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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

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- 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

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- 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

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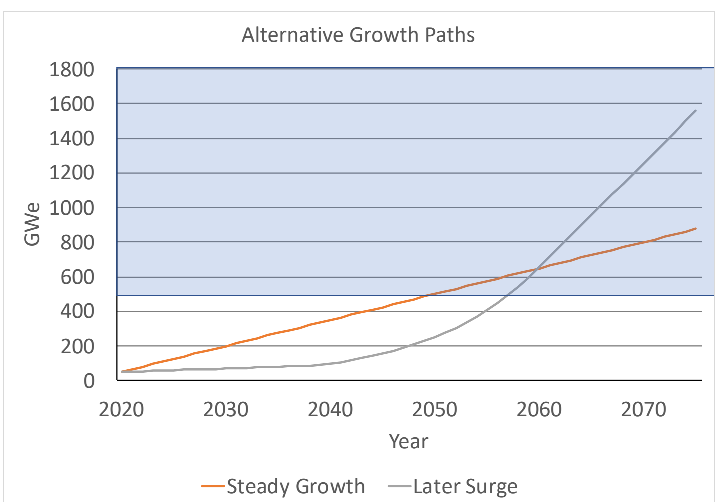

Nuclear energy provides a tiny share of China's energy today

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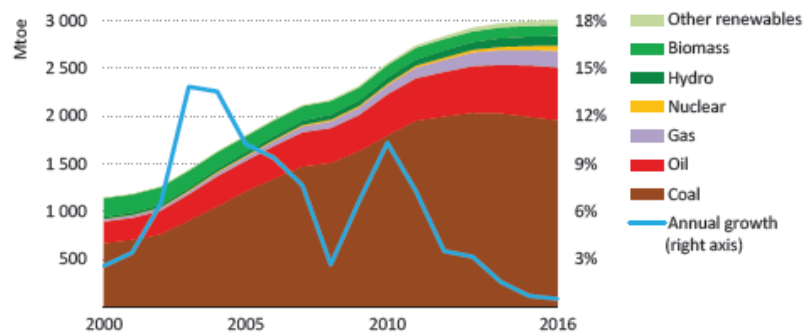
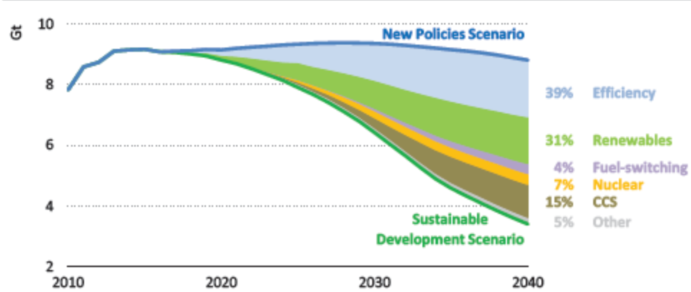


Growth in energy demand has slowed, coal (probably) has peaked, developments suggest that China's energy future may look quite different from its past

Source: IEA, *World Energy Outlook 2017*

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

Contributions to Emissions Reduction in China through 2040



Energy efficiency and renewables are China's key mitigation options

Source: IEA, *World Energy Outlook 2017*

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

Particulates may be more important than climate in driving clean energy in China

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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

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- 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

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- 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

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- 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

Degree of constraint	Moderate
Policy impact	High
Technology impact	Moderate-High

Nuclear costs: most experts are not expecting a breakthrough

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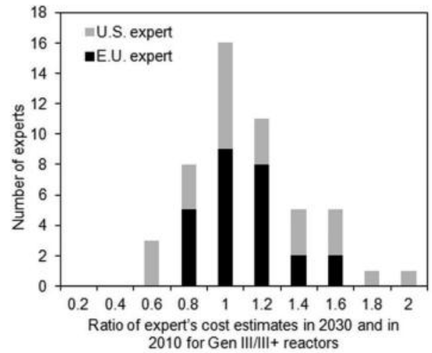

Source: Anadon, Bosetti, Bunn, Catenacci, Lee, *Environmental Science & Technology,* Vol. 46, 2012

- Most experts in 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

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- 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

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- 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

Degree of constraint	High
Policy impact	Moderate
Technology impact	High

Security risks – also important

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- 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

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- 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

