Pew Center/NCEP 10-50 Workshop

Nuclear Power and Climate Change – Overview Paper

Ernest J. Moniz
Professor of Physics
and
Director of Energy Studies
Laboratory for Energy and the Environment

Massachusetts Institute of Technology

I. Introduction and Summary

An interdisciplinary MIT study on The Future of Nuclear Power [1] was issued in Summer 2003 with a defining framework very close in spirit to that of this workshop: a mid-century scenario was established in which nuclear power could make a significant contribution to mitigating greenhouse gas (GHG) emissions, and policy options and actions for the next decade that sustain the nuclear option were described. Indeed, the rather diverse faculty study group – drawn from the Schools of Science, of Engineering, of Humanities and Social Sciences, and of Management, and from Harvard’s Kennedy School of Government – came together for the study because of the shared conviction that GHG emissions must be reduced dramatically relative to the expected increase in energy use and that the United States will eventually join with others to do so. Further, a prudent target of achieving GHG emissions below today’s levels at mid-century, when energy use will probably have increased two to two and a half times today’s, is so daunting that all energy options – greatly increased efficiency, renewables, carbon capture and sequestration, and nuclear power – are likely to be needed. For nuclear power, economic, safety, nuclear waste, and nuclear proliferation all present challenges that must be overcome technically, operationally, and in terms of public acceptance. The report provides integrated recommendations to address these challenges. Key observations and recommendations include:

- A mid-century growth scenario on a scale that substantially impacts GHG emissions would be realized with thermal reactors operated principally in a once-through mode [2], with economic criteria being crucial in driving this technology pathway.
- A merchant plant model of costs shows that, if nuclear power is to be competitive with coal and natural gas, industry must demonstrate reactor capital cost reductions that are plausible but as yet unproved, and the social costs of GHG emissions need to be internalized. For the United States, overcoming the “first mover” problem is key to determining the role of nuclear power. We recommend electricity production tax credits for “first movers”, modeled after those in place for wind. First mover demonstration of the economics and safety of new nuclear plants must occur within the next decade or so if nuclear power is to make a significant contribution to mitigating climate change in the first half of this century.

- Long-term storage of spent fuel prior to geological emplacement, specifically including international spent fuel storage, should be systematically incorporated into waste management strategies. The scope of waste management research and development (R&D) should be expanded significantly; an extensive program on deep borehole disposal is an example. Successful operation of geological disposal facilities and public acceptance of the soundness of this approach are essential for large-scale new nuclear power deployment.
- The current international safeguards regime should be strengthened to meet the nonproliferation challenges of globally expanded nuclear power. The International Atomic Energy Agency (IAEA) Additional Protocol [3] needs to be implemented, and the accounting and inspection regime should be supplemented with strong surveillance and containment systems for new fuel cycle facilities. The Nonproliferation Treaty implementation framework should evolve to a risk-based framework keyed to fuel cycle activity; central to this is having growth in global nuclear power deployment realized by having fuel cycle services, in particular fresh fuel supply and spent fuel removal, provided by a relatively small number of suppliers under international oversight. Such an approach needs to be established over the next decade, prior to a possible acceleration in nuclear power deployment.
- A major international effort should be launched to develop the analytical tools and to collect essential scientific and engineering data for integrated assessment of fuel cycles (advanced fuels, reactors, irradiated fuel reprocessing, waste management). Large demonstration projects are not justified in the absence of advanced analysis and simulation capability.
- Public acceptance is critical to expansion of nuclear power in many countries. In the United States, the public does not yet see nuclear power as a way to address global warming.

II. Global Growth Scenario

Our policy recommendations are strongly influenced both by the mid-century time scale for meaningful response to global climate change and by the concomitant scale and spread of the needed technology deployment. To help guide the analysis, we constructed a scenario for global growth of electricity demand and for nuclear power's share of that growth. The scenario for electricity demand was based on U.N. world population and urbanization projections and an assumption of national per capita electricity consumption rising towards a world standard. The resulting projection for global electricity production is consistent with U.S. Energy Information Administration (EIA) projections over the next two decades (slightly below the EIA reference case) and yields an increase of nearly a factor of three by mid-century. The nuclear power market share, assuming a strong impetus to deploy nuclear power (presumably because of GHG emission "caps" and of satisfactory resolution of the challenges noted above), is based upon national capabilities and infrastructure. The resulting scenario is shown in Table 1.

