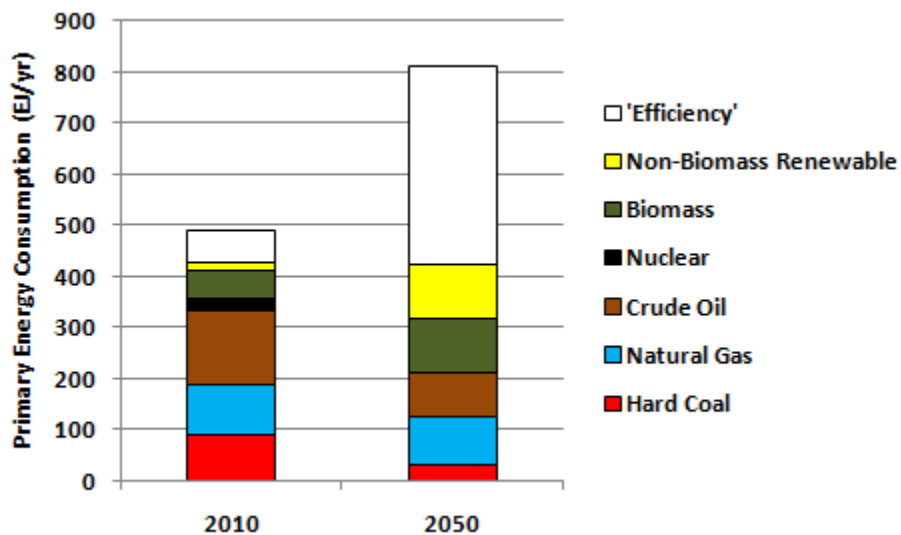


Analysis by IPCC (2000b) also indicates that differences in technological innovation within the scenarios gives rise to as much difference in final emissions as population growth, economic activity, and energy consumption combined.

2.2.6 Krewitt et al., 2007

Krewitt et al. (2007) used a backcasting approach similar to FOE/TC (2006) to examine potential pathways leading to global annual CO₂ emissions of around 10 GtC/yr by 2050 (judged necessary by the authors to achieve climate stabilization at a 2°C increase over pre-industrial levels). Based on input from the European Renewable Energy Council, Krewitt et al. conclude that CO₂ stabilization is possible without new nuclear capacity and without CCS for fossil fuels if energy efficiency improvements roughly offset all growth in energy demand between 2003 and 2050 and if renewable sources, especially biomass, are extensively deployed. Results are summarized in Figure 2.2.6.a below.

Figure 2.2.6.a – Global Primary Energy Consumption in Krewitt et al. (2007)



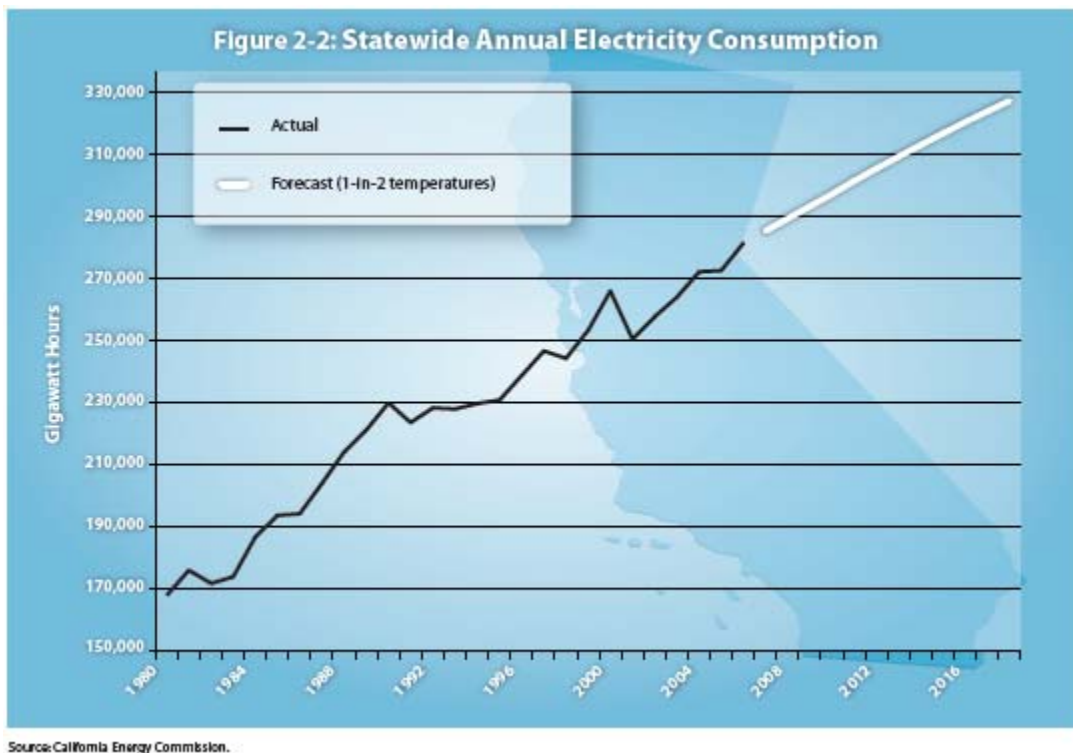
While Krewitt et al. “acknowledge the potential strong role CCS technologies might play in some regions of the world”, due to the authors’ judgment of current technical and economic uncertainties CCS technologies are excluded from their analysis and they conclude that “the availability of CCS technologies is not necessarily a prerequisite” for achieving their stabilization target.