Degree of constraint	Moderate
Policy impact	Moderate
Technology impact	High

Extensive Belfer analysis on nuclear security in China is available

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- 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

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- 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

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- 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

Degree of constraint	High
Policy impact	Moderate
Technology impact	Moderate-High

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

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- *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

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- 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)

Degree of constraint	Moderate
Policy impact	Moderate-High
Technology impact	Moderate

Limited government and industry capacity may prove to be important constraints

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- 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

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- 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

Degree of constraint	Moderate
Policy impact	High
Technology impact	Moderate-High

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

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- 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

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- 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

Degree of constraint	Moderate
Policy impact	High
Technology impact	Low

Integration into renewable-heavy energy system may require different approaches

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- 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

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- 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

Degree of constraint	Moderate
Policy impact	Low
Technology impact	Moderate-High

Proliferation resistance – an often overlooked issue

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- 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

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- 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…

Degree of constraint	Moderate
Policy impact	Moderate-High
Technology impact	Moderate

Uranium supply – not likely a serious constraint in this century

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- 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

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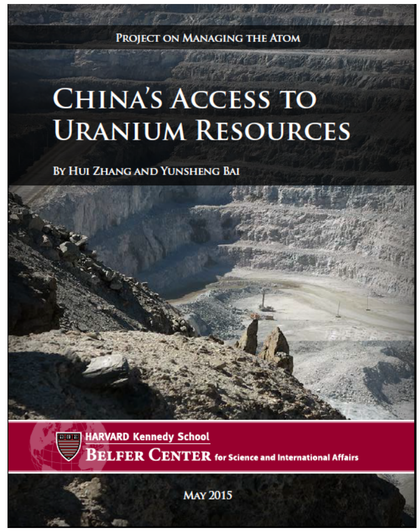
- Policy:
  - Invest in ensuring adequate supply (including in further exploration)
  - Avoid being snowed by claims of imminent shortage
- Technology (advanced reactors and fuel cycles):
  - Extending the U resource not urgently needed
  - Some "breeding in place" systems can potentially extend U resource 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

Degree of constraint	Low
Policy impact	Moderate
Technology impact	High

Belfer analysis on uranium supply for China's nuclear growth

31

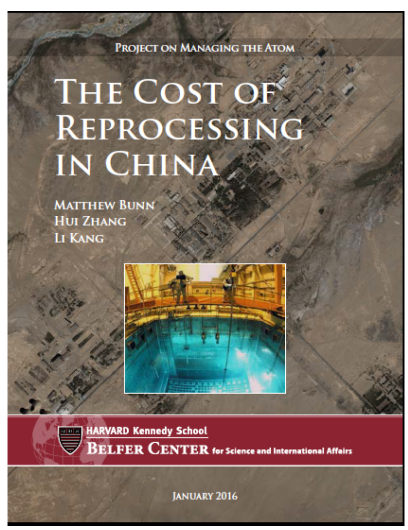
- Hui Zhang and Yunsheng Bai, *China's Access to Uranium Resources,* May 2015
  https://tinyurl.com/y7dvw556



Belfer analysis on reprocessing in China

32

- Matthew Bunn, Hui Zhang, and Li Kang, *The Cost of Reprocessing in China,* January 2016
  https://tinyurl.com/ybtsaqvs



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

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- 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)

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- 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)

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- 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

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

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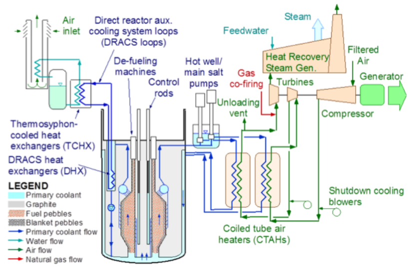
- Idea:
  - Fluoride salt coolant (> 1300° C boiling temp)
  - Fuel in TRISO particles embedded in graphite pebbles
  - High temperature → high efficiency, ability to make chemicals when electricity price is low → much better economics
  - Excellent safety: "I can't figure out how to cause a release with this reactor"
- Conceived at MIT, Berkeley, and Wisconsin
  - China funding 1st test systems



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

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?

