Nuclear energy’s role in decarbonizing China’s energy system: Loosening constraints, mitigating risks

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belfercenter.org/managingtheatom

The questions, and why they matter

- What are the key constraints on, and risks of, growth of nuclear energy on China to a scale large enough to play a substantial role in decarbonizing China’s energy system later this century?
- What can be done about these constraints and risks through:
  - Improved policies
  - Improved technologies
- What policies can China adopt in the next few years that would maximize its nuclear options decades from now?
- China is building more reactors than any other country (23 of 38 reactors started up since 2012 were in China) – if nuclear energy does not play a major role in decarbonizing China’s energy system, it will not play a major global role.
The huge scale of growth required

- In 2nd half of 21st century, China is likely to be consuming ~ 3-6 TW of energy
  - To provide 15-50% of total energy would require 0.5-3 TW of nuclear power
  - Many hundreds of 1 GWe plants, or thousands of small plants – of order 15-50x current
  - More than entire world nuclear energy today
- Growth on this scale would mean transforming China’s nuclear enterprise in many ways
- Currently China has 34.5 GWe of nuclear energy; 19 GWe under construction; goal of 58 GWe in 2020 will be delayed several years
  - China is also funding RD&D on several advanced nuclear technologies
  - China is also moving into nuclear export markets

Growth could follow multiple paths: e. g. steady, or slow with a later surge
Nuclear energy provides a tiny share of China’s energy today

Growth in energy demand has slowed, coal (probably) has peaked, developments suggest that China’s energy future may look quite different from its past

Source: IEA, World Energy Outlook 2017

Nuclear is currently expected to play only a small role in China’s decarbonization

Decarbonization likely to occur more slowly than this
- Nuclear may play bigger role later in 21st century

Source: IEA, World Energy Outlook 2017
Particulates may be more important than climate in driving clean energy in China

Smog in Beijing. Source: inhabitat.com

- ~1 million deaths/yr in China from outdoor fine particulates

Key constraints on large-scale nuclear energy growth in China

- Cost – and financing
- Safety risks – real and perceived
- Security risks – real and perceived
- Siting and public acceptance
- Nuclear waste management – mostly politics
- Limited government and industry capacity
  - Including human resources
- Regulatory delays
- Integration into future renewables-heavy energy system
- Proliferation risks – mainly from the nuclear fuel cycle
- U supply: Not likely to be a constraint this century

Both policy and technology could help address these constraints
Economics are a smaller constraint in China than elsewhere – for now

- Nuclear energy costs driven by:
  - 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 is uncompetitive
  - Rarely chosen by utilities in competitive markets
- But China’s market currently provides favorable conditions:
  - State-owned nuclear companies can finance plants at low rates (HUGE effect on overall economics compared to United States)
  - Reactors built somewhat faster, at lower costs, with less uncertainty
  - Government can (and does) enforce higher rates for favored electricity sources
- Future reforms MAY change some of those conditions

Policy + technology for improving nuclear economics

- Policy:
  - Maintain cheap financing (n.b.: only changes apparent cost, not total social cost…)
  - Maintain high, predictable electricity prices for nuclear
  - Avoid undue regulatory delays, uncertainty
- Technology (advanced reactors):
  - Some advanced systems MAY offer lower capital cost
  - Some are factory-built (shorter build times, potentially better learning)
  - Some designed to provide both electricity and process heat, could increase electricity output when prices are high
  - Offshore systems MIGHT offer lower land, foundation costs

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Nuclear costs: most experts are not expecting a breakthrough

Most experts in an elicitation expected Gen. III reactor costs to increase by 2030.

Higher projected costs for Gen. IV and small reactors in 2030.