The Krewitt et al. study rests on several key assumptions regarding energy efficiency, deployment of renewable energy, and both the production and greenhouse gas mitigation potential of biofuels use in transportation. Because this is the only global study we have encountered which does not rely on substantial amounts of CCS for climate stabilization these assumptions are reviewed briefly below:

1. Krewitt et al. employ “very ambitious” (in their terms) efficiency assumptions relative to the reference scenario against which they measure energy demand reductions. Relative to the IEA World Energy Outlook 2004 reference scenario, demand reductions assumed by Krewitt et al. *displace all expected global demand growth*, implying a nearly 3% decrease in global energy intensity *every year* between now and 2050. For reference, this

is substantially more than the annual intensity decreases seen in the OECD during the 1980's and 1990's.¹² The Krewitt et al. analysis, for example, assumes electricity consumption per capita in South Asia (including India) growing but never exceeding roughly a third the per capita level experienced by transition economics such as Bulgaria today and never exceeding roughly a fifth of the level achieved by transition economics like Bulgaria in 2050. The analysis does assume shrinking energy demand in the OECD over this period but it is worth noting that even California, often cited as a world model for policy-driven energy efficiency improvements, has significantly increased its energy consumption over the last two decades, as Figure 2.2.6.b, below, suggests.

Figure 2.2.6.b – California Electricity Consumption, 1980 - 2020¹³



2. Krewitt et al. employ similarly ambitious assumptions about deployment of renewable energy. In their analysis 80% of the developed world's electricity in 2050 (and as much as 90% of the developing world's electricity in 2050) is assumed to come from renewable sources, for example (principally wind), and one quarter of the world's transportation fuel is assumed to come from biomass. For reference, global production of wind energy in Krewitt et al. in the year 2050, 25730 PJ/a, implies roughly 2700 GW of installed wind capacity, which would require complete wind turbine installation over an area of land roughly the size of Montana, and which is more than 25 times the currently installed wind capacity.¹⁴ Yet substantial land use and other siting conflicts have emerged over the wind power capacity already proposed and constructed in the last decade in the OECD. With respect to biomass, many researchers have begun to question whether plant-derived transportation fuels can have *any* net greenhouse gas benefits when indirect market and land use impacts of large scale energy cropping are considered.¹⁵ In addition to

greenhouse gas concerns, there is substantial controversy over the impact of biofuels development on other environmental imperatives as well as food security and price.¹⁶

The results of Krewitt et al. appear to be substantively similar to the results published by Greenpeace (2007). Greenpeace (2007) is not reviewed directly here.

2.2.7 US Climate Change Science Program, 2007

The United States Climate Change Science Program (“CCSP”) evaluated future energy and emissions scenarios for the US and world as part of its ongoing responsibility to provide climate change synthesis and analysis products to the President and US Congress. CCSP (2007) developed new climate stabilization scenarios by applying integrated assessment models (“IAMs”) developed by Stanford University and the Electric Power Research Institute (the “MERGE” model), the Massachusetts Institute of Technology (the “IGSM” model containing MIT’s EPAA model), and Pacific Northwest National Laboratory and the University of Maryland (the “MiniCAM” model). Scenarios included BAU reference growth as well as several levels of stabilization target (from 4 to 1, corresponding to atmospheric CO₂ stabilization targets of 750 ppmv to 450 ppmv).

