Princeton University
Woodrow Wilson School
Graduate Program

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Woodrow Wilson School 585b/Mechanical and Aerospace Engineering 580

Living in a Greenhouse: Technology and Policy

2006 COURSE INFORMATION AND SYLLABUS
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Mondays 7 – 10 pm, 15 Robertson Hall

CONTENTS

Course Information

The emphasis of the course is on the solutions to the global carbon problem, rather than the problem itself. Solutions take the form of multiple deep changes in the energy system and, to a lesser extent, in the way we use land. The course will argue that: 1) the global carbon problem can be solved; 2) the world will be changed by doing so; 3) the changes are largely for the good.

The premise of the course is that the global carbon problem has been made more opaque than necessary. The student will be empowered to discuss solutions to the climate-and-carbon problem quantitatively, to assess the promise of new industries, to formulate the policies that could foster these industries, and to envision the campaign strategies that might elicit such policies.

The focus of the course is on the next 50 years. Much of the literature of climate mitigation has been framed by the next 100 years, which exceeds the longest time horizons of business strategy and public policy, thus discouraging concrete discussion. We pose a choice: we can ignore climate change mitigation for 50 years, attending to other priorities, but thereby leaving a world for our grandchildren's generation where certain solutions have become impossible and other solutions are much harder to contend with. Alternatively, those alive today have the opportunity to "solve" the carbon problem, in the sense that we can present a carbon management problem to our grandchildren's generation that we guess now will be comparably difficult – neither immensely harder nor much easier.

The focus of this course will be on "mitigation," rather than "science," or "impacts," the other members of the triad that organizes scholarship dealing with the climate problem. Accordingly, the course will treat in depth neither the greenhouse problem itself (the major sources of uncertainty and how quickly they are being resolved) nor human impacts (climate change, sea level rise, biodiversity degradation, disease).

Although the course has a global, not a U.S. focus, when we look at international mechanisms for carbon management, we will look not only at the Kyoto Protocol, which went into effect early in 2005 without the participation of the U.S., but also at U.S. proposals for a parallel technology-based track.

The course builds on work by the course's professor and Prof. Steve Pacala, (Ecology and Evolutionary Biology, Princeton), first published in *Science* in August 2004 ("Stabilization Wedges: Solving the Climate Problem for the Next 50 years with Current Technologies." *Science*, Vol. 305, pp. 968-972, August 13. 2004). A restatement has just been published in the September 2006 *Scientific American* ("A Plan to Keep Carbon in Check," *Scientific American*, Vol. 295, No. 3, pp. 50-57).

Obligations of the students

1. Active participation in all classes.

2. Readings. Correcting a failing in 2005, readings will be organized hierarchically and more closely related to classes. Each week, a few readings will be chosen for discussion in class, and two to four students will be asked to lead these discussions. Additional readings will be in two categories: "Additional required readings" and "Recommended readings (useful for term papers)." All articles in the September 2006 *Scientific American* will be assigned. *Prospective students: please buy this issue, on newsstands in late August and early September, and read several articles before the first class.* We will reimburse costs.

3. Term papers. Because the course has such breadth, it is essential that the student plunges into one or two areas in depth via term papers. There will be a short (6-10 page) and a long (12-20 page) paper. The second paper may be a deeper discussion of the topic of the first paper, or it may deal with a completely different topic. Depending on class size, students may be asked to give an oral presentation about one of their papers.

4. Problem sets: One goal of the course is to increase the student's capacity for critical quantitative reading of analytical work. To this end, occasional problem sets will foster this goal.

There will be no final exam.

