



HARVARD Kennedy School
BELFER CENTER
FOR SCIENCE AND INTERNATIONAL AFFAIRS

Nonproliferation, nuclear security, and the U.S. role in nuclear energy markets

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belfercenter.org/managingtheatom

The past: nonproliferation and U.S. nuclear energy market leadership

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- ❑ In the past, the United States has repeatedly used its market leadership in nuclear energy to achieve nonproliferation objectives
 - Convince states to join NPT (or equivalent), accept full-scope safeguards, implement export controls
 - Restrain the spread of enrichment and reprocessing technology
- ❑ This has been only one element of a broader exertion of U.S. power for nonproliferation – often not the most important
 - U.S. has imposed sanctions, threatened military force, threatened to abandon allies, applied diplomatic pressure...
 - But market leadership one important contributor to larger effort
 - U.S. supply contributed to U.S. nuclear security leadership – but much of that leadership came from other sources

Nonproliferation and U.S. market leadership: some examples

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- ❑ China:
 - In 1980s, China wanted U.S. nuclear cooperation – U.S. was biggest supplier – but also wanted broader U.S. relationship
 - Under U.S. pressure, China joined NPT, NSG
 - In 1990s, Clinton administration used possibility of Congressional disapproval of 123 to pressure China to implement export controls
- ❑ S. Korea:
 - U.S. has used nuclear cooperation to restrain enrichment and reprocessing
 - But U.S. threats of abandonment (in response to secret reprocessing-based nuclear weapons efforts in 1970s and 1980s) were much more important
- ❑ Several countries:
 - Desire for U.S. nuclear cooperation contributed to decision to join NPT, accept full-scope safeguards

The questions: nonproliferation, nuclear security, and U.S. market leadership

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- ❑ U.S. will not have similar market leadership in the future – certainly in the near term
- ❑ Question 1:
 - How important will this change in the U.S. role in the nuclear market be to nonproliferation and nuclear security outcomes?
- ❑ Question 2:
 - How can the United States best achieve its nonproliferation and nuclear security objectives without a leading role as a supplier of nuclear reactors?
- ❑ Question 3:
 - What actions and investments are justified to help regain U.S. nuclear market leadership, and how effective might they be, in the near, medium, and long terms?

A radically changed U.S. market position

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- ❑ The U.S. market position has changed dramatically:
 - Previously: U.S. the dominant supplier to the “free” world – Soviet Union largely restricted to sales to its clients
 - Today:
 - Competition from Russian, French, Korean, Chinese suppliers (India likely soon to come) – often offering state-supported financing, spent-fuel takeback (Russia), fewer nonproliferation constraints
 - U.S. nuclear reactor vendors owned by Japanese firms, reactor business of both in serious trouble (esp. with Westinghouse bankruptcy) – few additional reactor sales likely in next decade
 - No new reactor designs likely to actually be built commercially before 2030 (long R&D, regulatory, demonstration timelines)
 - U.S. does not provide enrichment or reprocessing services (except URENCO-owned facility in New Mexico)
 - But U.S. has very important role in other nuclear services – and Korean, some Chinese reactors include U.S.-origin technology

Question 1: How important will the changed U.S. market position be?

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- ❑ Certainly constrains U.S. nuclear-energy leverage:
 - If the United States tries to insist on particular nonproliferation controls, recipients can turn to other suppliers who don't
 - That would further reduce U.S. nonproliferation influence
 - Hence, major new control initiatives (e.g., insisting on “gold standard” agreements banning enrichment and reprocessing) not likely to be feasible
 - Except in cases where supplier coalition can be formed (e.g., NSG agreement on standards for E&R transfers, Carnegie Endowment-led suppliers Code of Conduct)
- ❑ But U.S. retains important influence, for now:
 - Recognized as nuclear energy, nonproliferation, nuclear security leader – countries want U.S. 123 agreements
 - Key officials, experts in many countries trained in U.S.
 - U.S. regulation seen as “good housekeeping” seal of approval

Question 1: How important will the changed U.S. market position be? (cont.)

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- ❑ If U.S. industry continues on current trajectory, U.S. influence may fade further
 - Countries tend to rely heavily on training, advice, regulatory approaches from the country that provided their reactors
 - Selling a large LWR creates a decades-long relationship with many elements – including nonproliferation influence
 - In the absence (mostly) of reactor exports and further new reactor construction in the United States, U.S. industry's expertise, reputation, will likely decline over time
- ❑ BUT:
 - U.S. will retain a large nuclear complex, major expertise
 - U.S. will remain a leading world power
 - U.S. will retain a central role in the IAEA, other international for a
 - In recent years, U.S. leadership on nuclear security mostly from sources other than being the supplier of the items to be secured

Many of the most achievable U.S. objectives have already been reached

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- ❑ NPT and full-scope safeguards:
 - Nearly all countries except ones with nuclear weapons (North Korea, India, Pakistan, Israel) are already parties to the NPT, have accepted full-scope safeguards
 - U.S.-driven NSG "exception" for India from full-scope safeguards makes it less likely nuclear cooperation could be used in this way in the future
- ❑ Restraining enrichment and reprocessing:
 - NSG countries have already effectively stopped officially transferring enrichment and reprocessing technology to states that do not already operate such facilities
 - Particularly after accepting reprocessing outside the NPT (India deal) and enrichment in Iran (JCPOA), U.S. pressure on advanced nuclear states (e.g., South Korea) likely less effective in the future
 - Few states likely to be willing to sign "gold standard" agreement signing away "right" to enrichment and reprocessing

Question 2: How to pursue U.S. objectives without a leading market position?