Figure 2.2.7.a below displays CCSP results for global energy supply, with IGSM on the left, MERGE in the middle, and MiniCAM on the right. Figure 2.7.7.b contains the key for Figure 2.2.7.a. The modeling approaches used in developing the Level 1 scenario vary considerably, as can be seen both in the reference scenarios (represented by the full height of each colored bar in Figure 2.2.7.a) as well as the potential role of energy efficiency (represented by the grey portion of each bar) and the role of CCS (the striped bars) and nuclear power (the orange bars).

Figure 2.2.7.a – Global Energy Use Projections of CCSP¹⁷

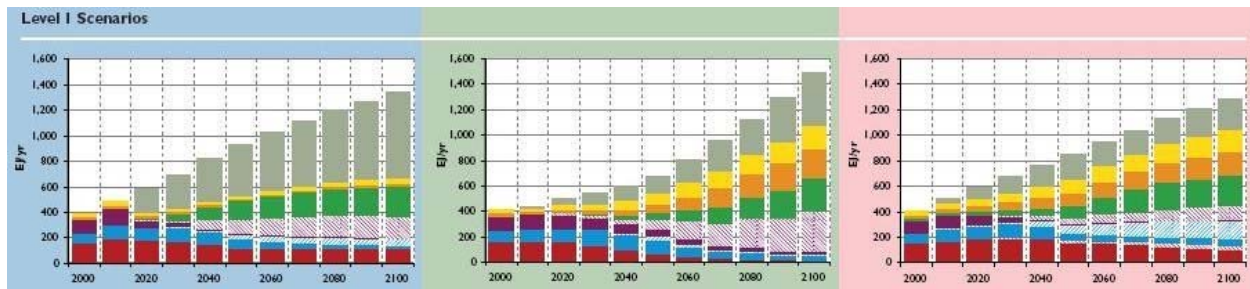
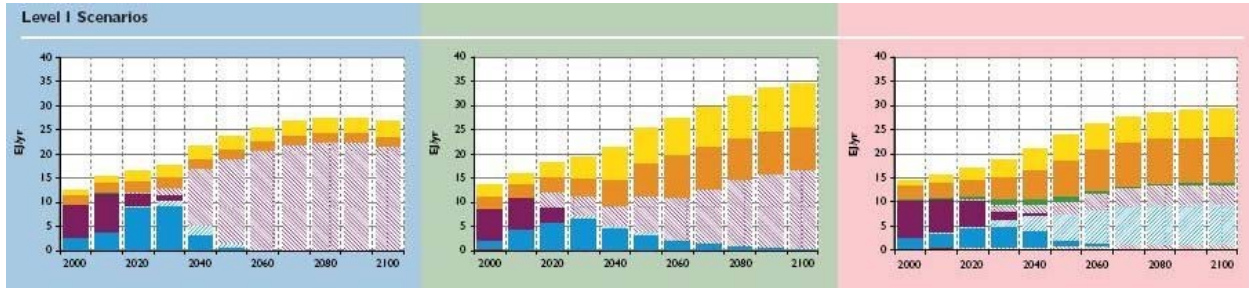


Figure 2.2.7.b – Key to Figure 2.2.7.a



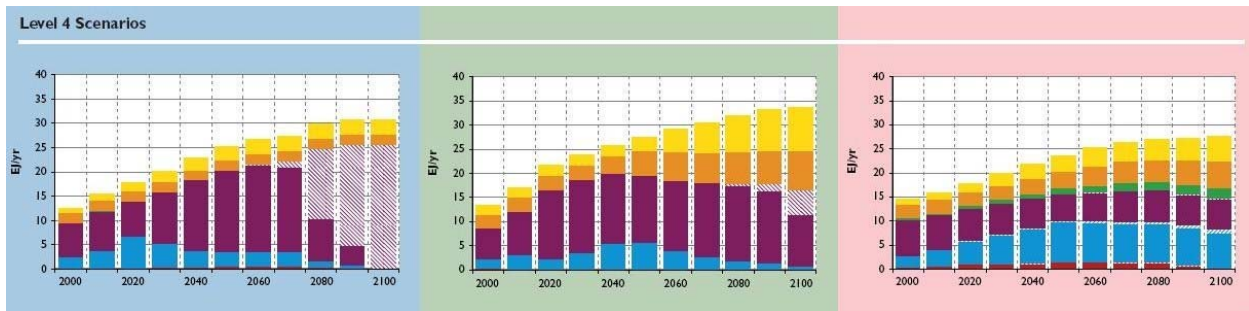
Figure 2.2.7.c displays the modeling results associated with each model for US electricity generation. It is worth noting in this figure the shared result of the modeling teams that climate stabilization suggests almost complete de-carbonization of the US electricity sector by the year 2050.

