Strategy 6:

Initiate Aggressive Carbon Capture/Sequestration Projects for Coal-Generated Electricity in Kentucky

GOAL **By 2025, Kentucky will have evaluated and deployed technologies for carbon management, with use in 50 percent of our coal-based energy applications.**

INTRODUCTION

Kentucky must recognize the unique challenges we face in a carbon-constrained world, given our reliance on coal-fired power generation. The threats associated with climate change will require Kentucky to make a concerted effort to control emissions of carbon dioxide, while at the same time recognizing that coal will be a vital component of our energy mix. We must find a way to reduce carbon dioxide emissions and meet our energy needs for the future.

Kentucky's Energy Profile

More than 90 percent of Kentucky's electricity is derived from coal-fired power. And historically, Kentucky has enjoyed some of the lowest electricity rates in the country. This, in turn, has allowed energy-intensive industries to flourish in our commonwealth. As noted previously, our low rates have encouraged Kentuckians to be some of the largest consumers of electricity in the country. Kentucky's per capita consumption of residential electricity is among the highest in the United States (EIA-767, EIA906, 2006).

Electric-power industry carbon dioxide emissions for Kentucky totaled more than 93 million metric tons in 2006, which constitutes 3.8 percent of the U.S. total. Furthermore, we project a need of 7,000 extra megawatts of generation capacity by 2025. There will also be a need for capacity required to replace our aging fleet of plants (Kentucky Public Service Commission, 2005).

In 2004, Kentucky ranked thirteenth nationally in total emissions of carbon dioxide. The top 20 states are listed in Table 9 (EIA, 1990-2004). See Appendices B, C, and D for additional details.

Table 9: Carbon Dioxide Emissions in 2004 from the Top 20 States

Rank	State	Million Metric Tons of CO_2	Rank	State	Million Metric Tons Tons of CO_2
1	TX	625.2	11	LA	183.1
2	CA	395.5	12	NC	155.6
3	PA	284.0	**13**	**KY**	**153.8**
4	OH	274.0	14	MO	142.8
5	FL	262.6	15	AL	142.2
6	IL	250.4	16	NJ	133.4
7	IN	237.9	17	VA	130.6
8	NY	212.2	18	TN	125.9
9	MI	192.3	19	WV	114.3
10	GA	185.7	20	WI	112.1

These factors place us in a difficult position as we face the prospects of a carbon-constrained world. And it is indeed the world's problem – one that will require action on a global scale.

Pacific Northwest National Laboratory announced on Nov. 17, 2008 that scientists have new evidence suggesting that carbon dioxide can be safely and permanently sequestered in deep, underground basalt rock formations. The new information reveals how water-saturated liquid carbon dioxide can help seal cracks within the rock that otherwise might allow the carbon dioxide to escape. Adequate amounts of molecular water are present in the supercritical carbon dioxide so that the injected carbon dioxide reacts directly with minerals in the basalt. Thus, the carbon dioxide can "self-seal" cracks or fissures that might otherwise allow the carbon dioxide to migrate upward. Though the tests were conducted with basalt, the findings would also be applicable to other geologic formations.

Source: Pacific Northwest National Laboratory, http://www.pnl.gov/topstory.asp?id=333

Scale of the Problem

Worldwide there are annual emissions of 26 gigatons of carbon dioxide from fossil fuel combustion, with another 9,000 gigatons of carbon dioxide projected to be emitted during the next century. Carbon dioxide is the most abundant anthropogenic (human-caused) greenhouse gas in the atmosphere. In recent years, atmospheric concentrations of carbon dioxide have been rising at a rate of about 0.5 percent per year (EIA, 2007). To stabilize atmospheric carbon dioxide concentrations at a safe level, the 9,000 gigatons of carbon dioxide needs to be lowered to no more than 2,600 to 4,600 gigatons of carbon dioxide (GTSP, 2006).