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- ❑ U.S. should take maximum advantage of its continuing strengths
 - World-leading safety and security expertise, regulation
 - Revitalize U.S. nuclear security programs
 - Launch a global nuclear reactor safety and security initiative
 - Expand funding for NRC international cooperation
 - World-leading nuclear energy training capacity
 - Expand funding for lab- and university-based international training programs, integrate with promotion of sales, services
 - Leading role in IAEA, other international fora
 - Continue, strengthen U.S. support, provision of expertise and ideas to, IAEA, NSG, etc.
 - Work to build supplier consensus on key issues
 - Build training, regulatory, services supply relationships with newcomer states

Major obstacles to regaining U.S. nuclear energy market position

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- ❑ Competition is stiff
 - Russian, French, Chinese competitors state-supported
 - Can offer terms, integrated national approach not plausibly available to U.S. firms
 - Even Korean, Japanese firms more integrated with governments
 - Other countries will also be pursuing advanced reactors, likely willing to invest more in R&D
- ❑ Multi-billion-dollar U.S. government investments unlikely
 - Government-sponsored demo program for advanced reactors as envisioned in SEAB report seems unlikely to get executive, Congressional support at scale and over time required
 - Major subsidies and other supports for exports unlikely
- ❑ Major obstacles to purely private success
 - Huge capital costs, regulatory hurdles create immense barriers to entry – utility customers extremely conservative

Question 3: What actions are justified to regain some portion of the U.S. position?

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- ❑ U.S. should take integrated, “Team USA” approach
 - Bundle reactor sales, services, training and education, regulatory support...
 - Support from all agencies – DOE, State, Commerce, NRC (to the extent independence permits)
- ❑ U.S. should reduce the barriers to advanced reactors as much as plausible given cost, political constraints
 - Streamlined regulatory approaches allowing “test as you go”
 - Government-supported R&D and testing infrastructure
 - R&D support for innovative ideas
 - Focused approach to international collaboration (especially with countries more willing to invest)
 - Purchase power: possible financing (e.g., long-term purchase agreements) for small number of small reactors to power government sites

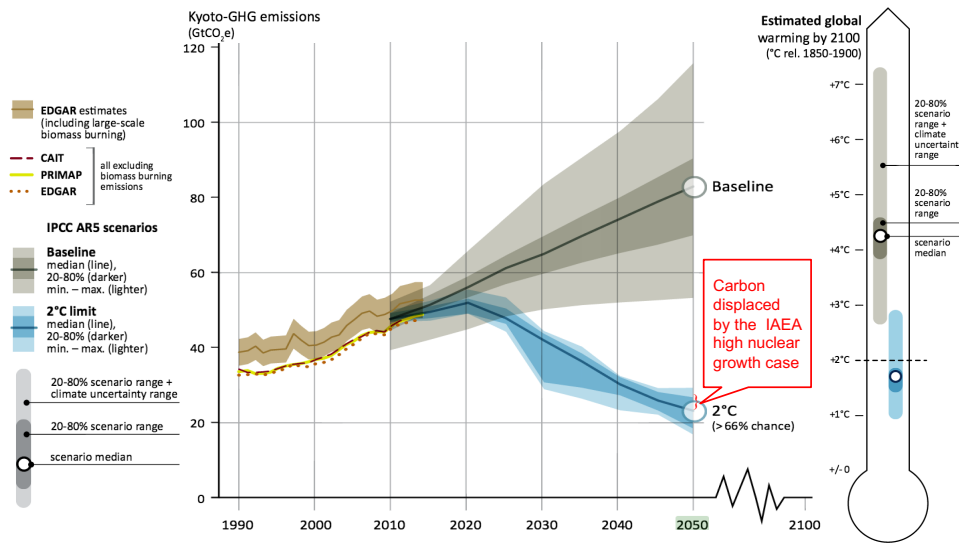
Some steps that would not be justified

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- ❑ Building a U.S. reprocessing plant
 - Higher cost, lower safety, higher terrorism risk, higher proliferation risk than dry cask storage followed by direct disposal
 - Not “leadership” to be the last to jump into a failing industry
- ❑ Building a U.S. enrichment plant
 - Enrichment market is oversupplied, incumbents have highly efficient technologies, no major profit opportunities available
 - Can “bundle” with existing enrichers if desired for reactor sales
 - Should explore other options for long-term tritium supply before committing to multi-billion-dollar investments
 - Weakens U.S. argument that countries can rely on the international market if the United States unwilling to do so itself
- ❑ Building sodium-cooled fast-neutron reactors
 - No evidence to date that these will be cost-competitive
 - Sufficient uranium to fuel many decades of nuclear growth