Safety risks – a key constraint

- Fukushima accident significantly slowed nuclear energy in China
  - All new starts put on hold temporarily during safety review
  - New requirements imposed, increased focus on Gen. III reactors
  - Planned construction pace significantly reduced
  - Inland sites still not yet approved to start construction
- Another major accident – particularly one in China – could make it impossible for nuclear energy to grow at the scale needed for major part in China’s decarbonization
- China has taken many steps to ensure nuclear safety, but:
  - Poor overall safety record elsewhere in China’s economy
  - Rapid, low-cost construction raises concerns over whether corners are being cut
  - Regulator has smaller staff/reactor, less experience, than U.S. or European counterparts
Policy + technology for reducing real and perceived safety risks

- Policy:
  - Strengthen nuclear regulator
  - Establish industry-level group comparable to INPO
  - Training, incentives, other programs to build up safety culture
  - Counter corruption

- Technology (advanced reactors):
  - Most advanced systems offer increased passive safety
  - FHR: “I can't figure out how to engineer a release from this reactor”
  - Some advanced systems underground or offshore
  - Some passive safety systems more demonstrable, understandable

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Security risks – also important

- Terrorists could cause a Fukushima-scale release – or worse
  - More reactors does NOT lead to more risk of theft of nuclear bomb material – UNLESS China shifts to use of plutonium or HEU fuels
  - More reactors DOES create more targets for sabotage
  - Fire in spent fuel pool could cause release larger than Chernobyl (but tricky for saboteurs to achieve)

- China experiencing increased terrorism
  - Mostly low-level so far

- China has put substantial security measures in place
  - Armed guards, extensive alarms, barriers
  - Substantial influence from U.S. advice
  - Insider protections may be less effective
  - Regulator, industry devote less attention to security than to safety (as is true in most countries)
Policy + technology for reducing real and perceived security risks

- Policy:
  - Avoid plutonium reprocessing, recycling, and use of HEU fuel
  - Strengthen nuclear security requirements (national design basis threat, realistic testing, strengthened insider protection…)
  - Training, incentives, other programs to build up security culture
  - Regular briefings for managers, staff on real terrorist nuclear threats

- Technology (advanced reactors):
  - Making it more difficult for releases to be caused accidentally also makes it more difficult to cause them intentionally
  - Some small or underground reactors may be easier to protect

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Extensive Belfer analysis on nuclear security in China is available

- Hui Zhang and Tuosheng Zhang, Securing China’s Nuclear Future, March 2014
  https://tinyurl.com/yc8jp8ut

- Hui Zhang, China’s Nuclear Security: Progress, Challenges, and Next Steps, March 2016
  https://tinyurl.com/y7gfestm
Siting and public acceptance are key constraints – even in China

- Siting and public acceptance issues have slowed or stopped multiple nuclear plants in China
  - Several facilities abandoned after protests
  - Inland sites not yet approved – concerns over contamination of rivers
  - No commercial nuclear plants within >50 km of Beijing or Shanghai
  - Few plausible coastal sites for additional plants (except at existing sites)
  - Corruption scandals (e.g., arrest of the head of the largest nuclear corporation) could undermine public confidence

- Chinese government has launched major public acceptance campaigns
  - Propaganda, public meetings, benefits for host communities
  - Research suggests real but limited impact of these efforts
  - Local administrations being judged in part by ability to avoid large-scale public protests – affecting their enthusiasm for nuclear energy

Policy + technology for addressing siting and public acceptance constraints

- Policy:
  - Most important: avoid accidents, sabotage, scandals
  - Engage in depth with local communities – build trust over time by fulfilling all promises, addressing concerns, step-by-step
  - Avoid rushing, railroading projects through – “go slow to go fast”

- Technology (advanced reactors):
  - Some advanced systems may offer more demonstrable, easy-to-understand safety and security
  - Offshore plants may be able to address many siting issues, allow large-scale deployment close to energy demand of coastal cities
  - Some designs do not need water for cooling, broadens siting options

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Nuclear waste management likely less of a constraint in China than elsewhere