Two things we shouldn't do

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- 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 produced 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

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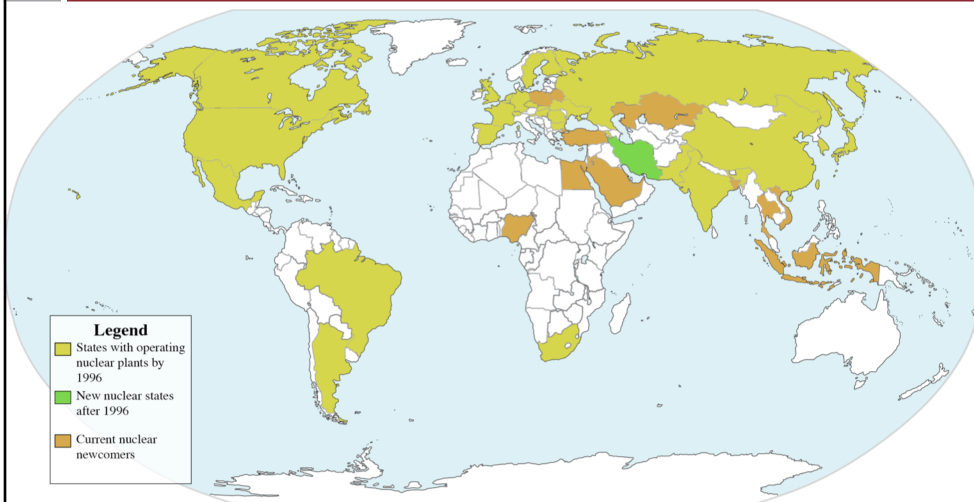
- We should be doing what we can to fix the problems that have constrained nuclear growth, so that it can really be an expandable option to help cope with climate change
- Will be more difficult to cope with climate without a significant contribution from nuclear – but will be difficult to get a significant 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

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.**

Safety culture matters: Davis-Besse vessel head hole

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Source: FirstEnergy

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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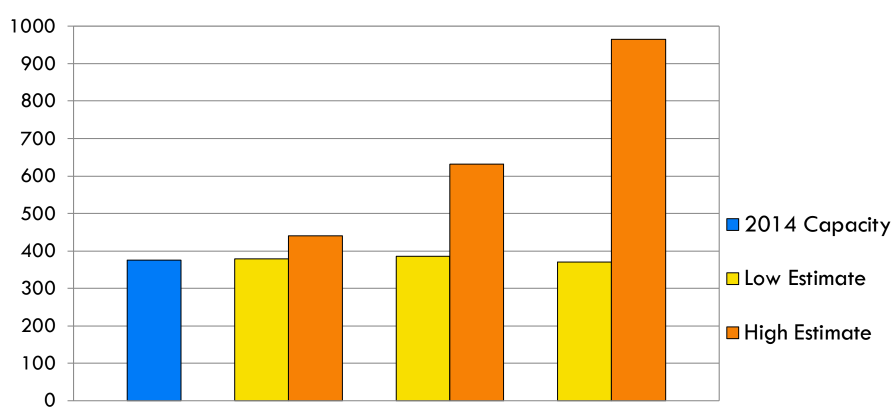
- **Electricity beyond the baseload**
  - Nuclear reactors could generate electricity when needed, storable products (e.g., hydrogen) when not
  - Hydrogen could provide additional peaking power – could even back up intermittent renewables
  - Economics as yet unproven
- **Transportation fuel**
  - Electricity 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

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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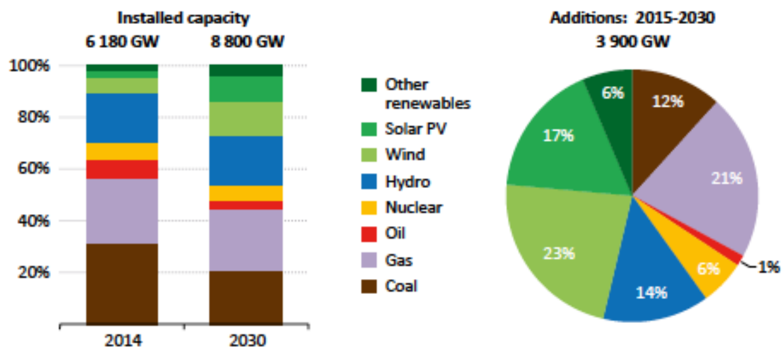

Source: International Energy Agency, *World Energy Outlook 2015*

- 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?