Global Growth Scenario			
		NUCLEAR ELECTRICITY MARKET SHARE	
REGION	PROJECTED 2050 GWe CAPACITY	2000	2050
Total World	**1,000**	**17%**	**19%**
Developed world	625	23%	29%
U.S.	300		
Europe & Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWhrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

Table 1

Several features of the scenario deserve note. The total deployment of 1000 Gigawatts electric (GWe) globally is nearly a tripling of today's deployment. This corresponds to an approximately level world market share and would displace about 1.8 Gigatonnes of carbon (equivalent) emissions annually from coal plants of equivalent capacity [4]. Such a displacement might represent about 25% of incremental GHG emissions from energy use in a business-as-usual scenario, a significant amount. Indeed, one may question whether difficult public policy steps are worthwhile from a climate change perspective unless one envisions nuclear power contributing to the "solution" at this level.

To reach such a level, the developed world will need to increase its nuclear market share substantially, up to about 30%. In particular, the United States must play a lead role, because of the combination of high per capita demand and projected population increase of about 100 million people. The reality that no new nuclear plants have been ordered in the United States for a quarter century is one indicator of the difficulty in realizing this global scenario. In contrast to the U.S. situation, projected stable (e.g., France) or declining (e.g., Japan) populations in countries seen today as more favorably disposed to nuclear power serve to limit demand growth.

A substantial part of the growth also occurs in the developing economies, but in a relatively small number of countries. This has important implications for addressing proliferation concerns, particularly since China, India and Pakistan already have nuclear weapons capabilities and thus are not major concerns for fuel cycle-associated proliferation (since they are likely to continue with dedicated weapons programs).

III. Economics

The economic comparison of new nuclear plants with baseload coal and natural gas plants and the economics of closing the fuel cycle underpin many of the recommendations. The baseline costs for new plants were compared within a framework of:

- merchant plants (i.e., a competitive generation market in which investors bear the primary risk)
- experience, rather than engineering analyses
- lifetime levelized costs.

Comparative Power Costs

CASE (Year 2002 $)	REAL LEVELIZED COST Cents/kWe-hr
Nuclear (LWR)	6.7
+ Reduce construction cost 25%	5.5
+ Reduce construction time 5 to 4 years	5.3
+ Further reduce O&M to 13 mills/kWe-hr	5.1
+ Reduce cost of capital to gas/coal	4.2
Pulverized Coal	4.2
CCGT[a] (low gas prices, $3.77/MCF)	3.8
CCGT (moderate gas prices, $4.42/MCF)	4.1
CCGT (high gas prices, $6.72/MCF)	5.6

a. Gas costs reflect real, levelized acquisition cost per thousand cubic feet (MCF) over the economic life of the project.

Table 2

Table 2 shows that, with gas prices of about $4.50/MCF (typical of the last year), both pulverized coal and natural gas combined cycle plants have a substantial cost advantage relative to the nuclear plant baseline in the absence of a carbon "tax" (detailed discussions of the methodology and of the input parameters can be found in the MIT report). An independent analysis performed by Deutsche Bank [5] is in quite close agreement. This comparison may be altered significantly by two factors.

- First, as shown in Table 2, plausible reductions in new nuclear plant costs can bring them in line with coal and gas. Reducing capital costs by 25% to $1500/kWe, a target that has not yet been met but appears plausible with new systems approaches and enough experience, has a large financial impact. A similar impact would arise from eliminating the risk premium (higher equity requirements and higher return on equity) for financing nuclear plants. Presumably, this reduction in the cost of financing would be achieved only by building and operating several plants successfully.
- The second major factor is the uncertainty surrounding internalization of carbon emission costs. Table 3 shows the impact of a carbon "tax" on the levelized costs for coal and gas. Clearly, the competitiveness of nuclear power would be enhanced significantly if carbon emission costs are internalized at $50 to $100 per tonne, which is considerably less than the cost of carbon dioxide capture and sequestration using today's technologies for either pulverized coal or natural gas [6].

