The Future of Nuclear Energy in a Carbon-Constrained World

- Findings from a new MIT study -

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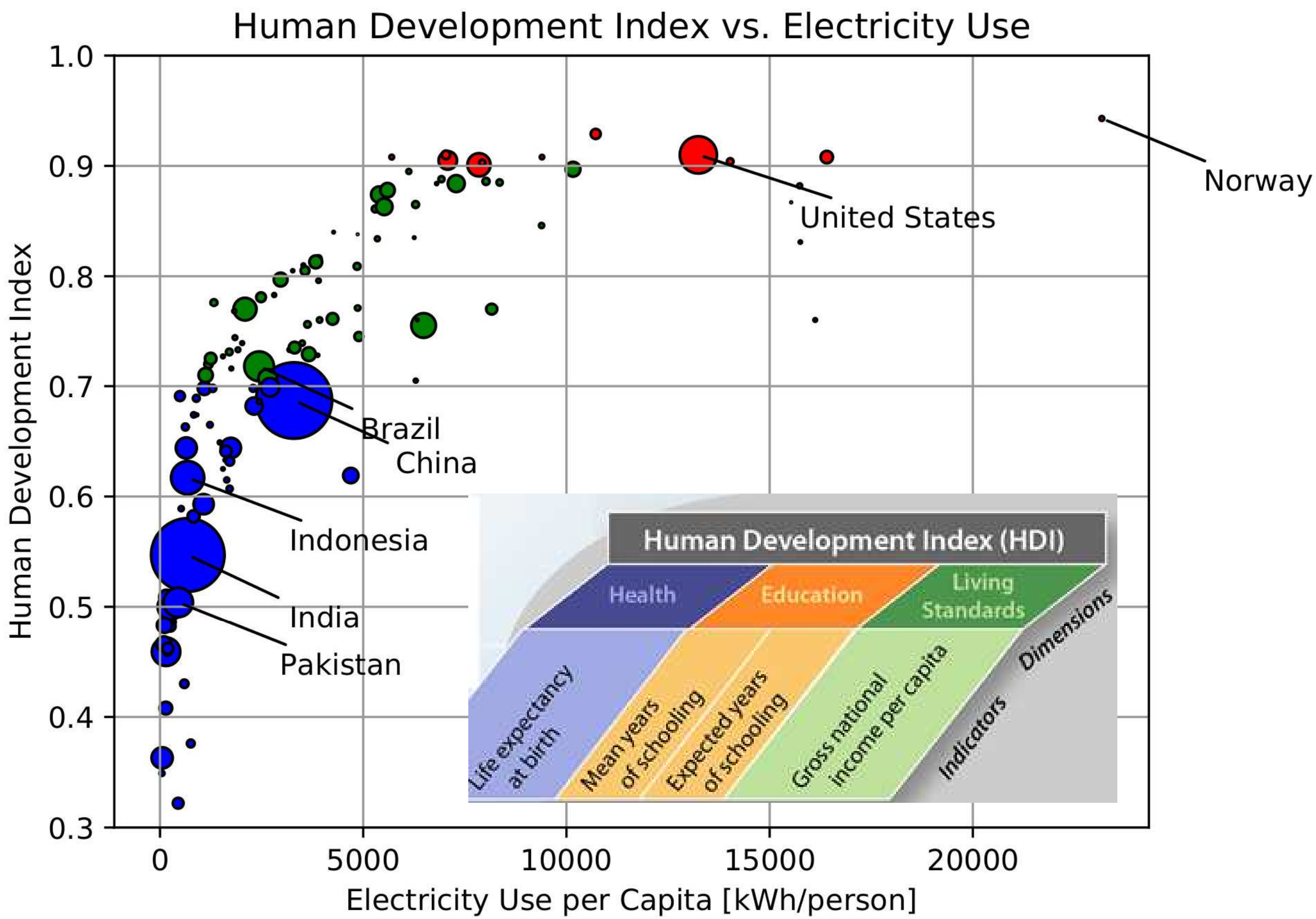
MIT

MITei
MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

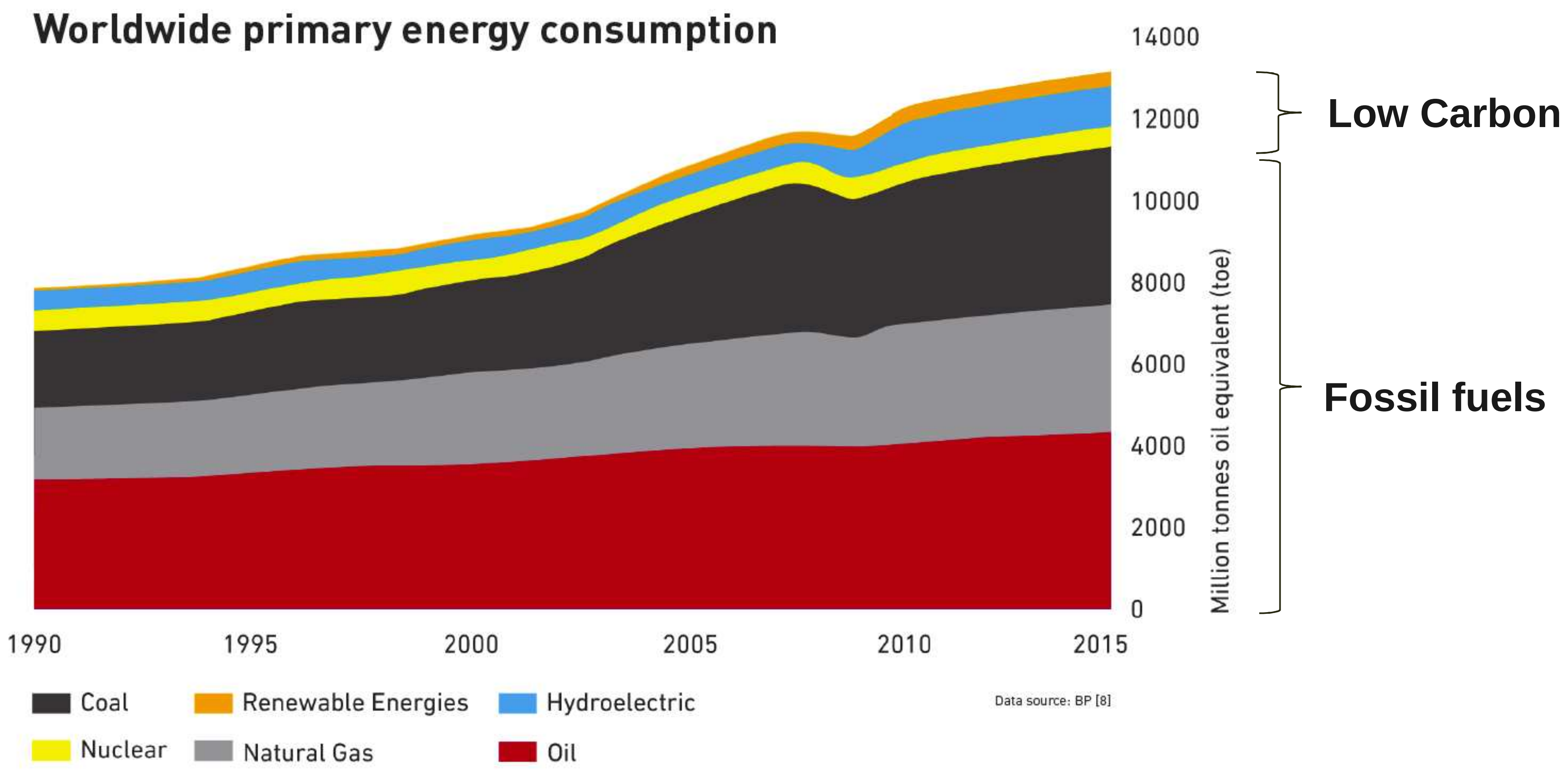
The big picture

The World needs a lot more energy



Global electricity consumption is projected to grow 45% by 2040

The key dilemma is how to increase energy generation while limiting global warming



CO_2 emissions are actually rising… we are NOT winning!

Can we decarbonize using *only* wind and solar?

Some say yes

IPCC: Renewables to Supply 70%-85% of Electricity by 2050 to Avoid Worst Impacts of Climate Change

Mark Jacobson
(Civil and Environmental Eng., Stanford)
"There is no technical or economic barrier to transitioning the entire world to 100 percent clean, renewable energy with a stable electric grid at low cost"

Barbara Hendricks
(Minister for the Environment, Germany)
"The Energiewende is the cornerstone of our climate policy. We want to encourage other countries to follow our example."

Some say no

Union of Concerned Scientists For Nukes!

Activist group finally recognizes that it can't achieve its energy and climate goals without nuclear power.

We need a low-carbon electricity standard. A well-designed LCES could prevent the early closure of nuclear power plants while supporting the growth of other low carbon technologies.

Emmanuel Macron (President of France)

"My priority in France, Europe and internationally is CO_2 emissions and (global) warming… What did the Germans do when they shut all their nuclear in one go?… They developed a lot of renewables but they also massively reopened thermal and coal. They worsened their CO_2 footprint, it wasn't good for the planet. So I won't do that."

Ken Caldeira, Kerry Emanuel, James Hansen, Tom Wigley (Climatologists)

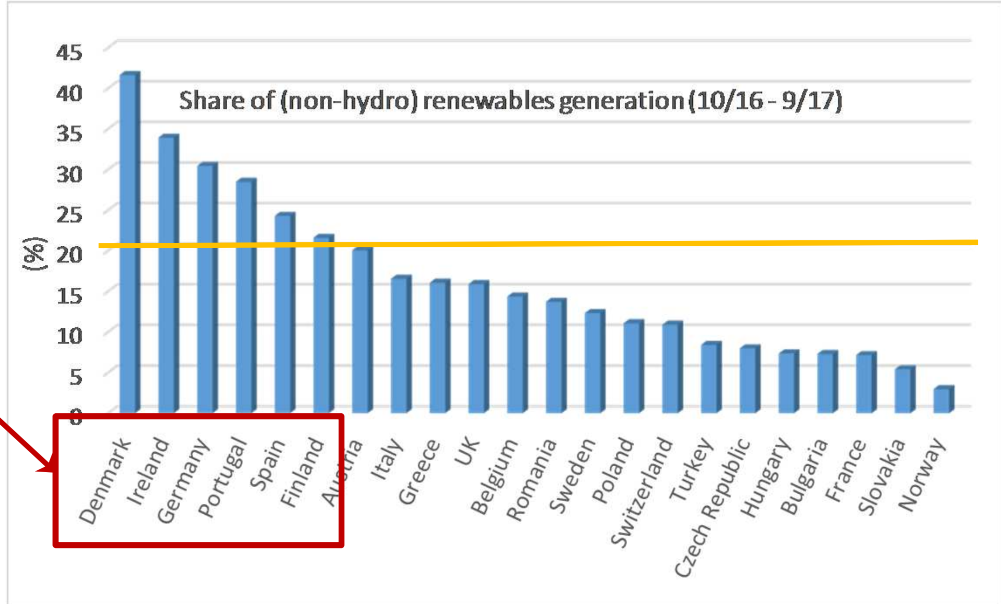
"There is no credible path to climate stabilization that does not include a substantial role for nuclear power."

Ernie Moniz (former U.S. Energy Secretary)

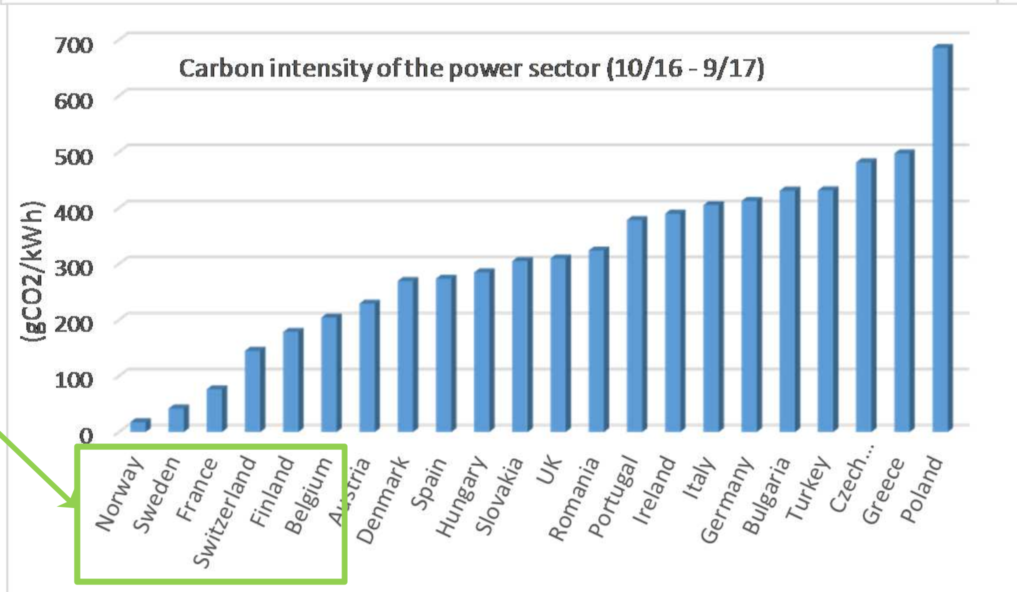
"I know we can't get there [meeting carbon dioxide reduction goals] unless we substantially support and even embolden the nuclear energy sector."

