Can We Solve the Energy Problem Without Nuclear Power?

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Can we solve the energy problem without nuclear? I'll come to my own views on this question shortly. But first I want to make a few comments about other people's views.

In recent months, some prominent and previously antinuclear environmentalists have been declaring their support for a larger nuclear role, citing the risks of climate change for their change of mind.

But many other environmentalists continue to oppose nuclear, and it is interesting to think about why.[1] In theory there are three possible explanations for this. One is that they don't think that climate change is a serious enough problem to reconsider their opposition. Another is that they do see climate change as a serious problem, but that they also believe that other technologies which in their view are preferable to nuclear, like solar and wind, are either already adequate to the need, or will soon become so -- so there's no contradiction in advocating for strong climate policies while continuing to oppose nuclear.

A third possibility is that they see climate change as a serious risk, but they see nuclear energy as a bigger risk. In this view the question of whether

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[1] In a recent comment to CNN on the nuclear issue, NRDC's Ralph Cavanagh said, "I have a pretty good idea of where the mainstream environmental groups are and have been. I've seen no movement." (http://www.cnn.com/2013/11/03/world/nuclear-energy-climate-change-scientists/).

other ways of addressing climate change will be effective is irrelevant, because the nuclear cure is worse than the disease.

We can safely rule out the first possibility. Most likely it's a combination of the second and the third. Exactly what that mix is is an interesting question, not least for those on the other side of the debate who think it's important to try to change more minds in the environmental community.

Certainly there are people who believe that we can't afford to have nuclear energy under any circumstances. But I suspect that the organizers of this session have the other group in mind – the people who are seriously worried about climate change but who would prefer not to have to rely on nuclear and think we'll be able to get by without it.

Roughly speaking, there are four counter arguments to this view – namely, that:

- the risks of climate change are bigger than they think;
- the required scale of an effective response to the problem is bigger than they think;
- the potential of non-nuclear low carbon sources isn't as big as they think; and
- nuclear isn't as bad as they think.

I've deployed all these arguments in the past, and I think that's why I've been invited here today. I don't think I've been invited to talk about what I consider to be an equally important argument -- which is that the U.S., as the world's richest and most innovative economy and second largest source of carbon emissions, should be leading a grand global innovation challenge encompassing the entire range of low-carbon options, and that one of our most urgent tasks is to build an energy innovation system that's much more effective at mobilizing America's innovation resources towards this goal than the one we have today. This is a different sort of argument. It's about the need to be as creative about the design of the institutions for innovation as we must be about the innovations themselves. And I would hope that people on both sides of the nuclear debate could come together in support of it.

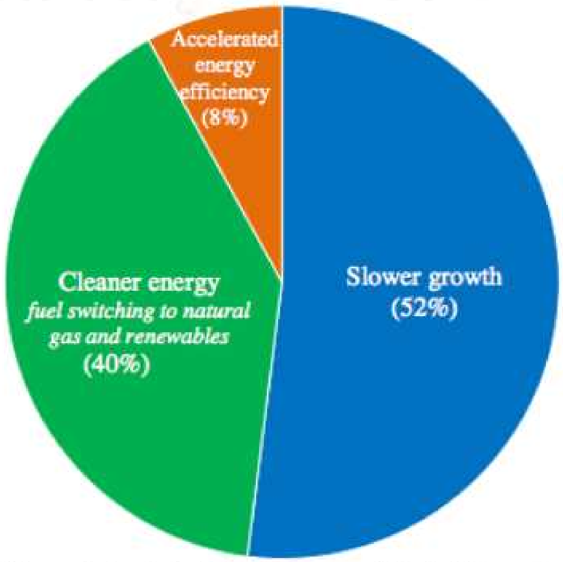
But to return to today's question, I have a few points to make.

First, the goal here isn't just to reduce C emissions. It's to achieve this while delivering energy services that are affordable, reliable, and secure, and whose local as well as global environmental impacts are minimized. And most important, it’s about reducing carbon emissions without undermining economic growth.

The energy problem would be easier if we didn’t also care about economic growth. U.S. carbon emissions have been falling recently, and this has brought relief as well as a measure of self-congratulation. But, as the latest Economic Report of the President points out (Fig.1), more than half of U.S. emission reductions since 2005 are the result of weak economic performance.[2] If the U.S. economy had continued to grow at the same rate after the year 2000 as it did during the 1990s, instead of at about half that rate, which is what actually happened, our carbon emissions would be 25% larger today. I don’t know of very many elected officials who would willingly forego an extra 3 trillion dollars of annual economic output for a 25% decline in carbon emissions.