Nuclear energy and climate change – it takes terawatts to matter

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Key constraints on large-scale nuclear energy growth

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- ☐ Cost – and financing
- ☐ Safety risks – real and perceived
- ☐ Security risks – real and perceived
- ☐ Nuclear waste management – mostly politics
- ☐ Siting and public acceptance
- ☐ Limited government and industry capacity
- ☐ Stringent regulation
- ☐ Proliferation risks – mainly from the nuclear fuel cycle
- ☐ U supply: Not likely to be a constraint this century

Policy changes likely to be more important than new technologies for next couple of decades – new technologies could be key in longer term

Backup slides if needed

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Will new technology help? Ex.: fluoride high-temperature reactors

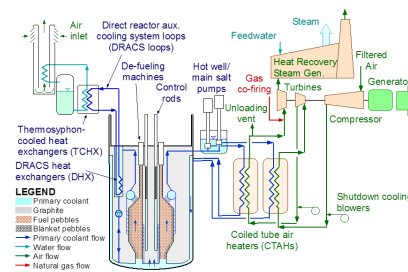
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□ Idea:

- Fluoride salt coolant ($> 1300^{\circ}\text{C}$ boiling temp)
- Fuel in TRISO particles embedded in graphite pebbles
- High temperature $\rightarrow$ high efficiency, ability to make chemicals when electricity price is low $\rightarrow$ much better economics
- Excellent safety: “I can’t figure out how to cause a release with this reactor”

□ Conceived at MIT, Berkeley, and Wisconsin

- China funding 1st test systems



Flow schematic for Mark 1 pebble-bed fluoride high-temperature reactor

Source: fhr.nuc.berkeley.edu

Nuclear innovation: reasons for optimism

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- ❑ Exciting new ideas:
 - Hoped-for lower costs (and smaller size to ease financing), passive safety, high temperature to provide process heat
 - 2 classes of concepts:
 - Near term: variants on light-water reactors
 - Longer term: different coolants, fuels, etc.
- ❑ Dozens of start-up firms
 - Drawing in venture capital, new people
 - Some large firms also pursuing new concepts
- ❑ New technologies that were not available before, e.g.:
 - Radically improved computer simulation
 - New materials
 - Modular and factory construction approaches

Nuclear innovation: reasons for pessimism

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- ❑ Market and technology structure:
 - Commodity market
 - Low-cost gas means little profit potential
 - EXTREMELY conservative buyers – utilities
 - Product life-cycle measured in decades
 - Billion-dollar tests – few real “shots on goal”
 - Stringent, conservative regulation
 - HUGE barriers to entry
- ❑ Past experience:
 - No really new reactor concept has been commercialized for >50 years
 - 0% of past predictions of new cheap systems have proved to be correct
 - Current “Gen. III” reactors were supposed to be cheaper than Gen. II – are more expensive

Rickover: Paper reactors will always beat real reactors

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"An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now.

On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering problems. (6) It is large. (7) It is heavy. (8) It is complicated."

-- Admiral Hyman Rickover, memo, June 5, 1953,
http://ecolo.org/documents/documents_in_english/Rickover.pdf

Nuclear innovation: a thought experiment

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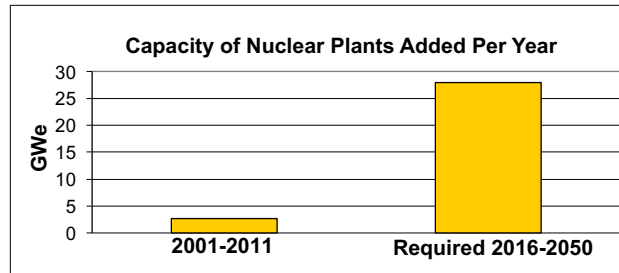
□ Imagine:

- Prototype of a new reactor concept starts operation in 10 years (very aggressive schedule)
- 2 years of operation is enough to sell 10 GWe of commercial plants, which take only 3 years to build
- 2 years after those sales, 20 GWe more are sold
- Then increases to 40, 60, etc. every 2 years, and stabilizes at 100 GWe/yr (reaching that level in 2048)
- Even that extremely aggressive (and highly unlikely) schedule leads to ~1100 GWe in 2050 – an important, but ultimately modest, contribution

- For near-term bending of the climate curve, new policies likely to be more important than new technologies – most electrons from nuclear power by 2050 likely to be from existing reactors or types