Figure 2.2.7.c – US Electricity Generation Projections of CCSP¹⁸



Comparing results between the models, the role of nuclear power is increased where CCS is deployed less. In addition, as Figure 2.2.7.d below indicates, CCS adoption comes later and is less pronounced where only Level 4 stabilization is assumed (much higher atmospheric CO₂)

Figure 2.2.7.c – US Electricity Generation Projections of CCSP¹⁹



The clear implication of the CCSP results is that early and aggressive CCS deployment is a major factor in achieving global atmospheric CO₂ stabilization.

In Table 2.2.7 below global installed capacity of fossil fuel electricity generation is given based on CCSP data for Level 1 stabilization and a CATF calculation assuming 85% capacity factor for the CCS generation. In the table, data for year 2035 is interpolated based on data for year 2030 and year 2040.

Table 2.2.7 – Global Fossil Fuel Electric Generation Capacity with CCS, GW Installed

	2020	2035	2050
Level 1 Stabilization	38-116 GW	604-768 GW	1495 – 2076 GW

Appendix 1 contains further CATF analysis of CCSP results.

2.2.8 McKinsey & Company, 2007

McKinsey & Company (“McKinsey”) (2007) evaluated potential greenhouse gas emissions reductions for the United States for the year 2030 relative to the US DOE Annual Energy Outlook 2007 reference scenario projections for that year. McKinsey developed a projection of the technical-engineering costs of hundreds of abatement options and the potential magnitude of each abatement using three cases representing low, mid-range, and high levels of ‘national commitment’ to emissions abatement, and based on current technology penetration, costs, cost drivers, the potential for cost reductions, the potential for limitations on deployment, and estimates of technology improvement for each option based on industry and academic expert opinion and technology analogues.

McKinsey did not consider the effects of regulatory mechanisms to limit CO₂ emissions (such as GHG cap-and-trade regulations or a ‘carbon tax’), and do not include macroeconomic feedbacks from climate change or abatement policy effects. Instead, McKinsey assumed a national and global economy similar to today’s, with energy prices based on US DOE reference case projections and constant ‘consumer utility’ (defined as functionality and usefulness for people, e.g., vehicle size, home size, or home thermostat setting).

Significant results from McKinsey (2007) include the following:

1. In the mid-range case (which would result in annual CO₂-equivalent emissions of 3 Gt less than the US DOE reference scenario for 2030, or annual emissions on par with 2005 levels) ‘negative cost’ abatement options account for 40% of the total reductions at year 2030. Negative cost abatement options are those options, such as CFL and LED lighting, improvements in building construction, and improvements in the efficiency of electronic devices, that carry a net benefit to the economy over their lifetime. McKinsey notes the persistent barriers to realizing these ‘negative cost’ reductions, which include a high consumer discount rate (40% on household investments), affordability (even when a 2-3 year payback period is possible consumer capital is often limited), agency (often the costs and benefits of these options accrue to different parties), and quality (real or perceived limitations on the quality of energy efficient devices).
2. In the mid-range case CCS is assumed to be commercialized by 2020 and contributes significantly more to abatement than any other single option studied. In the high-range case CCS is assumed to be commercialized in 2015, and due to the increased deployment time period plays an even larger role. Table 2.2.8 below summarizes key McKinsey results for the mid-range case for selected abatement options, including abatement potential and average cost.

