What are the key challenges for nuclear and how to address them

- Findings from a new MIT study -

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MITei
MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

First challenge:
don’t lose ground

Existing NPPs are approaching the end of their original license

Decommission **vs.** **License extension**

- **Lose jobs and tax revenues**
- **Emissions increase**

US examples: Vermont Yankee, SONG, Pilgrim, Diablo, etc.

- **Investment needed**
- **Will plant be profitable?**

License extension for current NPPs is usually a cost-efficient investment with respect to emission-equivalent alternatives

(the example of Spain)

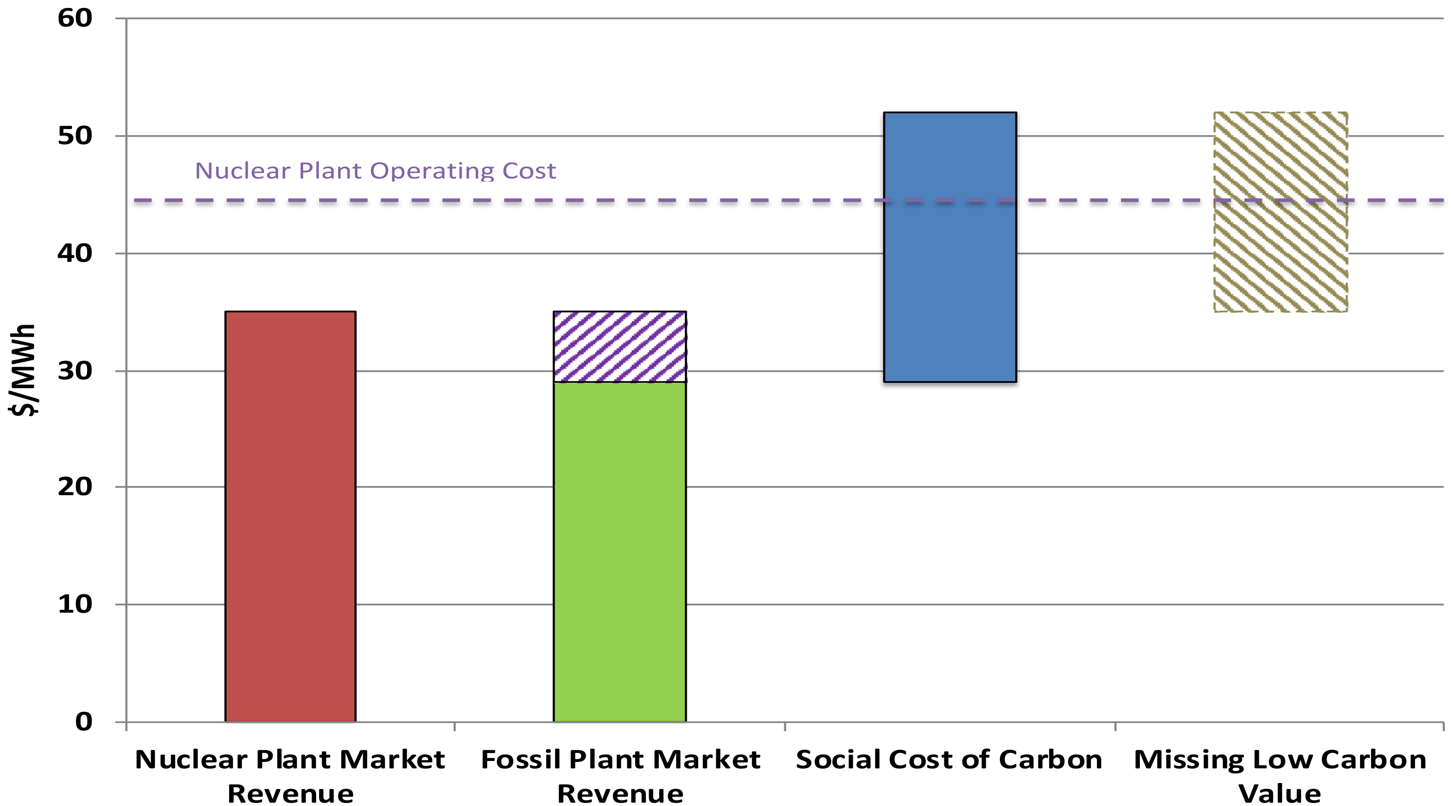
License extension for all 7 reactors

All reactors are shutdown and replaced by renewables + batteries to keep same emissions

		[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%

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

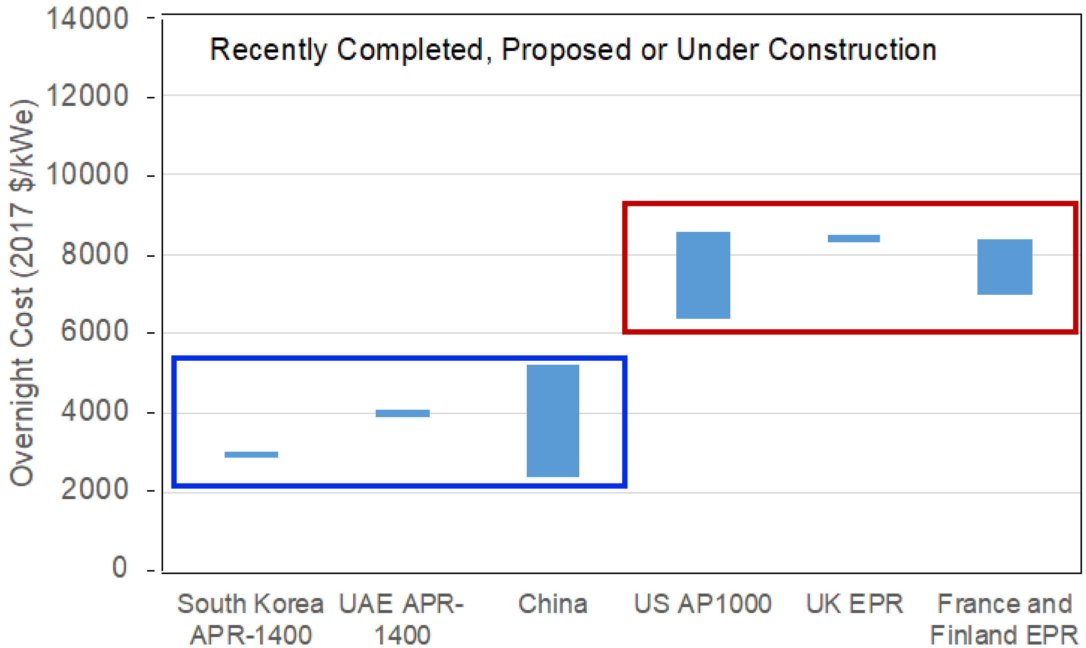
Preserving the existing NPP fleet in the US will require compensating it for its zero-carbon value



- A $12-17/MWh credit is enough to keep US nuclear power plants open
- *Zero Emission Credits* are doing the job in NY, IL and NJ
- Approach endorsed also by some nuclear-skeptical orgs (e.g., Union of Concerned Scientists)

For new NPPs it is all about cost

Why are new NPPs in the West so expensive and difficult to build?