Power Costs with Carbon Taxes			
CARBON TAX CASES LEVELIZED ELECTRICITY COST cents/kWe-hr	$50/tonne C	$100/tonne C	$200/tonne C
Coal	5.4	6.6	9.0
Gas (low)	4.3	4.8	5.9
Gas (moderate)	4.7	5.2	6.2
Gas (high)	6.1	6.7	7.7

Table 3

If nuclear power is to be deployed at mid-century on the scale being discussed, substantial construction of new plants must be underway within ten to fifteen years. Both the economics and new regulatory procedures need to be demonstrated. We recommend, for the United States, that production tax credits be offered to first mover nuclear plants at a rate set by that for wind. This is currently 1.8 cents/kWh, which can be thought of as about $75/tonne [4] of avoided carbon from a coal plant (and with the public benefit of carbon avoidance for decades following expiration of the credit). A production tax credit has the advantages of fundamentally keeping the risk with the private sector and of being applicable to any carbon-free option. Because of the very different natures of nuclear power and wind with respect to baseload characteristics, we recommended limiting the credit to 10 GWe of first mover capacity and to a total of about $200/kW. This recommendation is reflected in the 2003 energy bill conference report, although with less eligible capacity and a potentially much higher credit per installed kilowatt. The public good argument for such a mechanism rests with the importance of having government, industry, and financial markets understand whether new nuclear power will be competitive with fossil fuels and thus a serious option for meeting electricity demand and addressing climate change.

The utility view, as represented in the workshop submission [7] of Marilyn Kray (Exelon), for moving to new nuclear construction supports this approach. Three principal criteria are offered:

- operational confidence based on familiarity with the system designs and standardization of both design and operation;
- licenseability, for which the extensive regulatory history with light water reactors is very important; and
- economics, requiring large reductions in overnight capital costs compared to past experience.

The “first mover” reactors are overwhelmingly likely to be evolutionary advances of operating reactors, with passive safety features replacing some of the active systems in today’s plants. This addresses the first two criteria, while the tax credit provides the incentive to determine the economics. Clearly other criteria will also need to be met to make a business decision; Kray [7] mentions: reliable demand for baseload electricity; cost of alternatives, especially natural gas prices; continued successful operations of existing nuclear plants and a path to resolve plant security and spent fuel disposal issues; regulatory predictability through the Combined Operating License process; possible risk sharing through a “first mover consortium;” and recognition of the environmental benefits.

Tom Cochran (NRDC), in another workshop submission [8], argues against the first mover production tax credit as a subsidy that will not reduce the real cost of U.S. nuclear power plants. The MIT study group agrees that the tax credit will not itself reduce costs; rather, it is an incentive to take the first mover risk. If the industry is not confident in meeting cost targets with a substantial production tax credit available for several plants (allowing cost reduction through experience and by spreading one-time costs), then the credit will go unused with the obvious implications for nuclear power's role in meeting GHG challenges.

The MIT study also looks at the economics of plutonium recycling in the PUREX/MOX [9] fuel cycle. Not surprisingly, the once-through fuel cycle costs less. This is reflected indirectly in the difficulty of funding military plutonium disposition programs, where MOX fabrication costs alone are seen to equal the entire once-through fuel costs, and in the indefensible accumulation of about 200 tonnes of separated plutonium from power reactors. The arguments given in the past for pursuing PUREX/MOX have been inadequacy of uranium resources, which is no longer a credible argument, and the energy value in the plutonium, which is basically answered by the unfavorable economics. The current reason offered is the benefit to long-term waste management, to which we now turn.

IV. Nuclear Waste Management

The management and disposition of irradiated nuclear fuel has not yet been dealt with anywhere in the world. This is a major impediment to the growth of nuclear power. The Yucca Mountain repository is moving towards a licensing decision and, if it proceeds to successful implementation, a major milestone will have been achieved. Nevertheless, the MIT study's growth scenario calls for a dramatically expanded capacity for waste management in any fuel cycle.