- If managed properly, environmental impacts of nuclear waste are small and VERY long-term
  - Tiny potential deaths/MW-hr, occurring >10,000 years in future
  - But nuclear waste very important to public attitudes toward nuclear

- China has several advantages for managing nuclear waste
  - Most recent reactors and future reactors designed with decades of fuel storage capacity in their pools
  - Authoritarian government could establish centralized interim stores, repositories in remote, desert areas with limited opposition
  - Technology of dry cask storage is cheap, safe, secure for decades, while permanent repositories are developed
  - Available time makes it possible to proceed cautiously, build trust with potential host communities, allow technology to develop, financing to accumulate interest…
  - No near-term need for reprocessing of spent fuel

Policy + technology for managing the nuclear waste constraint

- Policy:
  - Design, plan, for life-of-reactor fuel storage
  - Focus on voluntary citing approaches for centralized stores, building trust with potential host communities
  - Avoid rushing, railroading projects through

- Technology (advanced reactors and fuel cycles):
  - Some concepts involve high burnup (less volume of waste per MWh)
  - Some concepts involve multiple recycling to burn long-lived species (still undemonstrated, likely to involve higher costs for modest environmental benefit)

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Limited government and industry capacity may prove to be important constraints

- Even current construction rate is straining available capacity
  - Capacity includes ability to provide sufficient trained, experienced personnel; ability to build reactors safely; ability to operate reactors safely and securely; ability to regulate all aspects of the enterprise
  - Non-nuclear firms being brought in to help with construction
  - Rapid training of new personnel — but result is that many in both industry and regulator have limited experience
- Growth at scale required would demand huge expansion in capacity for construction, operation, regulation
  - If growth accelerates slowly over decades, system should be able to adapt and respond
  - Path of slow growth followed by rapid surge may strain capacity — unless advanced designs require far less human capacity

Policy + technology for addressing capacity constraints

- Policy:
  - Provide resources needed for training, recruitment, retention at all levels
  - In particular, ensure regulator has adequate personnel, resources, independence, authority, expertise to ensure safety and security
  - Continue construction to keep industry building experience
  - Maintain several firms building, operating reactors
- Technology (advanced reactors):
  - Many advanced systems potentially offer simpler construction, operation, more inherent safety, requiring fewer people
  - Factory manufacturing could greatly increase construction capacity

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Regulatory delays are likely to be less of a constraint in China than elsewhere

- So far, regulatory issues have only rarely imposed major delays for nuclear projects in China
  - Nevertheless, regulator does examine proposals in detail before approval
- In some cases, larger government decision-making delays — including, but not limited to, the regulator — have been substantial
  - Approval of inland sites being debated for 7 years since Fukushima
  - No new construction approved in 2016 or 2017 (in part because of lack of need for new capacity)
  - Reprocessing plant and fast reactors have moved slowly for over a decade — justifiably, since pilot facilities have not performed well, and projected costs of large facilities is high

Policy + technology for addressing regulatory delays

- Policy:
  - Ensure a focused, step-by-step, and cooperative regulatory process
  - Ensure the regulator has adequate personnel, resources, expertise, and authority to identify and address key issues
  - Avoiding loading up too many issues to be addressed at the same time
  - Increase focus on small number of reactor types
- Technology (advanced reactors):
  - Increased passive safety and simpler designs may reduce regulatory complexity and uncertainty

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Integration into renewable-heavy energy system may require different approaches

- A future decarbonized energy system is likely to involve large fractions of intermittent renewables
  - For 20-80% decarbonization of electricity, renewables backed up by natural gas and limited storage may be cheapest
  - For 90-100% decarbonization, low-carbon alternatives to natural gas backup likely to be needed to reduce costs
- Ideal backup would provide both steady baseload power and ability to ramp up and down to compensate for renewable intermittency – and contribute to other energy needs
  - Existing nuclear designs can do limited load-following, but rapid ramp-ups and downs are difficult, cannot readily provide peaking power
  - Existing nuclear designs mainly provide baseload electricity – future systems could also provide process heat, other products, fill larger portion of total energy demand