The Risks

A recent federal government report determined that "climate change is already affecting U.S. water resources, agriculture, land resources, and biodiversity, and will continue to do so." Furthermore, the impacts are significant, and "alterations are very likely to accelerate in the future, in some cases dramatically." Examples include a wide range of direct and indirect effects on regional ecosystems such as: increasingly arid conditions that increase the risks of forest fires, changing precipitation trends and outbreaks of pests and invasive species that will affect agricultural production, and widespread modifications to the life cycles of plant and animal species (CCSP, 2008).

Solutions to the Problem

There are a number of factors that can affect total carbon dioxide emissions. For instance, carbon dioxide emissions in the United States during 2006 were 110 million metric tons below their 2005 level of 6,045 million metric tons due to favorable weather conditions; higher energy prices; a decline in carbon intensity of electric power generation that resulted from increased use of natural gas, the least carbon-intensive fossil fuel; and greater reliance on non-fossil energy sources (EIA, 2007).

But there is a growing recognition that the solution lies in a strategy that employs a wide array of technologies. These include: increasing energy efficiency throughout all sectors, increasing electricity generation from sources other than fossil fuels (such as hydroelectric, wind, solar, and nuclear); and separating and capturing the carbon dioxide from industrial and energy-related sources, and transporting it to a storage location for either beneficial reuse or sequestration. Carbon capture and storage has the potential to reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reductions (IPCC, 2005).

Information is Imperfect

There is a wide discrepancy in carbon dioxide storage capacity estimates. There are preliminary estimates of 11,000 gigatons of carbon dioxide in potential geologic storage capacity worldwide. And many geologic storage locations are also near large groupings of power plants and other industrial facilities. About 95 percent of large U.S. point sources are within 50 miles of candidate carbon dioxide reservoirs (GTSP, 2006).

According to the Intergovernmental Panel on Climate Change (IPCC), it is likely that there is a technical potential of at least 2,000 gigatons of storage capacity in geological formations worldwide. And CCS could contribute 15 percent to 55 percent to the cumulative global carbon dioxide mitigation effort until 2100 (IPCC, 2005).

Weyburn Oilfield - Canada

No discussion of carbon capture and sequestration would be complete without a mention of the success story that is the Weyburn Oilfield. Located in Saskatchewan, this oilfield receives injected carbon dioxide, complements of Dakota Gasification's Great Plains Synfuels facility in North Dakota. The oilfield receives, via a 325-km pipeline, 2.7 million cubic meters per day of carbon dioxide. By injecting the carbon dioxide into this seemingly-depleted oilfield, the life of the field has been extended more than 25 years, with another 122 million barrels of crude oil extracted. Soil sampling conducted at the site indicates there is no leakage of carbon dioxide from the reservoir.

Source: U.S. DOE, National Energy Technology Laboratory

Kentucky's Challenge

In Kentucky, 93 million metric tons of carbon dioxide are emitted from electric power generation each year. According to a report from the Kentucky Geological Survey, carbon dioxide sequestration capacity of as much as 28 billion tons total could potentially be found in the deeper and thicker parts of the Devonian shales, which underlay two-thirds of the state (Nuttall et al., 2005). If all carbon dioxide generated could be stored in these formations, then there could potentially be enough storage capacity for over 100 years of Kentucky's power generation.

No Perfect Solutions

There are different types of carbon dioxide capture systems: post-combustion, pre-combustion and oxyfuel combustion. Post-combustion capture requires a solvent to absorb the carbon dioxide from the flue gases, but net power generated is reduced by 29 percent and the costs of the electricity produced increase by as much as 65 percent. The technology required for pre-combustion capture is typically applied to integrated gasification combined cycle plants, and is already widely applied in fertilizer manufacturing and in hydrogen production (EPRI, August 2007). There are no IGCC plants in Kentucky.

Oxyfuel combustion results in high carbon dioxide concentrations in the gas stream and, hence, easier separation of the carbon dioxide. Unfortunately, there is also an increase in energy requirements (20 percent – 30 percent of the net power generated) to separate the oxygen from air (GOEP, 2007).

