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Anticipating climate mitigation: The role of small modular nuclear reactors (SMRs)

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Abstract

Global warming is likely to force assertive redirection of global energy markets in order to achieve a prudent standard of mitigation; the resulting process of energy transformation will fundamentally alter prevailing policies and institutional relationships. Efficiency gains and renewable technologies—wind, solar, and biomass—will presumably make substantial contributions, as will carbon sequestration to some extent. But at the moment it seems quite apparent that global mitigation cannot be achieved without a very substantial expansion of nuclear power generation. While current light water reactor technology will likely play a role, this paper argues that smaller modular reactors (SMRs) of innovative design, with innovative institutional arrangements, could contribute to meeting energy demands in a more safe and secure manner. Though many SMR designs are currently being developed, it is doubtful that any of them will be brought to the point of serial production by their current developers under currently projected market conditions. Completed prototype development would almost certainly have to be a public sector initiative undertaken in support of eventual mitigation. This paper explores the potential of developing international structures whereby multiple states and entities could develop several SMR prototypes and serial manufacturing hubs. The International Thermonuclear Experimental Reactor development process could prove to be a useful analogue to the arrangements necessary to support such large-scale SMR development and deployment.

What we do know

There are good, even compelling reasons to expect: first, that global warming will eventually force assertive redirection of global energy markets in order to achieve a prudent standard of mitigation (e.g., stabilization at less than 500 ppm of CO2 equivalent); and second, that the resulting process of energy transformation will fundamentally alter prevailing policies and institutional relationships.

Admittedly those expectations are well outside the bounds of actionable consensus at the moment, but they are driven by circumstances that are as reliably known as anything ever is. Most notably, we know that the thermal impulse currently being imparted to the earth's atmosphere by human activity is unprecedentedly large and that the process of restoring equilibrium will assuredly have commensurately large consequences. That is basic physics, and it is beyond question. The timing, character, location and exact magnitude of those consequences are all massively uncertain, but the inevitable appearance of very large ecological adjustments is not.

Put in common sense terms, there is a major storm assuredly coming, and it is powerful enough to alter the landscape—that is, the operating conditions, the prevailing attitudes, the institutional arrangements and the organizing policies of all human societies. For those who like adventure and are able to contemplate radical change, it is a gripping time to be alive.

In terms of basic numbers, according to the IPCC fifth assessment report (AR5), total primary energy production is currently running just over 500 EJ/year, 85 percent of which derives from carbon emitting sources. It is prudent to assume that primary energy production will have to double by 2050 in order to support raising standards of living for a total human population of 8 to 10 billion people. As that doubling occurs, the proportion of primary energy production produced by sources that do not emit carbon will have to increase to 80 percent to achieve the mitigation standard.[1] AR5 projects that total demand will fall in the 950-1150 EJ/y range by 2050 in baseline scenarios but only 800 EJ/y in their 480-530 ppm mitigation scenarios, 60 percent of which would have to come from carbon-free sources. Efficiency gains and renewable technologies—wind, solar, and biomass—will presumably make substantial contributions, as will carbon sequestration to some extent. But at the moment it seems quite apparent that global mitigation cannot be achieved without a very substantial expansion of nuclear power generation.

For the purpose of visualizing the potential implications, one can surmise that the current 370 GWe installed nuclear generating capacity might have to increase up to 1900 GWe to meet the mitigation standard. Even a doubling of the current inventory of light water reactors—354 of the 434 operating reactors—would provide less than half of that requirement, and it is very doubtful a doubling of reactors dependent on emergency cooling could be managed at adequate standards of safety. The impending storm presents some very big problems.

[1] IPCC WGIII AR5, chapter 7 p 10 ff.