Syllabus, Condensed, Week-by-Week

Part One: Living in a Greenhouse

Week One: ***Carbon-cycle science, the abundance of hydrocarbon resources, and the world's new goal of "stabilization" of atmospheric CO_2 concentration***

Week Two: ***Carbon mitigation and stabilization wedges***

Week Three: ***Carbon, consumption, and affluent lifestyles. Energy diaries.***

Part Two: Stabilization wedges to decarbonize electricity (40% of current CO_2 emissions) and enabling policy

Week Four: ***Efficient use of electricity; the many forms of renewable electricity***

Week Five: ***Carbon dioxide capture and storage and the future of coal***

Week Six: ***International governance and nuclear power***

BREAK WEEK

Part Three: Stabilization wedges to decarbonize fuel used directly (60% of current CO_2 emissions) and enabling policy

Week Seven: ***Oil markets, interactions of fuel security with carbon mitigation***

Week Eight: ***Enhanced oil recovery, synthetic fuels from coal and natural gas, biofuels***

Week Nine: ***Efficient use of fuels: miles per gallon, miles per year***

Part Four: Managing and sharing planet Earth

Week Ten: ***Carbon and economic development***

Week Eleven: ***Our problematic destiny: Geoengineering and planet-scale mitigation***

Week Twelve: ***Summary: What have we learned?***

Syllabus, Expanded, Week-by-Week

Note: The material presented here is meant as a guide to discussion.

Part One: Living in a Greenhouse

Week One: *Carbon-cycle science, the abundance of hydrocarbon resources, and the world's new goal of "stabilization" of atmospheric CO_2 concentration*

The Earth in thermal equilibrium, absorbing heat from the sun and radiating it to space.

The atmosphere and the greenhouse effect. CO_2 concentrations in the past and today. The fossil-carbon source and the land-use source. The terrestrial sink and the ocean sink.

The carbon problem within the climate problem: aerosols, methane and other greenhouse gases, stratospheric ozone, air pollution. Ecological vs. direct human impacts. The changing ocean. Linear and non-linear change. Are we running an experiment on ourselves? How fast are we learning?

Solving the carbon problem versus using the carbon problem as a surrogate for other goals. Among the surrogate goals that motivate individuals are the curtailment of consumerism and human centeredness; the promotion of self-sufficiency; and the diminishment of the power of technological elites. In this course we assume that the carbon problem is worth solving for its own sake.

Week Two: *Carbon mitigation and stabilization wedges*

Stabilization at what level? The answer should depend on both the risks of disruption and the level of effort required to mitigate. The centrality of fossil fuels in global energy supply, and the centrality of the energy problem in the carbon problem

Wait or act now? With delay comes greater knowledge of risks. With prompt action comes the avoidance of further system momentum in counterproductive directions. The usefulness of interim goals. Kyoto goals (2008-2012) and mid-century goals.

The "stabilization triangle" as a representation of 1) a 50-year interim goal (*no greater global CO_2 emissions in 50 years than today)* consistent with "avoiding doubling" and 2) Business As Usual in the absence of carbon policy. What is the range of reasonable expectations about CO_2 emissions in the absence of deliberate carbon policy?

The "stabilization wedge" as a useful decomposition of the stabilization triangle and a useful unit of action. A stabilization wedge is a strategy, using technology already deployed somewhere in the world at industrial scale, that avoids the emissions of one billion tons of carbon per year in 2056. A wedge is a substitution: a less carbon-intensive activity replaces a more carbon-intensive activity.

Filling the stabilization triangle with stabilization wedges requires parallel campaigns. No single strategy can provide the required carbon emission reductions. On the other hand, not every available wedge is required. The formulation in terms of parallel campaigns and co-benefits elicits new thinking about collaborations and coalitions.

"Solution science": the study of the environmental and social costs and benefits of the stabilization wedges. There are no trouble-free ways to manage global carbon: Every wedge strategy can be implemented well or poorly. Although every wedge has co-benefits that generate alliances and improve the prospects of implementation, every wedge also has a dark side, generating opposition that thwarts implementation. Some of elements of carbon-reduction technologies are problematic at the level of individual projects, while others appear only with scale-up to hundreds or thousands of projects.

Week Three: *Carbon, consumption, and affluent lifestyles. Energy diaries.*

The carbon problem is a problem of modernity, a problem of prosperity. It is a byproduct of choices about how to live well: what to consume, how to spend time. Today, it is nearly universally believed, a good life is one lived with exuberance: with a wide variety of experiences. Of great value are privacy, safety, convenience, and excitement. The pursuit of these goals drives resource use upward.

Balancing some of this upward pressure is an emerging negative feedback of prosperity on resource use: the correlation of greater wealth with a desire for fewer children. Global population may soon peak and then fall.