Policy + technology for integration in renewable-heavy energy systems

- Policy:
  - Ensure reactors operated in a way that permits some load following
  - Design energy system to integrate all planned sources, make use of their strengths and weaknesses
- Technology (advanced reactors):
  - Some advanced systems designed to shift energy from electricity to other products depending on needs, prices – even provide peaking power
  - Example: FHR might make hydrogen for chemical synthesis when electricity prices are low, burn hydrogen to speed up turbine when peaking power is needed – creates more revenue for reactor

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Proliferation resistance – an often overlooked issue

- China is already a nuclear weapon state, but its decisions matter for nuclear nonproliferation
  - China likely to have the world’s largest reactor fleet, be the nuclear energy leader of the 21st century
  - Large-scale reprocessing, use of plutonium fuels could encourage others to do the same, increasing chance that reprocessing would spread
  - Reprocessing, use of plutonium or HEU fuels would also increase danger of theft of nuclear material, transfer to terrorists
  - China’s enforcement of nuclear and dual-use export controls (and sanctions) to date is weak – much of the key technology Iran and North Korea have acquired has come from China or through China
  - Potentially sensitive technologies are dual-use, with many civilian applications – more and more countries in China will be able to provide them (irrespective of the future growth of China’s nuclear industry)

Policy + technology for proliferation resistance

- Policy:
  - Postpone reprocessing, fast reactors indefinitely
  - Avoid HEU fuels
  - Limit sensitive exports, and institute more effective export controls and other measures to stop illicit trade
  - Participate actively in global nonproliferation initiatives

- Technology (advanced reactors and fuel cycles):
  - Avoid those systems based on reprocessing, plutonium fuels
  - Some advanced systems could offer advantages: no need for enrichment or reprocessing after initial fuel load; sealed cores; offshore plants could be towed away if a serious issue arose

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Uranium supply – not likely a serious constraint in this century

- Uranium is abundant
  - Current use ~ 57,000 tU/yr
  - IAEA estimates 15 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

- China has access to plenty of uranium
  - “3 markets” policy – domestic, foreign markets, foreign mines
  - ~ 2M tons domestic resource, though much of it high cost

- Hence, plutonium reprocessing and breeder reactors are not needed at least for many decades
  - Reprocessing – separating plutonium from spent fuel to recycle it – is more expensive and raises proliferation, safety, and terrorism risks

Policy + technology for uranium supply

- Policy:
  - Invest in ensuring adequate supply (including in further exploration)
  - Avoid being snowed by claims of imminent shortage

- Technology (advanced reactors and fuel cycles):
  - Extending the U resource not urgently needed
  - Some “breeding in place” systems can potentially extend U resource 2-3x w/o reprocessing
  - If cost, proliferation, safety, security issues could be resolved, reprocessing and breeding could extend resource manifold
  - Fusion may become economic faster than reprocessing does

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Belfer analysis on uranium supply for China’s nuclear growth

  https://tinyurl.com/y7dvw556

Belfer analysis on reprocessing in China

  https://tinyurl.com/ybtsaqvs
Near-term choices China can make to maximize long-term nuclear options

- Invest in safety and security
  - Reaction to a major accident would greatly limit prospects for really large-scale growth
  - Beef up regulator, create industry-level INPO-like group
  - Training, incentives, other steps to strengthen safety and security culture
  - Emphasize Gen. III reactors and beyond

- Maintain, expand industry and government capacity
  - Continue construction, at least at modest pace
  - Strengthen training programs, consider expanded exchanges
  - Ensure regulator has needed capacity, independence, authority

- Ensure steady progress toward eventual nuclear waste repository – designed for range of potential wastes

Near-term choices China can make to maximize long-term nuclear options (II)

