New nuclear or same old approach?

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science : systems : society

THE PROBLEM

A “perfect storm” of unfortunate attributes

	System size	Factory fabrication	Testing and licensing	High-return product
Nuclear Plants	Large	No	Lengthy	No
Coal Plants	Large	No	Short	No
Offshore Oil and Gas	Large	No	Medium	No
Chemical Plants	Large	No	Medium	Yes
Satellites	Medium	Yes	Lengthy	No
Jet Engines	Small	Yes	Lengthy	No
Pharmaceuticals	Very Small	Yes	Lengthy	Yes
Automobiles	Small	Yes	Lengthy	Yes
Consumer Robotics	Small	Yes	Short	Yes

has resulted in long (~20 years) and costly (~$10B) innovation cycles for new nuclear technology

A POTENTIAL SOLUTION

Nuclear DD&D paradigm needs to shift to:

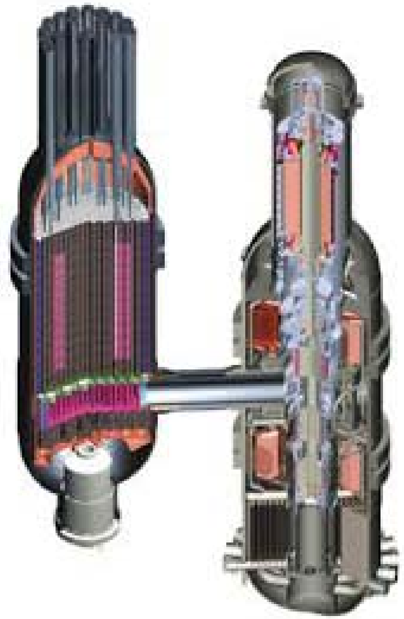
- ☐ *smaller, serial-manufactured* systems,
- ☐ with *accelerated testing/licensing,*
- ☐ producing *high added-value* energy products.

SMALLER SYSTEMS

Small Modular Reactors

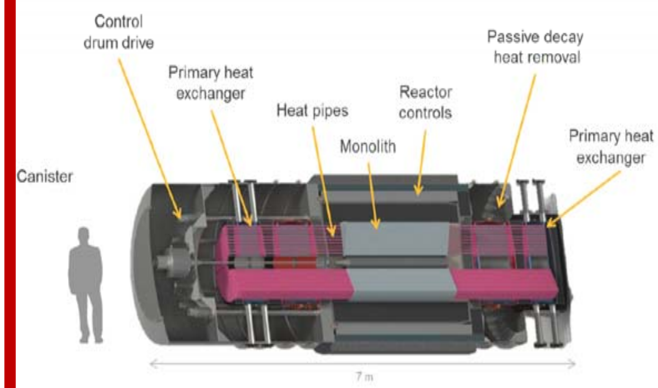
[NuScale, GE’s BWRX-300]
<300 MWe
Scaled-down, simplified versions of state-of-the-art LWRs

High Temperature Gas-Cooled Reactors



[X-energy]
<300 MWe
Helium coolant, graphite moderated, TRISO fuel, up to 650-700°C heat delivery