Partitioning of the spent fuel to remove plutonium and possibly other actinides unquestionably reduces long-term radioactivity and toxicity of the waste. Nevertheless, the MIT study group did not find the benefits of partitioning and transmutation to be compelling on the basis of waste management. There are several reasons. First, although successful implementation has not yet been demonstrated, the scientific basis for long-term geological isolation appears sound. Partitioning leads to a large volume and mass reduction, but these are not terribly important criteria for repository design. Heat and radioactivity, which are far more important criteria, are only marginally reduced on the century time scale, since the fission products remain with the waste. In addition, the trade-off of benefits – possibly of small consequence to human health - in the millennium time scale against near-term increases in waste streams, occupational exposure, and safety concerns is not clear. There is certainly little evidence that the public is more concerned with the millennium rather than the generational time scale. Finally, other approaches may yield even greater confidence in long-term isolation and may do so more economically and simply. This would include advanced engineered barriers and other disposal approaches, such as deep boreholes. These are modest diameter holes drilled 4 to 5 kilometers deep into stable crystalline rock. The approach looks promising and economical because of drilling advances, because the geochemical environment (highly reducing) is favorable, and because the emplacement is not subject to surface vagaries. This is not to say that deep boreholes will prove to be the best approach, since major uncertainties exist. The point is that important alternatives to partitioning exist for adding even greater confidence to long-term waste isolation and these should be explored vigorously through new R&D programs.

An important role for advanced fuel cycles well into the future cannot be excluded, although significant economic and technical barriers must be overcome. The MIT study recommends a program of analysis, simulation tool development, and basic science and engineering of advanced concepts, and eventually appropriate project demonstrations. Cochran [8] argues that such a program is in itself a proliferation risk. We concur that such a program carries risk. However, the U.S. approach of rejecting plutonium recycle and cutting off research and international cooperation on fuel cycles demonstrably proved ineffective, since other countries have moved forward anyway. Rejection of the civilian MOX option should continue. Our recommendation is one of U.S. engagement to shape international advanced fuel cycle R&D properly, with an open mind to its eventual outcome, even while pursuing and advocating the open fuel cycle with thermal reactors as the basis for growth over the next decades. We also recommend that the U.S. government offices responsible for nonproliferation have an explicit management role in defining the scope, scale and location of such international R&D programs.

V. Nonproliferation

Global expansion of nuclear power into numerous new countries raises concerns about proliferation. This is not new, since a similar concern formed the backdrop for President Eisenhower's "Atoms for Peace" speech fifty years ago. However, the nonproliferation regime rooted in the Nuclear Nonproliferation Treaty (NPT) framework faces new circumstances: the end of the Cold War has changed security threats and relationships; the dramatic spread of manufacturing capability and technology lowers the barriers for translating nuclear know-how into nuclear weapons; and the post-9/11 world is more aware of the capabilities of terrorist groups and their interest in nuclear materials. These realities have refocused attention on the control and elimination of weapons-usable fissionable material (HEU and plutonium) and on the uncomfortable recognition that countries can move to the threshold of a nuclear weapons capability within the NPT regime.

Strengthening the nonproliferation regime in the face of a possible global nuclear power growth scenario calls for many coordinated actions. One fundamental change to the NPT implementation regime, discussed in the MIT report, would focus on a risk-based framework rooted in the technology, as opposed to political views. The key issue is that power reactors are not themselves the major proliferation threat, as opposed to enrichment and reprocessing plants, in the fuel cycle. Thus, states that deploy only reactors, with international assistance as desired, would have internationally secured fresh fuel supply and spent fuel removal. This would involve either "fuel cycle states" or internationally operated fuel cycle centers. The advantages of a country taking a "reactor-only" path would be avoidance of significant nuclear fuel cycle infrastructure development and maintenance costs, of intrusive safeguards regimes (since spent fuel and refueling operations for light water reactors are relatively easily monitored), and, most important, of nuclear waste challenges. An insistence on developing a full fuel cycle infrastructure, given the option of internationally guaranteed, economically attractive fuel cycle services and avoidance of significant challenges (especially waste management), would greatly heighten suspicions about proliferation intent, presumably leading to toughened international control mechanisms with regard to such countries. The major obstacle is acceptance of the spent fuel in a multiplicity of countries. So far, only Russia has expressed interest in receiving such fuel. This willingness of Russia to accept return of spent fuel may yet facilitate a resolution of the concerns about Iran's nuclear infrastructure development, a resolution much along the lines being suggested here for broader application. Clearly, establishing the validity of long-term secure spent fuel and/or high-level waste geological isolation is a critical step for responsible growth of nuclear power in response to electricity supply and climate change imperatives.