Table 2.2.8 – Summary of McKinsey (2007) Abatement Options for Year 2030

Option Description	Potential⁽³⁾ (Mt CO₂e)	Cost⁽¹⁾ (\$/ton)	Comments
Power Sector and Industrial CCS ⁽²⁾	385	44 – 49	Power sector, 290 Gt, includes new build (23GW) and rebuilds(32GW), industrial CCS is 95 Mt; cost incl. EOR

Option Description	Potential⁽³⁾ (Mt CO2e)	Cost⁽¹⁾ (\$/ton)	Comments
Industrial Non-CO2 GHG Reduction	255	3	Methane management, N2O reductions, HFC reductions
Lighting Improvements	240	-87	Substitution of CFL and LED systems
Improved Fuel Economy ⁽²⁾	195	<0	Includes light cars and trucks and heavy trucks
Wind Power	120	20	Limitations due to wind resource, space, transmission; costs increase as good sites are used
Electronic Equipment	120	-93	Efficiency improvements for office equipment, PCs, televisions, audio, etc.
HVAC	100	45	Better HVAC equipment and installation, and exhaust tuning
Cellulosic Biofuels	100	-18	Various processes
Industrial CHP	80	-15	New CHP in metals, refining, chemicals, food industries with 5MW+ turbines
Industrial Process Efficiency	75	6	Process controls, energy recovery, motor upgrades, etc.
Nuclear	70	9	Includes new build, up-rates, and reactivations
Commercial CHP	70	-36	More CHP for large commercial, university, and hospital space
Generation Efficiency	60	-15	Improved heat rates of base-load coal plants
Solar PV	50	29	High costs now (to \$350/MWh) decrease with development (to \$70/MWh for some sites)
Plug-In Hybrid Vehicles	20	15	Abatement only if high efficiency battery (3.5+ mile/kWh) and lower-carbon electric grid
Other Power Sector	210	-	CSP, biomass co-firing, geothermal, small hydro, poor-class wind

Option Description	Potential ⁽³⁾ (Mt CO2e)	Cost ⁽¹⁾ (\$/ton)	Comments
Other Industrial ⁽²⁾	115	-	Emerging industrial technology, composting, small-scale electric generation, restoration
Other Transportation	25	-	Hybrid trucks, aircraft efficiency
Other Buildings and Appliances ⁽²⁾	120	-	Water heaters, building controls, appliances, residential and commercial fuel switching

Notes on Table 2.2.8: (1) McKinsey & Company caution that the study cost estimates are 'social costs' representing, among other things, a 7% discount rate and 2005-level dollars, and should not taken to be the CO2 emission cost or price level at which an option becomes economic; (2) Results for several categories are condensed in the table; (3) McKinsey & Company note that their calculated abatement potentials are sensitive to 'sequencing' of options, so that the potential of efficiency improvements in power generation, for example, might depend on the extent of demand reduction accomplished through lighting improvement.

- McKinsey finds that fuel switching in the power sector can play a meaningful abatement role, but at a cost exceeding the cap of \$50/ton set for the study. The study notes:

Gas-fired generation may serve as a tactical solution in the short term, but it does not appear to be an economically efficient option for sustainable long-term abatement, given the likely sources of incremental gas supply (new well development, liquefied natural gas imports, and unconventional gas resources) and the corresponding implications for the price of gas. Consequently, we estimated nearly 60 megatons of abatement potential for natural gas-fired power at a marginal abatement cost of \$64 per ton, which, because of its high cost, we did not include in our abatement ranges (p.64).

2.3 Lessons from the Stabilization Studies

Critical evaluation of the studies discussed above leads to several general conclusions regarding the potential role of CCS in helping to mitigate climate change risks. First, there appears to be general agreement that CCS holds great promise and importance for reducing greenhouse gas emissions to stabilization target levels by 2030-2050, second only to energy efficiency (see, e.g., IEA (2006b)). The one study positing a no-CCS stabilization path, Krewitt et al. (2007), does not deny CCS's potential importance, but assumes efficiency increases and biomass deployment that differ substantially from most other researchers' estimates of practical potential and appears not to reflect substantial uncertainties surrounding the net CO2 effects of large scale biomass development. Second, in many studies, incomplete deployment of CCS results in larger deployment of nuclear power (see, e.g., UK DTI (2005), CCSP (2007)). Third, in a number of studies (e.g., IEA (2006b) and Edmonds (2000)) mitigation scenarios that include CCS have a significantly lower overall abatement cost than scenarios without CCS. Finally, in those modeling runs where CCS is deployed later, the ultimate CO2 stabilization level tends to be higher (e.g., CCSP (2007)).