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- 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 <u>need not</u> 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

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 <u>successful</u> + <u>resilient</u>
  - 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

Nuclear role in 3 greatest global energy challenges

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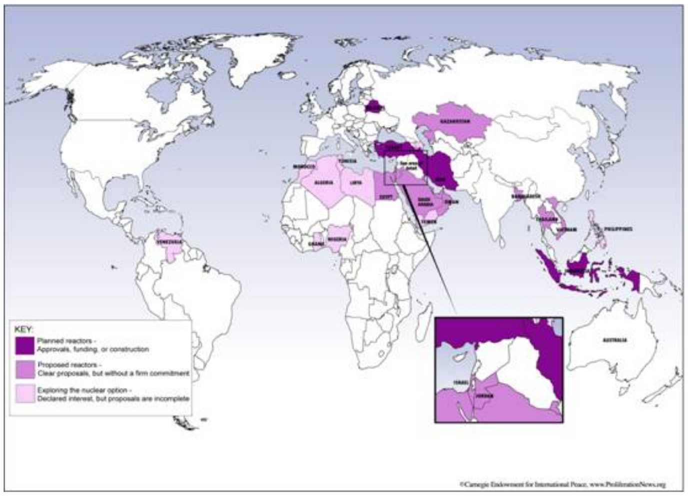
- Energy supply without greenhouse emissions
  - Massive growth required for nuclear to play a significant role
- Reducing energy supply vulnerabilities (esp. oil)
  - Nuclear currently provides baseload electricity, oil little-used for that purpose in most countries
  - Nuclear cannot currently make 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

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

57



Source: **Carnegie Endowment for International Peace**

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

A fragile revival? TMI + Chernobyl stopped nuclear growth

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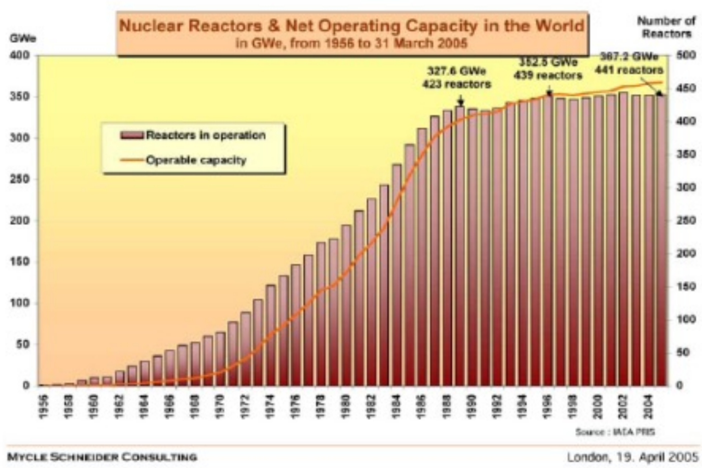

Fukushima – what happened?

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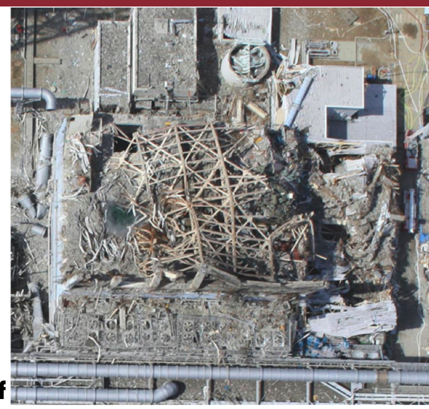
- Prolonged station blackout
  - Earthquake cut off off-site power
  - Tsunami swamped diesel generators (in basement)
- Also loss of heat sink
  - Tsunami swamped ocean pumps
- Result: cooling systems failed
  - Units 1-3 melted
  - Hydrogen explosions destroyed buildings
  - Major radiation releases (est.: ~15% of Chernobyl, but high uncertainty)
  - Large-scale evacuation, economic disruption, fear and stress
  - Many questions remain



Source: Air Photo Service, Japan

Recommended next steps to respond to Fukushima

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- 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

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- 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

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- 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

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

Fukushima: global reactions

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- 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?

