The Climate Change Imperative and The Future of Nuclear Energy

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Much of the recently renewed interest in nuclear energy is driven by the desire to reduce emissions of carbon dioxide and thereby mitigate global climate change. The climate-change imperative is described well in Article II of the Framework Convention on Climate Change:

> The ultimate objective of this Convention…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

"Dangerous anthropogenic interference" now seems inevitable, inasmuch as there is growing evidence of changes in climate that are already well underway, which are likely to damage or destroy vulnerable ecosystems. The main challenge is not to avoid "dangerous" climate change, but to avoid "catastrophic" change.

There is at yet no consensus on the level at which carbon dioxide and other greenhouse gases should be stabilized. Most climate-change impact studies focus on the effect of a doubling of the carbon dioxide concentration, from the preindustrial level of 275 parts per million by volume (ppmv) to 550 ppmv. The resulting change in global-average surface temperature is expected to be about 3 °C. For comparison, the change in average surface temperature from the last ice age to the current interglacial period was roughly 5 °C, which demonstrates that seemingly modest changes in average temperature can correspond to dramatic changes in environmental conditions.

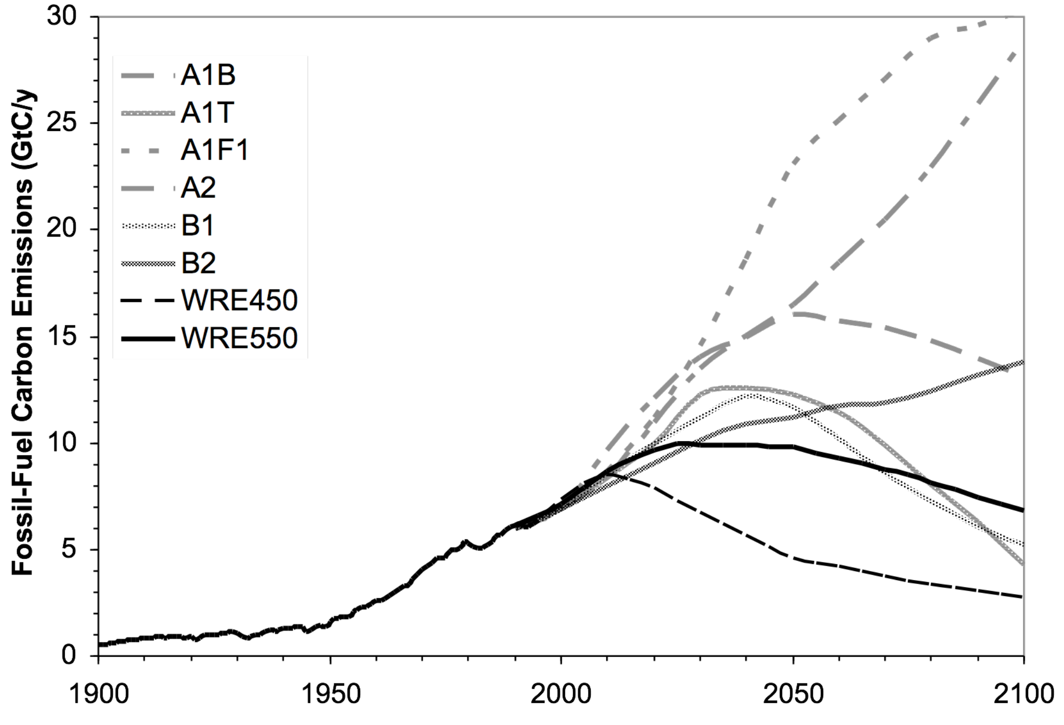
More significant than the change in global-average temperature—but more difficult to quantify—are the temporal patterns of regional changes in temperature, precipitation, cloudiness, soil moisture, winds and ocean currents, and changes in variability as well as the mean. There is good reason to believe that a doubling of carbon dioxide would produce a significant increase in sea level and in the intensity of storms, significant changes in the availability of fresh water, and significant decreases in biodiversity.

But, according to today's best estimates, it seems that a doubling of carbon dioxide is unlikely to trigger truly catastrophic events, such as a rapid collapse of West Antarctic ice sheet (which would raise sea level by 6 meters), a collapse of the global thermohaline circulation (which would cause temperatures in Europe to plummet), or a run-away positive feedback in which the melting of tundra and forest die-back release of huge amounts of carbon dioxide and methane (which would trigger much larger increases in temperature).