For a nuclear “wedge,” huge increase in construction needed

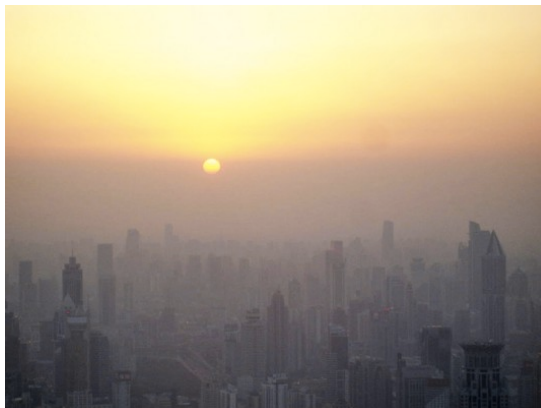
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- ❑ Need to shift from 3 to 28 GWe/yr
- ❑ Nuclear must become dramatically more attractive to governments and utilities than it was before Fukushima – a difficult challenge
- ❑ Any further disaster, from accident or terrorism, would doom any realistic prospect for growth on this scale

Particulates may be more important than climate in driving clean energy

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Smog in Beijing. Source: inhabitat.com

- ❑ >3 million deaths/yr globally from fine particulates

Both policy and technology might help address constraints

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- ❑ New policies, e.g.:
 - Lower-cost financing
 - Flexible regulation – faster approvals, siting
 - Strong safety regulation, incentives – reduced accident risk
 - Strong security regulation, incentives – reduced terrorism risk
 - Controls, incentives to limit spread of enrichment and reprocessing
 - Capacity-building for newcomer states
- ❑ New technologies, potential to:
 - Reduce overnight capital cost
 - Allow plants to produce both electricity and process heat (e.g., for producing transport fuels)
 - Increased passive safety (also helps security)
 - Reduced need for enrichment
 - More efficient use of uranium resources
 - Reduced and/or shorter lifetime waste

New policies likely more important than new technologies – for now

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- ❑ Financing
 - Can we find politically acceptable ways to reduce financing costs?
- ❑ Regulation
 - Can all relevant countries maintain very high safety and security standards?
 - At the same time, can we develop more flexible, less cumbersome approaches – especially for new technologies?
- ❑ Public acceptance
 - Can we build real dialogue with host and neighbor communities, address their concerns in a way that genuinely builds trust?
- ❑ Fuel cycle
 - Can we manage the fuel cycle in ways that minimize proliferation risk?

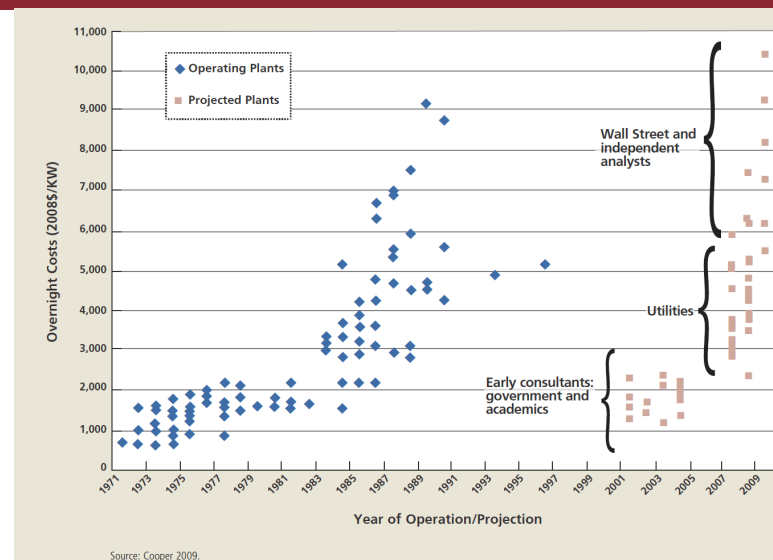
Cost is the biggest constraint on nuclear energy growth

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- ❑ In many markets, new nuclear is not competitive:
 - Very high capital costs
 - High costs of financing (with extra premium for nuclear risks – delays, cost over-runs...)
 - Where there are low gas prices, no carbon prices, no government-backed financing, nuclear uncompetitive
 - Rarely chosen by utilities in competitive markets
- ❑ Some markets provide favorable conditions:
 - Government financing or government-enforced high prices (e.g., UK guarantee of ~2x current electricity price)
 - Same reactor cost can be competitive in one market, uncompetitive in another – because of different financing costs
 - Government choice or government-influenced choice of plant
- ❑ Growth on scale required for 1-2 “wedges” likely to require substantial progress on cost reduction

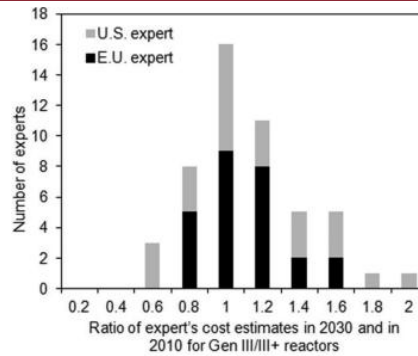
Nuclear costs: a forgetting curve?