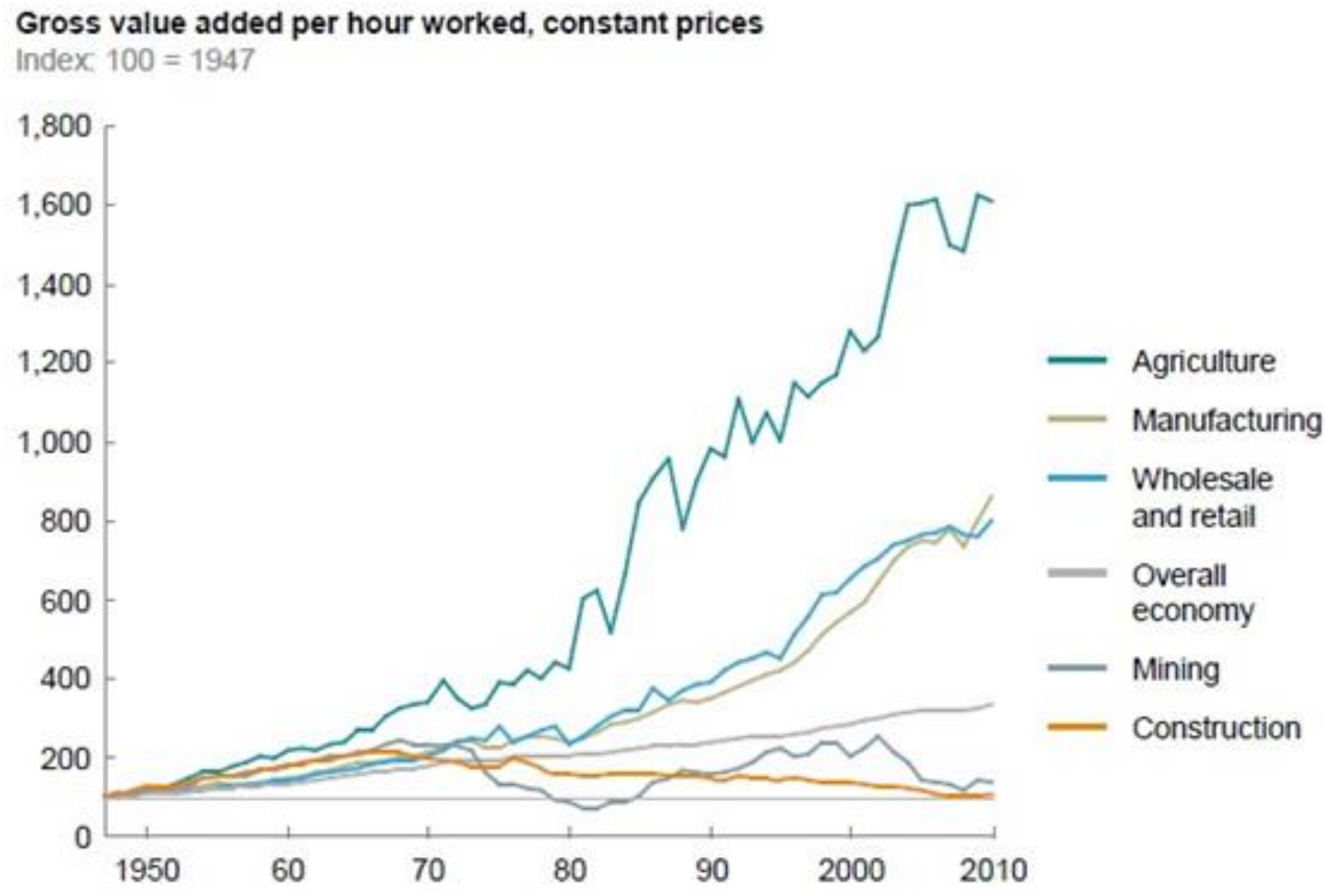
ASIA

- >90% detailed design completed before starting construction
- Proven NSSS supply chain and skilled labor workforce
- Fabricators/constructors in included in the design team
- A single primary contract manager
- Flexible regulator can accommodate changes in design and construction in a timely fashion

US/Europe

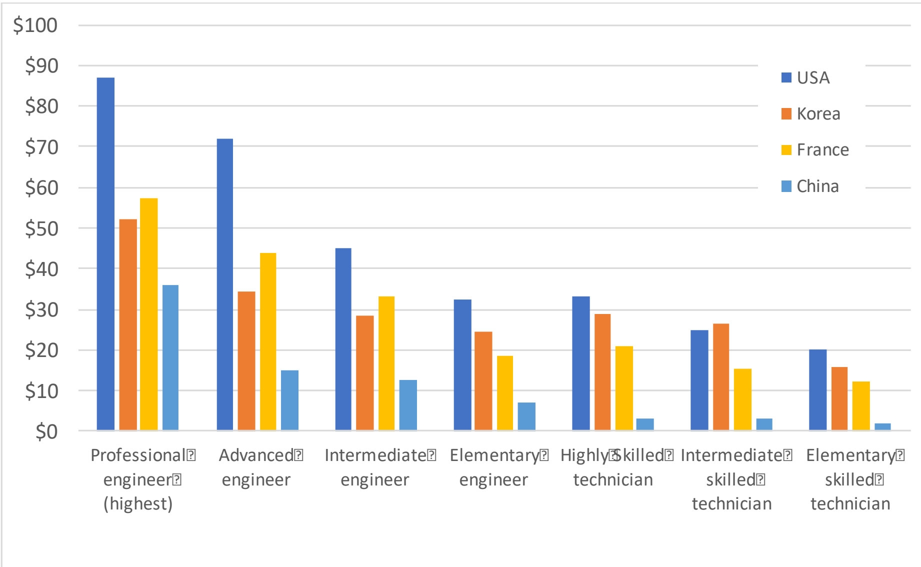
- Started construction with <50% design completed
- Atrophied supply chain, inexperienced workforce
- Litigious construction teams
- Regulatory process averse to design changes during construction