Retrofitting existing plants with carbon dioxide capture is expected to cost more, and result in lesser plant efficiencies, than for newly built power plants designed for carbon dioxide capture. However, technological advances are occurring in this area. Researchers have developed an innovative approach to speeding up the natural mineralization process which involves permanent storage of carbon dioxide in silicate minerals. Reaction times are being reduced to a matter of minutes, which is a key factor in whether the technology can be applied to retrofits of existing plants. The process involves dissolving the flue gas carbon dioxide in a water slurry of sodium bicarbonate, sodium chloride, and a mineral reactant such as olivine or serpentine, resulting in a precipitate of magnesium carbonate (O'Connor et al.). Researchers at the University of California-Los Angeles have also developed a new class of materials known as zeolitic imidazolate frameworks, or ZIFs, that can be used in high-heat conditions to selectively capture carbon dioxide (Banerjee et al., 2008).

The Sleipner Project - Norway

A private company has successfully demonstrated geologic carbon sequestration. Statoil's wells in the North Sea extract natural gas from a reservoir (the Sleipner field) 3,500 feet below the sea floor. The gas contains excess amounts of carbon dioxide which must be removed in order for the gas to be pipeline quality. Given that the carbon dioxide was already being removed, and facing taxes for carbon dioxide emissions, the company elected to capture, compress, and inject the carbon dioxide into a geologic formation 1,000 feet below the seabed (a location actually more shallow than the gas reservoir). The U.S. Department of Energy has conducted monitoring and verification and recently announced that data show no migration of the carbon dioxide.

Source: U.S. DOE, National Energy Technology Laboratory

Sequestering Carbon Dioxide

Carbon dioxide, once captured using today's technologies, must be compressed to a supercritical state in order to be transported to a suitable storage location. The carbon dioxide is then injected into a geologic reservoir several thousand feet deep. The formations into which the carbon dioxide is injected must be porous, such as deep saline formations, and be covered with an impermeable caprock layer. Oil and gas fields are attractive in that the carbon dioxide, once injected, can force out more oil and gas from seemingly depleted reservoirs. And given that oil and gas were once trapped in these formations, it is reasonable to speculate that the voids left behind can act as a similar storage site for carbon dioxide. There are questions on the long-term viability of this approach as a means of storage that must be addressed (EPRI, 2007).

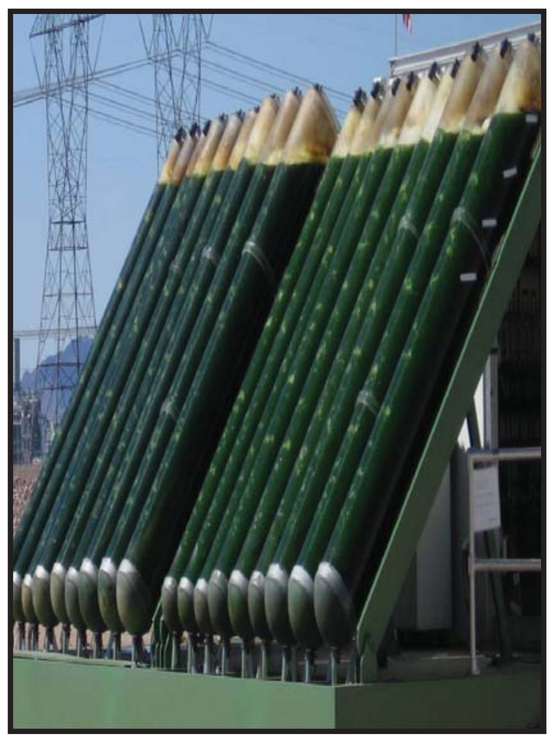

Figure 22: Arizona Public Services' Redhawk power station where algae is harvested and used to produce biodiesel. (Image provided by Raymond Hobbs, APS Senior Engineer, at the *Illinois Basin Energy Conference*, held March 6, 2008, in Henderson, KY.)