Figure 1

Decomposition of U.S. CO_2 emissions reductions, 2005-12



Source: Bureau of Economic Analysis, National Income and Product Accounts; EIA (2013); CEA calculations.

2013 Economic Report of the President, p. 196

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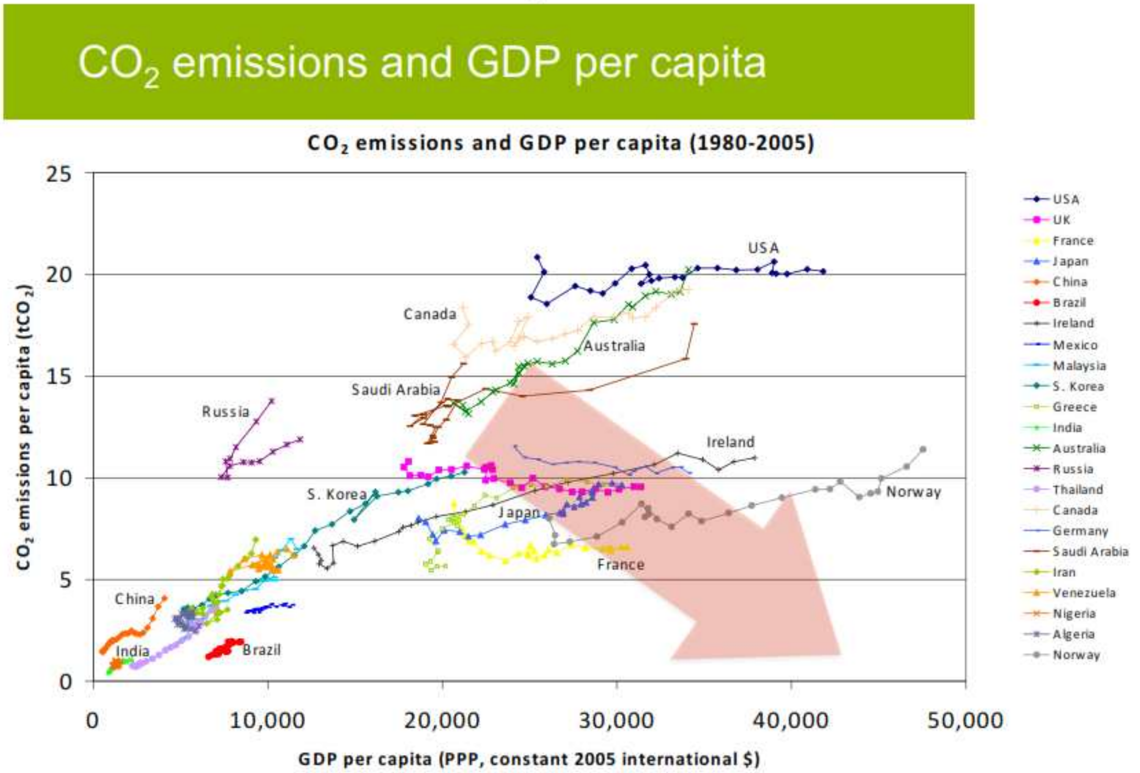
[2] Economic Report of the President, 2013, Chapter 6, p. 194-196 and Fig. 6-3, at http://www.whitehouse.gov/sites/default/files/docs/erp2013/ERP2013_Chapter_6.pdf

Here is a chart, borrowed from Steve Koonin, that makes a similar point at the global level (Fig. 2). It shows the historical correlation between per capita carbon emissions and per capita economic growth. (The graph for each country represents 25 years of annual output and annual emissions.) To address the climate change problem effectively, we must decouple growth from emissions. But we can't do this by running history backwards and going back down and to the left. We have to convert the general trend line in this chart – up and to the right – into an arrow going down and to the right. And we have to do this quickly.

Figure 2



Source: DOE EIA database (2008)
Russia data 1992-2005, Germany data 1991-2005

S. Koonin, "America's Changing Energy Future", August 2013

Here is where we are today: an annual rate of carbon emissions of 1.25 tons per person (or 4.6 tons of CO_2 per person), averaged over the world's population. (This average is below most of the lines on the chart because most of the world's population is in the lower left hand corner.)