Looming large are the carbon emissions of the world's new arrivals into the "middle class," perhaps another two billion people, no longer living in abject poverty, driving first mopeds and then cars, living in apartment buildings and then detached or semi-detached houses. Patterns of consumption result, in considerable measure, from emulation of the choices of the rich.

Many cultures in the history of the world have defined the good life differently than prosperous people do today. Are serious challenges to the values of the prosperous in view, anywhere in the world?

With these issues in mind, each student, as a Problem Set, will prepare an Energy Diary, where he or she estimates the amount of energy expended to carry on the activities of some recent week. The student will be encouraged to present only a few areas of consumption thoughtfully, while indicating which other areas that have been omitted. These diaries will be discussed in class.

Part Two: Stabilization wedges to decarbonize electricity (40% of current CO_2 emissions) and enabling policy

Week Four: *Efficient use of electricity; the many forms of renewable electricity*

The division of CO_2 emissions into those related to power and to fuels used directly: Trends toward greater electrification. The greater abundance of decarbonization options for electricity than for direct use of fuels. Cross-over strategies, where electricity invades new domains, include the plug-in hybrid car and the electric heat pumps for space and water heating, which reduce CO_2 emissions provided that the electricity is decarbonized.

End-use efficiency: Complementing a supply perspective, and at least as important, is an end-use perspective on energy use and carbon emissions. From this perspective, very particular small systems, repeated billions of times, dominate carbon emissions for buildings, industry, and transport. Examples are the house window, the light bulb, the electric motor, and the car engine.

Efficient use of electricity: Historical perspectives, current trends, ranges of outcomes, insights from the behavioral sciences. Two thirds of electricity consumption occurs in buildings; an immense amount of new construction lies ahead. Relevant policies.

Efficient power plants: Fuel shifts among the fossil fuels (gas power for coal power)

Electricity directly from solar energy: High-temperature solar collectors (parabolic troughs and dishes), photovoltaic collectors

Electricity from natural systems that enhance solar energy: Hydropower, wind, biofuels for power

Geothermal power

Week Five: *Carbon dioxide capture and storage and the future of coal*

CO_2 capture and storage (CCS) at coal power plants: A carbon-smart coal power plant does not vent the CO_2 producing during combustion. Rather, it captures the CO_2 and sends it deep underground ("capture and storage," or "sequestration"). All the individual elements needed for CCS have been demonstrated, the first full-scale integrated plants are being planned. CCS is indispensable if coal is to play in reducing CO_2 emissions.

"Clean coal" technologies with CCS offer a particularly important opportunity to constrain emissions in rapidly growing economies with large coal reserves, such as China, India, and the U.S. In the U.S., consideration of the demography of capital facilities highlights the replacement rate for currently operating coal plants as an important policy variable.

CCS cannot be broadly deployed unless there is a price on CO_2 emissions, because it will nearly always be cheaper to vent CO_2 than to capture and store it.

CO_2 capture: Equipping a new coal power plant to achieve CO_2 capture adds complexity and cost. It also reduces the efficiency of turning coal into power: capturing carbon dioxide means mining and burning more coal. The emerging competition among capture strategies challenges policy design: how to avoid "picking winners" while still accelerating commercialization with limited government resources.

CO_2 capture can also be incorporated into natural-gas-based power plants and large industrial facilities.

CO_2 storage: Capture is just half the job. The best destinations for CO_2 in most cases will be sedimentary formation deep underground whose pores are filled with brine, and, sometimes, with oil or gas, as well. Geologists expect to find sufficient storage capacity in most regions of the world to accommodate the carbon dioxide captured from a significant fraction of the fossil fuel used in this century. A recent estimate of storage capacity in geological formations is 80 times the annual rate of production of CO_2 today for *all* purposes.

Uncertainties of licensing and permitting could dominate total sequestration costs. Policy areas related to storage currently being developed include the required retention time for the buried CO_2, insurance and liability, and monitoring and verification.