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Nuclear costs: most experts are not expecting a breakthrough

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Source: Anadon, Bosetti, Bunn, Catenacci, Lee, Environmental Science & Technology, Vol. 46, 2012

- ❑ Most experts in a recent elicitation expected Gen. III reactor costs to increase by 2030
- ❑ Higher average projected costs for Gen. IV and small reactors

Nuclear costs: financing, schedule are crucial

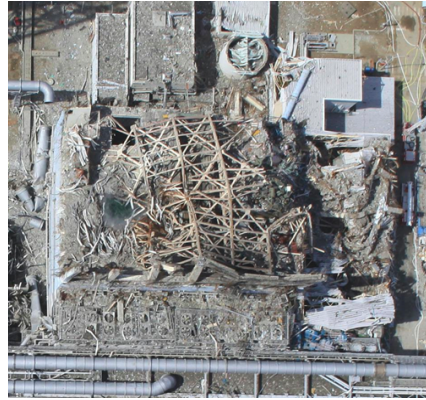
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- ❑ For capital-intensive energy sources, cost of capital is key:
 - 3% government rate radically different from 10-12% private, unregulated rate
 - Same physical construction cost can be better than other energy sources with one financing package, worse with another
- ❑ Risk from huge scale of financing required
 - 'Betting the company' on \$10-\$20B project
 - Requires complex, time-consuming deals to spread risk
- ❑ Schedule has a major effect on cost
 - Interest during construction
 - Inflation (nuclear inflation higher than other)
- ❑ South Korea, China build reactors for lower costs on shorter schedules – with lower-cost financing

Post-Fukushima, perceptions of safety are also a major constraint

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- ❑ Nuclear energy is an unforgiving technology
 - Requires high performance of operators, regulators
 - Raises deep issues of organizational performance and culture
 - “Newcomer” states have not had chance to build up safety infrastructure – and on average are more corrupt and have weaker regulation
- ❑ New designs are safer
 - But a week with no power or heat sink, as at Fukushima, would be a problem for any available design



Source: Air Photo Service, Japan

Safety culture matters: Davis-Besse vessel head hole

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Source: FirstEnergy

Sabotage is also an issue

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- ❑ Terrorist action *could* potentially cause a reactor melt-down comparable to Fukushima
 - Redundant safety systems, defense in depth make sabotage more difficult
 - But actions that could cause prolonged loss of cooling, power could lead to catastrophes
 - Sabotage of spent fuel pools, reprocessing plants, spent fuel transports also a concern
 - Effective nuclear security measures required – not in place everywhere
- ❑ Terrorists have considered nuclear sabotage
 - Threats, plans by Chechen terrorists
 - Al Qaeda seriously considered attacking U.S. reactors
 - 5 Americans arrested in Pakistan, charged (among other things) with planning to attack a nuclear reactor

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NUCLEAR SAFETY

Preventing the Next Fukushima

Matthew Bunn* and Olli Heinonen

While this year's disaster at Japan's Fukushima Dai'ichi plant, the worst since Chernobyl in 1986, was caused by the one-two punch of a huge earthquake followed by an immense tsunami—a disaster unlikely to occur in many locations—it revealed technical and institutional weaknesses that must be fixed around the world. If nuclear power is to grow on the scale required to be a significant part of the solution to global climate disruption or scarcity of fossil fuels, major steps are needed to rebuild confidence that nuclear facilities will be safe from accidents and secure against attacks (1).

It is too soon to draw all the lessons from the Fukushima disaster. But it is clear that the reactors' abilities to maintain cooling in the event of a prolonged loss of power and to vent dangerous gas buildups were insufficient, as were the operators' ability to respond to large-scale emergencies and the regulators' degree of independence from the

IAEA. Will Fukushima lead to new action to strengthen the global nuclear safety and security system?

So far, the signs are not promising. With competing proposals from several countries, little understanding of which ideas would help, and a lack of sustained leadership focused on building support for key initiatives beforehand, little consensus emerged at June's IAEA ministerial meeting, although the ministers directed the agency to prepare a suggested action plan. That plan, a 22 September United Nations conference on nuclear safety and natural disasters; reviews of the CNS; and the ongoing WANO effort to find ways to strengthen its operations all represent opportunities for progress.

Over the long term, new reactor designs with greater reliance on "inherent" safety measures, e.g., not requiring active pumps and valves to maintain safe operation, may reduce risks. But for the next few decades, most nuclear energy will be generated by

Weak authority and largely voluntary standards limit global institutions' impact on nuclear safety and security.

Operators should be required to install filtered vents, as some countries have done, which could greatly reduce the amount of radiation released if a dangerous pressure buildup in a reactor forces operators to vent gases, as occurred at Fukushima (4). Operators should also be required to put in place measures to prevent spent fuel from melting or burning if a spent fuel pool drains, such as installing survivable systems to spray the fuel in the pool with water. Ultimately, much of the fuel now stored in spent fuel pools should be moved to safer dry casks (5).

Institutionally, regulators must be wholly independent of those they regulate and have the authority, resources, expertise, and culture to be effective. For example, Japan has decided to separate its regulator from the ministry responsible for nuclear power.