Where we need to be depends on the climate mitigation goal. Here we can look at two illustrative scenarios from the IPCC's latest assessment, the first part of which was released last September.[3]

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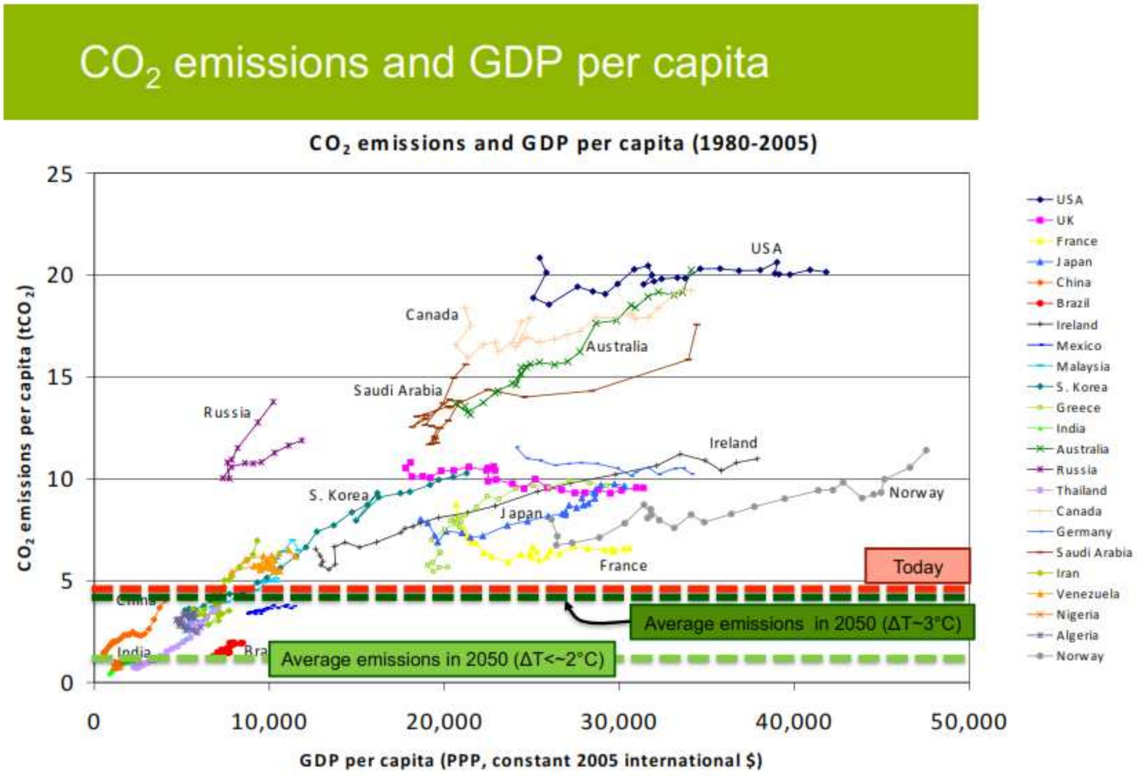
[3] IPCC Fifth Assessment Report (AR5), Report by Working Group I, "The Physical Science Basis", accepted 27 September 2013, available at http://www.ipcc.ch/report/ar5/wg1/#.Uv06ODkb2mA

One of these scenarios – the most stringent one analyzed – is associated with an 80% probability that the global surface average temperature increase will remain below 2°C at the end of the century. This is roughly equivalent to an equilibrium atmospheric CO_2 concentration of 450ppm, and it is aligned with the mitigation goal notionally adopted by many governments, including our own.

In the second scenario, there is an 80% chance that the end-of-century temperature increase will exceed 2°C, and a 50% chance that it will eventually exceed 3.1°C. This is roughly equivalent to a 550ppm equilibrium CO_2 concentration, and is well beyond what many climate scientists and others regard as a prudent limit.