The co-benefit of enhanced oil recovery: When the captured CO_2 can be used below ground for enhanced oil recovery (EOR) at mature oil fields, total CCS costs are reduced and can even be negative in some cases. A combination of high oil prices and incentives for CO_2 storage could lead to a dramatic expansion of CO_2 capture projects paired with nearby enhanced oil recovery operations.

Week Six: *International governance and nuclear power*

Nuclear science: The Earth's endowment of energy stored in nuclei, releasable via fission of heavy elements and fusion of light elements. Stable and unstable isotopes. Forms of radioactive decay. Neutrons and chain reactions.

Nuclear fission power: No other energy source generates as much controversy as nuclear power. Nuclear power contributes substantially to electricity production in the United States, Europe, and Japan, but few new nuclear power plants are being built. The technology's advocates struggle to regain public confidence, lost after the economic debacle at Three Mile Island and the human tragedy at Chernobyl.

Until very recently, nuclear power politics were dominated by reactor siting and safety and radioactive waste disposal. Recently, nuclear weapons proliferation is becoming a more salient issue. The global expansion of nuclear power may be thwarted by its links to nuclear weapons proliferation, most especially, through the dual-use technologies for uranium enrichment and plutonium recycle. Events unfolding in Iran draw attention to the civilian-military couplings inherent in nuclear power: Iran is nominally playing by the international rules governing nuclear power embodied in the agreements administered by the U.N.'s International Atomic Energy Agency. The world's responses suggest that these rules need to be changed.

Nuclear fusion power: Even though fusion shares most of the problems of fission, these problems appear in less challenging forms. The level of R&D support will determine the rate at which the promise of this technology can be fully scoped. Fusion has had a unique role in internationally coordinated R&D.

BREAK WEEK

Part Three: Stabilization wedges to decarbonize fuel used directly (60% of current CO_2 emissions) and enabling policy

Week Seven: *Oil markets, interactions of fuel security with carbon mitigation*

Reserves and resources: The abundance of buried hydrocarbons, from the perspective of climate change. The carbon problem would not be a global priority if the fossil fuel era were to end with the end of conventional oil and gas. Easily accessible high-quality oil, easily extractable from large formations *is* being used up. But buried hydrocarbons exist in abundance, in all kinds of qualities, at all levels of accessibility. Many times as much coal, unconventional oil (e.g., oil sands) and unconventional gas (e.g., methane clathrates) than conventional oil and gas exist. The CO_2 emissions from their use can drive CO_2 levels in the atmosphere to many times the "pre-industrial' concentration.

"Peak oil": Complementary perspectives from geology, technology, economics, geopolitics, and ethics.

The special problem of oil and the Middle East: Current and anticipated oil markets. Oil production in the Middle East from the producer country and consumer country perspective.

Week Eight: *Enhanced oil recovery, synthetic fuels from coal and natural gas, biofuels*

Interactions between fuel security and carbon mitigation: Many oil substitution strategies are beneficial from the perspectives of both energy security and climate change. A notable example is enhanced oil recovery (EOR), which is more profitable the higher the price of oil and which can result in CO_2 storage. a notable exception is the production of liquid fuels from coal.

Enhanced oil recovery (EOR): Based on CO2 injection into mature oil fields, it is potentially a big factor in extending production of oil from already worked fields, in the U.S. and also in the OPEC countries. The amount of oil likely to be produced by EOR greatly increases, the lower the effective price for the CO_2. The higher the economic value of storing the CO2 below ground (presumably in these same reservoirs) the lower the net cost of CO_2 delivered to these fields. The mischief molecule in the atmosphere is the miracle molecule below ground.

Synthetic fuels from coal and natural gas: The current U.S. debate. A role for CO_2 capture and storage at coal-to-liquids plants.

Biofuels: Upstream issues (what to plant, yield, ecological sustainability). Downstream issues (thermochemical vs. biochemical energy conversion).

Hydrogen from various sources: Systems challenges (chicken and egg), scale, storage, safety, fuel cells vs combustion engines.

Electrification: The plug-in hybrid vehicle.

Policies to foster supply alternatives: To improve the relative competitiveness of supply strategies that substitute for oil, what is the role of public policies that reduce the risk of falling oil prices?