Let’s look at the evidence

EU countries with high capacity of solar and wind



EU countries with low carbon intensity

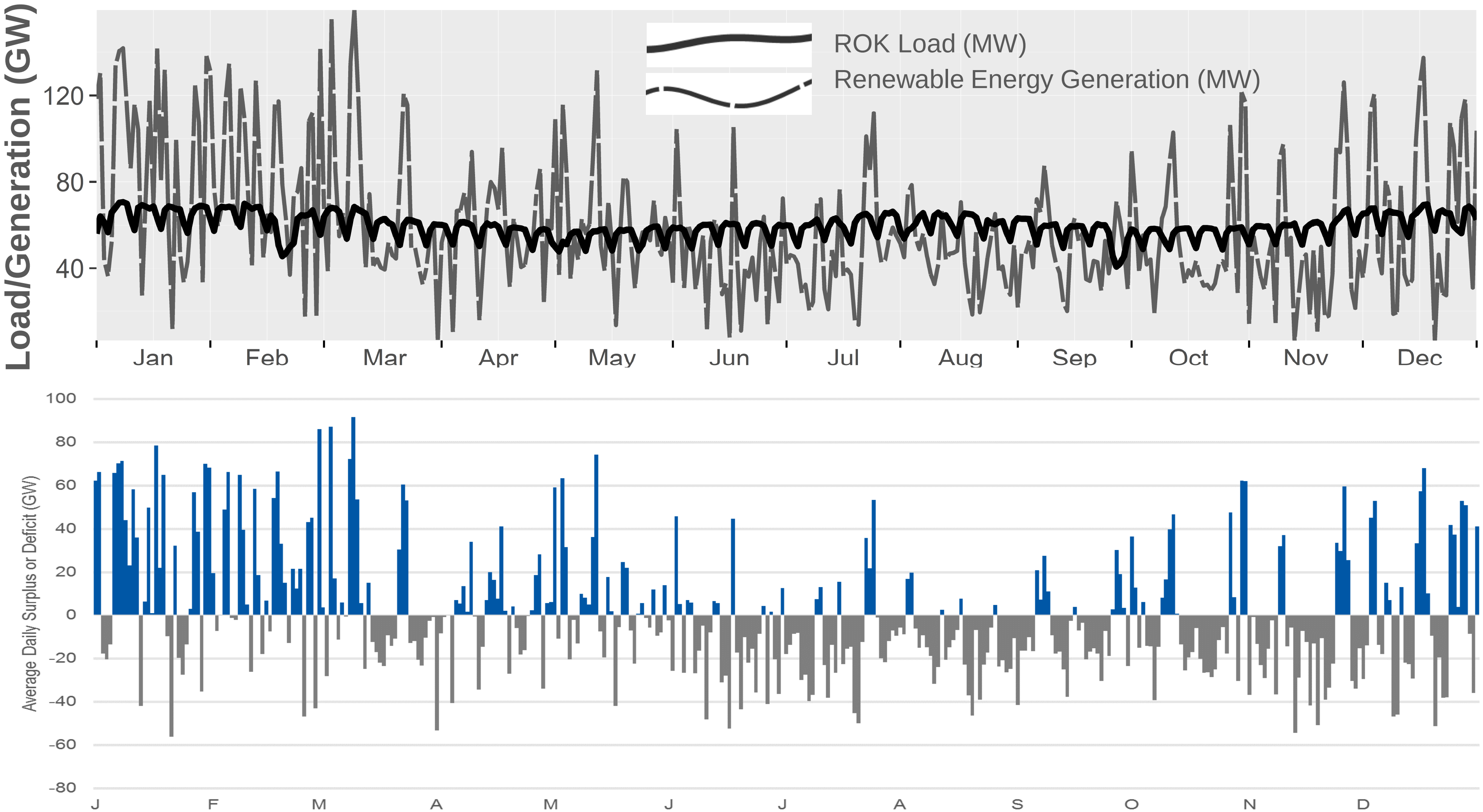


Data source: European Climate Leadership report 2017 (Energy for Humanity, Tomorrow, the Electricity Map Database)

Low carbon intensity correlates with nuclear and hydro

The problem with the all-renewable scenarios (South Korea example)

Scenario: 50% solar + 50% wind; used 2015 Korea wind and solar daily-averaged capacity factors

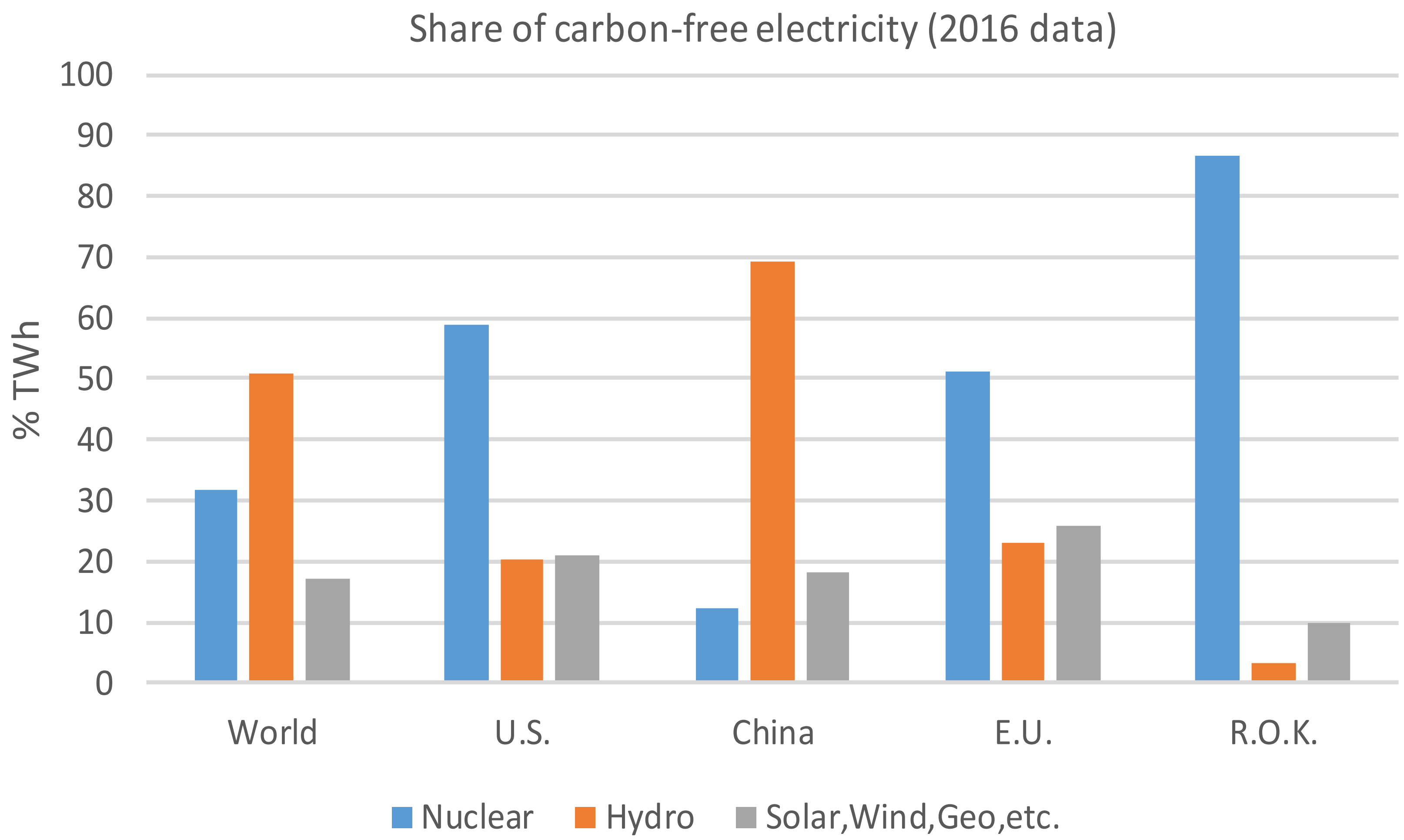


Requires >80 GW of energy storage capacity (batteries) ⇒ cost is going to be enormous, even assuming Korea has enough land to accommodate all the required solar/wind capacity

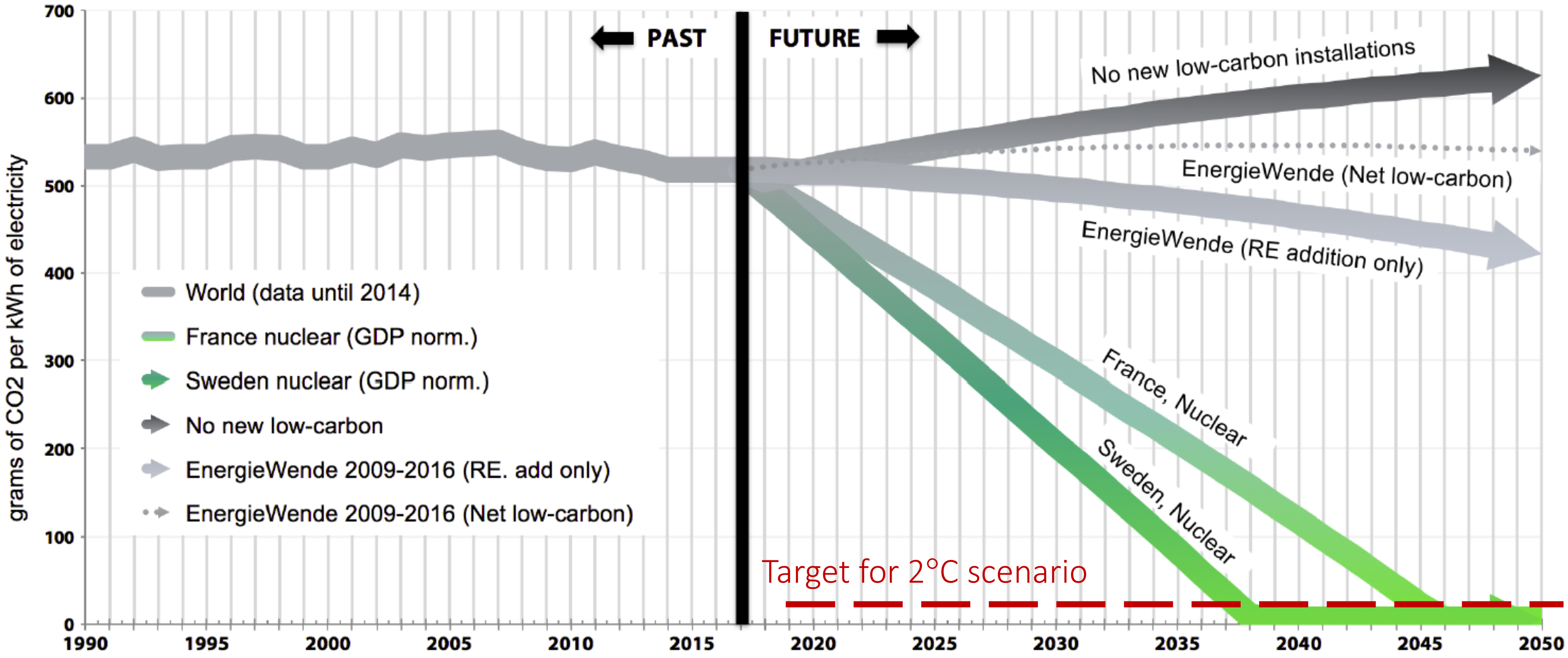
(Source: Clean Air Task Force, Cambridge, MA, January 2019)

Do we need nuclear to *deeply* decarbonize the power sector?

Nuclear is already the largest source of emission-free electricity in the US and Europe now



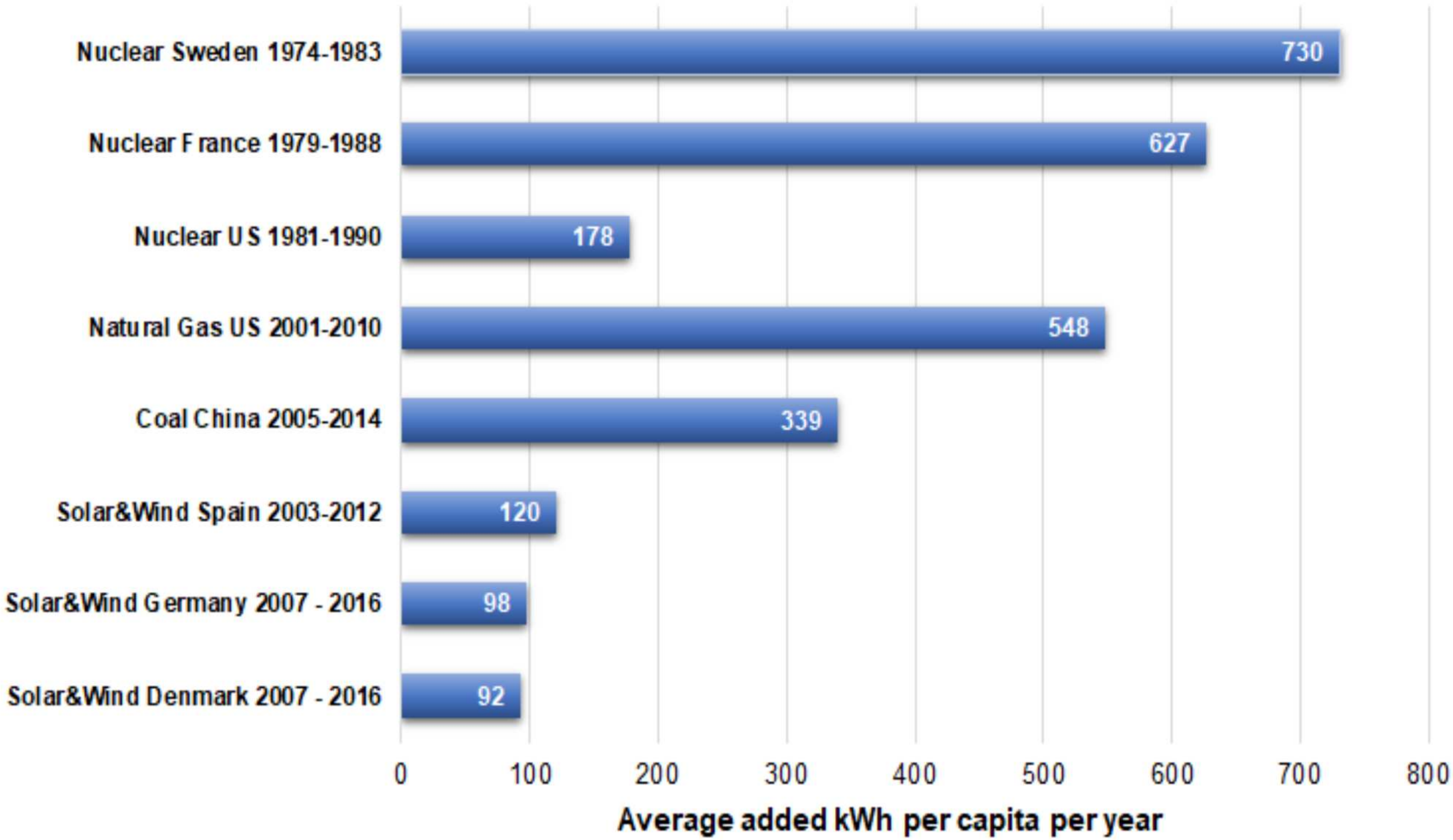
The scalability argument



Source: Staffan Qvist, 2018

A nuclear build-up (at historically feasible rate) can completely decarbonize the World's power sector within 30 years