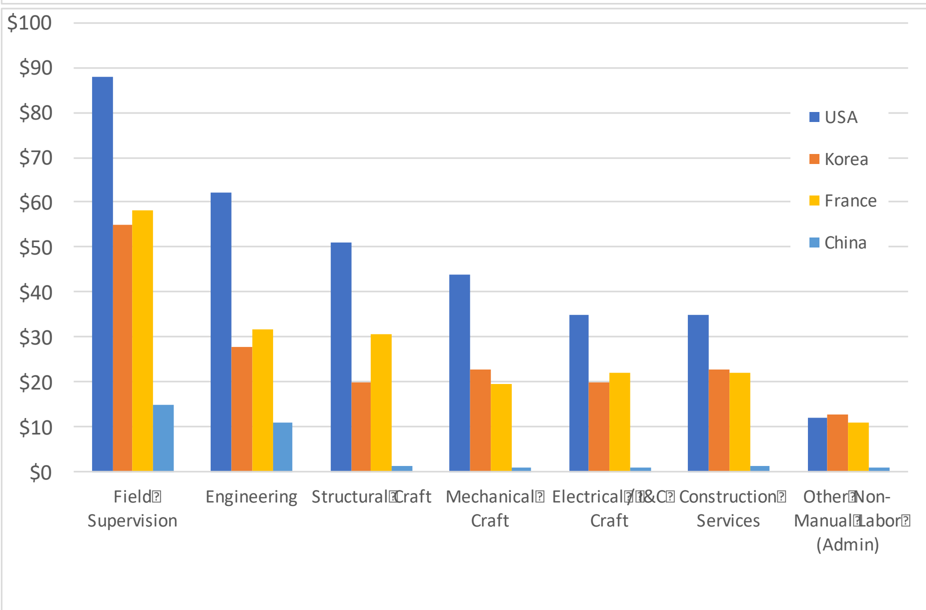
Aggravating factors



Construction labor productivity has decreased in the West

Aggravating factors (2)



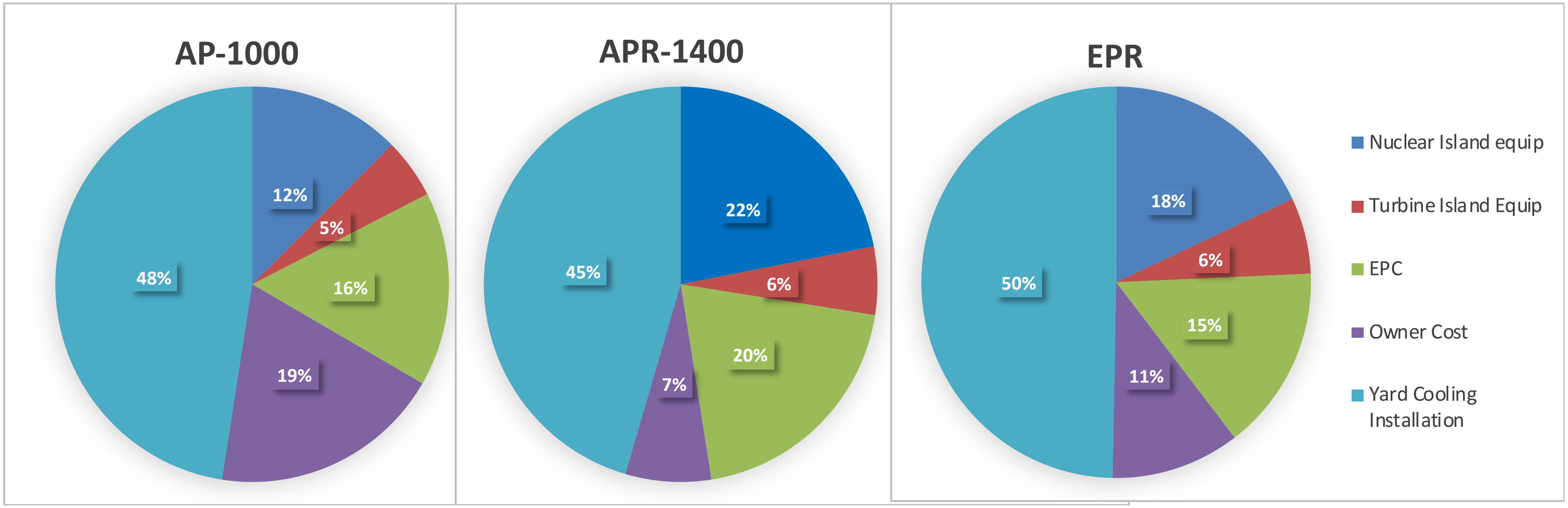


Construction and engineering wages are much higher in the US than China and Korea

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

Source: Bob Varrin, Dominion Engineering Inc.

Where is the cost of a new NPP?



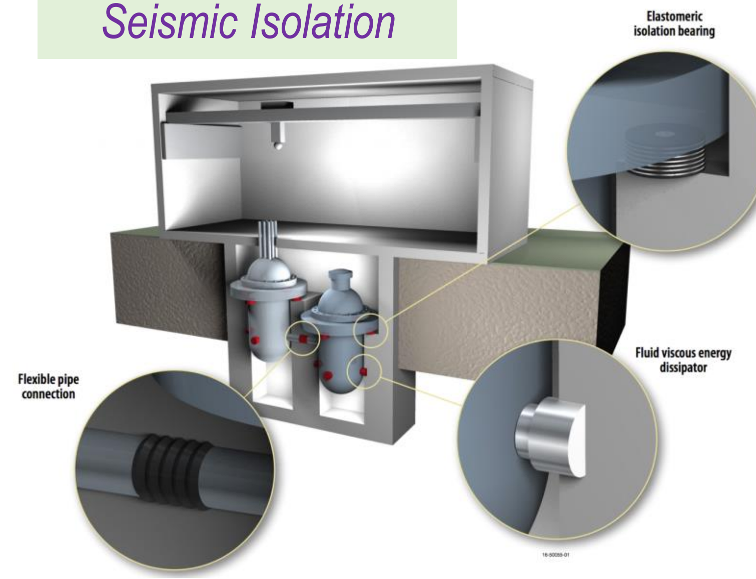
Sources:
AP1000: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11
APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication,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