Nuclear Batteries



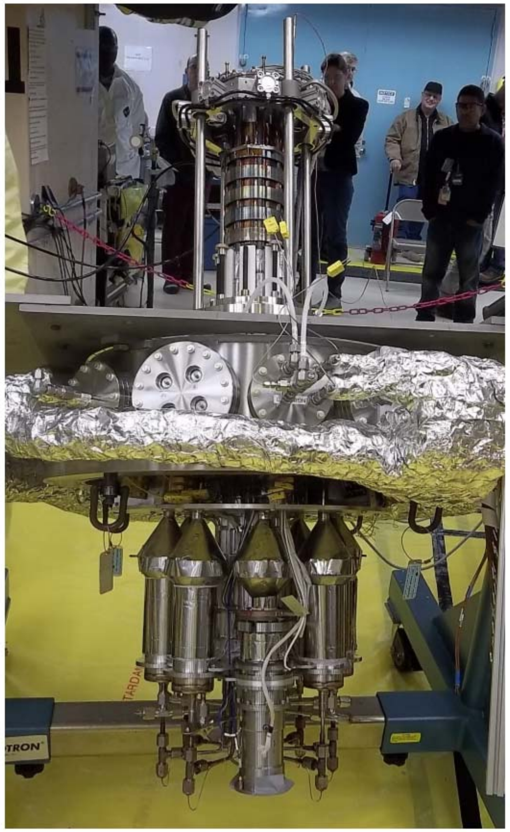
[Westinghouse’s eVinci]
<20 MWe
Block core with heat pipes, self-regulating operations, Stirling engine or air-Brayton

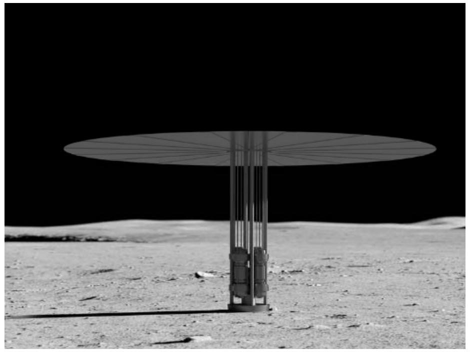
Must reduce scope of civil structures
(still ~50% of total capital cost)

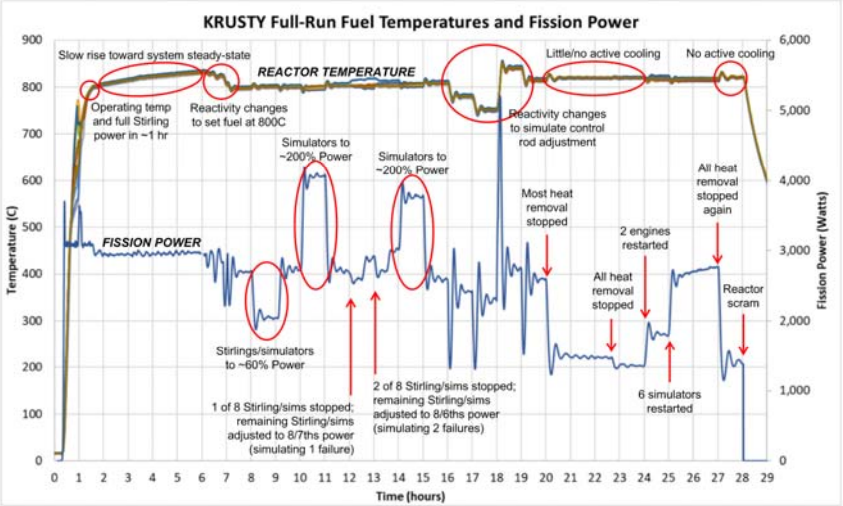
ACCELERATED TESTING/LICENSING
ENABLED BY SUPERIOR SAFETY PROFILE

(i.e., ‘infinite’ coping time + small EPZ)