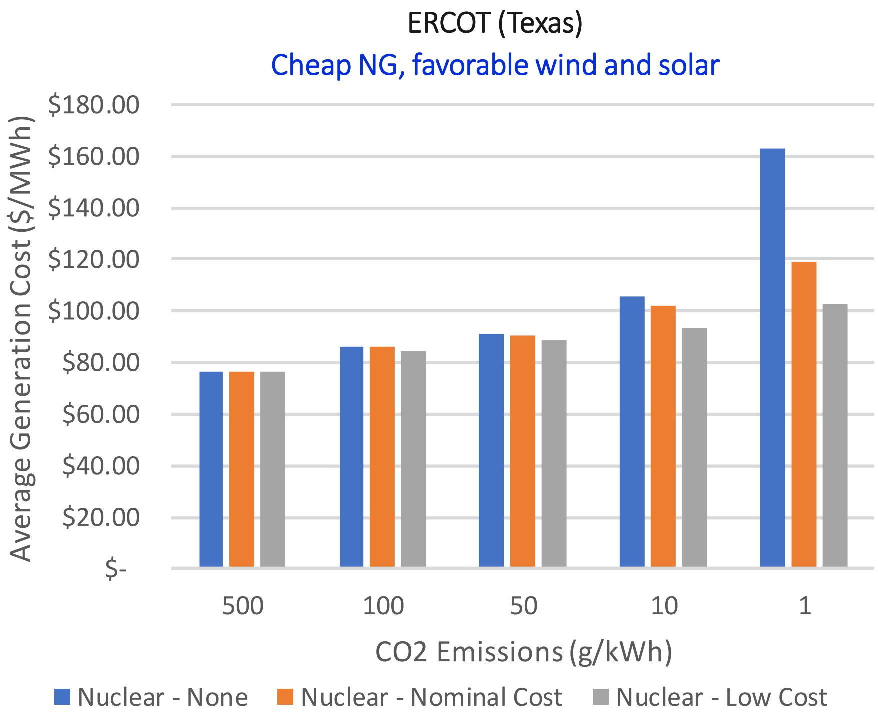
The scalability argument (2)

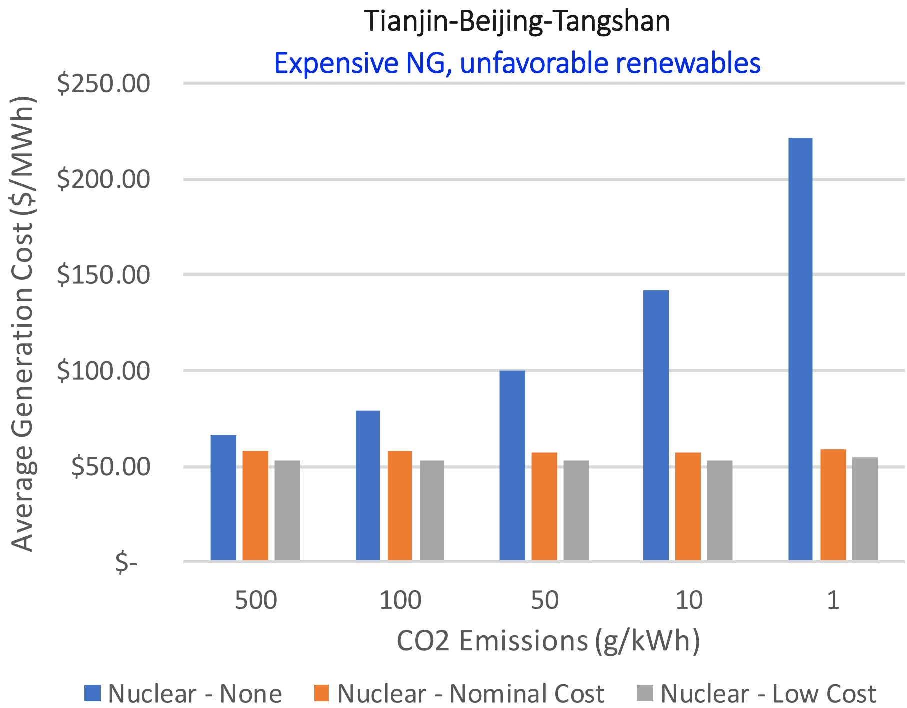


Nuclear electricity can be deployed as quickly as coal and gas at a time of need

The economic argument

Excluding nuclear energy drives up the average cost of electricity in low-carbon scenarios

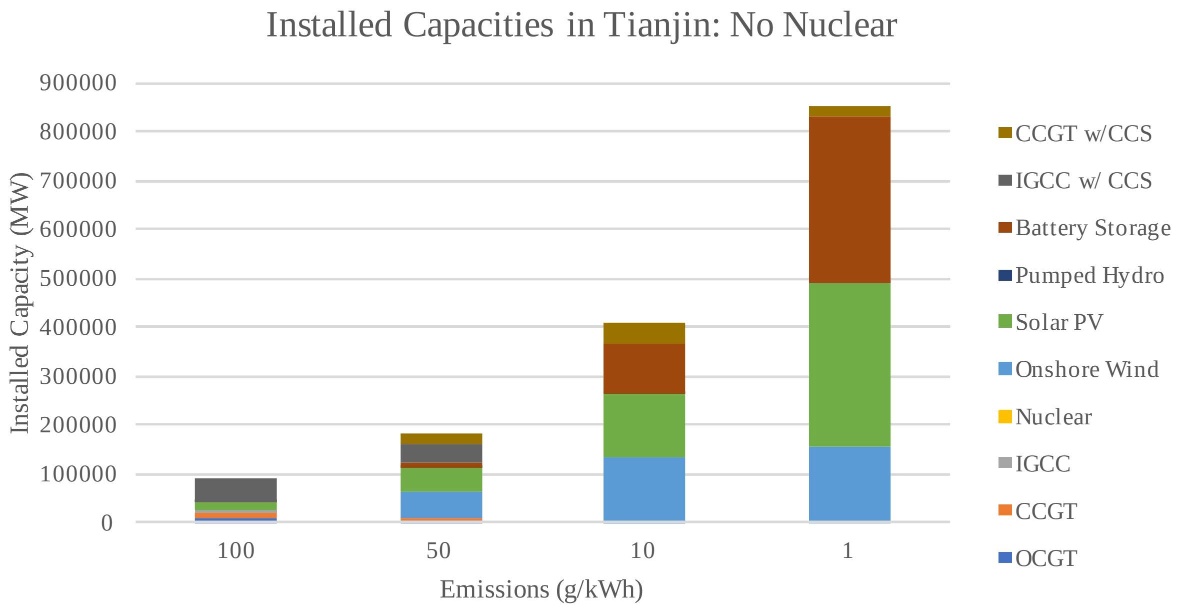




Simulation of optimal generation mix in power markets

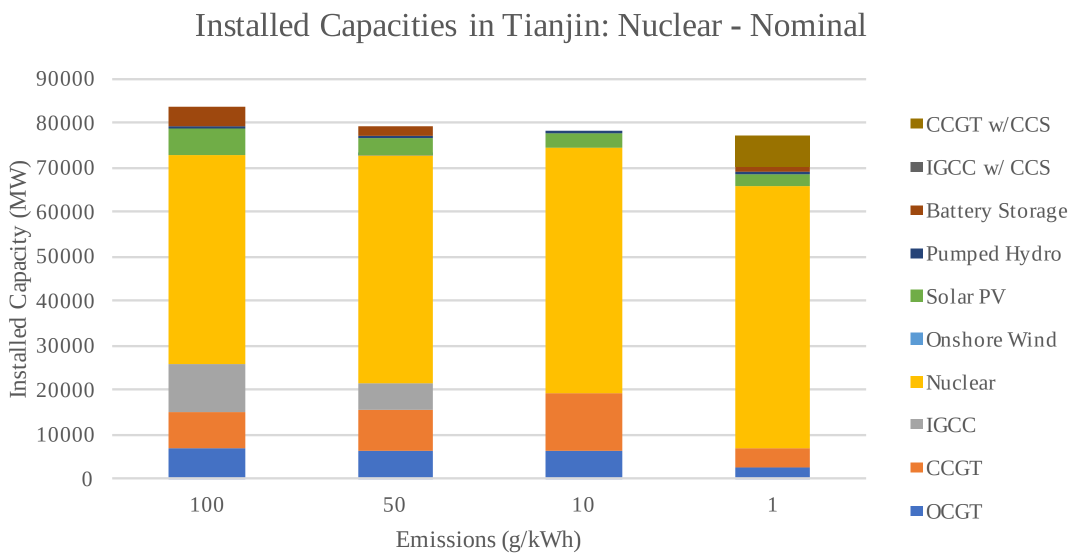
MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates

Tianjin-Beijing-Tangshan Results

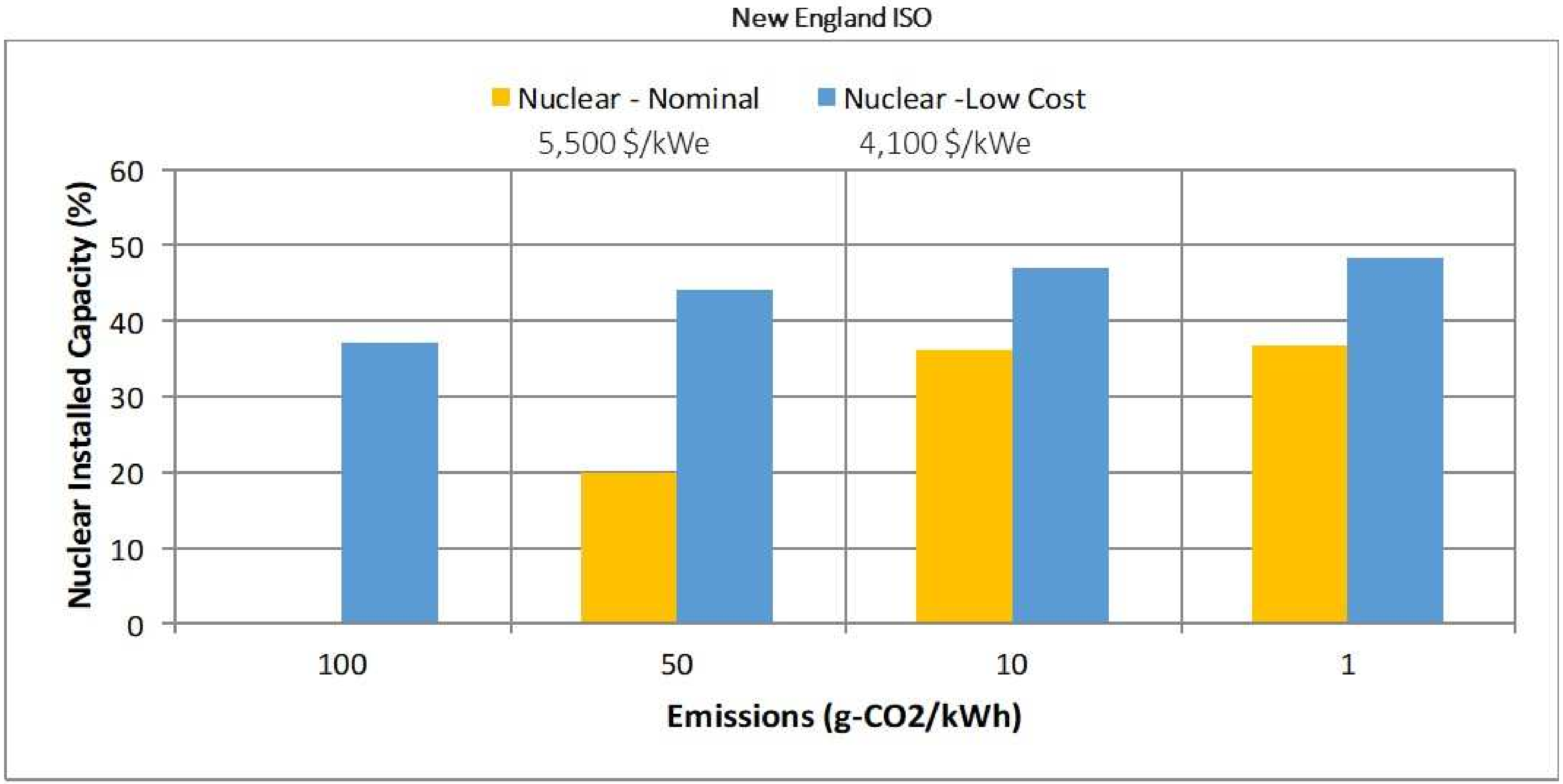


To meet constraint without nuclear requires significant overbuild of renewables and storage