- Civil works, site preparation, installation and indirect costs (engineering oversight and owner's costs) dominate overnight cost
- Schedule and discount rate determine financing cost

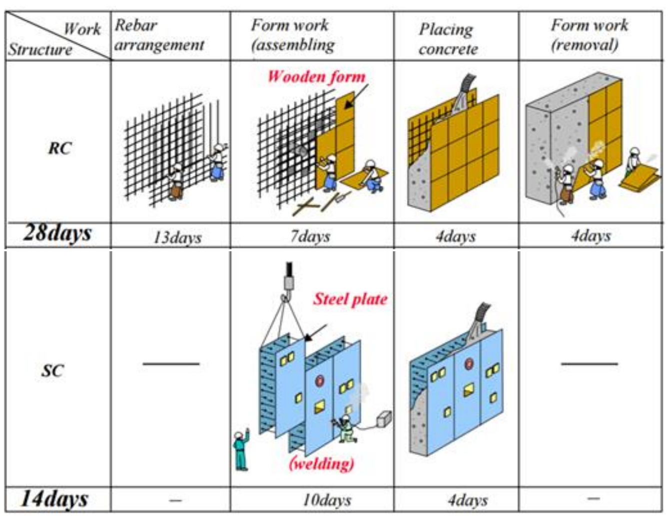
What innovations could make a difference?

Standardization on multi-unit sites

Seismic Isolation



Advanced Concrete Solutions



Work / Structure	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/Shipyard Fabrication

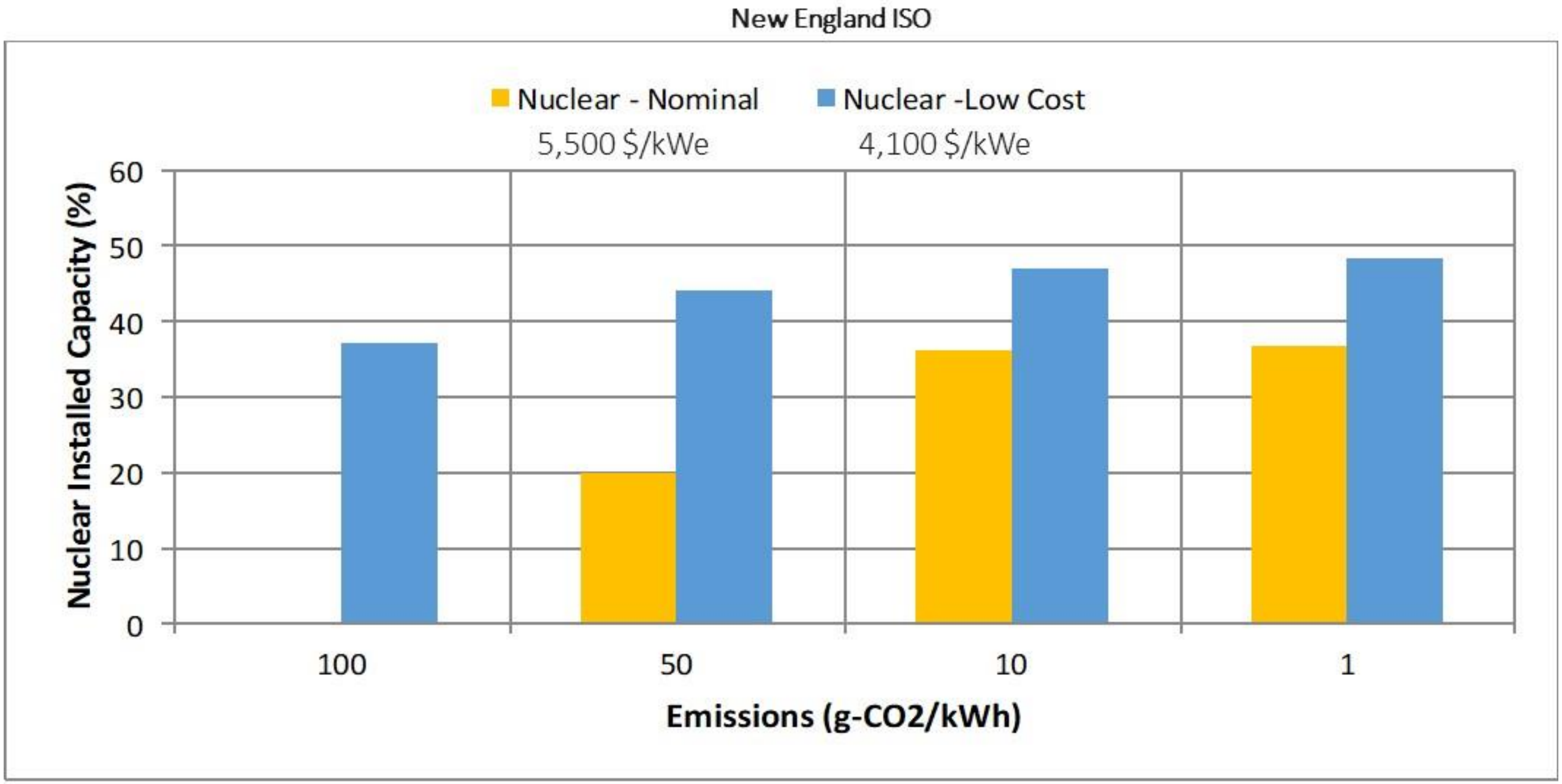
Applicable to all new reactor technologies

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

In other industries (e.g. chemical plants, nuclear submarines) the capital cost reduction from such approaches has been in the 10-50% range