CAN SAVE A DECADE AND AN EARLY BILLION DOLLARS



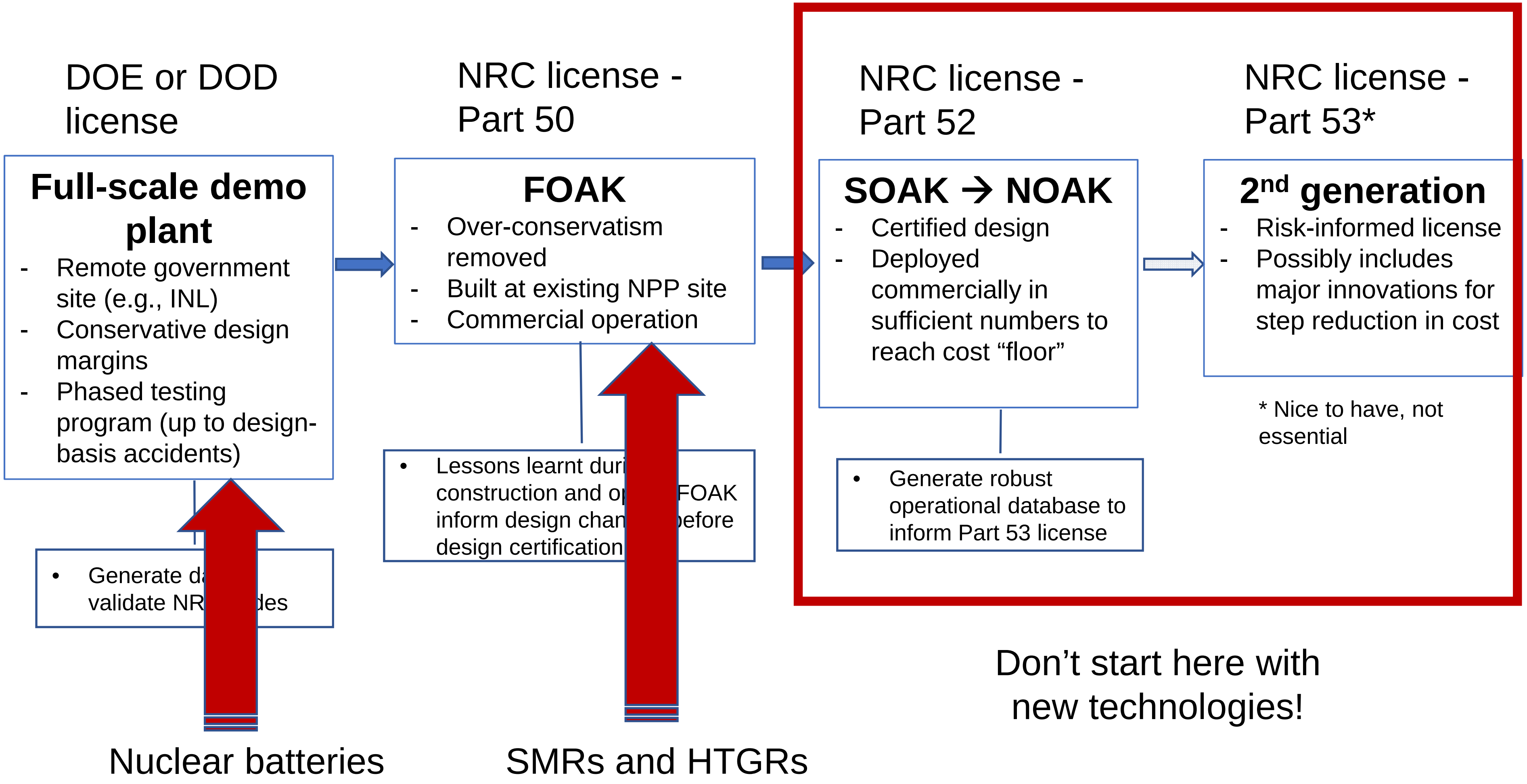




Actual test data from Kilopower nuclear test performed Mar 20-21, 2018 – reactor temperature is measured by thermocouples on fuel perimeter, fission power is directly scaled from neutron flux.

NASA/LANL recently designed, fabricated and tested a nuclear battery (<1MW) for space applications at a total cost of <$20M, in less than 3 years

NEW REGULATORY FRAMEWORK IS NOT ESSENTIAL



DOE or DOD license

Full-scale demo plant

- Remote government site (e.g., INL)
- Conservative design margins
- Phased testing program (up to design-basis accidents)

- Generate d validate NR des

NRC license - Part 50

FOAK

- Over-conservatism removed
- Built at existing NPP site
- Commercial operation

- Lessons learnt duri construction and o FOAK inform design chan efore design certification

NRC license - Part 52

SOAK → NOAK

- Certified design
- Deployed commercially in sufficient numbers to reach cost “floor”

- Generate robust operational database to inform Part 53 license

NRC license - Part 53*

2nd generation

- Risk-informed license
- Possibly includes major innovations for step reduction in cost

* Nice to have, not essential

Nuclear batteries

SMRs and HTGRs

Don’t start here with new technologies!