By contrast, installed capacity is relatively constant with nuclear allowed

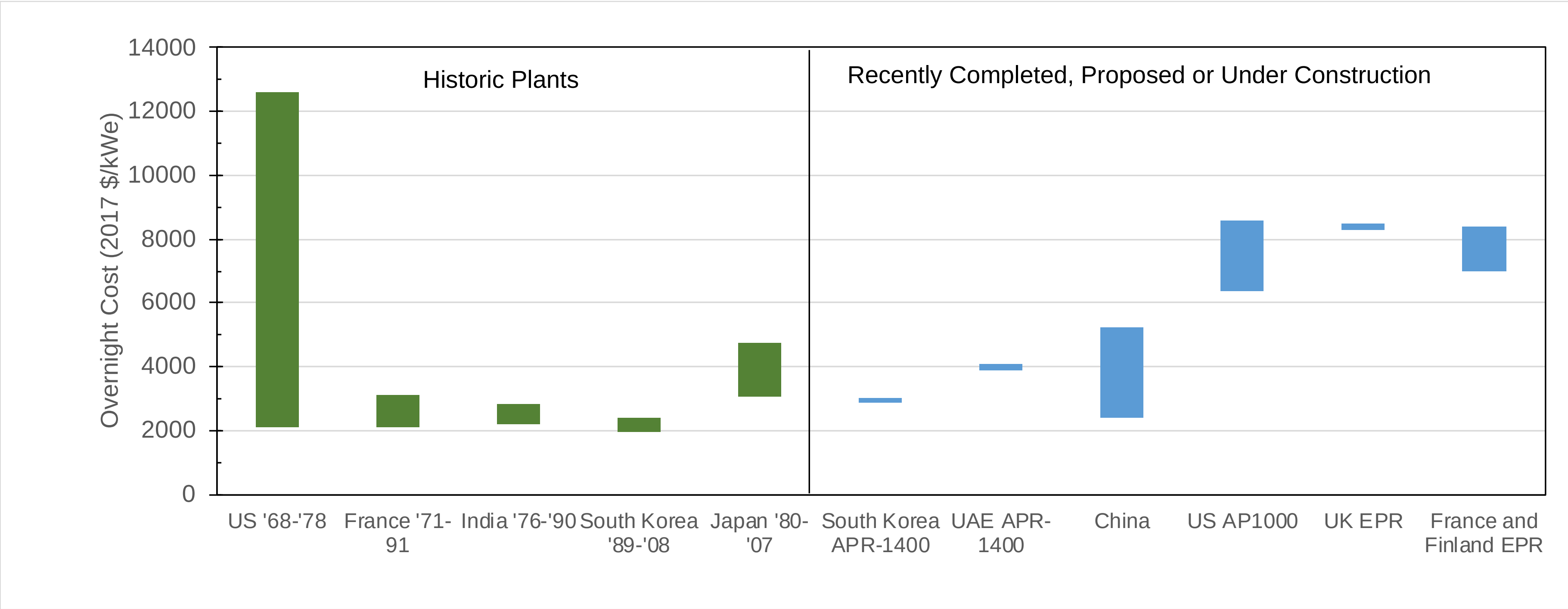


The business opportunity for nuclear expands dramatically, even at modest decarbonization targets, if its cost decreases



The cost issue

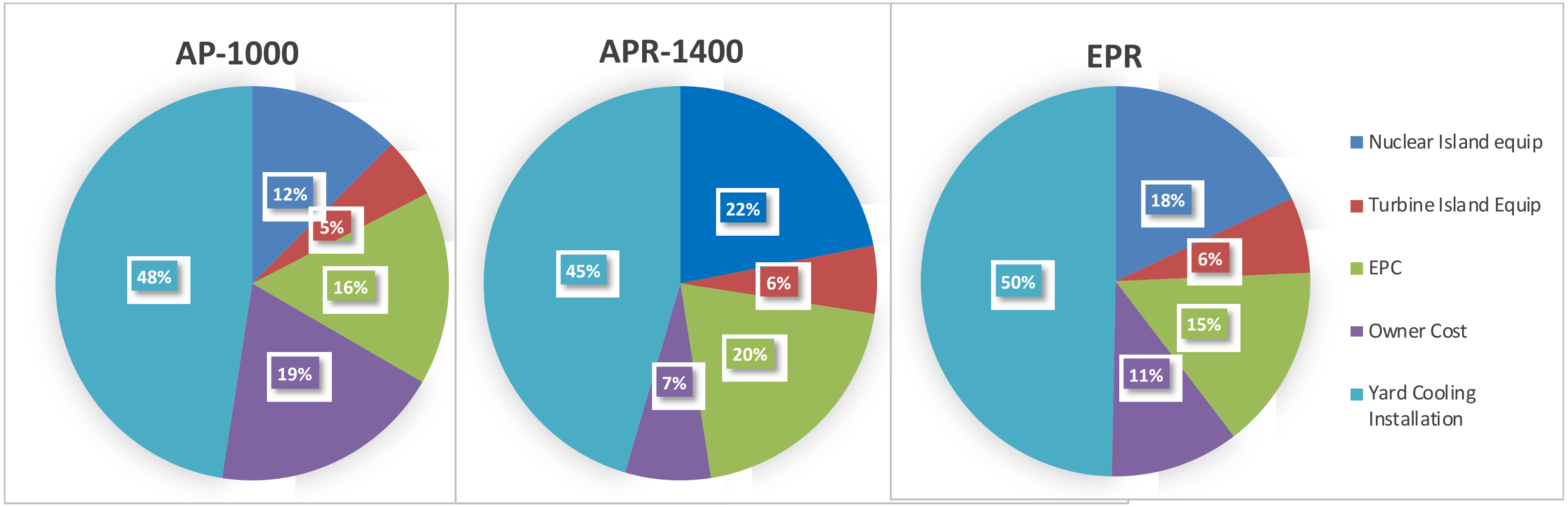
Nuclear Plant Cost



An increased focus on using proven project/construction management practices will increase the probability of success in execution and delivery of new nuclear power plants

- Complete design before starting construction,
- Develop proven NSSS supply chain and skilled labor workforce,
- Include fabricators and constructors in the design team,
- Appoint a single primary contract manager,
- Establish a successful contracting structure,
- Adopt a flexible contract administrative processes to adjust to unanticipated changes,
- Operate in a flexible regulatory environment that can accommodate changes in design and construction in a timely fashion.

Nuclear Plant Cost (2)



Sources:
AP1000: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11
APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication, 2017

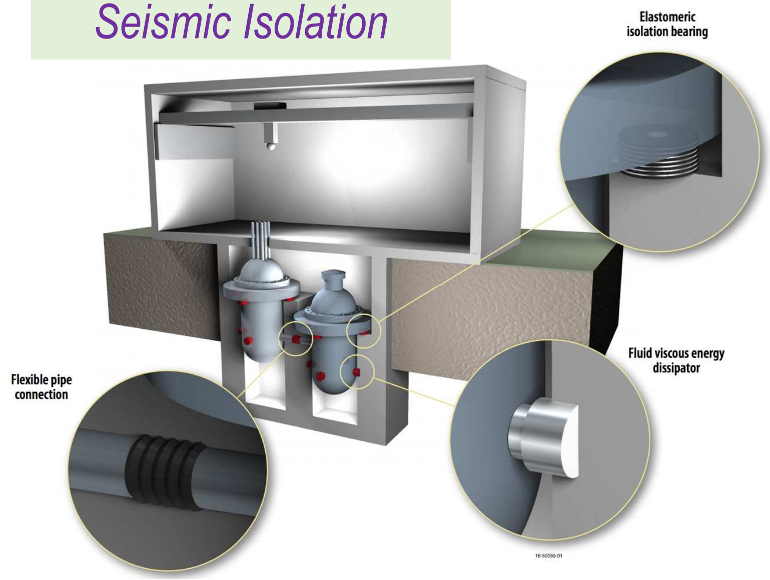
Civil works, site preparation, installation and indirect costs (engineering oversight and owner's costs) dominate

A shift away from primarily field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants

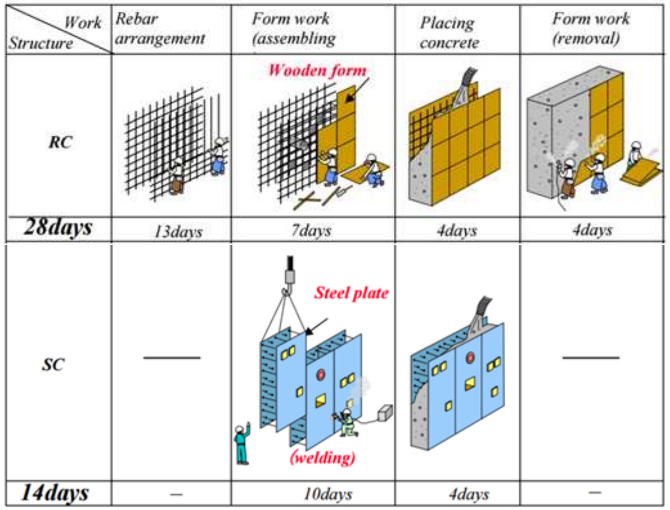
(True for all plants and all technologies)

Standardization on multi-unit sites

Seismic Isolation



Advanced Concrete Solutions



Structure \ Work	Rebar arrangement	Form work (assembling)	Placing concrete	Form work (removal)
RC		Wooden form		
28days	13days	7days	4days	4days
SC	—	Steel plate (welding)		—
14days	–	10days	4days	–

Modular Construction Techniques and Factory Fabrication

With these innovations it should be possible to:

- Shift labor from site to factories $\Rightarrow$ reduce installation cost
- Standardize design $\Rightarrow$ reduce licensing and engineering costs + maximize learning
- Shorten construction schedule $\Rightarrow$ reduce interest during construction

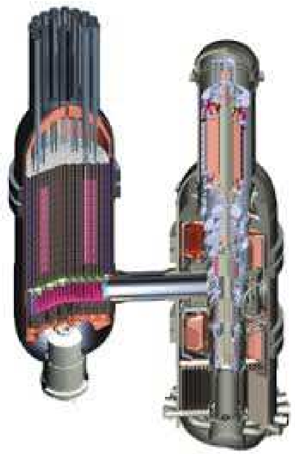
We judge the potential capital cost reduction in the range of 20-50%

Advanced reactors

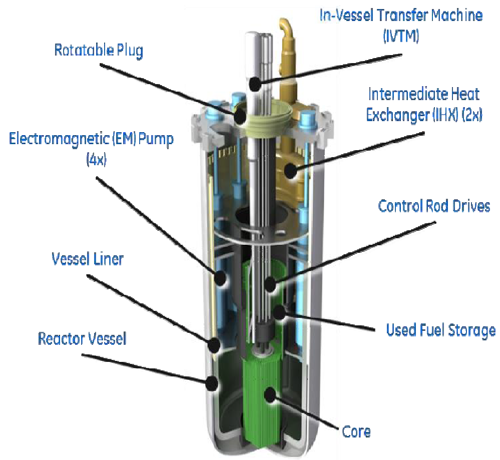
Advanced Reactors (SMRs and Gen-IV)

Small Modular Reactors

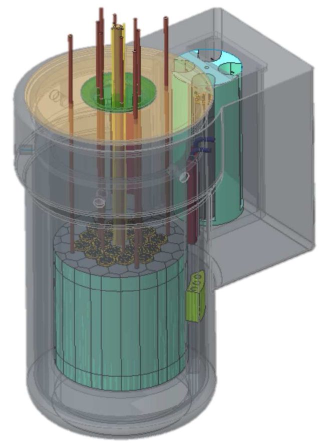
High Temperature Gas-Cooled Reactors



Sodium Fast Reactors

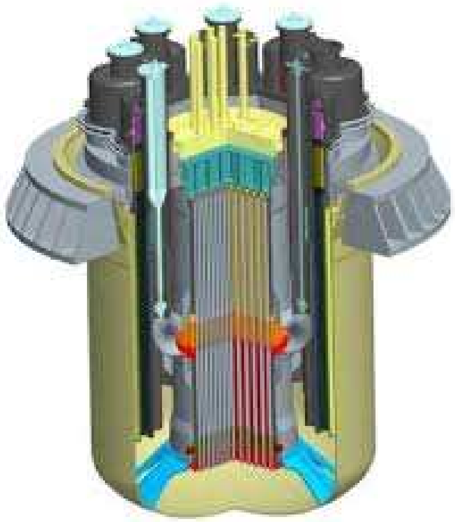


Fluoride High Temperature Reactors

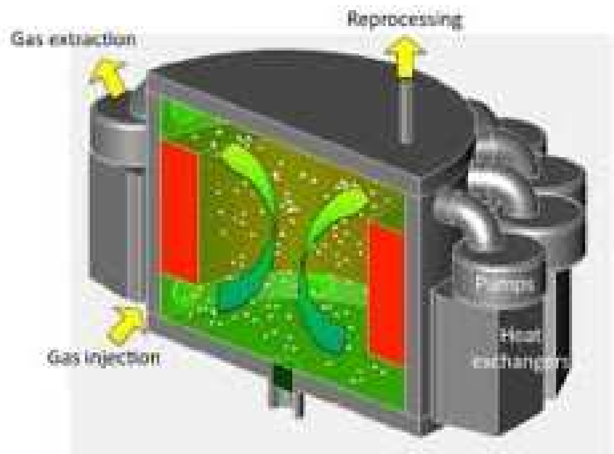


Gas-Cooled Fast Reactors

Lead-Cooled Fast Reactors



Molten Salt Reactors



Potential Advanced Reactor Missions

- Cheap grid-connected electricity
- Process heat and high temperature applications
- Flexible operation
- Microreactors for off-grid electricity and heat
- Desalination
- Improved fuel cycle (fuel recycling/waste burning)

What is the value proposition for advanced reactors?