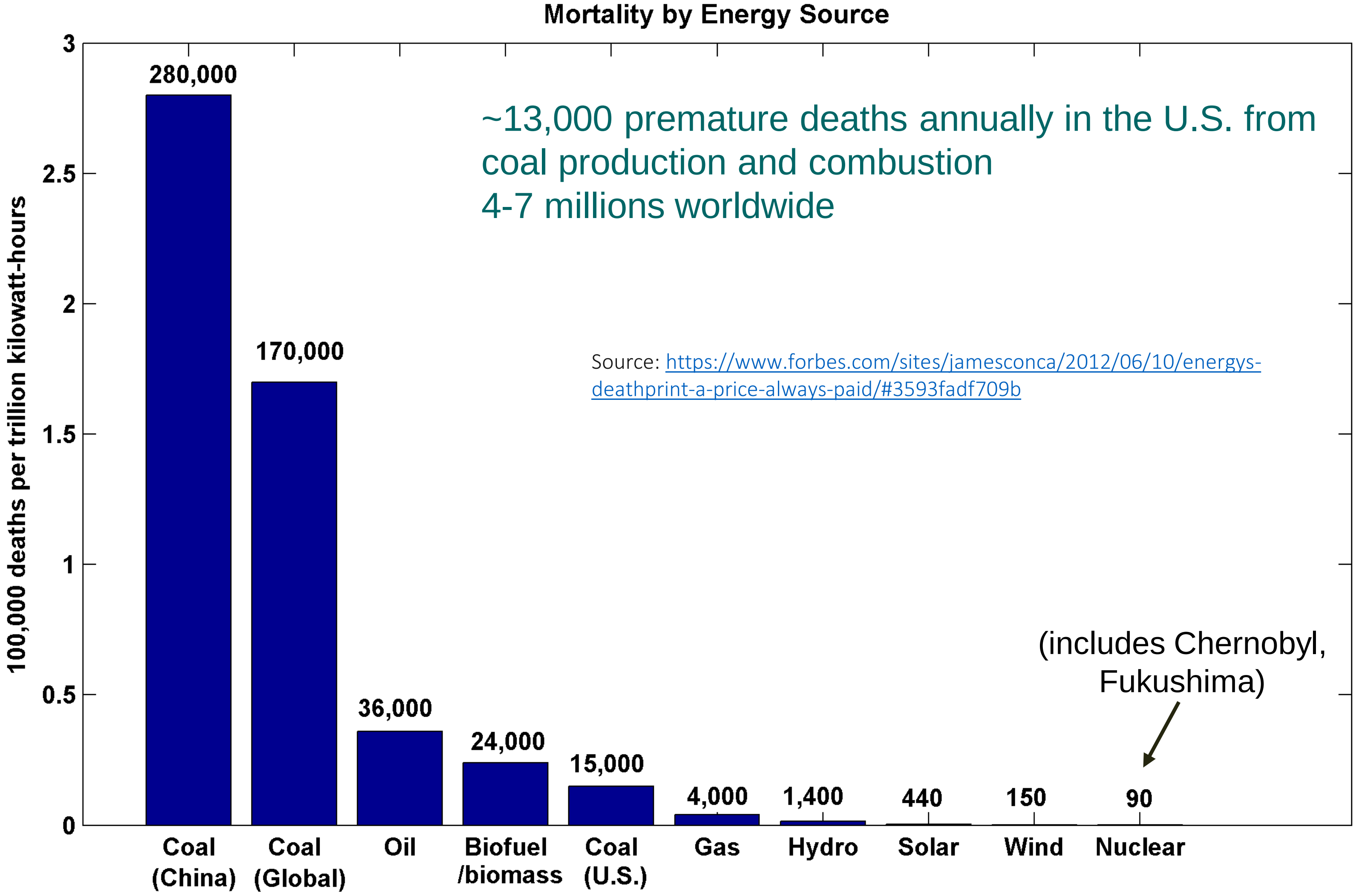
The reward



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

Societal concerns about NPP safety and HLW

Nuclear actually has the lowest public heath impact of *all* energy sources



Source: https://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/#3593fadf709b

Fukushima has changed perceptions about nuclear energy once again

New safety goals are in order:

- Extend coping time during station blackout (post-Fukushima retrofits are doing the job + ATF will help further)
- Demonstrate passive safety with 'infinite' coping time
- Eliminate need for evacuation of locals after severe accidents

Existing NPPs

New designs

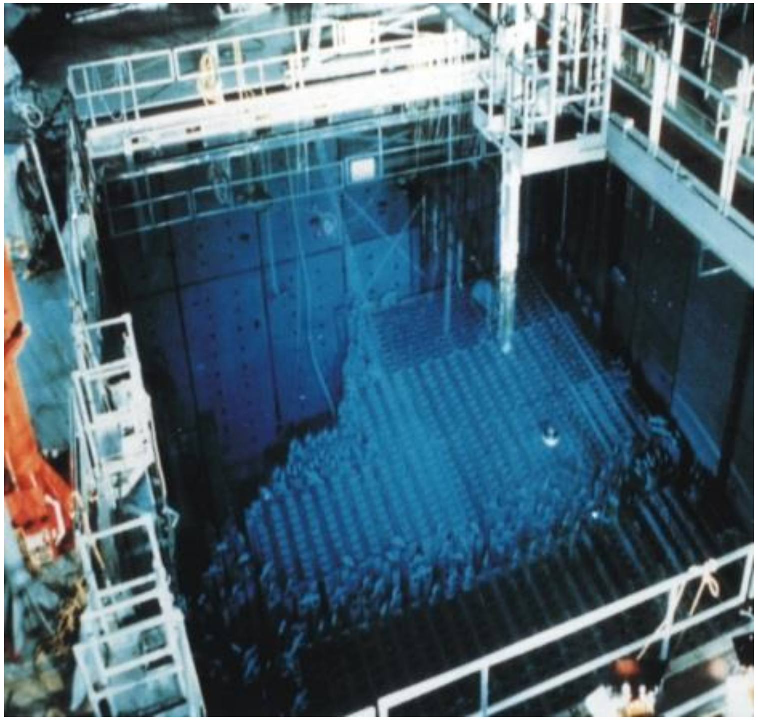
High Level Waste (HLW)

One person’s total lifetime volume of HLW if they used nothing but nuclear energy for their whole life

The volumes are small!