Figure 3



Source: DOE EIA database (2008)
Russia data 1992-2005, Germany data 1991-2005

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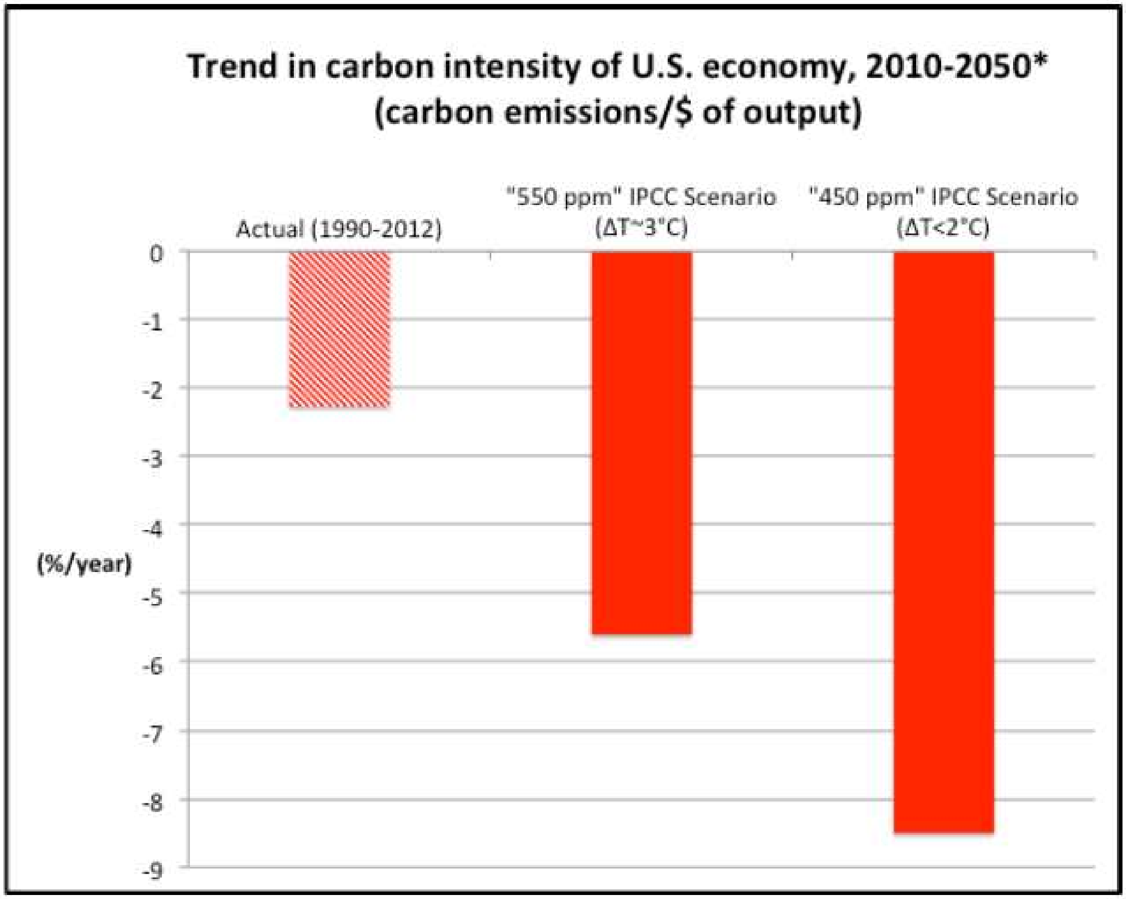
The average per capita emissions in the year 2050 that are associated with these two scenarios are shown in Figure 3.

Now, suppose we say that the emissions of every nation, rich or poor, should converge to that same global average per capita rate by 2050. This is a goal that many would see as only minimally equitable, and others – especially in poorer countries -- wouldn't view it as equitable at all, given that the rich countries have been responsible for most carbon emissions until now. But perhaps it might become the basis for some sort of global agreement. In the 2°C scenario it would require the U.S. to reduce its overall emissions by more than 90% by mid-century. Even the 3°C scenario would require a reduction of about 70%.

Obviously, this will be extremely difficult under any circumstances. How difficult will depend partly on what happens to our economy.

Suppose we say that we want a per-capita economic growth rate of 2% per year. (This would be well above the dismal 0.7%/year achieved during the first decade of this century, but it would be a bit below the average growth rate during the previous 30 years – which was not, incidentally, a particularly strong period in U.S. economic history from a growth perspective.) Given this growth rate, it's straightforward to calculate, for each of the two IPCC scenarios, how quickly the carbon intensity of the U.S. economy would have to decline between now and mid-century (Fig. 4).

Figure 4



*Assumes economic growth rate of 2%/yr per capita, 2010-2050

In both cases it will mean a major acceleration in the rate of decline of carbon intensity relative to trend. (Over the past couple of decades, the carbon intensity of the U.S. economy has been declining at a rate of about 2.3%/yr. Since 2000 this has accelerated a bit, to about 2.6%/year. But even for the less aggressive IPCC scenario the rate of decarbonization of our economy would have to increase to an average of 5.6%/year through the year 2050, and for the more aggressive 2°C scenario it would have to increase to 8.5%/year – an enormous jump relative to recent performance.)