Week Nine: *Efficient use of fuels: miles per gallon, miles per year, well designed buildings*

Efficient use of fuels: upstream in extraction and refining, and downstream in buildings, vehicles, industrial processes

Efficient transportation systems: Technologies for efficient cars, trucks, and planes, and the leverage of associated policies. Reduced vehicle use via car pooling, mass transit, city planning, and regional growth policy.

Reduced demand in residential and commercial buildings: Fossil fuels are used directly principally for space and water heating. Walls, windows, roofs. Passive solar architecture. Low-temperature solar thermal energy (flat-plate collectors). Efficient furnaces. Electric heat pumps. Thermal comfort and behavioral choice.

Part Four: Managing and sharing planet Earth

Week Ten: *Carbon and economic development*

Specific international arrangements for carbon management were embedded in the Framework Convention on Climate Change and the Kyoto Protocol. The world was divided into a group of more industrialized countries and a group of less industrialized countries. Each of the more industrialized countries was assigned a national target. A “clean development mechanism” encourages nations in the first group to invest in carbon management in the second group. Emissions trading is also encouraged.

Embedded in the Framework Convention and the Kyoto Protocol is a view that the more industrialized countries have an obligation to act first, because their emissions have dominated global emissions in the past and because their average per capita income levels are higher. This formulation can be criticized for ignoring the consequences for developing countries resulting from their current investments in long-lived capital facilities, like power plants and buildings.

There would appear to be little merit in encouraging investments that result in wasteful outcomes, from the standpoint of carbon emissions, anywhere in the world.

The Framework Convention and the Kyoto Protocol say little about technology. But in recent years a complementary organizing principle for carbon management is being formulated, focusing more on the technology that needs to be developed and less on the targets that need to be achieved. Several of the first international efforts to develop carbon-responsive technology do not express any bipartite division of the world. A technological structure can encourage "leapfrogging," the development of low-carbon technologies *first* in developing countries.

The goal of bringing to an end the abject poverty present in developing countries is sometimes perversely presented as being at odds with the goal restricting global carbon emissions. Quantitative argument can establish that bringing the first water pumps, light bulbs, cell phones, televisions, and refrigerators to the nearly two billion people in the world's villages who today are without electricity, and producing this electricity from a mix of power sources that includes fossil fuels, will scarcely affect the world's carbon accounts.

Week Eleven: *Our problematic destiny: Geoengineering and planet-scale mitigation*

What is our role on the planet, looking forward and beyond 2056? The Framework Convention on Climate Change envisions our perpetual engagement in carbon management in order to achieve and maintain a constant concentration of carbon dioxide in the atmosphere. What sort of goal is this, and how might it generalize?

"Stabilization" is a word from control theory. The climate regime currently envisioned is a world where human beings actively control the composition of the atmosphere and manipulate the land and ocean sinks, for example by titrated reforestation. We are placing ourselves in the role of managers of the Earth – first of all, for our own benefit, but also, to some extent, for the benefit of other forms of life. Using another word that captures this new role for our species, we are about to become "geoengineers."

The cultural implications of active management are very different from those of minimizing the human impact on natural system, which has been the objective of much of environmentalism. Active management creates challenges to democratic processes within and across countries: by what processes will decisions be reached about ends and about means?

Today, the "industrialized" countries (the members of the Organization for Economic Cooperation and Development) emit about half of the world's CO_2, and the "developing" countries plus the countries formerly part of the Soviet Union emit the other half. If global emissions are the same in 2056 as today (the objective suggested in the wedges model), how much smaller could the aggregate CO_2 emissions in 2056 of today's OECD countries? And what are the implications of the relatively small upper bound on aggregate 2056 emissions from the non-OECD countries?

What are the prospects for entirely revolutionary approaches to managing global carbon, especially if we adopt a frame of reference of 100 years instead of 50 years? Examples are nuclear fusion and solutions based in advances in genetic engineering.

Implicit in active management of the Earth is a planetary consciousness – an affinity greatly enlarged, relative to the tribalism and nationalism of the current day.