AR5 notes without elaboration that small modular reactors (SMR's) are a potentially effective response to the power generation problem. That comment implicitly alludes to a radically different conception of how the nuclear power industry would work. The basic idea is that smaller reactors of standard design would be produced at manufacturing facilities rather than assembled on site. Cooling would be accomplished by natural circulation thereby precluding any possibility of a nuclear explosion or a core meltdown. The reactors would be transported to the service site by rail or truck for those in the 35 to 50 MWe range or by barge for those up to 300 MWe. In the more advanced version of the concept a fuel load sufficient for 30 or more years of operation would be sealed in the reactor at the time of manufacture, and the reactor would be returned to the manufacturing site for disposition of its fuel at the end of its service life. In a yet more advanced version of the concept, operating reactors would be owned by the manufacturer throughout their lifetimes and would be operated remotely from the manufacturing site. Users would purchase power generation services not the reactors themselves.

If nuclear power generation is to provide what would appear to be a minimum essential contribution to global mitigation by midcentury, then something like 170 EJ in primary energy would have to come from that source in 2050 providing some 15,000 TWh/y of electricity generation and requiring about 1900 GW of installed capacity. That would be about one-third of the notional 500 EJ requirement. Those levels could be reached if nuclear power generation increases by an average of 5 percent per year from 2012 to 2050, but sustained incremental growth from the current base is neither a feasible nor a desirable path from here to there. Scaling up to the levels required on the basis of currently available reactor designs and those currently projected under existing market conditions would pose operational safety and proliferation risks that are unlikely to be sustainable over the time required. Advanced SMR designs that would minimize those risks will not be available for at least a decade and not even then without policy initiatives that have not yet occurred. Moreover, the design requirements are not merely or even primarily technical in character. If we are to produce 170 EJ of primary energy by nuclear technology by midcentury at acceptable levels of safety, we will need more advanced coordination among national governments, higher standards of nuclear materials accounting, a global waste disposal arrangement and more fluid and more reliable provisions for equitable sharing of technical information.

All that will, of course, require a dramatic change in prevailing attitudes. One of the main features of the global warming process is that it pits relentless circumstance against entrenched sentiment. One of the main questions posed is whether natural selection in this situation favors competition or collaboration. Given the magnitude and scope of the transformation required, it is prudent to bet on collaboration but important to recognize that over the next several decades, as environmental pressure accumulates and intensifies, we are destined to learn quite a bit about that.

Incremental evolution

Anyone who hikes any distance in rough mountainous terrain quickly learns to balance attention between immediate steps and the intended destination. Regardless of how scenic the setting might be, as a practical matter, most of the time a hiker is obliged to watch the immediate placement of his or her foot. But unless the horizon is occasionally scanned and the still distant path visualized, the hiker in question is likely to become lost in the wilderness. In general, one moves in incremental steps but needs to keep the destination in mind, especially when there is serious question as to whether immediately available paths actually go there.

So, with a mid-century mitigation standard visualized and with recognition that current roadways do not go there, the question is how to redirect without falling off a cliff or some equivalent misadventure. There is an evident technical response to that question that provides an obvious, specifiable start. Whatever else is done, prototype development of advanced SMR designs is an obvious priority, even though it is not alone a complete answer. Beyond that, redirection involves disputable, even highly disputable imagination with all the associated doubts and uncertainties, but nonetheless if collaboration proves to be essential then there will have to be institutional arrangements for accomplishing it.

Prototype development. There are at least 26 nuclear reactor designs that fit the SMR concept to varying degrees.[2] Many of them have passively safe cooling features important for reducing operating risk, but only one of them has the sealed fuel feature with long term (>30 year) service life that is especially important for minimizing proliferation risk. The different designs are currently under varying degrees of development as well, but it is doubtful that any of them will be brought to the point of serial production by their current developers under currently projected market conditions. Their ability to compete with low-cost generation technologies—natural gas in particular—is too much of a question to sustain commercial financing, as is their ability to meet licensing requirements established for current reactor designs. Moreover, in order to realize the advantages of serial manufacturing, developers would need a large number of initial orders to set up a manufacturing facility. Those three impediments are likely to prevent commercial vendors from completing prototype development of most and probably all of the current designs.