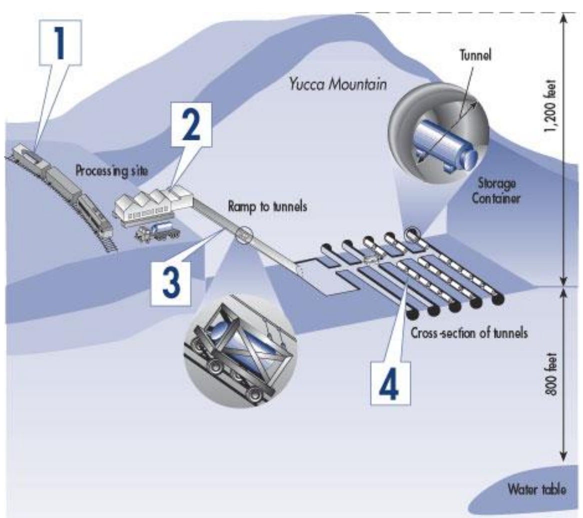
Current practice in the US

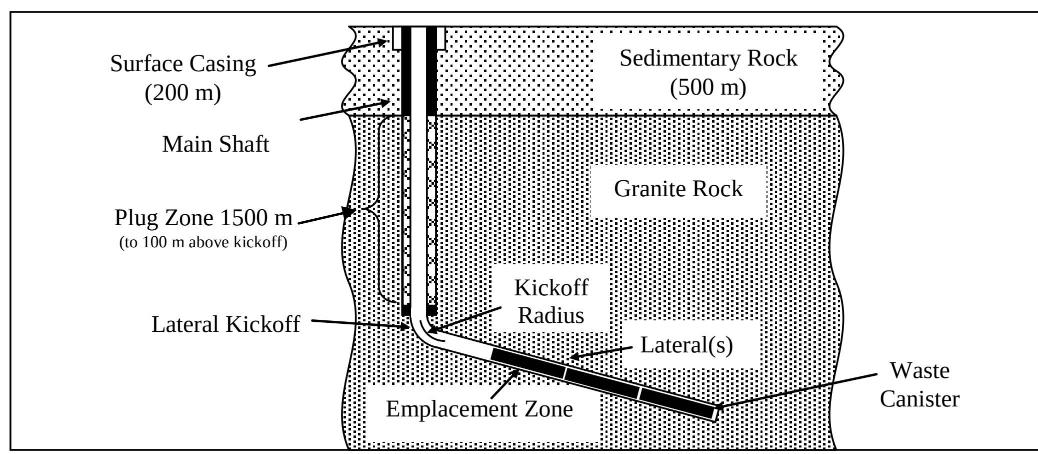
- Spent fuel in storage pools for 5-10 years
- Then transferred to sealed dry casks: 80 casks needed for all spent fuel produced by a 1000-MW reactor in 60 years (again small volumes)
- Dry casks are completely safe to handle and last for decades with minimal maintenance



Ultimate disposal is in geological repositories

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





Value proposition for advanced reactors

Small Modular Reactors

High Temperature Gas-Cooled Reactors

+ other Gen4

A richer set of potential missions:

- cheap grid-connected electricity (with flexible ops)
- process heat and high temperature applications
- microreactors for off-grid electricity and heat
- desalination

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

Hydrogen and/or synfuels could be the game changer for nuclear heat

An attractive safety profile

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

Design certification of NuScale in the US is showing NRC’s willingness to value new safety attributes

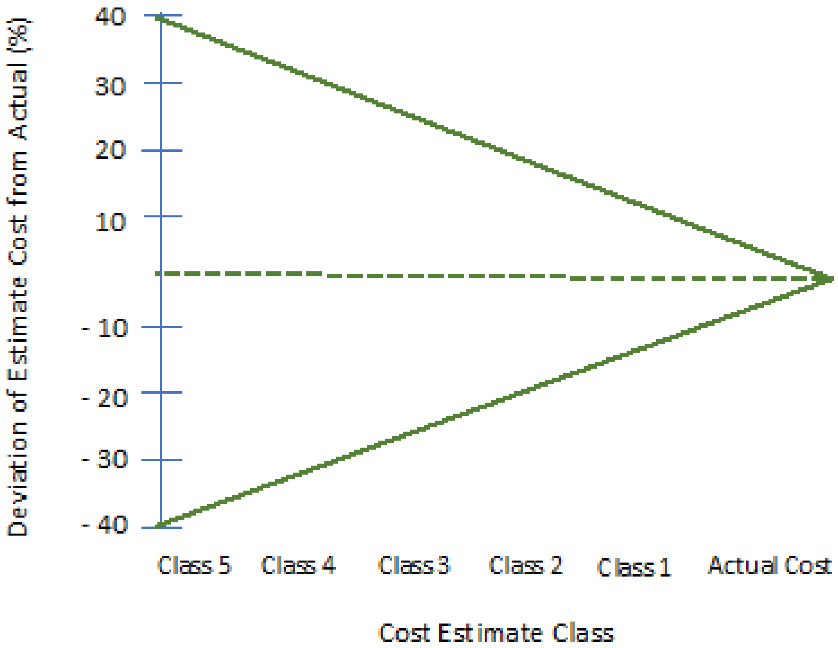
The jury is still (very much) out on the economic potential of advanced reactors

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

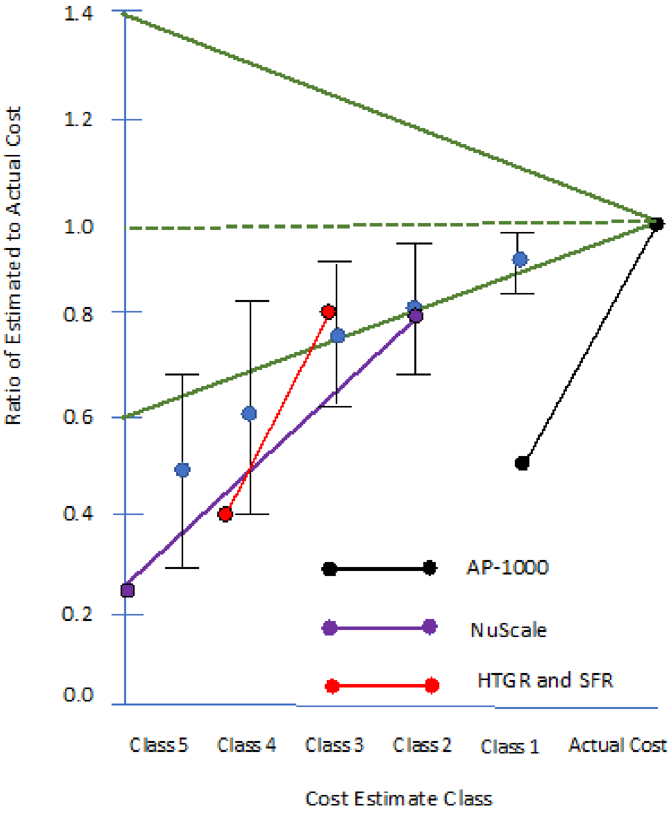
1. E. Ingersoll, "International Nuclear Project Costs, Proprietary and Confidential
2. F. Ganda et al., "Reactor Caital Costs Breakdown and Statistical Analysis of Historical US Construction Costs," ICAPP 206
3. A. M. Gandrik, "Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating 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