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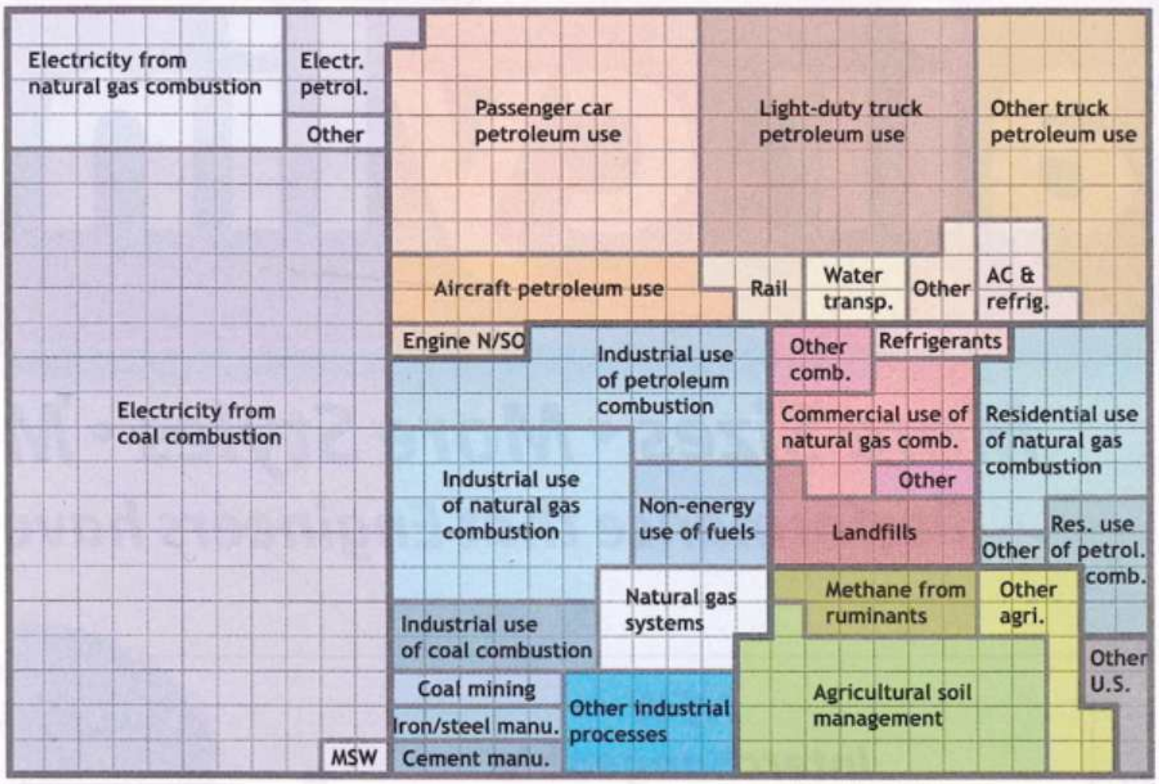
Charts like this are informative, but lines on a graph don't really convey how difficult this is going to be. We can gain a bit more insight from the well-known chart showing where in the economy our carbon emissions originate (Fig. 5). Each of the 726 small squares on this chart represents 10 million tons/year of carbon dioxide.[4]

Figure 5



▲ Derived from a 2007 U.S. EPA report, this chart breaks down the annual U.S. emissions of greenhouse gases by source. Each of the 726 squares represents the equivalent of 10 million tons of CO_2.

Mechanical Engineering Sept. 09

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[4] *Mechanical Engineering*, September 2009

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Even for the 3°C, "550ppm" scenario -- which, as I've noted, many would regard as an inadequate response – we'd have to eliminate 70% of these squares by 2050, while also meeting the energy needs not only of the current economy but also the equivalent of the roughly one more U.S.-sized economy that will be added between now and then, assuming we achieve the 2% per capita growth target.

It's also instructive to think about the physical scale of the task. For example, if all the coal we currently consume in the U.S. in a single year in our coal-fired power plants were loaded onto a single coal train, that train would be 83,000 miles long. And even to achieve the more modest 70% emission reduction target, essentially all of that coal would have to be replaced, or the carbon dioxide captured.

(By the way, if all that coal were replaced by natural gas, total U.S. emissions would decline by about 20% -- an important contribution, to be sure, but not even a third of what would be needed even in the less aggressive scenario.)

Can we do this without nuclear? The answer cannot be 'proved' in a mathematical sense. But it's a matter of basic common sense that when you have a very difficult task like this, the more options that are available, the more likely you are to succeed. And, if any option is taken off the table, the chances of failing will increase. That's especially because no two low-carbon options are alike. Solar, wind, geothermal, and nuclear each have their own strengths and weaknesses. Given the enormously varied nature of the energy system, this diversity is an asset. And the value of this diversity is all the greater because, in energy, there are always surprises. So, while it's an interesting academic exercise to think about whether a single option – e.g., wind or solar -- could do the trick, no serious strategy would advocate putting all our eggs in a single basket, especially given the magnitude of the stakes.

The advantages and disadvantages of nuclear energy have been much discussed, and I don't have time to review them here, except to mention two aspects that don't seem to me to be fully appreciated even now.