Demonstrated inherent safety attributes:

- No coolant boiling
- High thermal capacity
- Strong negative temperature/power coefficients
- Strong fission product retention in fuel, coolant and moderator
- Low chemical reactivity

+

Engineered passive safety systems:

– Heat removal
– Shutdown

=

- ✓ No need for emergency AC power
- ✓ Long coping times
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary

Leading Gen-IV systems exploit inherent and passive safety features to reduce the probability of accidents and their offsite consequences. Their economic attractiveness is still highly uncertain.

We judge that advanced LWR-based SMRs (e.g. NuScale), and mature Generation-IV concepts (e.g., high-temperature gas-cooled reactors and sodium-cooled fast reactors are now ready for commercial deployment.

What is the value proposition for advanced reactors? (2)

There exists a small (but not insignificant) potential market for nuclear heat

Industry	300 MW_{th} Reactor		150 MW_{th} Reactor	
	U.S. Capacity (MW_{th} Installed) (%)	Global Capacity (MW_{th} Installed) (%)	U.S. Capacity (MW_{th} Installed) (%)	Worldwide Capacity (MW_{th} Installed) (%)
Co-Generation Facilities	82,800 (61.7%)	340,800 (59.8%)	86,250 (57.5%)	355,050 (55.7%)
Refineries	15,600 (10.4%)	76,800 (12.1%)	17,250 (11.5%)	84,750 (13.3%)
Chemicals	7,800 (5.2%)	36,600 (5.7%)	7,050 (4.7%)	34,200 (5.4%)
Minerals	2,100 (1.4%)	8,700 (1.4%)	2,100 (1.4%)	8,700 (1.4%)
Pulp and Paper	12,600 (8.4%)	51,900 (8.1%)	21,300 (14.2%)	87,750 (13.8%)
Other	13,200 (8.8%)	55,200 (8.7%)	16,050 (10.7%)	66,450 (10.4%)
Total	**134,100 (100%)**	**570,000 (100%)**	**150,000 (100%)**	**636,900 (100%)**

~240 million metric tons of CO_2-equivalent per year (>7% of the total annual U.S. GHG emissions)

Methodology:

- EPA database for US sites emitting 25,000 ton-CO_2/year or more
- Site must need at least 150 MW_{th} of heat
- Nuclear heat delivered at max 650°C (with HTGR technology)
- At least 2 reactors per site for assured reliability
- Heat from waste stream not accessible
- Costs not evaluated

The government role

Government should

1) **Help to preserve the existing fleet as an essential bridge to the future to avoid emission increases:**
   - Keeping current NPPs is the lowest cost form of constraining carbon emissions
   - *Zero Emission Credits* are doing the job in NY, IL and NJ

OBSERVER
New Jersey Lawmakers Finally Pass Nuclear Subsidy Bill

Forbes
Illinois Sees The Light -- Retains Nuclear Power

The New York Times
N.Y. / REGION
New York State Aiding Nuclear Plants With Millions in Subsidies

Extending the lifetime of existing reactors is the lowest-cost approach to avoiding a CO_2 emission increase (the example of Spain)

Table 14: Relative System Costs for Incremental Low Carbon Generation from Alternative Portfolios Benchmarked to 7 Nuclear Plant Life Extension

		[A] N7	[B] S7	[C] W7	[D] SW7	[E] WS7
[1] Incremental Capacity	(MW)	7,117	109,800	30,160	49,134	32,411
[2] Incremental Generation	(GWh)	46,015	46,011	46,014	46,838	46,014
[3] Incremental Capacity Factor		74%	5%	17%	11%	16%
[4] Incremental Unit Cost	(€/MWh)	34.96	157.02	61.24	76.27	60.95
[5] Incremental System Cost, gross annual	(€ millions)	1,609	7,225	2,818	3,572	2,804
[6] Incremental System Cost, gross PV 10 years	(€ millions)	11,298	50,743	19,793	25,091	19,697
[7] Difference to Nuclear	(€ millions)		39,446	8,495	13,794	8,399
			349%	75%	122%	74%

Life-Extensions for all 7 reactors.

No nuclear scenarios.

The Climate and Economic Rationale for Investment in Life Extension of Spanish Nuclear Plants, by Anthony Fratto Oyler and John Parsons, MIT Center for Energy and Environmental Policy Research Working Paper 2018-016, November 19, 2018. http://ssrn.com/abstract=3290828

Government should also…

2) Improve the design of competitive electricity markets

- Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits
- Ensure technology neutrality in capacity markets
- Enable investors to earn a profit based on the full value of their product (including reduction of CO_2 emissions)

3) Help to remove the roadblocks (waste and cost)

- Develop a durable political solution for spent fuel disposal to spur private investment in new nuclear
- Focus government research spending on innovations that lower capital cost of NPPs vs. fuel cycle innovations, reductions in waste streams and recycling

Study Team

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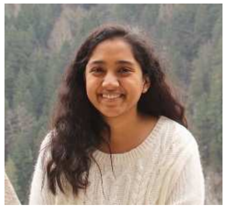

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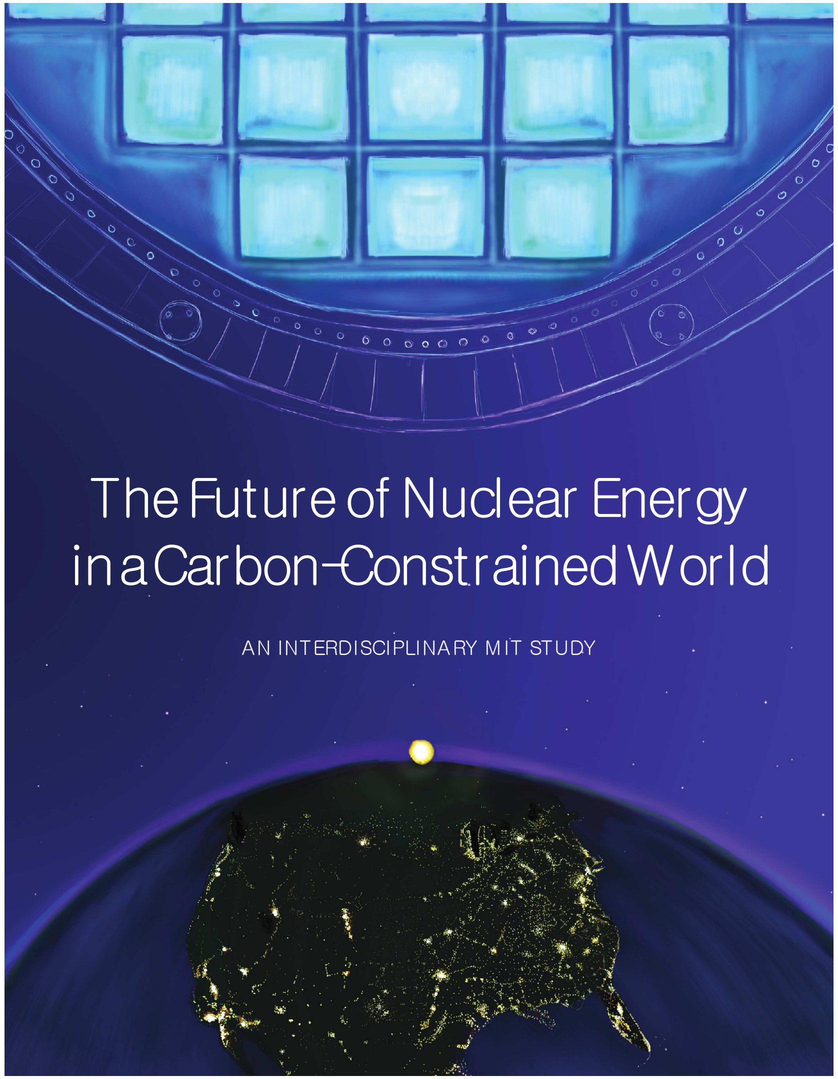
DISCLAIMER: MIT is committed to conducting research work that is unbiased and independent of any relationships with corporations, lobbying entities or special interest groups, as well as business arrangements, such as contracts with sponsors.

Download the report at
http://energy.mit.edu/studies-reports/



Dissemination

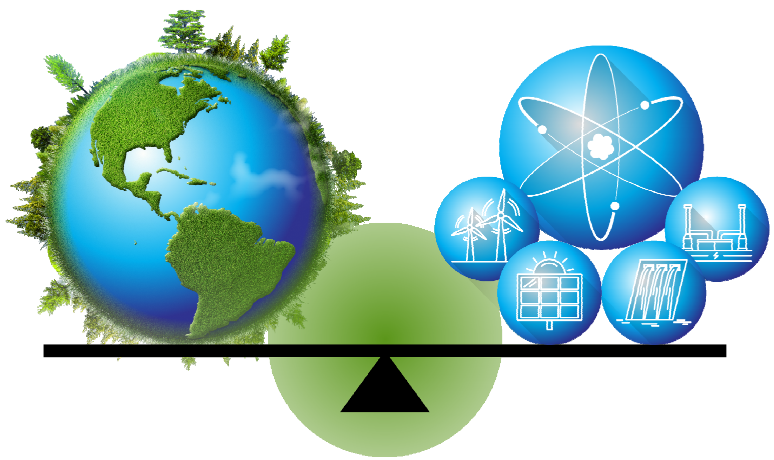
Report Online Release: Sep 3, 2018
Executive summary translated in
French, Japanese, Korean and Chinese

Rollout Events
London (Sep 2018), Paris (Sep 2018), Brussels (Sep 2018)
Washington DC (Sep 2018)
Tokyo (Oct 2018)
Seoul (Jan 2019), Beijing (Jan 2019)

54 presentations at universities, industry organizations, government, conferences, research labs
BEIS UK June 2017 (JB), ICAPP Plenary 2018 (JB), CEA Oct 2017 (JB), RMIT Jan 2017 (JB), Yale Univ. Mar 2018 (JB), Imperial College, June 2017 (JB), Zhejiang Univ. Sep 2017 (JB), Curtin Univ. Jan 2017 (JB), TAMU, Oct 2017 (JB), U-Houston, Oct 2017 (JB), Harvard Univ. HBS, Nov 2017 (JB), Harvard Belfer Center, June 2018 (JB), National Univ Singapore (NUS) Jan 2018 (JB), EPRI (Engineering, Procurement, and Construction Workshop), Nov 2017 (JB), Royal Acad. Eng. Nov 2017 (JB), Nuclear Insider SMR Summit, Apr 2017 (JB), MITEI Advisory Board Oct 2017 (JB, Parsons), Forum of India's Nuclear Industry, Jan 2018 (JB), Canadian Nuclear Society, Nov 2018 (JB), MIT Alumni Association of New Hampshire, Jun 2018 (JB), 49th Annual Meeting on Nuclear Technology, Berlin, May 2018 (JB), U-Edinburgh Aug 2018 (JB), Duke Energy Aug 2018 (JB), NSE May 2018 (JB, Petti, Parsons), Golay Fest, Mar 2018 (JB, Petti), Nuclear Bootcamp at UCB, July 2018 (Corradini), GA visit to MIT April 2018 (all), Armstrong and Moniz August 2017 (all), ANS Orlando, Nov 2018 (Corradini), Mark Peters INL Lab Director June 2017 (Petti), JASONs June 2017 (Petti, Parsons, Corradini), Wisconsin Energy Institute (MLC) Mar 2018 (Corradini), CNL Oct 2017 (Petti), CSIS Sept 2017 (Petti), DoE Dep Sec and Chief of Staff and NE-1 Jan 2018 (Petti, Parsons, Corradini), NRC Sep 2018 (Corradini), NEI Sep 2018 (Corradini), EPRI/NEI roadmapping meeting Feb 2018 (Petti), INL March 2018 (Petti), Gain Workshop March 2018 (Petti), Golay Workshop March 2018 (Petti), WNA September 2018 (Petti), NENE Slovenia September 2018 (Petti), PBNC SF September 2018 (Petti), Zurich December 2018 (Petti), Undersecretary of Energy – Science P. Dabbar Aug 2018 (JB), INPO CEO Conf Nov 2018 (JB), Total S.A. at MIT Nov 2018 (JB), G4SR-1 Conf. Ottawa Nov 2018 (JB), Masui ILP MIT Nov 2018 (JB), Lincoln Labs MIT Nov 2018 (JB), Foratom Spain Madrid Nov 2018 (JB), Orano Paris Nov 2018 (JB), NAE Dec 2018 (Corradini), AGH Univ Science Cracow Jan 2019 (JB), Poland Ministry of Energy Jan 2019 (JB), Swedish Energiforsk Nuclear Seminar Jan 2019 (JB)

Take-away messages

- The opportunity is carbon
- The problem is cost
- There are ways to reduce it
- Government's help is needed to make it happen



Backup slides

Challenge # 3:
Nuclear Waste Disposal

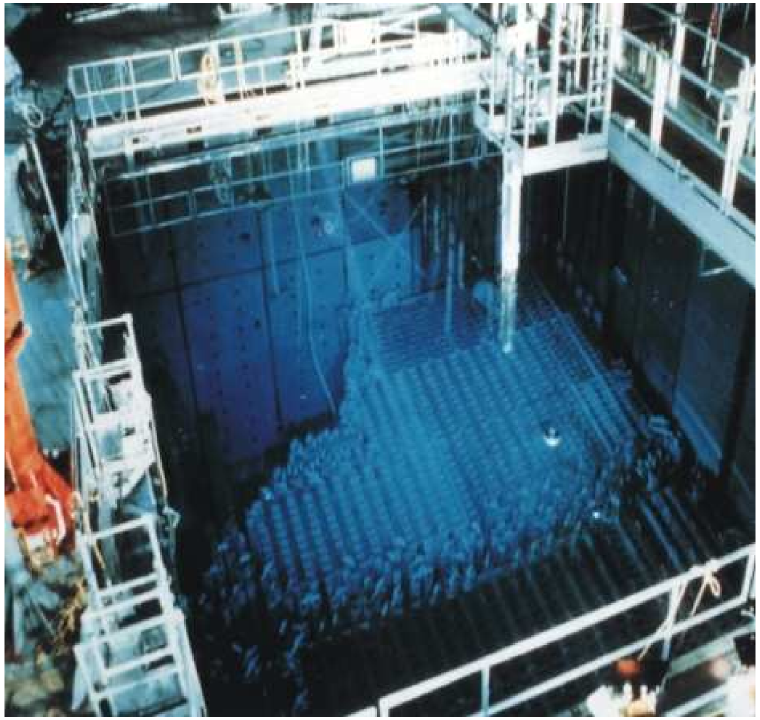
The volumes are SMALL!