The costs for a CCS system are significant. A GTSP report predicts costs for coal-fired power plants to be roughly \$20-\$60 per ton of carbon dioxide captured (GTSP, 2006). A National Energy Technology Laboratory (NETL) study of carbon capture retrofits to an existing plant determined the costs to be roughly \$46 per ton with 90 percent carbon dioxide capture (NETL, 2006). Thus, the costs of electricity, once CCS is in place, are expected to increase. The application of capture technology would add about 1.8 to 3.4 cents per kilwatt-hour to the cost of electricity from a pulverized coal power plant (EIA, 2007). For comparison Kentuckians, on average, pay 5.43 cents per kilowatt-hour (EIA, 2007).

Actual costs, of course, are determined by a variety of factors including: the methods used in carbon dioxide capture; the means of conveyance (pipeline length and dimensions); the source's proximity to geologic sequestration sites; the depth required for geologic sequestration; and any economic gains obtained through enhanced oil and gas recovery or resale of the captured carbon dioxide.

Clearly, the carbon management challenges are significant, and solutions will be costly. It is imperative to mobilize our limited resources to their greatest effect, and to do so as expeditiously as possible.

The Potential of Algae

There is a growing body of work supporting the use of microalgae, the material we typically think of as "pond scum," to take up carbon dioxide emissions from power plant flue gases. There are active projects at MIT and at the Arizona Public Services' (APS) Redhawk power station (Figure 22) where algae is harvested and used to produce biodiesel.

The benefits are significant: high algae growth rates, no need for arable land, no need for potable water, no competition with food crops, and a large variety of natural algae species (50,000+). But perhaps the most important factor is that microalgae can produce roughly 30 times as much oil per unit growth area as typical food crops (Baum, 1994).

The use of algae to mitigate carbon capture has been studied for many years (NREL, 1998). This natural alternative deserves careful and extensive consideration to solve our carbon problem. Researchers at the University of Kentucky's Center for Applied Energy Research (CAER) are moving forward on several fronts to determine the feasibility of algal systems for carbon dioxide capture. The EEC has funded two research projects on algae research and process design.

At the CAER, researchers are examining outcomes from the MIT and APS projects to determine if these processes can succeed in Kentucky. Though algae are amazingly versatile, controlled conditions are nevertheless required in order for algae to thrive at the scale necessary for capturing flue gas carbon dioxide from a power plant.

Light is crucial. When large volumes of algae are growing (in either open ponds or closed, tubular photobioreactors) there are "dark zones" that receive less light, thus inhibiting growth. Salinity, temperature, pH, light intensity, and the strain of algae species are all factors in finding the proper balance to achieve our goal. If not monitored closely, algal growth can progress to the point of taking in too much carbon dioxide as the photosynthesis rate increases, and creating an unsustainable level of dissolved oxygen (Andrews, 2008). Thus, algae sequestration holds a lot of potential, but optimizing the conditions for success can be difficult.

The second project underway at CAER is construction of a demonstration-scale system using a commercially available photobioreactor. This system will be deployed at CAER with the goal of testing algal growth under Kentucky climatic conditions and with a source of carbon dioxide similar to flue gas from an actual power plant. The system will be closely monitored with researchers paying particular attention to any detrimental effects of sulfur dioxide on algal growth. The algae will be dewatered and oils extracted. The dried algae cake (the material remaining after oils are extracted and water is removed) will be examined to determine its nutritional value to determine if this material could be suitable feed for livestock or fisheries.

This program will be ramped up to include further testing of different algal strains, different reactor designs, and different scales of gas streams. If early tests show promise, the EEC and CAER will eventually seek to deploy an algal system at a coal-fired power plant in Kentucky. If successful (80 percent carbon dioxide capture or greater) at a 300 megawatt coal-fired power plant, the system could capture over 1.3 million tons of carbon dioxide per year.

ACHIEVING THE GOAL

By 2025, Kentucky will have evaluated and deployed technologies for carbon management, with use in 50 percent of our coal-based energy applications.