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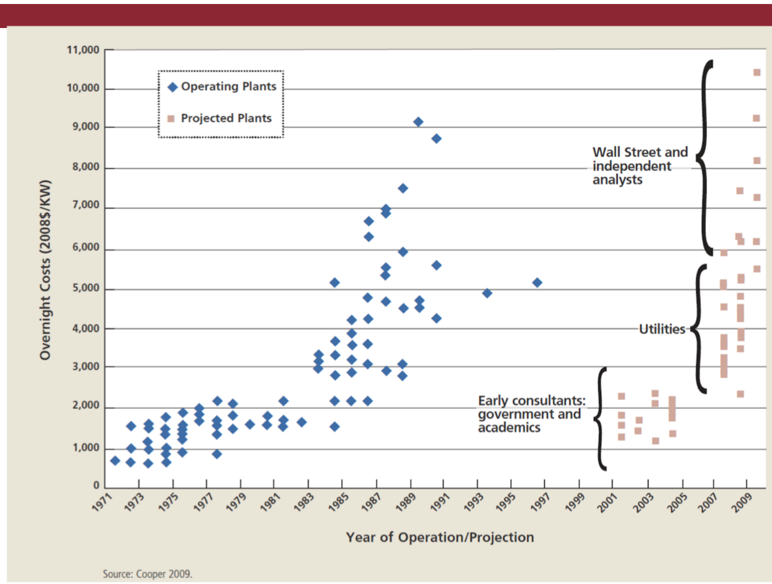

Nuclear energy's share of the emissions gap under the IAEA high growth case

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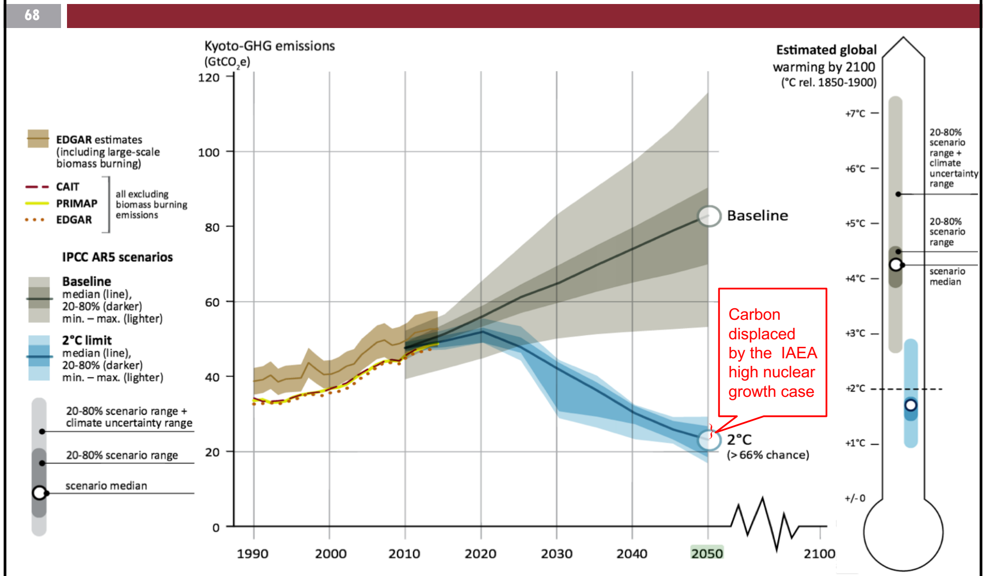

For a nuclear "wedge," huge increase in construction needed

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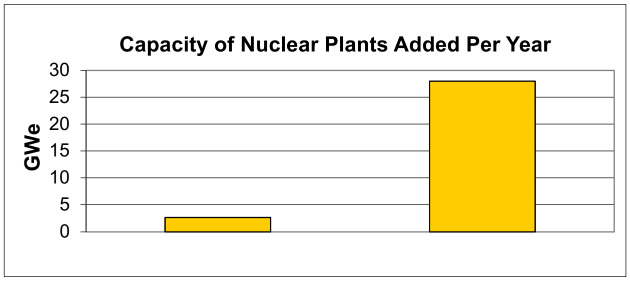

- Need to shift from 3 to 28 GWe/yr
- Nuclear must become dramatically *more* attractive to governments and utilities than it was before Fukushima – a difficult challenge
- Any further disaster, from accident or terrorism, would doom any realistic prospect for growth on this scale