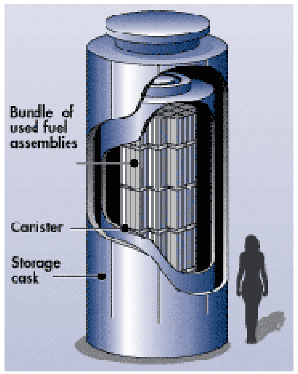
One person's total lifetime's volume of high level radioactive waste if they used nothing but nuclear energy for their whole life.

Mostly a political problem (e.g. in Germany transport of high-level waste routinely draws scores of anti-nuclear protesters)

Current practice in the US

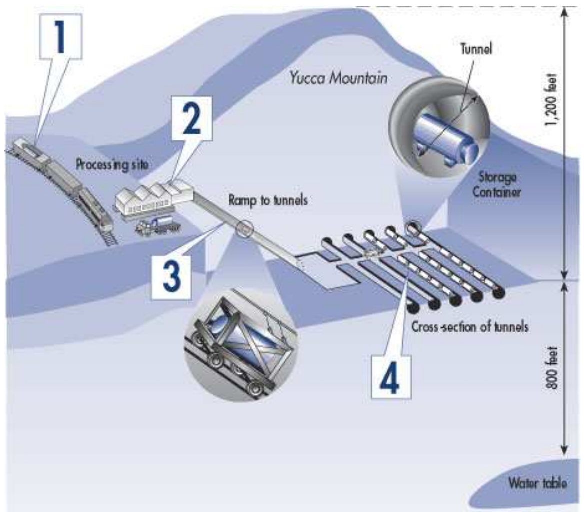
- Spent fuel in storage pools for 5-10 years
- Then transferred to sealed dry casks: 80 casks needed for all spent fuel produced by a 1000-MW reactor in 60 years (small volumes!)
- Dry casks are completely safe to handle and last for decades with minimal maintenance

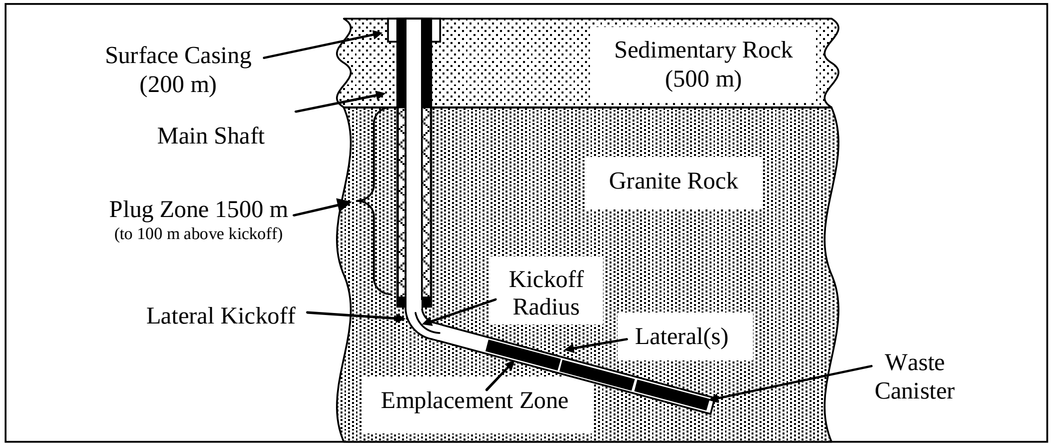




Ultimate disposal is in geological repositories

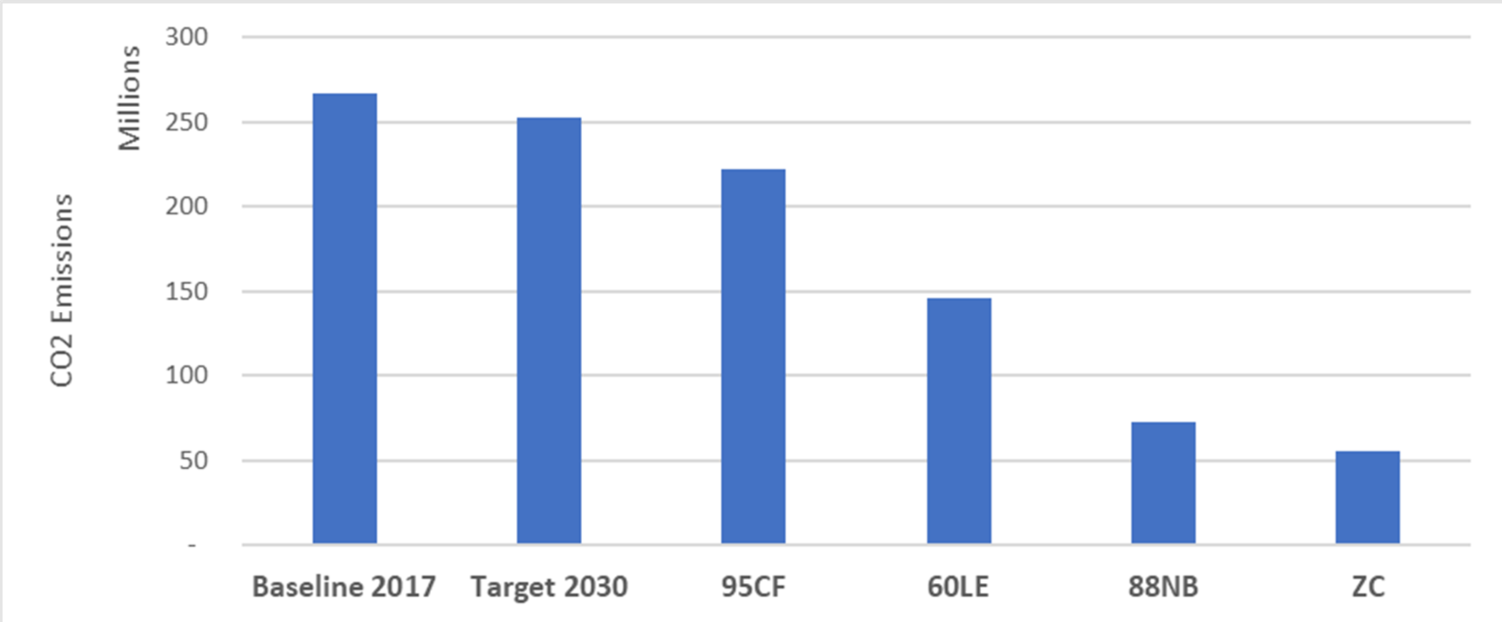
Robust technical options are available (e.g., excavated tunnels or deep boreholes); challenges are always political, with examples of success (Finland, Sweden) and failure (U.S.)





Korea could deeply decarbonize its power sector with nuclear in 4 cumulative steps

95CF:	Existing reactors achieve 95% capacity factor. Retirements at 40 years. Ongoing construction projects completed. No new builds.
60LE:	Existing reactors extended to 60 years.
88NB:	8.8 GW of cancelled reactors reinstated as new builds. (Assumes $2300/kWe OCC for new APR14000 units.)
ZC:	Remaining coal generation replaced by LNG.



Estimated impact on overall system power costs in the ROK from this deep decarbonization could be quite small (<$10/MWh)

Preliminary results from "**U.S.-ROK Cooperation on Nuclear Energy to Address Climate Change**", Nuclear Innovation Alliance, December 2018

Why a new study

BBC
Switzerland votes to phase out nuclear power

REUTERS
South Korea's president says will continue phasing out nuclear power

The State
SCANA leaves failed nuclear project to rot, upsetting some who want it finished

The Telegraph
Hinkley Point's cost to consumers surges to £50bn

The Washington Post
San Onofre nuclear power plant to shut down

Political factors

FINANCIAL TIMES
Cheap gas has hurt coal and nuclear plants, says US grid study

The aftermath of Fukushima

THE BLADE
News • Sports • A&E • Business • Opinion • Jobs
Davis-Besse nuclear power plant to shut down permanently in 2020

NEW YORK POST
More problems with closing Indian Point

Competitive pressure from cheap natural gas

Los Angeles Times
Regulators vote to shut down Diablo Canyon

REUTERS
France will need to close nuclear reactors: minister

The New York Times
Westinghouse Files for Bankruptcy, in Blow to Nuclear Power

The nuclear industry is facing an existential crisis

Self-inflicted wounds

(especially in the U.S. and Europe)

What is the value proposition for advanced reactors? (2)

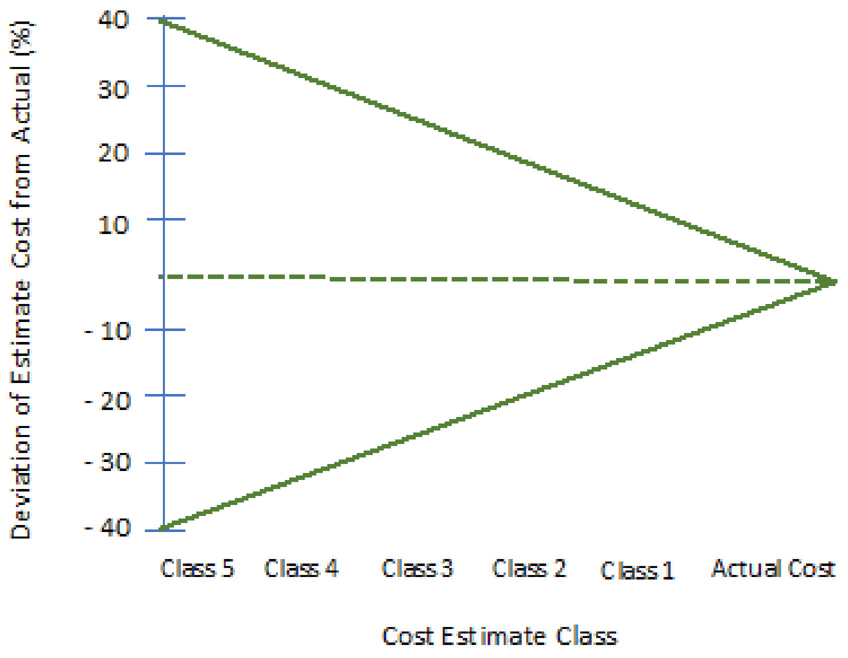
Cost ($/kWe)	HTGR	SFR	FHR (Large)	FHR (Small)	MSR
Machine Size	4 x 600 MWth	4 x 840 MWth	3400 MWth	12 x 242 MWth	2275 MWth
Design Stage	Conceptual approaching Preliminary	Conceptual approaching Preliminary	Early conceptual	Early conceptual	Early conceptual
Direct Cost	2400	2500	2100	2300	2500
Indirect Cost	1400	1600	1400	1300	1700
Contingency	800	800	1100	1100	1200
Total Overnight Cost	4600	4900	4600	4700	5400
Interest During Construction	600	700	600	700	700
Total Capital Invested	5200	5600	5200	5400	6100

1. E. Ingersoll, "International Nuclear Project Costs, Proprietary and Confidential
2. F. Ganda et al., "Reactor Caital Costs Breakdown and Statistical Analysis of Historical US Construction Costs," ICAPP 206
3. A. M. Gandrik, "Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating Costs," TEV-1196, Jan. 2012
4. F. Ganda, "Economcis of Promising Options," FCRD-FCO-2015-000013, Sept. 2015
5. D. E. Holcomb et al., "Advanced High Temperature Reactor Systems and Economic Analysis,' Sept. 2011
6. J. Engle et al., "Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-through Fuelings, ORNL/TM-7207, July 1980
7. C. Andreades, "Nuclear AirBrayton Combined Cycle Power Conversion Design, Physical Performance Estimation and Economic Assessment," UC Berkely Thesis, 2015