The IAEA should recommend that states require steps such as these. The United States and other countries operating and exporting nuclear reactors, along with industry groups

Source: Science, Sept. 16, 2011

Expanding nuclear energy need not increase terrorist nuclear bomb risks

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- ❑ Could have global nuclear energy growth with no use of directly weapons-usable nuclear material in the fuel cycle
 - Low-enriched uranium (LEU) fresh fuel cannot be made into a bomb without technologically demanding enrichment
 - Plutonium in massive, intensely radioactive spent fuel beyond plausible terrorist capacity to steal and process
- ❑ If scale of reprocessing, transport, and use of plutonium from spent fuel expands, nuclear energy contribution to nuclear terrorist risks would increase
 - Reprocessing converts plutonium into portable, not very radioactive, readily weapons-usable forms
 - With major exception of Rokkasho in Japan, current trend seems to be away from reprocessing – reduced operations at La Hague and Mayak, phase-out at Sellafield

Standard nuclear reactors pose real but modest proliferation risks

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- ❑ Modern light-water reactors small contribution to a bomb:
 - Use low-enriched fuel that cannot be used in a bomb without technologically demanding further enrichment
 - Produce reactor-grade (but weapons-usable) plutonium in spent fuel (~1% by weight) – requires remotely-operated chemical processing to separate plutonium
 - Are under international inspection in non-nuclear-weapon states
- ❑ Key proliferation risks are from enrichment and reprocessing facilities – the nuclear fuel cycle
 - Facilities for civilian use can be readily turned to military use
 - International inspection can provide warning – but in time?
 - Potential for covert facilities (esp. enrichment)
- ❑ Reactors provide:
 - Means to build up expertise, bureaucratic power base
 - Rationale for pursuing more sensitive technologies

Nuclear waste, if properly managed, poses modest risks

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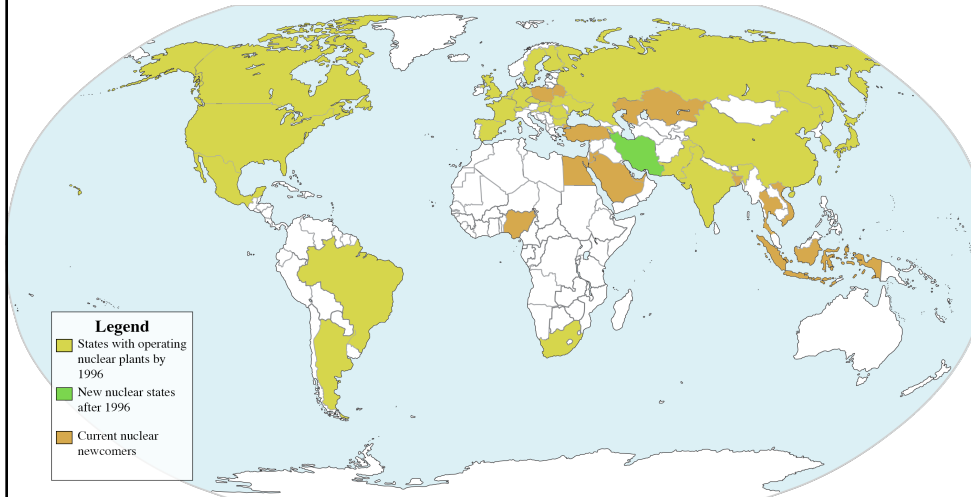
- ❑ After pool storage, spent fuel can be safely stored in dry casks for decades at low cost
 - Allows time, flexibility for more permanent options
- ❑ Scientific consensus that geologic disposal can provide safe management of nuclear waste
 - Risks are both modest and far in the future
- ❑ Recently, Finland and Sweden have successfully sited nuclear waste repositories with full support from the local communities
- ❑ But, the politics of nuclear waste and political perceptions of its dangers still pose a major problem for nuclear energy

Public acceptance of nuclear energy

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- ❑ Making nuclear energy a safe, secure, proliferation-resistant, reasonable cost option with well-managed waste would go a *long* way to addressing the public acceptance issue
- ❑ But deep fears (some rational, some not), deep distrust of government and industry (some justified) need to be addressed
 - Requires real engagement of broad range of stakeholders, genuinely voluntary approach for affected communities
 - Communication has to be two-way, not just industry “educating” the public
- ❑ Constraint is not as binding as some believe
 - In many cases, communities that have nuclear power plants (and the resulting jobs and tax revenue) are supportive of having more

Nuclear growth implies nuclear spread: the story so far



Source: IAEA PRIS Database, last retrieved April 15, 2016

Governance indicators of emerging nuclear power states

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Country	Control of Corruption	Regulatory Effectiveness
Bangladesh	23	17
Belarus	9	23
Chile	94	90
Egypt	49	41
Indonesia	43	28
Iran	3	22
Israel	81	75
Italy	78	59
Jordan	61	64
Kazakhstan	39	19
Kuwait	56	69
Malaysia	60	58
Morocco	52	51
Nigeria	26	15
Poland	79	71
Saudi Arabia	57	63
Thailand	62	51
Turkey	59	60
United Arab Emirates	69	81
Venezuela	4	8
Vietnam	31	37

Source: Drawn from World Bank Governance Indicators and World Nuclear Assoc.