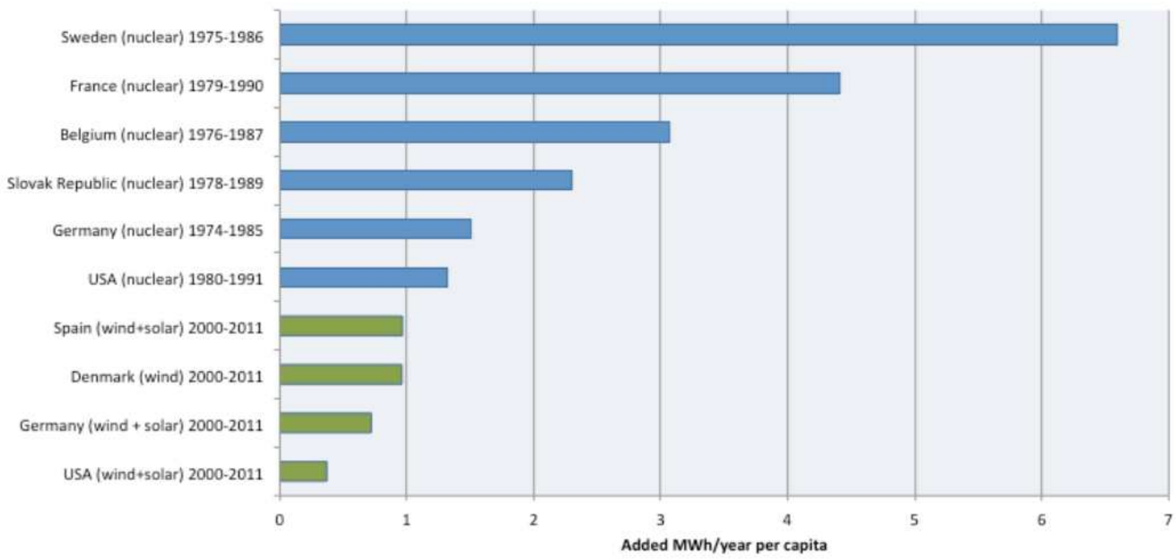
One is the extreme compactness of nuclear energy systems. For example, the same thought experiment that produced the 83,000-mile long coal train would yield a 1-mile long nuclear train – the train bearing all the nuclear fuel assemblies needed to power the nation's 100 nuclear power reactors for a year. (A train carrying all the spent fuel away from the 100 reactors would be about 2 miles long, because of the additional shielding and physical protection required.)

The second aspect is the ability of nuclear power programs to scale up quickly. The ability to scale up low-carbon energy sources rapidly is absolutely crucial if we're to have any chance of meeting the carbon reduction targets. There's a popular view that we can build out wind and solar very quickly. But, historically, it's nuclear energy that has scaled up the fastest. Referring back to the earlier chart (Fig. 2), although it's difficult to see, there is in fact only one example of sustained movement in the 'good' direction, i.e., down and to the right: France during the 1980s, when the rapid nuclear buildout reduced carbon emissions significantly even as the French economy was growing vigorously.

The next figure (Fig. 6) adds to this story. It shows that during the peak decades of nuclear installation in the 1970s and 80s, low-carbon kilowatt hours were being added in countries like Sweden, France and Belgium several times faster than have been added more recently in top-of-the-renewables-table countries like Denmark and Spain as a result of their aggressive deployment of solar and wind.

Figure 6

Scale-up of low-carbon electricity generation contributed by nuclear and renewables*



* For nuclear, the decade of most rapid scale-up; for solar and wind, the most recent decade.

And in Germany, which of course is now phasing out its nuclear plants, low-carbon kilowatt hours were added when those plants were being phased in twice as fast as has occurred over the past decade as a direct result of the heavy German investment in wind and solar.

And here in the U.S., nuclear expansion in the 1980s outpaced renewables growth in the most recent decade by almost 4 to 1.