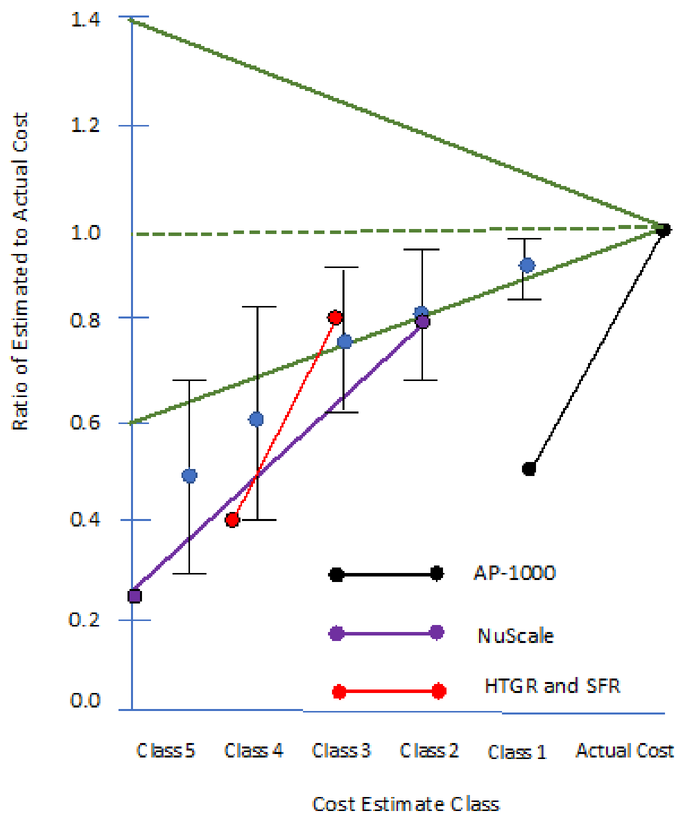
Independent cost estimates for advanced reactors confirm importance of civil works (buildings and structures) and indirect costs, and do not suggest significant cost reduction with respect to LWRs

Uncertainties in cost estimates for large, complex projects

Conventional View

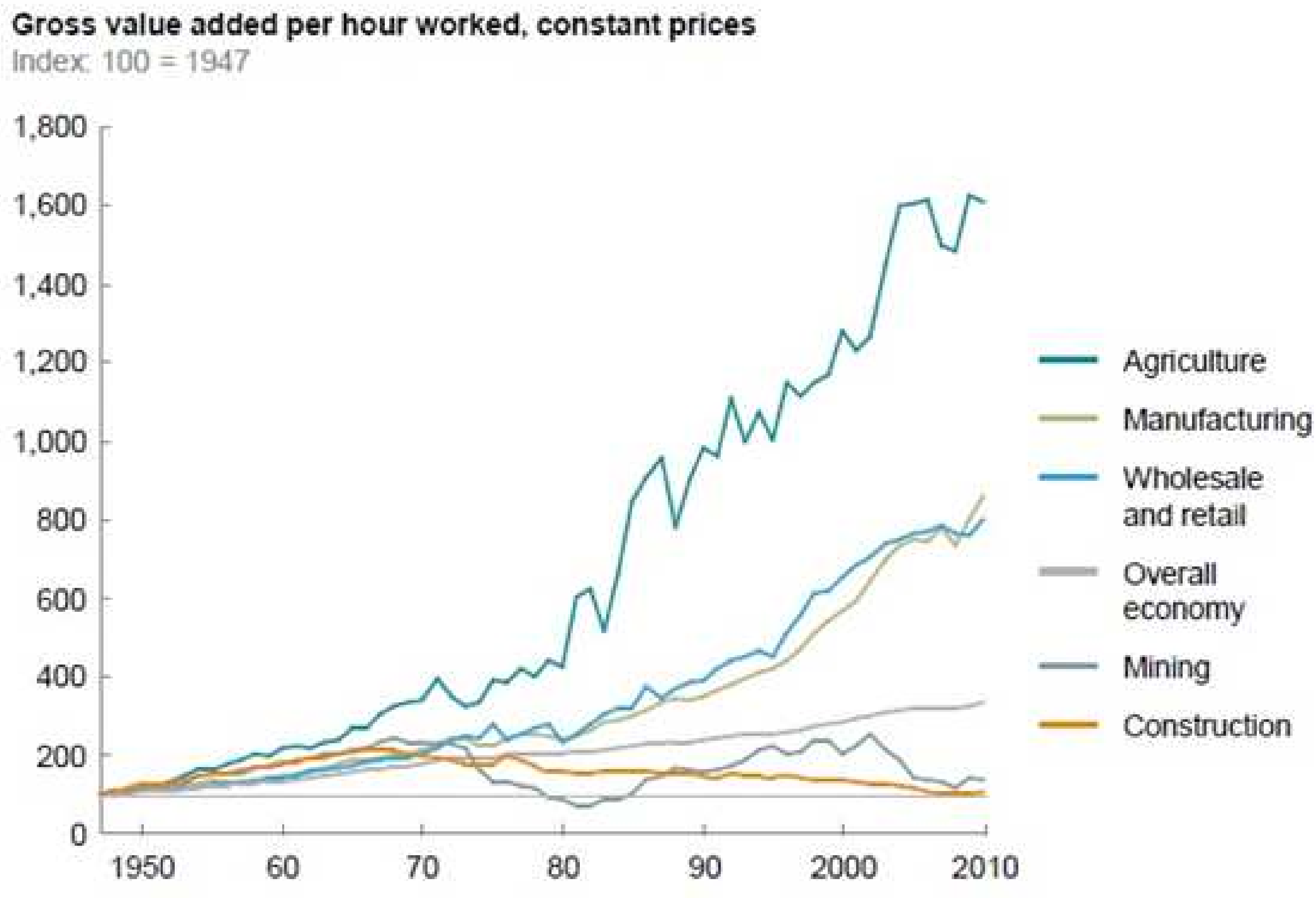


Reality



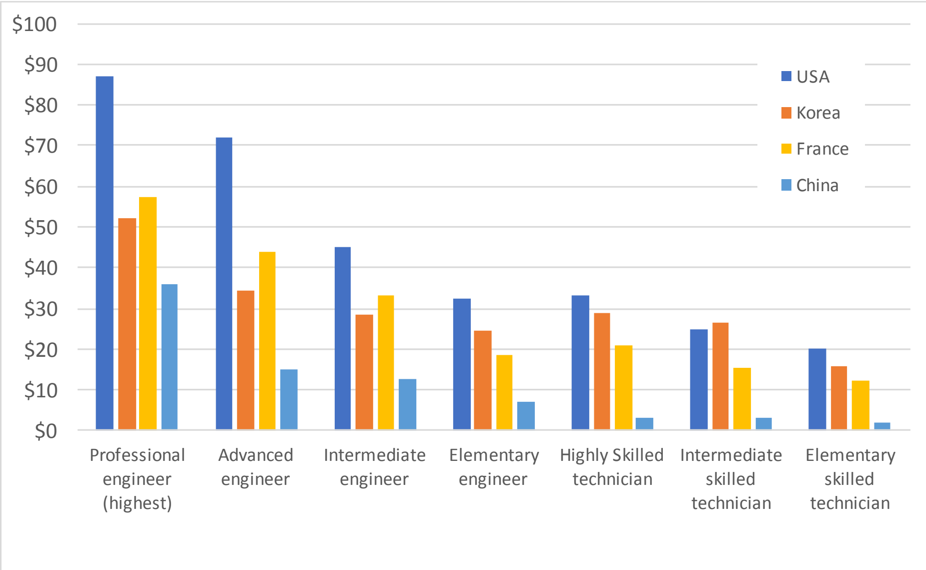
Early-stage cost estimates are unreliable predictors of the eventual cost of mega-projects. This is valid across *all* nuclear technologies and also large non-nuclear mega-projects.

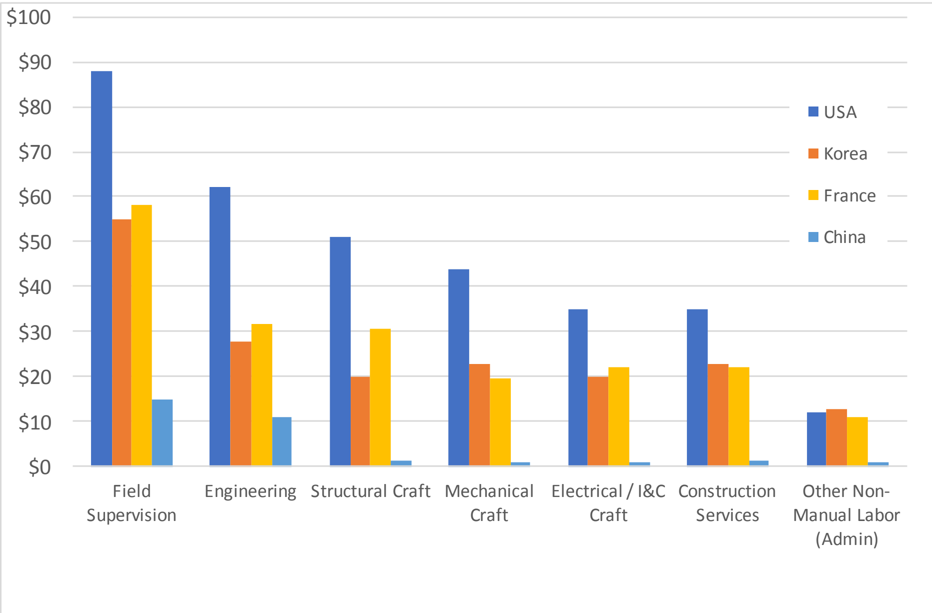
Why are nuclear construction projects in the West particularly expensive?



Construction labor productivity has decreased in the West

Why are nuclear construction projects in the West particularly expensive? (2)





Construction and engineering wages are much higher in the US than China and Korea

Estimated effect of construction labor on OCC (wrt US):
-$900/kWe (China)
-$400/kWe (Korea)

Source: Bob Varrin, Dominion Engineering Inc.

What innovations could make a difference?

Beware of buzzwords and distractions

Reduce Capital Cost		Reduce O&M and Fuel Costs	Boost Revenues	Boost Efficiency
Modular Construction	**Advanced Concrete**	Robotics	Energy Storage	Hydro-phobic/hydro-philic Coatings
Seismic Isolation, Embeddment	Accident Tolerant Fuels	Advanced Informatics and I&C (AI, machine learning)	Brayton Cycles	
3D Printing	Advanced Decommissioning	Oxide Dispersion-Strengthened Alloys	Chemicals Production	Supercritical CO_2

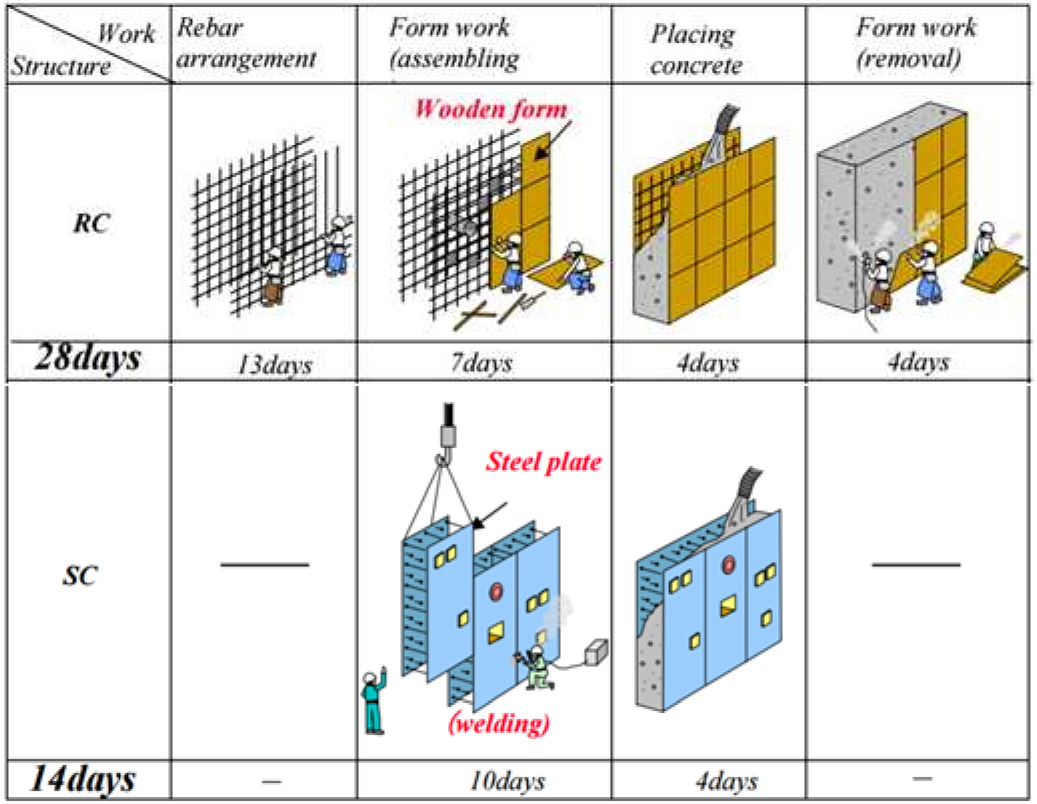
Must focus on:

- Shifting labor from site to factories ⇒ reduce installation cost
- Relentlessly pushing towards standardization and multi-unit sites ⇒ reduce licensing and engineering costs + maximize learning
- Shortening construction schedule ⇒ reduce interest during construction

Modular Construction

Experience from chemical plants, nuclear submarines, Japanese ABWR series suggests potential impact on capital cost reduction in the 10-50% range

Advanced Concrete



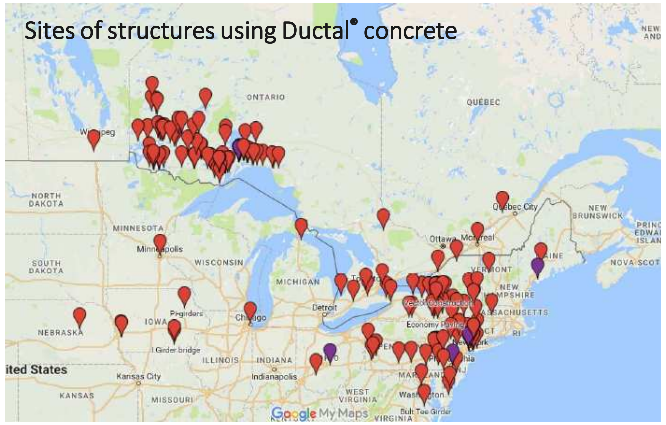
Work / Structure	Rebar arrangement	Form work (assembling)	Placing concrete	Form work (removal)
RC				
28days	13days	7days	4days	4days
SC	—			—
14days	–	10days	4days	–