- Fund, facilitate RD&D on selected advanced systems, with
  - Reduced cost and economics
  - Increased passive (and demonstrable, understandable) safety
  - Simplified, accelerated construction
  - Improved ability to integrate with renewables, meet other energy needs
  - Strong security, proliferation-resistance

- Establish institutional approach to setting RD&D approaches that focus on addressing the most important constraints, ensuring goals are being met, cutting less promising projects

- Ensure several options demonstrated, prepared for commercial deployment by mid-century
  - Don’t focus only on technologies available soon
Near-term choices China can make to maximize long-term nuclear options (III)

- Avoid long-term lock-in on expensive, risky technologies such as plutonium reprocessing
  - Near-term construction of a large reprocessing plant would be
    - Expensive
    - Unneeded
    - Less safe, secure, proliferation resistant than storage
    - A major constraint on shifting to future approaches

- Invest in building public confidence
  - Real engagement with local communities – listening to and addressing concerns, giving them oversight roles
  - Fulfill promises step-by step
  - Incorporate data collection to allow learning-by-doing to improve effectiveness of public engagement over time

Backup slides if needed
Will new technology help? Ex.: fluoride high-temperature reactors

- Idea:
  - Fluoride salt coolant (> 1300°C boiling temp)
  - Fuel in TRISO particles embedded in graphite pebbles
  - High temperature → high efficiency, ability to make chemicals when electricity price is low → 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

Nuclear innovation: reasons for optimism

- 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

- 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

"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."

Nuclear innovation: a thought experiment

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

New policies likely more important than new technologies – for now

- 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?
Two things we shouldn’t do

- Plutonium reprocessing
  - Separates plutonium from spent fuel to recycle as new fuel
  - Could also provide plutonium for bombs
  - Fortunately, there’s plenty of uranium, reprocessing is expensive and provides only modest benefits, dry cask storage provides a safe alternative for decades

- Widespread uranium enrichment
  - Same technology used to produce low-enriched fuel for reactors can produce highly enriched uranium for bombs
  - Most countries with nuclear power do not enrich their own fuel

- Institutional steps can help
  - E.g., “fuel leasing” — offering lifetime fuel supply and spent fuel take-back for states that rely on international fuel supply

A personal view

- 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
Nuclear growth implies nuclear spread: the story so far

Governance indicators of emerging nuclear power states

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Source: Drawn from World Bank Governance Indicators and World Nuclear Assoc.
Safety culture matters:
Davis-Besse vessel head hole

Making nuclear energy broadly available

- 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

- 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

IAEA low and high estimates of nuclear capacity up to 2050

Nuclear is not likely to dominate the climate answer


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

New nuclear power in the United States – what are the prospects?

- Subsidies: 2005 EPAct provides production tax credit for first 6 plants; $18.5B in loan guarantees authorized (industry wants $100B); insurance against reg. delays
- Projects finishing half-built reactors moving ahead (e.g., Watts Bar 2) — not Gen. III/III+ technology
- First approved new-design projects are Vogtle 1+2 and Summer 3+4 (both AP-1000) — Vogtle $14 billion estimate (nearly $6000/kW)
- Economics has led several companies to reconsider
  — $2-$5 natural gas; no carbon price
  — Escalating nuclear construction costs, nuclear “risk premium”
  — Post-Fukushima worries and politics a smaller factor
- Prognosis: no unsubsidized plants in unregulated markets likely
Expanding nuclear energy need not increase terrorist nuclear bomb risks

- 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

Preventing nuclear proliferation

- 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

- 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

Nuclear role in 3 greatest global energy challenges

- 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
Large-scale nuclear growth implies nuclear spread – the picture so far

The scale of the control problem...

- 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**

- 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

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**A fragile revival? TMI + Chernobyl stopped nuclear growth**

[Chart showing nuclear reactors and net operating capacity in the world from 1956 to 2004.]
Fukushima — what happened?