Compared to what? Every option has its problems

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❑ Oil and gas:	<i>Not enough resources?</i>
❑ Coal, tar sands, oil shale:	<i>Not enough atmosphere?</i>
❑ Biomass:	<i>Not enough land?</i>
❑ Wind & Hydro:	<i>Not enough good sites?</i>
❑ Solar:	<i>Too expensive and intermittent?</i>
❑ Nuclear fission:	<i>Too unforgiving?</i>
❑ Nuclear fusion:	<i>Too difficult?</i>
❑ Hydrogen:	<i>Energy to make it?</i> <i>Means to store it?</i>
❑ End-use efficiency:	<i>Not enough informed, motivated end-users?</i>

Nuclear role in 3 greatest global energy challenges

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- ❑ Energy supply without greenhouse emissions
 - Massive growth required for nuclear to play a significant role
 - ❑ Reducing energy supply vulnerabilities (esp. oil)
 - Nuclear currently provides baseload electricity, oil little-used for that purpose in most countries
 - Nuclear cannot currently make major contribution to transport fuel
 - May change in future
 - ❑ Providing energy to the world's poor
 - Current huge, complex, expensive nuclear plants not the technology that will provide electricity to rural villages
 - May also change (at least somewhat) in future
- Electricity < 1/3 global primary energy – and most future demand growth in developing countries with modest nuclear contribution so far*

Making nuclear energy broadly available

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- ❑ Complex 1-1.6 GWe LWRs not appropriate for many countries, regions
 - Requires substantial infrastructure of trained personnel, regulation, safety and security culture...
 - Grids can't support that much power at one spot
- ❑ Potential for small and medium factory-built reactors
 - More appropriate for smaller, less well-developed grids, or off-grid locations
 - Much lower capital cost per reactor eases financing (even in U.S.)
 - Smaller sizes make safety design easier – potential for “walk-away safe” designs (still to be demonstrated), underground siting
 - Could be built with lifetime fuel built-in, sealed core, no access to nuclear fuel by host state

Making nuclear energy available for a broader array of purposes

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- ❑ Electricity beyond the baseload
 - Nuclear reactors could generate electricity when needed, storable products (e.g., hydrogen) when not
 - Hydrogen could provide additional peaking power – could even back up intermittent renewables
 - Economics as yet unproven
- ❑ Transportation fuel
 - Electricity for electrics and hybrids
 - Heat and hydrogen for refineries and biorefineries (could cut land area needed for biomass fuels in half), and for oil shale recovery
- ❑ Heat for desalination and many industrial processes
 - Many applications require high-temperature reactors

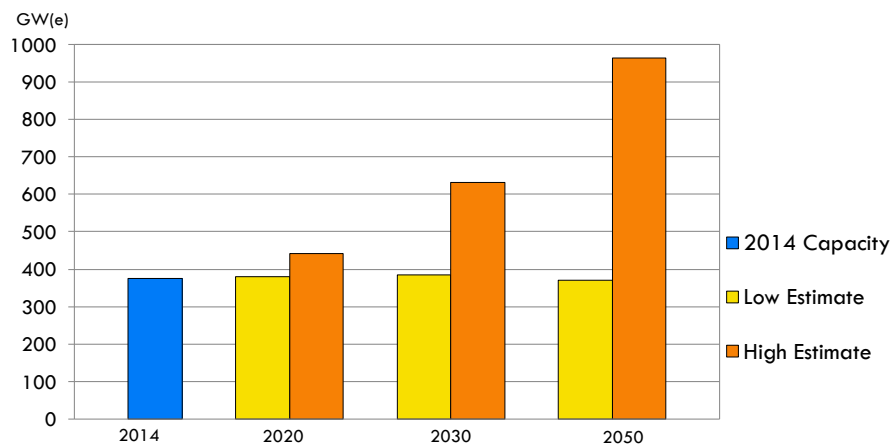
More R&D required to explore these many possibilities

Is nuclear energy sustainable?

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- ❑ Uranium is abundant
 - Current use ~ 60,000 tU/yr
 - IAEA estimates 15.8 M tU available (known+speculative)
 - U being found faster than it's being used – for decades
 - With huge nuclear growth, and no recycling, uranium resources *might* be an issue – in the 22nd century
 - 2010 MIT analysis suggests enough U to fuel 10x current nuclear fleet for 1,000 years before price increases enough to make reprocessing economic
- ❑ Hence, reprocessing and breeder reactors are not needed at least for many decades
 - Reprocessing – separating plutonium from spent fuel to recycle it – is much more expensive than not doing so, and raises proliferation, safety, and terrorism risks

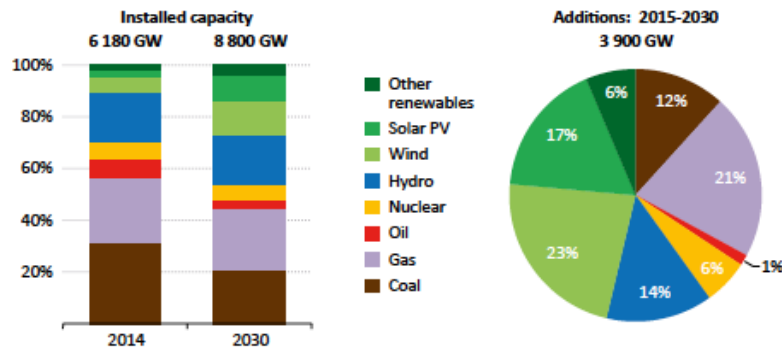
IAEA low and high estimates of nuclear capacity up to 2050



Source: IAEA, "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," 2015 Edition

Nuclear is not likely to dominate the climate answer

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- ❑ Electricity supply and additions by fuel type – “bridge” scenario (to achieve 2° C stabilization)
- ❑ Nuclear additions smaller than coal from now to 2030!