Uncertainty in cost estimates for large, complex projects

Conventional View

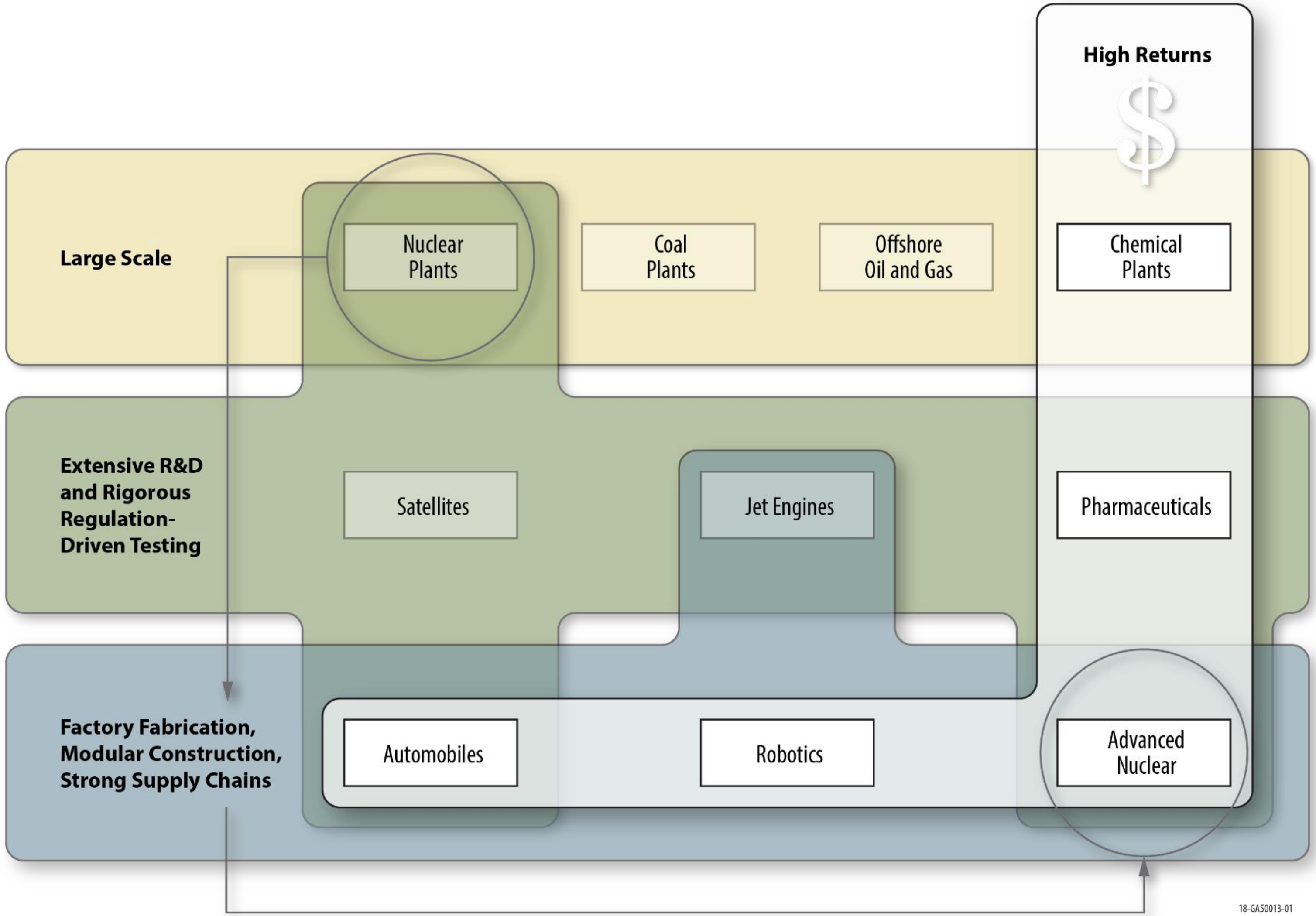


Reality



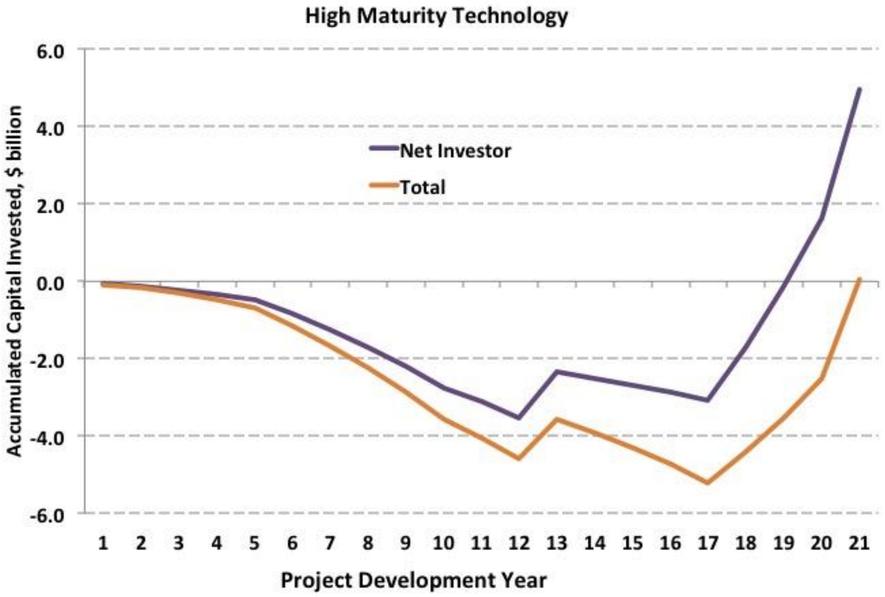
Don’t believe any cost estimates from vendors until design is mature (rule of thumb: ~2 million man-hours)