VI. Public Attitudes

The MIT study carried out a poll of well over 1000 Americans on their attitudes and understanding of energy-related issues. By and large, the public has a good understanding of relative costs and environmental impacts of different technologies; the cost of renewables was a notable exception, in that these were widely thought to be inexpensive. Nevertheless, it was interesting that perceptions of technology, rather than "external" factors such as politics or demographics, were at the core of their attitudes. A majority of respondents did not believe that nuclear waste can be stored safely for many years, and the typical respondent believed that a serious reactor accident is somewhat likely in the next ten years. The poll also showed that, in the United States, the public does not connect concern about global warming with carbon-"free" nuclear power. There is no difference in support for building more nuclear power plants between those who are very concerned about global warming and those who are not. This may prove to be either an opportunity for nuclear power advocates to better educate the public or a major obstacle to motivating the growth scenario.

VII. Concluding Remarks

The MIT study sought to define actions needed to enable nuclear power as an option for significantly mitigating GHG emissions while satisfying increasing global demand for electricity. If expansion of nuclear power is to contribute in a meaningful way up to mid-century, a robust growth period must commence within ten to fifteen years. This in turn means that very soon costs of new plants must be understood, including those costs driven by the licensing process and possible litigation, and issues surrounding waste management must be resolved. Recommendations for addressing the risks associated with first mover plants, in particular first mover production tax credits, were put forward and may be implemented. This is a necessary but not sufficient condition for the robust growth scenario. In addition, difficult international nonproliferation measures must be adopted and nuclear spent fuel management programs must demonstrate successful implementation and earn widespread public acceptance. These challenges are linked in ways that are complicated by the very different nuclear policies of the United States and some of its allies. Only if these challenges are met can nuclear power responsibly expand to the terawatt scale needed for seriously contributing to climate change mitigation at mid-century.

References and Notes

[1] *The Future of Nuclear Power*, ISBN 0-615-12420-8 (July 2003), available on-line at http://web.mit.edu/nuclearpower/; this workshop paper is largely drawn from this report. The study was funded principally by the Sloan Foundation. Study group members were Professors S. Ansolabehere, J. Deutch (co-chair), M. Driscoll, P. Gray, J. Holdren, P. Joskow, R. Lester, E. Moniz (co-chair), and N. Todreas.

[2] A nuclear reactor produces energy through fission, or splitting, of certain uranium or plutonium isotopes when struck by a neutron. The fission process itself produces neutrons, leading to the possibility of a chain reaction. A thermal reactor is one in which the produced neutrons are slowed down in order to increase greatly the probability of succeeding fissions. The light water reactors prevalent today are of this type. The once-through mode means removing the spent fuel for geological disposal. Closed fuel cycles are those in which the irradiated fuel is chemically processed to separate and recycle in the reactor components that have energy value, principally plutonium.

[3] The Additional Protocol permits the IAEA to inspect undeclared facilities suspected of use in a nuclear weapons development program.

[4] For the reference coal plant, we take a capacity factor of 85%, a heat rate of 9,300 Btu, and a carbon intensity of 25.8 kg-C/mmBtu.

[5] Adam Siemenski, Deutsche Bank, presentation at the 2002 EIA NEMS conference.

[6] David, J. and H. Herzog, "The Cost of Carbon Capture," Fifth International Conference on Greenhouse Gas Control Technologies (Australia, 2000); available at http://sequestration.mit.edu.

[7] Kray, Marilyn C. 2004. Long-Term Strategy for Nuclear Power. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004.

[8] Cochran, Thomas B., Critique of "The Future of Nuclear Power: An Interdisciplinary MIT Study." Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004.

[9] The PUREX/MOX fuel cycle is the closed fuel cycle in operation today in France and a few other countries. PUREX is a specific chemical process for separating plutonium and uranium from fission products (and minor actinides). MOX is the mixed plutonium oxide and uranium oxide fuel fabricated from the recycled plutonium.