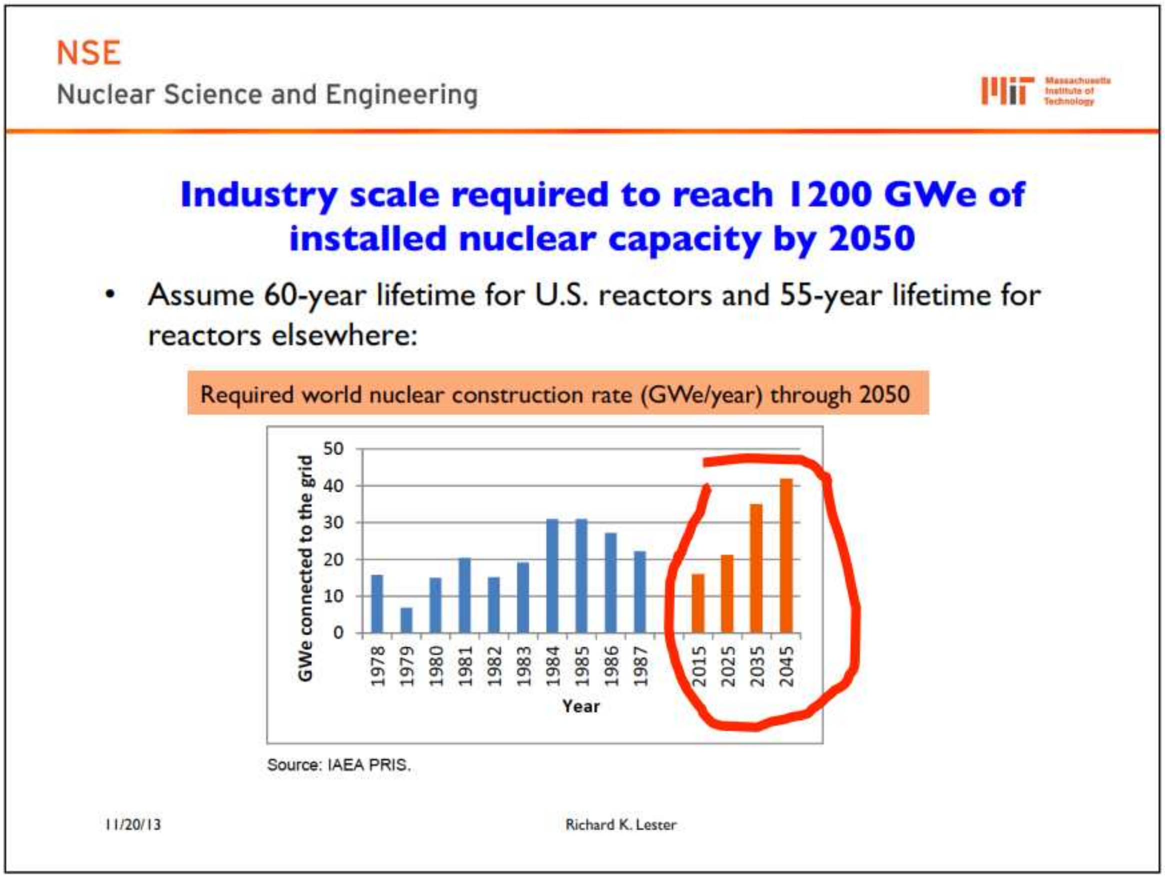
(In all these comparisons, the figures have been adjusted to correct for national population differences.)

Of course, this is history. And in the future the pace of solar and wind deployment may accelerate (although it's worth noting that the very aggressive subsidy policies that have been driving renewables growth in countries like Germany and Spain probably aren't sustainable and indeed may now have run their course.)

But the facts are that so far nothing else has come close to matching nuclear when it comes to being able to scale up low-carbon energy rapidly.

Now nuclear is obviously facing severe headwinds today. This isn't true everywhere; in some countries, most notably China, today's nuclear technologies are competitive with both fossil and non-fossil alternatives, and there are ambitious plans for nuclear expansion. But when you add up all these expansion plans, while also accounting for the expected retirement

Figure 7



NSE

Nuclear Science and Engineering

Industry scale required to reach 1200 GWe of installed nuclear capacity by 2050

- Assume 60-year lifetime for U.S. reactors and 55-year lifetime for reactors elsewhere:

Required world nuclear construction rate (GWe/year) through 2050

Source: IAEA PRIS.

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of much of the existing nuclear fleet as it reaches end of life, the nuclear role in carbon mitigation can be expected to grow only slowly in the coming decades.

If nuclear is to play a bigger role, much more will be needed – perhaps a two or three-fold expansion of current nuclear capacity over the next few decades. This will require a global rate of nuclear build comparable to what occurred during the previous peak period of nuclear installation in the 1980s (Fig. 7).

So this would not be entirely unprecedented. But, based on current evidence, there is a serious question as to whether current practices and technologies will suffice to get there – not just in China and a few other countries, but globally. Or, will an already safe technology have to be made demonstrably safer, as well as less expensive and more secure against the threats of nuclear proliferation and terrorism?

In other words, is there an innovation requirement here, and if so, what might it look like?

In any scenario, organizational and managerial innovations will be crucial -- most importantly:

- innovations in nuclear governance, to ensure broad adherence to the principles and standards of safe and secure nuclear operations, and to reassure the public that nuclear energy can be used safely; and

- innovations in nuclear education and training, to address the urgent need to replenish and strengthen the nuclear workforce as the wave of retirements accelerates.