Reduce rebar density:

- High-strength reinforcement steel (grades 80 and above)

Eliminate rebar and form work:

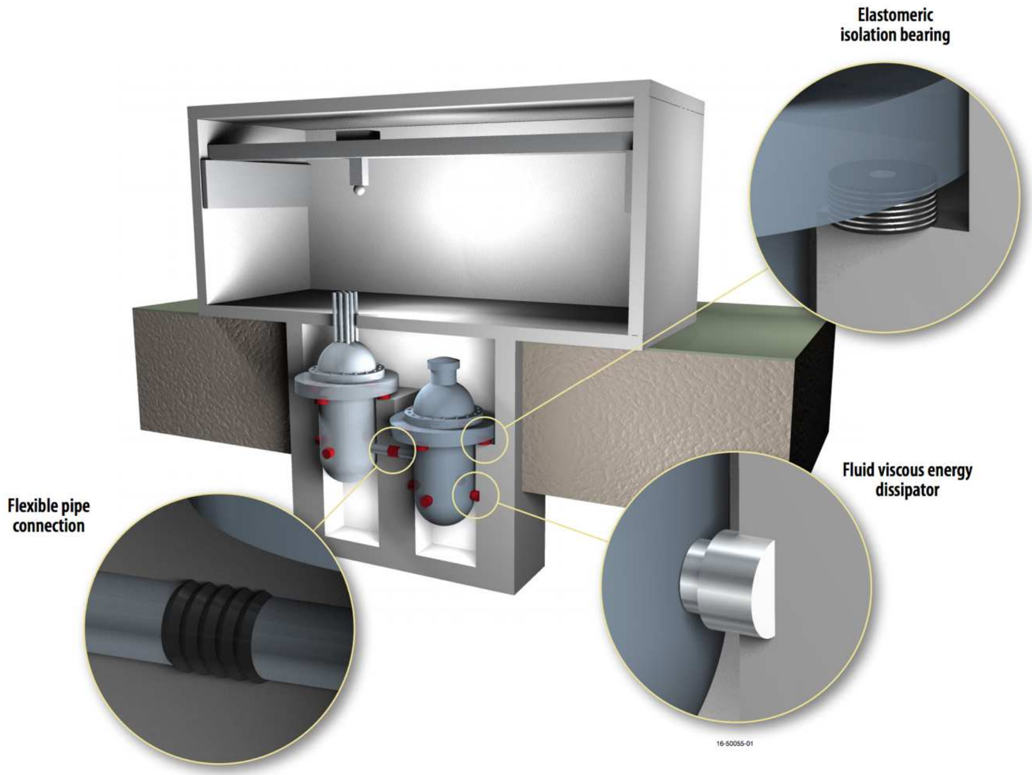
- Prefabricated Steel Plate Composites (SPCs) filled with concrete onsite
- Ultra-High Performance Concrete (UHPC) shells with metallic fibers



Adopted in many non-nuclear projects

Key challenge is extending to nuclear codes and standards

Seismic Isolation

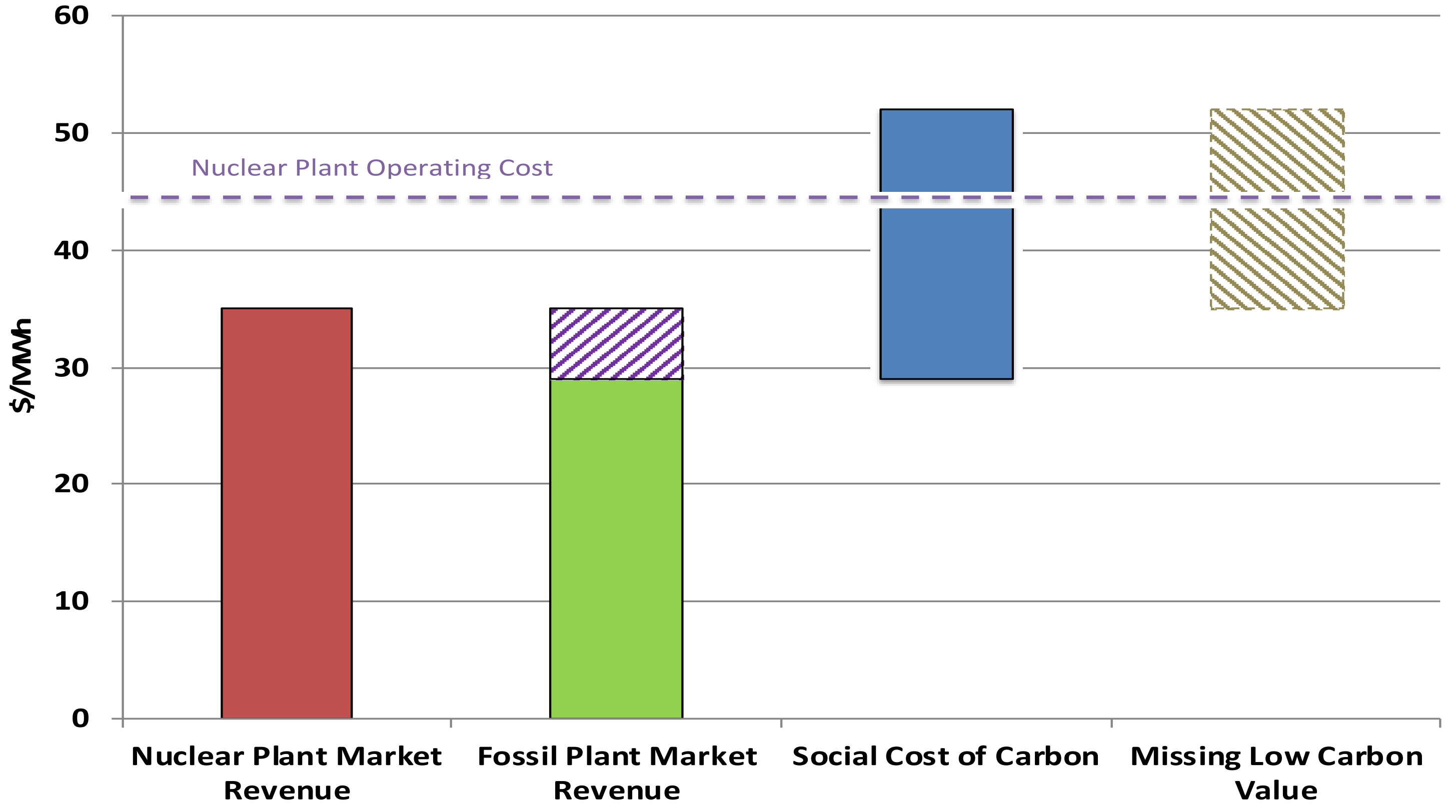


Courtesy of A. Whittaker (U-Buffalo) and J. Coleman (INL)

- Isolation is cost effective above peak ground accelerations of ~0.2 g
- External shield building cannot be thinned because of airplane crash protection

Lighter superstructure (especially SCC supports within shield building) and site-independent designs

Preserving the existing nuclear fleet requires compensating it for its zero-carbon value



A $12-17/MWh credit would be enough to keep US nuclear power plants open

Existing Reactors

- Existing nuclear reactors are cost-efficient providers of low-carbon electricity
  - Recognized in *Zero Emission Credits* established in US states NY, IL, NJ
- Premature closures undermine efforts to reduce CO_2 and other power sector emissions
  - Increase the cost of achieving emission reduction targets
- Life-extensions of existing reactors are usually a cost-efficient investment

Existing reactors (the example of Spain)

Table 14: Relative System Costs for Incremental Low Carbon Generation from Alternative Portfolios Benchmarked to 7 Nuclear Plant Life Extension

		[A] N7	[B] S7	[C] W7	[D] SW7	[E] WS7
[1] Incremental Capacity	(MW)	7,117	109,800	30,160	49,134	32,411
[2] Incremental Generation	(GWh)	46,015	46,011	46,014	46,838	46,014
[3] Incremental Capacity Factor		74%	5%	17%	11%	16%
[4] Incremental Unit Cost	(€/MWh)	34.96	157.02	61.24	76.27	60.95
[5] Incremental System Cost, gross annual	(€ millions)	1,609	7,225	2,818	3,572	2,804
[6] Incremental System Cost, gross PV 10 years	(€ millions)	11,298	50,743	19,793	25,091	19,697
[7] Difference to Nuclear	(€ millions)		39,446	8,495	13,794	8,399
			349%	75%	122%	74%

Life-Extensions for all 7 reactors.

No nuclear scenarios.

The Climate and Economic Rationale for Investment in Life Extension of Spanish Nuclear Plants, by Anthony Fratto Oyler and John Parsons, MIT Center for Energy and Environmental Policy Research Working Paper 2018-016, November 19, 2018.
http://ssrn.com/abstract=3290828

Electricity Market Policy

- Current wholesale electricity prices do not fully compensate nuclear plants for the low-carbon attribute.
- Out-of-market subsidies target renewables exclusively, reducing market revenues to nuclear.
  - Encourages premature closure.
  - Discourages investment in life-extensions.

- Public policies to advance low-carbon generation should treat all technologies comparably.
  - Recognized in recent solicitations by US state of CT.
  - Many alternatives: cap-and-trade, carbon tax, clean energy standards.

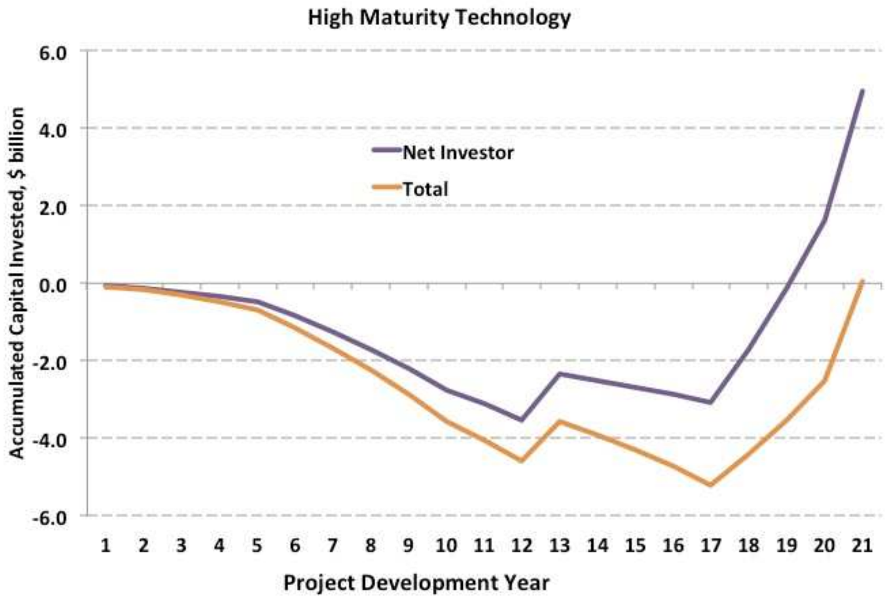
How the government can aid deployment of new nuclear technologies (1)

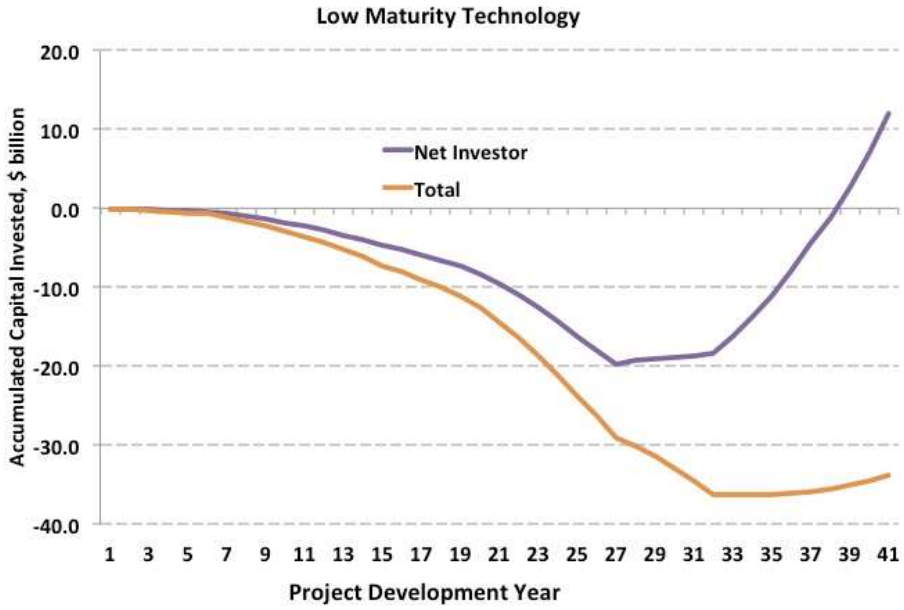
Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing.

- Government provides site security, cooling, oversight, PIE facilities, etc.
- Government provides targeted objectives, e.g. production of low-cost power or industrial heat, for which it is willing to provide production payments as an incentive
- Government takes responsibility for waste disposal
- Companies using the sites pay appropriate fees for site use and common site services
- Supply high assay LEU and other specialized fuels to enable tests of advanced reactors

How the government can aid deployment of new nuclear technologies (2)

High upfront costs and long time to see return on investment





Early government support helps. 4 "levers":

- Share R&D costs
- Share licensing costs
- Milestone payments
- Production credits