Thus, it would seem that a not-unreasonable stabilization target would be a doubling of the carbon dioxide concentration. But one must bear in mind that carbon dioxide is not the only greenhouse gas. Other gases—notably methane, nitrous oxide, and chlorofluorocarbons and their non-ozone-depleting substitutes—also contribute to greenhouse warming. Even in a world of tight controls, it is unlikely that these could be stabilized at levels equivalent to less than 100 ppmv of carbon dioxide. Thus, carbon dioxide must be limited at about 450 ppmv to stabilize greenhouse gas concentrations at an "equivalent doubling." One should also bear in mind that although today aerosols emissions are believed to have a cooling effect, efforts to control air pollution and acid deposition, as well as carbon emissions, will result in steep reductions of global aerosol emissions—just as we have witnessed such reductions in developed country aerosol emissions in the last 25 or so years.

Figure 1 shows past fossil-fuel emissions of carbon and allowable future emissions for stabilizing carbon dioxide concentrations at 450 and 550 ppmv. Also shown are reference scenarios of carbon emissions developed by the Intergovernmental Panel on Climate Change (IPCC), based on various assumptions about population, economic growth, and technological change. The concentration of carbon dioxide in the atmosphere is determined primarily by cumulative emissions (i.e., the area under the curve). In the median reference scenario, 550 billion tons of carbon (GtC) are emitted due to fossil-fuel burning from 2000 to 2050, and 1200 GtC from 2000 to 2100. For comparison, stabilization at 450 ppmv would permit emissions of only 300 and 550 GtC, respectively; for stabilization at 550 ppmv, the corresponding emissions are 450 and 900 GtC.

Figure 1. Fossil-fuel carbon emissions, 1900-2000 and IPCC reference emission scenarios (A1, A2, B1, B2) and stabilization scenarios (WRE450 and WRE550), 1990-2100.



To put this in perspective, a large coal-fired power plant with an electrical output of 1 gigawatt (GW_e) emits about 1 million tons of carbon per year. Thus, stabilization at 450 ppmv would require displacing roughly 200,000 gigawatt-years (GW_ey) of coal-fired plant operation by 2050, and 700,000 GW_ey by 2100. Stabilization at 550 ppmv would decrease the required reductions by roughly a factor of two.

The following four options are available to achieve these reductions:

- Demand reductions resulting from increased efficiency and fossil-fuel prices
- Capture and storage of carbon from fossil fuels
- Renewable energy (wind, solar, biomass)
- Nuclear energy

Modeling exercises typically show that all of these options would play a significant role in stabilizing carbon dioxide concentrations at 450 to 550 ppmv. The first option—increased efficiency and prices for fossil-fuel prices—is essential. At least two of the three energy supply options are needed. Of these carbon-free supply options, only one—nuclear energy—is deployed on a large commercial scale today.

Today nuclear power supplies about 16 percent of global electricity, and about 7 percent of total world energy demand. In order to make a substantial contribution to mitigating carbon emissions, nuclear energy would have to grow significantly over the next 50 years and beyond. Consider, for example, growth from the current level of about 360 GW_e to 1500 GW_e in 2050 and 4500 GW_e in 2100.[1] Reactors would come on line at a rate of about 35 GW_e/y in 2025 (roughly equal to the historical peak in 1984), increasing to 70 GW_e/y in 2050. Nuclear generation would total about 170,000 GW_ey from 2000 to 2100. Assuming that the nuclear reactors displace traditional coal-fired plants, they would supply about one-quarter of the reductions needed to stabilize carbon dioxide concentrations at 450 ppmv, and about half of the required reduction for stabilization at 550 ppmv.

In order for nuclear power to expand substantially, four issues must be addressed. First, nuclear electricity must be economically competitive with alternative carbon-free sources. Second, nuclear must be judged adequately safe, both by electricity producers and consumers. Investors will not build a reactor if they believe their investment might be lost in an accident, and a single serious accident anywhere could be sufficient to halt the growth of nuclear everywhere. Third, there must be sufficient long-term nuclear waste storage to prevent continuing uncertainties about ultimate disposal from preventing the building of large numbers of new reactors. Finally, an expansion of nuclear energy must not producing corresponding increases in the spread of nuclear weapons, risks of sabotage, or the theft of nuclear materials.

Over the next 50 years, these concerns are best addressed by advanced light-water reactors (LWRs) operating on a once-through fuel cycle with long-term storage of spent fuel. The LWR is the most mature reactor technology, with licensed designs and readily available production infrastructure. The LWR is the only nuclear technology that can be deployed on the required

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[1] This is consistent with scenarios developed in MIT, *The Future of Nuclear Power* (2003), and Son Kim and Jae Edmonds, "Nuclear Energy in a Carbon-constrained World" (University of Maryland, November 2005).

scale in the 2010-2030 time frame. Advanced or so-called "third generation" light water reactors (LWRs) are evolutionary improvements of the reactors most commonly deployed today. Construction and operation and maintenance costs are relatively well-known, and there is reasonable confidence that advanced LWRs can produce electricity at costs that will be competitive with carbon-free alternatives—about $70 per megawatt-hour (MWh), and possibly as little as $50/MWh with modest reductions in capital cost, construction time, and operations and maintenance costs.