But technological innovations will likely be necessary too. And I want to close by briefly suggesting some elements of a comprehensive nuclear innovation strategy.

One will involve placing more reliance on passive safety mechanisms in nuclear plant design. The new generation of light water reactors has moved in this direction, but more advanced designs go much further towards the goal of 'walkaway safety'. It doesn't seem far-fetched to speculate that such a goal will become a requirement for <u>all</u> nuclear power reactors 30 or 50 years from now.

Another key goal is to reduce nuclear cycle times, which have become almost pathologically long in the U.S. and elsewhere, and which are adding cost, reducing flexibility, and exposing investors to greater risk. Progress here will likely require further regulatory reform. But there are also opportunities for technically-driven cycle time reductions. For example,

dramatic advances in modeling and simulation of neutronics, thermal hydraulics, and fuel behavior are enabling much faster and more efficient approaches to reactor design. New construction methods promise to shorten project lead-times, as do small, modular reactor designs, whose hoped-for benefits also include reductions in capital-at-risk, faster learning cycles, and better matching with small power grids.

Related to this, power grids and markets will undergo technical and institutional changes over the next couple of decades that may well be more far-reaching than any in the previous 100 years, and nuclear systems will need to evolve to compete successfully in these new conditions.

Specific developments here are the continued penetration of distributed, non-dispatchable generation technologies, the emergence of local microgrid operating systems, and new roles for intelligent grid technologies, web-connected electrical devices, and large-scale data analytics.

The challenge here is to work out how to meet rapidly varying electrical loads affordably and reliably with low-carbon power systems consisting mainly of dispatchable nuclear and non-dispatchable renewables. In these new conditions, conventional base-load nuclear power technologies will need to be augmented by new, more flexible alternatives. Hybrid nuclear systems, capable of switching between selling electricity directly and producing storable fluid fuels depending on price conditions are one alternative. Another is the nuclear air-Brayton combined cycle system under development at MIT, in which a constant high-temperature nuclear heat source – in this case a fluoride salt-cooled reactor -- is integrated with fast-response natural gas-fired auxiliary heating to meet peak demand, with the additional capability to produce high-temperature process heat when electricity prices are low.

Perhaps we'll also see other possibilities, such as lifetime fueling of reactor cores – the so-called nuclear battery concept -- and integrated power plant-waste disposal systems, with spent fuel never leaving the power plant site and disposed of directly in modular deep boreholes several miles below the earth's surface in the stable, dry bedrock that is abundant in most countries.

Also, advances in computational power and new tools for materials synthesis may one day make it possible to design and build radiation-resistant materials from the ground up, atom by atom, and to create ultra- secure nuclear waste materials with lifetimes of tens of thousands of years.

All of these developments can be imagined today. Indeed, all of them -- and others too -- are currently being pursued vigorously in the Nuclear Science and Engineering Department at MIT. But much greater advances surely lie over the horizon. No one knows which technologies will prevail ultimately. The most that can be said – and I have said this before -- is that the nuclear power plants of the late 21st century are likely to have about as much resemblance to today's workhorse light water reactors as a modern automobile has to a 1914 Model T Ford.

The good news is that there is more new thinking and ferment in the nuclear field than has been seen in a long time. And the thought I'd like to leave with you is that era of nuclear innovation may actually just be getting started.

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Richard Lester is the Japan Steel Industry Professor and head of the Department of Nuclear Science and Engineering (NSE) at the Massachusetts Institute of Technology, where he is also the founding director and faculty chair of the Industrial Performance Center (IPC). His research focuses on the study of innovation systems, with an emphasis on the energy and manufacturing sectors. He is also active in research and teaching on the management and control of nuclear technology. As head of NSE, Professor Lester works to advance the Department's role at the forefront of research and education in energy and non-energy applications of nuclear science and technology. As director of the IPC, he has led several major studies of national and regional productivity, competitiveness and innovation performance commissioned by governments and industrial groups around the world. Professor Lester is the author or co-author of eight books, including *Innovation—The Missing Dimension* (with Michael Piore), *Making Technology Work: Applications in Energy and the Environment* (with John Deutch), *The Productive Edge: A New Strategy for Economic Growth,* and *Made in America: Regaining the Productive Edge* (with Michael Dertouzos and Robert Solow.) His latest book, *Unlocking Energy Innovation: How America can Build a Low-Cost, Low-Carbon Energy System* (with David Hart) outlines a strategy for mobilizing America's innovation resources in the service of a decades-long transition to a more efficient, low-carbon global energy system.

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