A personal view

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- ❑ We should be doing what we can to fix the problems that have constrained nuclear growth, so that it can really be an expandable option to help cope with climate change
- ❑ Will be more difficult to cope with climate without a significant contribution from nuclear – but will be difficult to get a significant contribution from nuclear
- ❑ Poorly managed nuclear energy with weak rules will not, and should not, grow at the scale required
- ❑ Well-managed nuclear, with stringent safety, security, and nonproliferation measures in place, and reduced costs, *might* grow on a scale that could contribute to climate change – but it won't be easy

Preventing nuclear proliferation

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- ❑ Global nuclear nonproliferation regime is under severe stress – Iran, North Korea, the A.Q. Khan network, the global spread of technology, potential growth and spread of nuclear energy, disputes over disarmament, India deal...
- ❑ But, the regime has been both successful + resilient
 - 9 states with nuclear weapons today – 9 states 25 years ago
 - More states that started nuclear weapons programs and verifiably gave them up than states with nuclear weapons – nonproliferation succeeds more often than it fails
 - Every past shock has led to parties introducing new measures to strengthen the system
 - All but 4 states are parties to the NPT, and believe it serves their interests
- ❑ With right policies today, can hope to have only 9 states with nuclear weapons 20 years from now – or fewer

Limiting fuel cycle proliferation risks

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- ❑ Incentives for states not to build their own enrichment and reprocessing facilities
 - International centers in which all states can participate (but not get sensitive technology), such as Angarsk IUEC
 - Fuel banks (including Russian, U.S., IAEA-controlled)
 - Offers of “cradle-to-grave” fuel services
 - Regional repositories
 - “Fuel leasing”
 - “Reactor leasing”
 - Potential role for marketing factory-built small and medium reactors, with “cradle-to-grave” fuel and reactor services
- ❑ Restrain technology transfers (licit and illicit)
- ❑ Move step-by-step to increased multinational control over sensitive fuel cycle facilities

Some longer-term measures to control the civilian-military link

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- ❑ Control of sensitive nuclear activities needs to be rethought if we are serious about deep nuclear reductions, possibly someday to zero
 - Purely national control of (a) stocks of nuclear material equivalent to thousands of bombs; (b) facilities capable of producing thousands of bombs' worth of material per year will likely no longer be acceptable
 - Need to move toward some form of international/multinational ownership/control
 - Need far-reaching verification measures, for all sensitive nuclear activities (military and civilian – incl. in weapon states)
- ❑ In a world with far more nuclear energy, will need to:
 - Satisfy fuel cycle needs without spread of nationally-controlled enrichment and reprocessing facilities
 - Develop, deploy more proliferation-resistant systems (e.g., “nuclear battery” reactors with small staffs, sealed cores, “cradle to grave” fuel services)

The scale of the control problem...

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- ❑ Making roughly 15 kilograms of highly enriched uranium (HEU) for one bomb requires ~ 3500 units of enrichment work
 - Current global civilian enrichment capacity enough to produce material for >13,000 weapons/yr – would have to triple for stabilization wedge on once-through fuel cycle
- ❑ Making one bomb from plutonium requires ~ 4-8 kilograms of plutonium
 - Current global civilian plutonium separation ~ 20 t/yr, enough for > 3,000 weapons/yr (capacity is larger, but underutilized)
 - Nuclear stabilization wedge with plutonium fuel cycle (mix of fast reactors and thermal reactors) would require reprocessing ~835 tonnes of plutonium and minor actinides/yr – amount needed to produce ~140,000 bombs
- ❑ Controls must prevent diversion of 1 part in 10-100,000, and limit the spread of the technology – daunting challenge

Addressing safeguards challenges

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- ❑ Convince states to give IAEA resources, information, authority, personnel, technology it needs to do its job
 - Provide substantial increase in safeguards budget
 - Press for all states to accept Additional Protocol, make this condition of supply
 - Limit spread of fuel-cycle facilities
 - Provide information from intelligence, export control (denials, inquiries, etc.), other sources
 - Reform IAEA personnel practices to attract, retain best-qualified experts in key proliferation technologies
 - Reinvest in safeguards technology, people (e.g., “Next Generation Safeguards Initiative”)
 - Adopt philosophy of “safeguards by design” for new facilities
 - Develop technologies and procedures to safeguard new fuel-cycle technologies before deploying them