- Prolonged station blackout
  - Earthquake cut off off-site power
  - Tsunami swamped diesel generators (in basement)

- Also loss of heat sink
  - Tsunami swamped ocean pumps

- Result: cooling systems failed
  - Units 1-3 melted
  - Hydrogen explosions destroyed buildings
  - Major radiation releases (est.: ~15% of Chernobyl, but high uncertainty)
  - Large-scale evacuation, economic disruption, fear and stress
  - Many questions remain

Recommended next steps to respond to Fukushima

- First: more stringent national and international standards
  - Ability to respond to prolonged loss of off-site power
  - Ability to respond to damage to cooling systems
  - Emergency response
  - Protection against terrorist attack
  - Seismic, flood safety
  - Management of spent fuel

- Second: independent, international peer review
  - All countries operating major nuclear facilities should request

- Third: toward more binding obligations

- Fourth: expanded int’l cooperation — exchanging experience and…

- Long-term: shift toward greater “safety by design” and “security by design” in new reactors
Fukushima: evolving narratives

- The 1st story: extraordinary bad luck, few lessons
  - Extraordinarily bad luck: tsunami was so far beyond what could reasonably be expected that no one could realistically be expected to be prepared for such things
  - Few real lessons for other facilities, keep on as before

- The evolving story: a preventable tragedy, many lessons
  - Japanese had clear data showing the danger of large tsunamis years before
  - Many aspects of Japanese system — lack of real independence of the regulator, lack of authority for on-site manager, belief in absolute safety, pro-nuclear bias of “nuclear village” contributed to disaster
  - Many of these weaknesses — and a variety of related vulnerabilities — exist in many other countries as well
  - Happened in one of the richest, most experienced countries, with high regulatory effectiveness, low corruption — sobering reality

Fukushima: questions and lessons

- Questions:
  - Why didn’t Japanese regulators, operators, respond to data indicating a risk of very large tsunamis?
  - How can we structure incentives in organizations to get people to focus on fixing low-probability, high-consequence risks?
  - How can we avoid regulators becoming “captured” by the industries they regulate?

- Lessons:
  - Need better ability to cope with prolonged loss of power
  - Need faster ability to maintain, restore cooling
  - Need safer management of spent fuel pools
  - Need stronger emergency response
  - Need better approaches to public, international information and communication
  - Existing regulatory approaches are insufficient
Nuclear safety: complexities

- Huge quantity of energy, radioactive toxicity in small volume in core
  - Must be cooled continuously, or “meltdown” will occur
  - “Fire that won’t go out” — reactor keeps generating heat from intense radioactive decay, needs cooling, long after shut-down
  - Reactors need (a) water and (b) electricity to operate cooling systems to prevent accidents

- “Defense in Depth” philosophy
  - Multiple layers of protection — the fuel itself, the reactor vessel, the containment
  - Redundant safety systems
  - Are complex, tightly coupled systems inherently prone to accidents?

- Two major radiation releases in 14,400 reactor-years for commercial reactor — >10x more than regulatory safety goals

Fukushima: global reactions

- National reviews, widely varying decisions
  - Many countries: “stress tests,” in-depth inspections and reviews, more stringent safety standards in key areas
  - A few countries: nuclear phase-out (e.g., Germany, Switzerland)
  - Largest markets: likely continued nuclear growth (e.g., China, India, Russia…)

- Global institutions: modest steps
  - Little consensus at IAEA ministerial — new IAEA safety plan quite limited (though still unfolding, could strengthen)
  - WANO reviewing its procedures
  - Key focus is still national sovereignty over international accountability
  - Stark contrast to the response to Chernobyl — which led to the construction of much of the current safety regime

Security being almost entirely missed in these discussions…
Nuclear costs: a forgetting curve?

Nuclear energy’s share of the emissions gap under the IAEA high growth case
For a nuclear “wedge,” huge increase in construction needed

- 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