3.0 FURTHER READING

Readers interested in further information on these topics are encouraged to consult IEA (1992) for a discussion of the MARKAL model and its application to energy system cost minimization, Edmonds et al. (2004) for a discussion of the MiniCAM model, IPCC (2001) for a general discussion of climate change mitigation options, and Edenhofer et al. (2006) for a discussion of long-term endogenous technological change in energy-environment models. IPCC (2005) includes a lengthy technical discussion of the global energy system, including CCS. CCSP (2007) includes an in-depth discussion of integrated assessment models. URLs for some of this material is included in the References section.

4.0 ACKNOWLEDGEMENTS

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5.0 REFERENCES

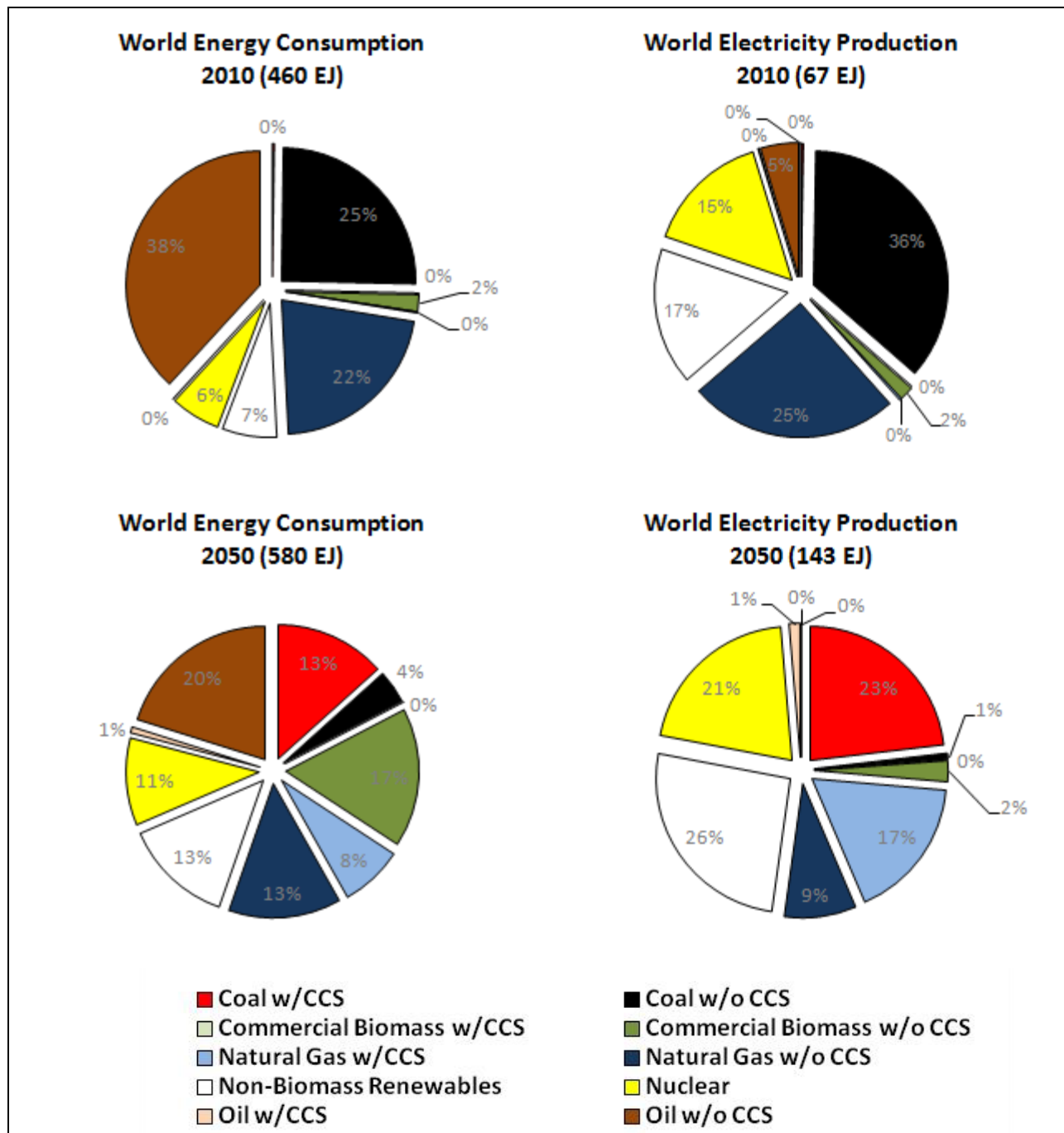
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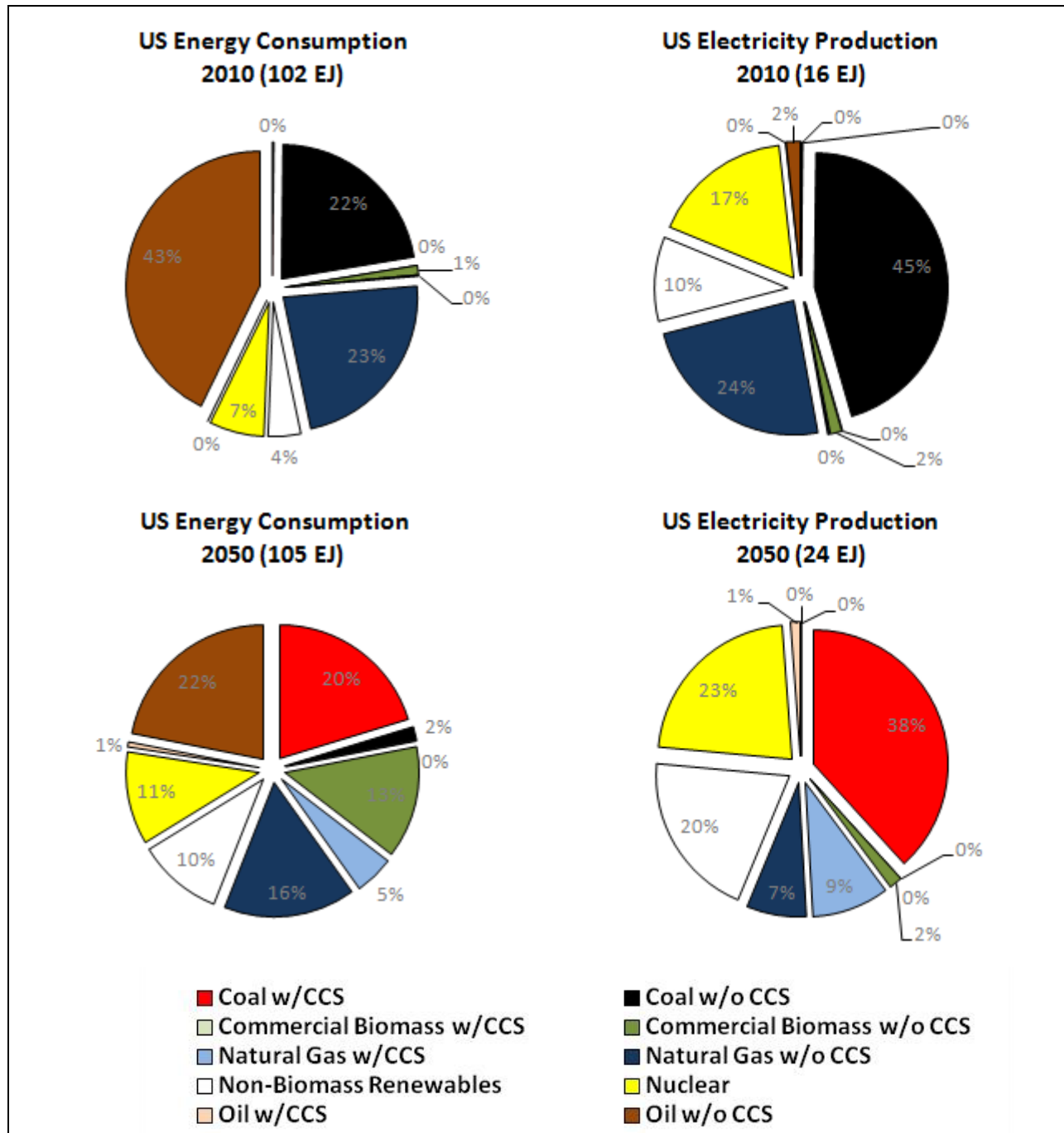
6.0 APPENDIX 1 – CATF Analysis of CCSP Results

CATF’s calculation of the average results of the 3 models used in the CCSP evaluation for Level 1 stabilization (450 ppmv CO₂) are displayed below for select variables. CCSP data is available at <http://www.climate-science.gov/>.