As a result of these conditions, completed prototype development would almost certainly have to be a public sector initiative undertaken in support of eventual mitigation. Some set of governments would first have to select candidates for prototype development from among the contending options and then to bring the selected designs to the point that serial production could begin. Along the way a number of specific material and design issues would have to be solved and critical operating characteristics would have to be determined, in particular potential failure modes and the initial cost of power generation. With regard to failure modes, it will be important to establish that neither an explosion nor a core meltdown could physically occur.

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[2] Ahmed Y. Abdulla, *Exploring the Deployment Potential of Small Modular Reactors,* PhD dissertation, Carnegie Mellon University, 2014

The financial requirements of doing that much appear to be quite modest. A $5 billion program conducted over a decade could reasonably expect to bring two large (100-300 MW) and two small (35-50 MW) designs to the point that serial manufacture could begin.

At that point the initial cost of generating power with the developed prototypes could be estimated with reasonable confidence, but the reduction that might be achieved by learning economies associated with serial manufacture would remain to be determined. Since ultimate competitiveness would depend on that effect, there is reason to believe that reactor production would have to depend on public financing well beyond the initial manufacturing phase. Moreover, the security and liability burdens imposed by the extreme destructive potential of nuclear technology might plausibly keep reactor production and associated fuel cycle services indefinitely dependent on public sector financial support.

If 170 EJ/y of primary energy is to be provided by nuclear power generation in 2050 and if 50 EJ/y is about the reasonable limit that might be provided by evolved variants of current LWR designs – roughly double the current amount – then the mitigation aspiration would have to be that by 2050 operational SMRs would provide 120 EJ/y of primary energy, generating 10,668 TWh/y. Notionally that implies some 3,200 units averaging 250 MWe output and 7,200 units averaging 50 MWe output for a total of 10,400 power generating units. If they were produced over a 30-year time span with a 30-year service life, that implies a production rate of about 350 units/year to be sustained indefinitely. It is, of course, unlikely to work out that neatly or decisively but those numbers give a rough idea of what mitigation would involve.

Serial production. The point of developing alternative reactor designs is initially to hedge against intractable design problems not foreseen at the outset but eventually to assure competition among the ultimate manufacturers. It seems evident, however, that competition would have to be structured differently than it currently is. In a world driven by threatening circumstance into global energy transformation, the indispensable discipline of competition will have to be balanced by measures of mutual reassurance. No commercial vendor and no national government will be trusted with exclusive control over vital technology or energy generating services in a situation in which deeply entrenched interests in traditional energy services are being uprooted. Documented compliance with global standards and equitable access to vital services will qualify traditional commercial and national proprietary claims. It will have to be a different world in that important sense, featuring carefully specified and reliably managed transparency arrangements that have no immediate precedent.

Among the many implications, one can reasonably surmise that both prototype development and serial production will have to be managed by one or more globally representative consortia open to qualified participation. Within the consortium all technology and all operating details would be equitably shared. What counts as globally representative would undoubtedly be a matter of spirited discussion and evolving judgment. It would certainly be impractical to include all UN members and probably even impractical to include all qualified aspirants. Membership would presumably be limited by imposing investment requirements, but there would have to be national diversity criteria as well. To be considered globally representative, technically well-informed, and financially sound, the consortia would probably need to include the US, the EU, Russia, China and India as well as Japan, South Korea, Brazil ,South Africa and at least one representative from the Middle East. But whether that combination would be considered either necessary or sufficient needs to be debated and ultimately resolved.