Near-Term Actions (1-3 Years)

1. Kentucky will support the work of the Carbon Management Research Group (CMRG). The CMRG is a consortium of major power companies, the CAER and the EEC. The CMRG will carry out a ten-year, $24 million program of research to develop and demonstrate cost-effective and practical technologies for reducing and managing carbon dioxide in existing coal-fired electric power plants. There are three main research projects envisioned:

   - Investigation of post-combustion carbon dioxide control technologies using the CAER pilot plant. The CAER will complete a detailed parametric testing for the particular coal that will be fired in a slip-stream field testing site and provide the optimum operational conditions as well as solvent management protocol by 2010.
   - Slip stream investigation of post-combustion carbon dioxide control technologies at a consortium power plant. The CAER will complete a portable slip-stream apparatus fabrication, installation and commissioning by 2010.
   - Development of chemical looping combustion/gasification for solid fuels. The CAER will complete design and fabrication of a bench-scale redox apparatus by 2011.
2. The EEC will examine legal hurdles to successful CCS and recommend legislative solutions to the 2010 General Assembly.
3. The EEC will create a carbon registry to identify source locations and emission levels.
4. Necessary staff positions in the Division of Oil and Gas will be funded to support Kentucky's primacy over the underground injection control permitting program.
5. Working closely with university researchers and industry partners, Kentucky will undertake one large-scale carbon mitigation project to utilize microalgae to capture carbon from flue gases, and then convert the algae to biofuels.
6. Kentucky will support the Consortium for Carbon Storage. With a $5 million seed grant from the state in 2008, the Kentucky Geological Survey (KGS) has established the Kentucky Consortium for Carbon Storage (KYCCS) to determine the potential for geologic sequestration, enhanced oil and gas recovery and enhanced coal-bed methane recovery using carbon dioxide. The research is being organized into three research projects:

   - Western Kentucky Sequestration,
   - Eastern Kentucky Sequestration, and
   - Enhanced Oil and Gas Recovery.

This project will complement work underway with federal regional carbon sequestration partnerships.

Mid-Term Actions (3-7 years)

1. The CMRG will complete membrane pilot-scale testing by 2014 and a catalytic scrubbing and stripping pilot-scale experiment by 2015.
2. The CMRG will finalize design specifications for a potential slip-stream apparatus by 2009; and complete three site investigations by 2014.
3. The CMRG will finalize design and fabrication of a bench-scale redox apparatus by 2012 and bench-scale testing by 2013.
4. The CMRG will deploy a carbon capture system (post-combustion system, chemical looping, or algae) at a power plant by 2014.
5. The KYCCS will complete well abandonment for the Western Kentucky Deep CO_2 Sequestration Project by 2012.

Long-Term Actions (>7 years)

1. The CMRG will complete its fifth site investigation by 2017.
2. The most technologically feasible and cost-effective CCS methods will begin being implemented by 2018.

IMPLEMENTATION SCHEDULE

Assuming success with capturing and sequestering carbon dioxide from Kentucky power plants and that all new plants are constructed to account for carbon dioxide emissions, the energy mix for the state in the short- to mid-term will be similar to today's situation. Coal will continue to provide significant energy needs in the short term, as we migrate towards a system where our electricity is derived from non-fossil sources such as biomass, wind, solar, and nuclear. Eventually, coal will become a source for liquid and gaseous fuels of the future.

ENVIRONMENTAL BENEFITS & LIMITATIONS

The primary measurement for *Strategy 6* is the amount of carbon dioxide emissions avoided. If Kentucky's power plants can capture 90 percent of the carbon dioxide they now emit, the emissions avoided will total 84 million metric tons. Kentucky will demonstrate the environmental gains to be made by reducing power plant carbon dioxide emissions from 93 million metric tons to 9.3 million metric tons. If we, as a coal state, can reduce our emissions by 55 percent, it will demonstrate Kentucky's leadership. Assuming no changes in the transportation sector (a very conservative assumption), this will result in a 55 percent reduction in carbon dioxide emissions, which is in line with the goals of the U.N. IPCC.