Regarding safety, advanced LWRs are estimated to have accident probabilities 10 to 100 times smaller than the current generation of LWRs. If these probabilistic risk assessments are correct, this would mean a probability of core damage of less than one per million reactor-years, and a probability of a large release of radioactivity (sufficient to produce one or more off-site deaths) of less than one per ten million reactor-years. In the nuclear growth scenario outlined above, there would be 0.3 to 3 percent risk of core damage at one of the more than 1000 reactors operating by 2050, and 0.03 to 0.3 percent risk of a large release. In my view, these are acceptable risks for both investors and the public, given the associated benefits of climate change mitigation.

The once-through fuel cycle will continue to be less costly than reprocessing and recycle for at least the next 50 years, and probably through the remainder of the century. All fuel cycles require a geologic repository for the disposal of either spent fuel or high-level reprocessing wastes. There is now no doubt that geologic disposal can be both safe and economical. Although repositories are being built in several countries, none have received spent fuel or high-level wastes from commercial nuclear reactors. The most pressing need, therefore, is centralized national or international dry storage for spent fuel. Spent fuel can be stored safely, securely, and inexpensively in such facilities for 50 to 100 years at low cost—less than one percent of the cost of nuclear-generated electricity. In 50 years, the future of nuclear energy will be much clearer, and we will know whether the stored spent fuel should be reprocessed or placed in a repository. In the meantime, the possibility of international geologic disposal should be explored, to avoid the need for every state with nuclear power to develop its own repository.

Advanced LWRs operating on a once-through fuel cycle are relatively easy to safeguard and are highly resistant to diversion and theft. The spent fuel assemblies are large and can be monitored easily using video cameras; the diversion of an assembly would be easy to detect. Although the spent fuel contains plutonium, very high levels of heat and radiation protect against theft for at least 150 years.

The main proliferation issue lies at the front end of the fuel cycle: the uranium enrichment required to produce the low-enriched uranium (LEU) fuel. In the MIT scenario, 16 countries would have at least 10 GW_e of nuclear capacity, each requiring at least 1.5 million separative work units (SWU) per year of enrichment capacity. For comparison, only 5000 SWU are needed to produce enough high-enriched uranium (HEU) for one nuclear weapon. Enrichment plant safeguards could be improved to ensure timely detection of a significant diversion of material, or of *any* production of HEU.

The problem is that any country capable of building a large commercial LEU enrichment facility could build a much smaller facility for the production of HEU. Small clandestine centrifuge enrichment facilities would be extremely difficult to detect. For this reason, it is essential to limit the spread of enrichment technology and commercial enrichment facilities. This might be accomplished by providing guaranteed fuel supply to countries that forswear uranium enrichment (and spent-fuel reprocessing). Still more attractive would be an agreement by the fuel supplier state to take back the spent fuel and assume all associated waste disposal burdens.

Although I believe that advanced LWRs offer the best nuclear-powered prospect for significant reductions in carbon emission for the next 50 years, it is worthwhile to invest in research to develop alternatives. Two concepts that may have significant advantages over advanced LWRs are (1) gas-cooled graphite-moderated reactors, and (2) small, long-lifetime, sealed-core reactors. Several variants of the former have been developed in previous decades. This concept promises a much higher degree of safety than the LWR, perhaps eliminating the possibility of a large release of radioactivity (assuming that graphite fires can be excluded). Gas-cooled reactors also can operate a much higher temperatures, allowing higher thermal efficiencies and correspondingly lower cost of electricity.

The small sealed-core reactor concept—sometimes referred to as the “nuclear battery”—is far less developed. Several U.S. national laboratories, as well as groups in Russia and Japan, are developing lead-cooled fast reactors with generating capacities ranging from 20 to 200 MW_e, and core lifetimes from 15 to 30 years. The reactor would be delivered to a prepared site as a sealed unit, ready to be installed and brought on-line. At the end of the core life, the entire reactor would be returned to the manufacturer for replacement. This concept also promises a high degree of safety. The host country would require a lower degree of nuclear expertise and no fuel-cycle services, making the concept more suitable for smaller developing countries and potentially far more proliferation resistant. Although the small size and very-high-burnup fuel tend to make this concept more expensive than the LWR, substantial economies of scale might be found in the mass production of such units in factories—much like airplanes are mass produced.

Looking beyond 2050, if nuclear power continued to grow (e.g., to 4500 GW_e by 2100), the price of uranium would likely increase to the point that alternatives to thermal reactors operating on a once-through fuel cycle would become attractive. The most obvious alternative is the fast breeder reactor, which would breed plutonium from natural uranium. Another possibility is the molten-salt reactor operating with a thorium fuel cycle. Although it is prudent to begin research on lowering the costs and increasing the proliferation resistance of these alternatives, there is no need to press for early commercialization of either fast reactors or reprocessing and recycle.