World Primary Energy Consumption and World Electricity Production, CATF-Derived Mean of MERGE, MiniCAM, and IGSM Model Results for Level 1 Stabilization



US Primary Energy Consumption and US Electricity Production, CATF-Derived Mean of MERGE, MiniCAM, and IGSM Model Results for Level 1 Stabilization



7.0 NOTES

¹ According to IPCC (2007a) best estimates from climate models indicate that limiting global average temperature increases to 2.0°C - 2.4°C above pre-industrial levels will require limiting atmospheric CO₂ concentrations to 350 - 400 ppmv. CO₂ concentrations between 400 and 440 ppmv are associated with temperature increases between 2.4°C and 2.8°C; concentrations between 440 ppmv and 485 ppmv are associated with temperature increases of 2.8°C - 3.2°C. At concentrations above 570 ppmv, associated temperature increases are above 4.0°C.

² The SRES scenarios are described in IPCC (2000a) and include a number of different “storylines” of future development representing a universe of assumptions encompassing a full range of assumptions about underlying drivers of greenhouse gas emissions (e.g., demographic change, economic development, and technological change). The A1 storyline, for example, represents rapid population growth, and within the A1 storyline the A1F1 scenario represents intensive fossil fuel use. The B1 storyline, on the other hand, represents more rapid reductions in material intensity, an emphasis on environmental sustainability, and introduction of more resource-efficient technologies.

³ Historically, non-land-use sources have accounted for more than 75% of all anthropogenic CO₂ emissions, and of that 75% more than 95% has been due to combustion of fossil fuels (with combustion of coal alone contributing almost 40%). See UNDP (2000). Global energy-related CO₂ emissions between 1850 and 2000 were 1,017 GtC (one GtC is 10⁹ tonnes, equivalent to 10¹² kg, of carbon contained in CO₂; 1 GtC is equivalent to 3.67 GtCO₂), and were approximately 27 GtCO₂/yr in 2004. See WRI (2007). Although many gases contribute to climate change, CO₂ is dominant. Since the dawn of the industrial revolution atmospheric concentrations of CO₂ have increased from roughly 280 parts per million by volume (ppmv) to 379 ppmv, or 35%. See IPCC (2007b).

⁴ WWF (2007), Figure 4.

⁵ For a discussion of backcasting see Anderson (2001) and Lovins (1973). For a discussion of the impacts of energy and carbon intensity on greenhouse gas emissions see Hoffert et al. (1998).

⁶ Participants in DTI’s data review workshop included representatives of the Policy Studies Institute, IEA Greenhouse Gas R&D Program, Imperial College, University of Ulster, and EON UK.

⁷ UK DTI 2005, Figure 5.

⁸ Results of cost-minimization models such as MARKAL can strongly favor technologies with marginally lower costs. UK DTI (2005) state: “In MARKAL the costs of base-load generation from CCS technologies and nuclear power are similar, but with nuclear marginally cheaper. However, the difference is less than the uncertainty applying to long-term cost and performance data used by MARKAL, and therefore the data do not have the precision to support differentiation between these options”.

⁹ Data adapted from IEA (2006) Table 2.2.

¹⁰ Many authors have commented that in recent years the actual distinction between the two approaches has diminished considerably

¹¹ Edmonds et al. (2001) Table 7.

¹² See, e.g., US DOE, International Energy Outlook 2007.

¹³ See California Energy Commission, 2007, Figure 2.2.

¹⁴ Comparison assumes a 30% annual capacity factor for wind turbines. According to Socolow (2005) one “stabilization wedge” represents 2000 GW of peak wind capacity, which would occupy 30 million hectares. For a summary of recent wind power capacity see *Mechanical Engineering*, Vol. 130, No. 3, March, 2008.

¹⁵ See, e.g., Searchinger et al. (2008).

¹⁶ See, e.g., CATF’s November, 2007 report “Looking Before They Leaped”, available at www.catf.us.

¹⁷ CCSP (2007) Figure TS.8.

¹⁸ CCSP (2007) Figure TS.12.

¹⁹ CCSP (2007) Figure TS.12.