Assuming other nations follow our lead, we can avoid widespread global impacts to natural ecosystems; we can avoid impacts to our food and water supplies; and we can avoid inestimable widespread economic damages to our state and nation.

REFERENCES

Andrews, R. *Feasibility of Capture and Utilization of $C0_2$ from Kentucky Power Plants by Algae Systems*, June 2008, Draft Report Submitted for Grant Number PO2-855-0700006898.

Banerjee, Rahul, Anh Phan, Bo Wang, Carolyn Knobler, Hiroyasu Furukawa, Michael O'Keeffe, Omar M. Yaghi. "High-Throughput Synthesis of Zeolitic Imidazolate Frameworks and Application to CO_2 Capture." *Science*. Volume 319. February 15, 2008. [http://yaghi.chem.ucla.edu/pdfPublications/2008hiThroughput.pdf]; accessed June 23, 2008.

Baum, R. 1994. *Microalgae are possible source of 'biodiesel' fuel*. Chemical and Engineering News 72(14):28-29.

CCSP, 2008: *The effects of climate change on agriculture, land resources, water resources, and biodiversity*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M. Ryan, S. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L Meyerson, B. Peterson, R. Shaw. U.S. Environmental Protection Agency, Washington, DC., USA, 362 pp.

Electric Power Research Institute. *Expanding Options for $C0_2$ Storage*. EPRI Journal, Spring 2007.

Electric Power Research Institute (EPRI). *The Power to Reduce CO_2 Emissions, The Full Portfolio*. August 2007 Discussion Paper.

Energy Information Administration. *Emissions of Greenhouse Gases in the United States 2006*. ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/ggrpt/057306.pdf *(accessed June 18, 2008)*. DOE/EIA-0573(2006). November 2007.

Energy Information Administration, *Environment, Electric Power Plant Emissions, Electric Power Industry Estimated Emissions by State* (EIA-767 and EIA-906), State Historical Tables for 2006: CO_2. [http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=KY] (accessed June 17, 2008).

Energy Information Administration, *International Energy Outlook 2007*. [http://www.eia.doe.gov/oiaf/ieo/emissions.html], (accessed June 18, 2008).

Energy Information Administration. *Kentucky Electricity Profile*. 2006 Summary Statistics. DOE/EIA-0348. November 2007. [http://www.eia.doe.gov/cneaf/electricity/st_profiles/kentucky.html] (accessed June 19, 2008).

Energy Information Administration, State CO_2 Emissions by Year, 1990-2004. [http://www.eia.doe.gov/oiaf/1605/ggrpt/excel/tbl_statetotal.xls], (accessed June 18, 2008).

Global Energy Technology Strategy Program (GTSP). *Carbon Dioxide Capture and Geologic Storage. A Core Element of a Global Energy Technology Strategy to Address Climate Change*. A Technology Report from the Second Phase of the Global Energy Technology Strategy Program. JJ Dooley (lead author), RT Dahowski, CL Davidson, MA Wise, N Gupta, SH Kim, EL Malone. April 2006.

IPCC, 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

Kentucky Governor's Office of Energy Policy (GOEP). *Carbon Management Report*. December 2007.

Kentucky Public Service Commission. *Kentucky's Electric Infrastructure: Present and Future, An Assessment Conducted Pursuant to Executive Order 2005-121*. September 2005.

Massachusetts Institute of Technology. *The Future of Coal-Options for a Carbon-Constrained World*. 2007.

National Energy Technology Laboratory. *Carbon Dioxide Capture from Existing Coal-Fired Power Plants*. DOE/NETL-401/120106. December 2006.

National Renewable Energy Laboratory. *A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae*. NREL/TP-580-24190. July 1998. [http://www.nrel.gov/docs/legosti/fy98/24190.pdf] (accessed July 3, 2008).

O'Connor, W.K., et al. *Carbon Dioxide Sequestration by Direct Mineral Carbonation: Results from Recent Studies and Current Status*. U.S. DOE, Office of Fossil Energy, Albany Research Center, Albany, OR.