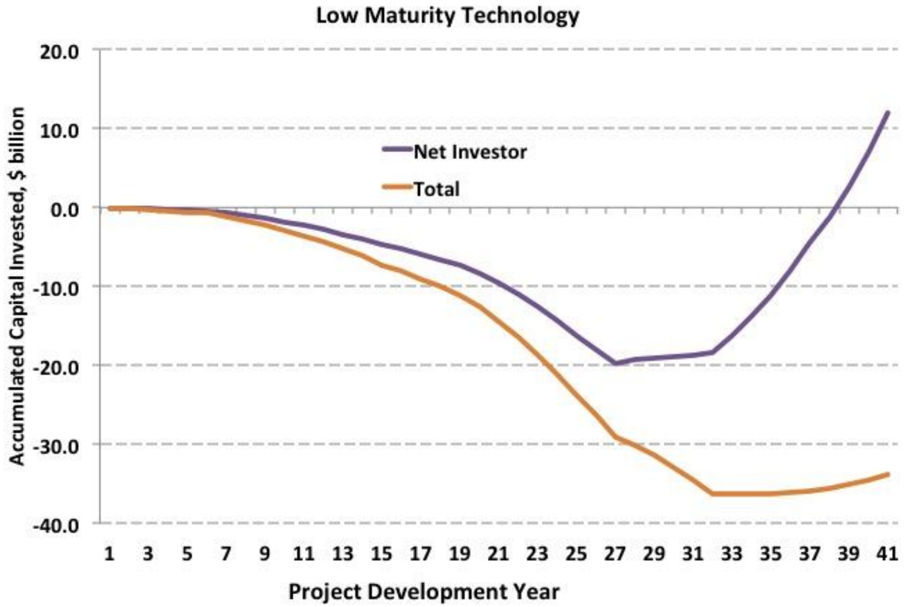
What stifles innovation in the nuclear industry?



- Current large, stick-built, baseload product is the perfect storm of negative attributes
- Need paradigm shift to smaller, serial-built systems with broader mission and recognized low-carbon value

High upfront costs and long time to see return on investment for new reactor technologies





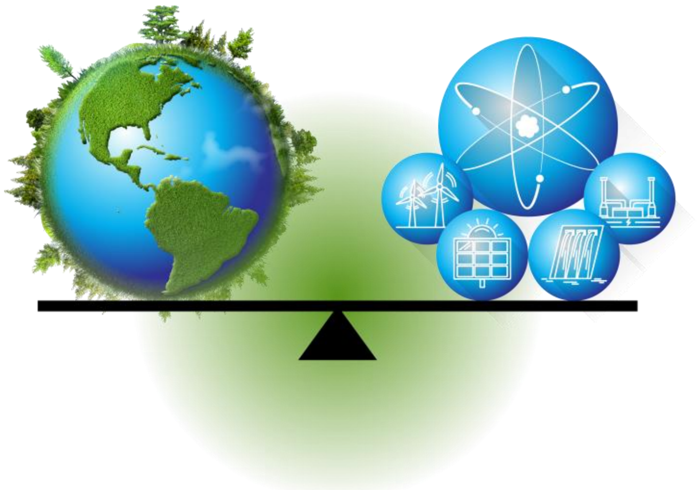
Early government support is needed.

Four "levers":

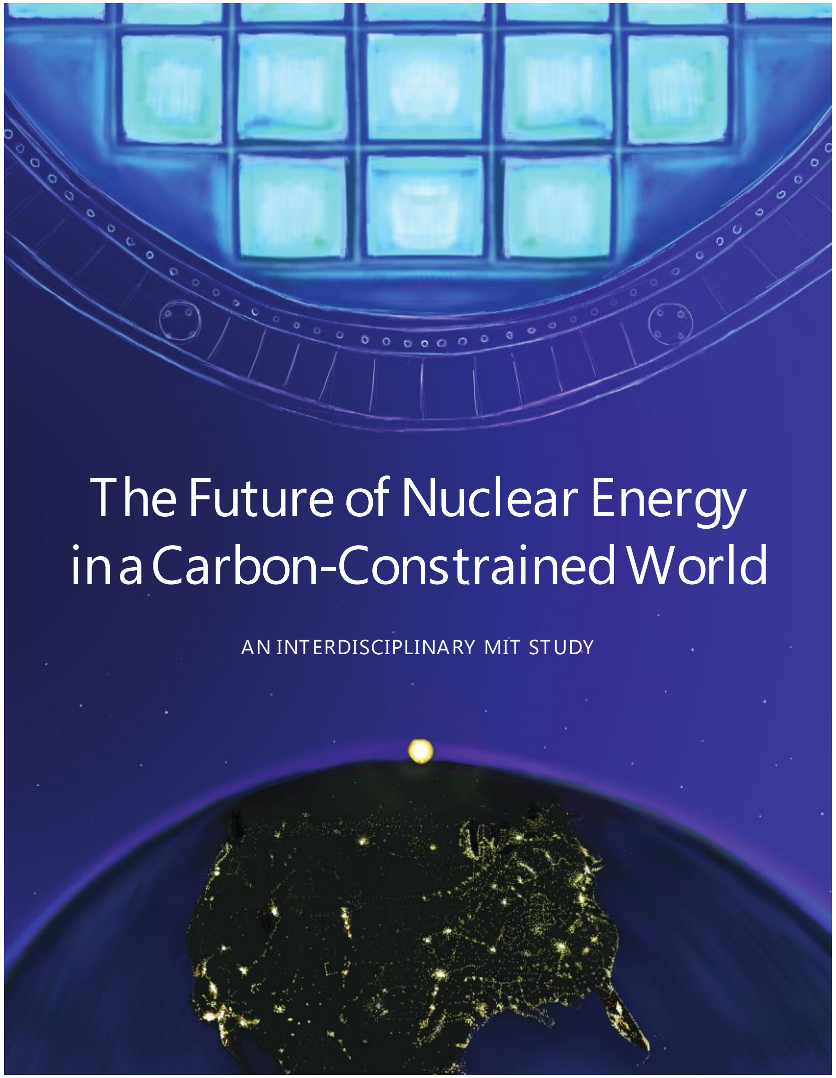
- Share R&D costs
- Share licensing costs
- Milestone payments
- Production credits

Take-away messages from the MIT study

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



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



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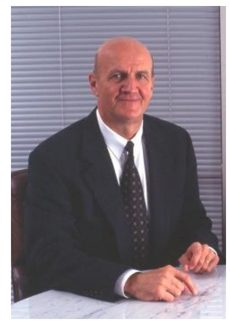

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