Week Twelve: *Summary: What have we learned?*

Books to be Placed on Reserve

Deutch, John and Richard K. Lester, *Making Technology Work: Applications in Energy and the Environment.* Cambridge University Press, 2004

> Deutch and Lester have written a set of case studies dealing with topics addressed in the course. book. The emphasis is on teaching the techniques of the policy analyst to the undergraduate engineer.

International Energy Agency, *World Energy Outlook, 2004 and 2005*. Paris, France: OECD/IEA

> The projections for the world energy system, typically twenty five years into the future, published by the International Energy Agency in its biannual World Energy Outlook, are cited by the energy industries and frame their worldview.

Parson, Edward A., *Protecting the Ozone Layer: Science and Strategy*. Oxford University Press, 2003

> Parson conducted hundreds of interviews on the way to a book of deep scholarship about the formation of a regime of global management of stratospheric ozone. There are important parallels between ozone and CO_2,

Smil, Vaclav, *Energy at the Crossroads: Global Perspectives and Uncertainties*. MIT Press, 2003.

> Smil's book is an excellent overview of "energy."

Speth, James Gustav, *Red Sky at Morning: America and the Crisis of the Global* Environment. Yale University Press, 2004

> Speth has written a call to action. He identifies new routes to policy innovation, by providing a fresh perspective on the relationship between government and civil society.

Tester, Jefferson W., Elisabeth M. Drake, Michael J. Driscoll, Michael W. Golay, and William A. Peters. *Sustainable Energy: Choosing Among Options*. MIT Press. 2005.

> This tome is a comprehensive quantitative introduction to energy technologies, with extensive discussion of non-technical issues.

Trefil, James. *Human Nature: A Blueprint for Managing the Earth – By People, For People.* Times Books, 2004

> Trefil, a prolific science writer, has written an affirmatively non-technical book. He unifies a presentation of genomics, biodiversity, and the greenhouse problem with an argument that new knowledge is providing human beings with an unprecedented capacity to manage the natural world. His chapter on the greenhouse problem deals with the ambiguities of climate science but not with the technologies, policies, and lifestyle dimensions of carbon mitigation.

Weart, Spencer. *The Discovery of Global Warming.* Harvard University Press, 2003.

> Weart, a historian of science, tells a story of many small steps and lots of wrong turns.

Useful Websites

BP, 2003. *BP Statistical Review of World Energy*
http://www.bp.com/subsection.do?categoryId=95&contentId=2006480

Energy Information Administration, U.S. Department of Energy, 2004. *International Energy Annual 2002*.
http://www.eia.doe.gov/emeu/iea/contents.html

Energy Information Agency, U.S. Department of Energy, 2004. *International Energy Outlook, 2003*. Report # DOE/EIA-0484.
http://www.eia.doe.gov/oiaf/ieo/index.html.

Gale, J. and Y. Kaya, eds., 2003. *Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1-4 October, 2002, Kyoto, Japan.* Two volumes. Amsterdam: Pergamon.
http://www.ieagreen.org.uk/ghgt6.htm

International Energy Agency, 2002. *World Energy Outlook 2002*. Paris, France: OECD/IEA. By subscription:
http://library.iea.org/dbtw-wpd/Textbase/nppdf/stud/02/weo2002_1.pdf.

International Energy Agency, 2003. *Key World Energy Statistics. 2003*.
http://www.iea.org/dbtw-wpd/bookshop/add.aspx?id=144

Intergovernmental Panel on Climate Change, 2000. *Land Use, Land Use Change and Forestry.* R.T. Watson et al. eds. Cambridge University Press.
http://www.grida.no/climate/ipcc/land_use/index.htm

Intergovernmental Panel on Climate Change, 2001. *IPCC Third Assessment Report—Climate Change 2001*. Cambridge University Press.
http://www.ipcc.ch/index.html

IPCC, 2001. *Special Report on Emissions Scenarios*.
http://www.grida.no/climate/ipcc/emission/index.htm

IPCC, 2004. *Seventh International Conference on Greenhouse Gas Control Technologies*, Vancouver, Canada (papers presented)
http://www.ghgt7.ca

National Research Council, 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. Washington, D.C., National Academy Press.
http://www.nap.edu/books/0309091632/html/