In judging how many competitive manufacturers a global market of 350 reactor units per year could sustain, experience with the production of wide-body aircraft is available as a crude analogy. Two manufactures have emerged in that market producing on the order of 80 planes per year between them. The technical demands of producing SMRs are not likely to be greater and probably would be less than producing highly quality aircraft. Operating at 40 units per year there would have to be 9 SMR manufacturing sites worldwide. If each site could produce 60 units per year, 6 sites would cover the notional market demand, and that is a convenient number for working out geographic distribution. There is a strong presumption that China and India with 40 percent of the world population between them would each host one of the sites. If the EU, Russia and the US all host a site, then countries in the Southern hemisphere could aspire to two sites at a minimum and could consider up to four.

A coherent plan for specific site selection would feature highly quality security protection against armed assault, clandestine penetration and cyber intrusion. Probably that means isolated locations with dedicated power supply that nonetheless provide ready access to sea, road and railway transportation. In addition to reactor assembly lines, the sites would include uranium enrichment, fuel fabrication, and other services necessary to provide fuel for initial fabrication and to prepare depleted fuel for removal to a permanent depository at the end of the reactor’s service life. Under an advance arrangement, with each manufacturer operating the reactors it produces, the control facilities would be located at the site as well.

In the institutional design of the consortium arrangement there is a central question as to whether there would be a single consortium overseeing all of the competing manufacturing sites or separate consortia operating each of the sites. In order to assure the discipline of competition among the sites, each would have to be vested with executive authority, but that would have to be qualified by common regulatory rules and reporting requirements. The vital importance of the product and the inherent dangers in producing it makes nuclear power generation a public utility not merely a private enterprise designed to make money.

Material accounting. Since each significant quantity of a nuclear explosive isotope—25kg for highly enriched uranium 235 and 8 kg for plutonium—is capable of putting up to one million people at risk, it would certainly be desirable and is in principle technically feasible to keep track of that material with at least enough accuracy to assure responsible use. Institutionally, however, the world as a whole is very far from being able to do that. Nuclear material production has occurred under national control managed by separate national accounting systems, none of which measured their historic isotope production with that degree of accuracy. Nor do the separate national systems inform each other about their level of isotope production to anything like that level of accuracy. At the moment, global accounting of nuclear explosive isotope production has uncertainties ranging in the thousands, even tens of thousands of significant quantities – that is, weapon equivalents.

Given this historical legacy, it is doubtful that accuracy to the level of a significant quantity could ever be achieved, but it certainly can be very substantially and very meaningfully improved. And the formation of consortia for SMR production would provide both the incentive and the opportunity for doing so by establishing a common nuclear material accounting system that encompasses all of their nuclear material holdings. Even if that system covered only the consortium producers at the outset, it would provide the institutional basis for a comprehensive system including national as well as consortium inventories. By applying advanced sensing and information processing technology, such a system could enable a much higher standard of nuclear material inventory control and could become progressively more accurate and more reliable over time.

A comprehensive and progressively improving accounting system is certainly important and arguably vital for preserving the nonproliferation regime. As is often noted, the Non-proliferation treaty (NPT) established a discriminatory regime allowing five states to possess nuclear weapons and prohibiting all other signatories from doing so. But, as is less frequently mentioned, Article VI of the treaty also commits all signatories to the ultimate elimination of nuclear weapons thereby subordinating initial discrimination to an ultimately equitable standard. Since it is evident as a practical matter that any close approach to elimination would require more accurate accounting than currently prevails, the development of a more advanced accounting system is an essential requirement for any serious effort to implement Article VI of the treaty. There is as yet no official effort to develop such a system, but arguably that would be the single most telling test of good faith.

Although the issue of accounting is not currently prominent, it has potential to become so in response to any serious incident in which custody of nuclear explosive isotopes eludes responsible national control. There have been many minor incidents of that sort, but none as yet prominent enough to command sustained scrutiny. It is essentially impossible to determine the objective probability of such an event, but if one occurred, current accounting arrangements are likely to be subjected to withering criticism and more advanced arrangements would command attention.

Alternatively the idea of consortium control over fuel cycle services with embedded accounting arrangements might well acquire immediate prominence in the context of the ongoing dispute over Iran's nuclear materials production activities. The United States accuses Iran of preparing a nuclear weapons program in violation of its NPT obligations. Iran denies any intention to acquire a nuclear weapon but insists on its right to enrich uranium and to produce plutonium under the provisions of the NPT. In seeking a consensual outcome, the United States has been attempting to impose restrictions on Iran's enrichment capacity thereby abridging or at any rate restricting the right it proclaims. Iran is resisting any such restriction but appears open to a limitation on its accumulated nuclear material such that the potential for weapons production would remain perpetually beyond a reasonable time horizon. A compromise agreement might involve construction of a reactor fuel fabrication facility in Iran to be jointly operated with a collaborating partner with the understanding that consortium arrangements would eventually become the dominant arrangement for access to fuel cycle services for all countries From Iran's point of view that would remove the element of discrimination, would establish its rights, would assure equitable access to economically efficient fuel cycle services, and would give it access to state of the art technology it is unlikely to be able to match on its own anytime soon. From the U.S. point of view that would impose a reliable time constraint on any Iranian attempt to acquire nuclear weapons, would assure timely detection of any such attempt, and would legitimize coercive measures in response.

How might it happen?

If incremental evolution is to occur in anticipation of eventual mitigation, there will have to be some immediate initiative to begin the process of consortium formation and reactor prototype development. That will not spontaneously occur under current and reasonably projected market conditions, and it cannot occur as the exclusive initiative of any national government. It is nonetheless plausibly realistic to imagine that such an initiative might emerge from a G20 summit meeting in which the participants were eager to signal serious concern for global warming mitigation while remaining unwilling to impose a common price on carbon emissions. By pooling their resources, the G20 members could provide a $5 billion development fund with another $5 billion contingency supplement without creating a burdensome budget allocation problem for any one of them. That much is not beyond the immediate limits of practical politics.

There is partial precedent for such an initiative in the International Thermonuclear Experimental Reactor project commonly known as ITER, a consortium project to develop and operate a fusion reactor. The original idea was advanced at a U.S.-Soviet summit meeting in 1985, but it evolved into an EU-hosted project with the participation of China, India, Japan, Russia, South Korea, and the United States that was formally initiated in 2007. As host, the EU is to bear 45 percent of the development and operating costs with the six other partners providing equal 9 percent shares. The original plan envisaged a 30-year project—10 years for construction of the reactor and 20 years of operation—at an estimated cost of €5billion. That estimate has subsequently grown to €16billion. It was the cost burden and questionable practicality of the project that inspired the consortium arrangement. ITER is designed to produce 500 MW output but only for up to 1,000 seconds.

An SMR development consortium would be far more practical, in that it would produce reactor designs that are technically much less demanding and could actually be used for base-load power generation. Like any development project it would be susceptible to cost increases beyond the original estimates but nothing like ITER has been. ITER remains in the realm of basic research rather than prototype development. But an SMR consortium would have to be more integrally organized as well. ITER assigns separate responsibility for developing specific reactor components to each of the national partners. An SMR consortium would have to involve the participating partners in all aspects of the design and manufacture of the resulting reactor prototypes. The skill of the project managers would be a critical determining ingredient, but there are people in all of the candidate participating countries who could do it. If the G20 could manage not only to finance a development project but to mandate an integrated organizational design and to select a competent team, there is good prospect that incremental development could be set on a transformative path. That would not relieve the burden of ultimately setting a global carbon price, but it would provide the basis for response when and if that occurs. It would provide meaningful incentive as well.

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Returning to the hiker metaphor, response to global warming will surely occur in incremental steps, but in terrain as uncharted as this situation is it is quite import to visualize the ultimate outcome in undertaking incremental measures. We are not likely to achieve mitigation unless we keep the evident requirements immediately in mind, daunting as they do appear to be.

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