HIGHER ADDED VALUE CAN COME FROM

- A strong policy signal recognizing the non-emitting nature, economic impact, and contribution to energy security of nuclear *electricity*

Unlikely and beyond our control

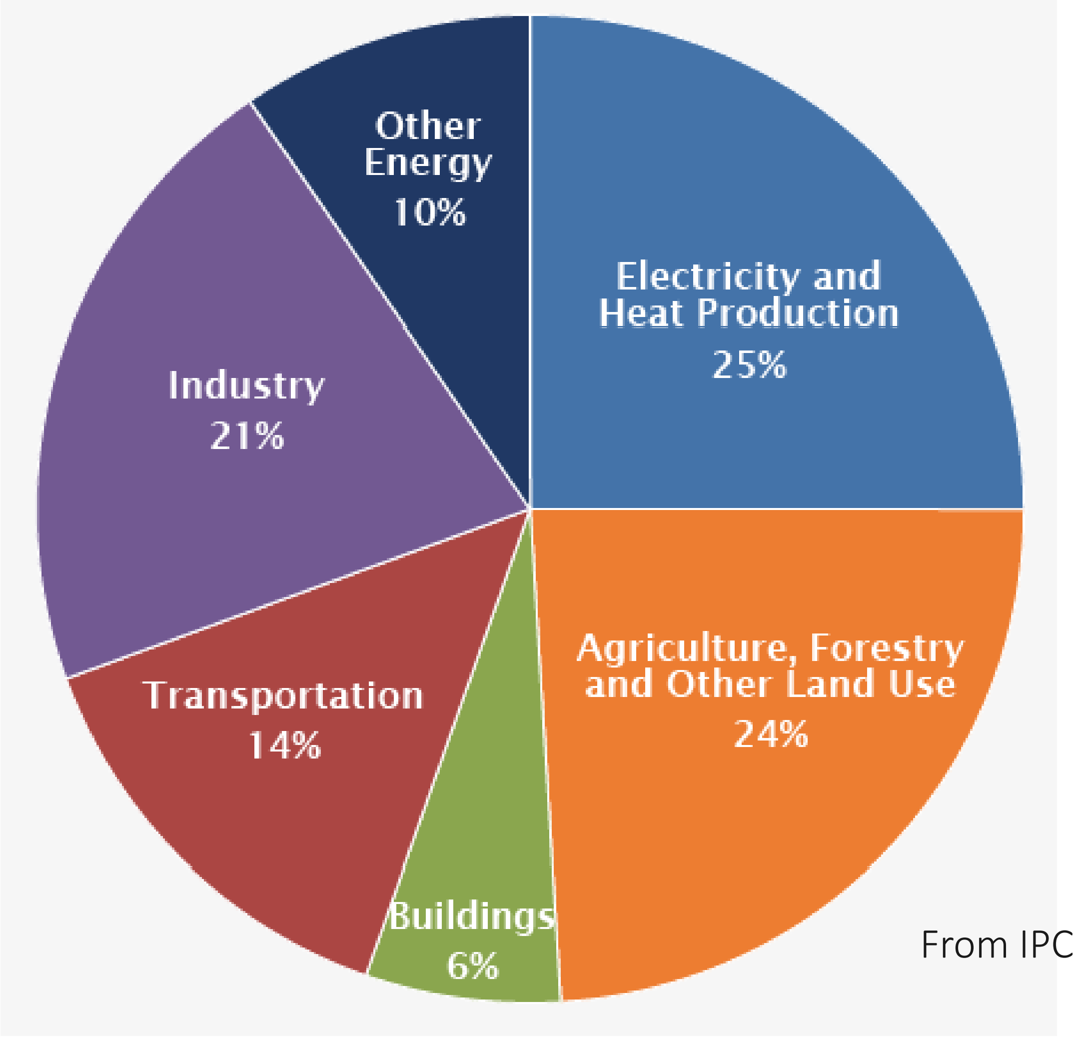
AND/OR

- Capture of new markets in which nuclear products could sell at a premium

Within reach with the right technology

BEYOND THE GRID

Where are the carbon emissions?



From IPCC 2014

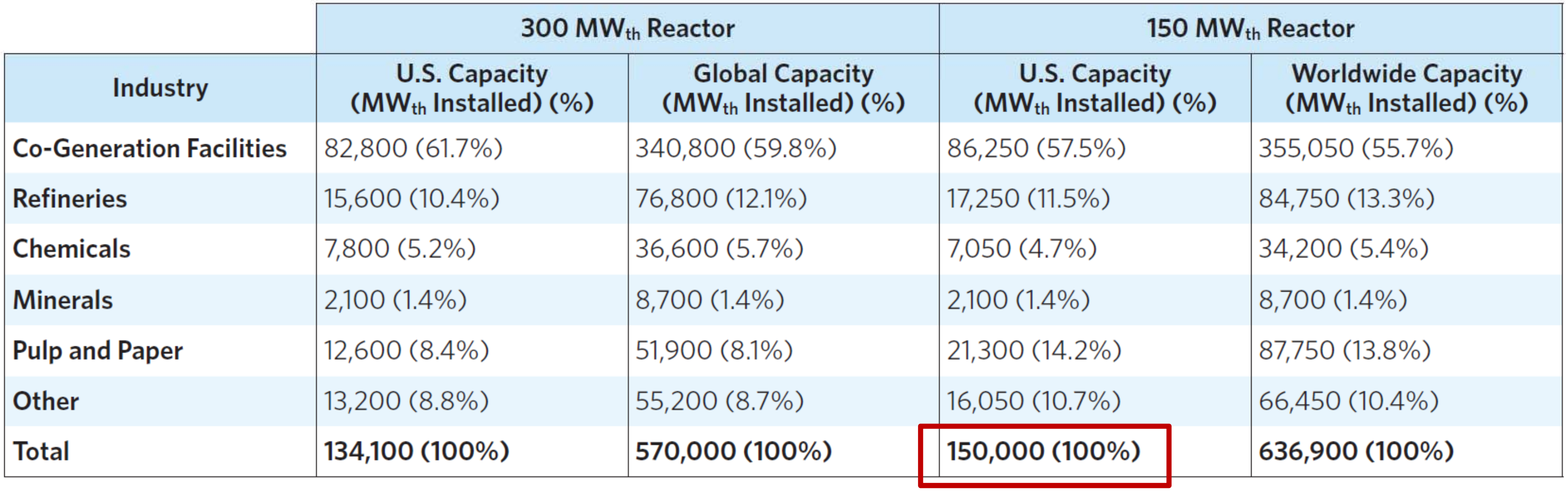
Much more than electricity

In a low-carbon world, nuclear energy is the lowest-cost, dispatchable heat source for industry

Technology	LCOH $/MWh-thermal	Dispatchable	Low carbon
Solar PV: Rooftop Residential	190-320	No	Yes
Solar PV: Crystalline Utility Scale	45-55	No	Yes
Solar PV: Thin Film Utility	40-50	No	Yes
Solar Thermal Tower with Storage	50-100	Yes	Yes
Wind	30-60	No	Yes
Nuclear	**35-60**	**Yes**	**Yes**
Natural Gas (U.S. price)	20-40	Yes	No

LCOH = Levelized Cost of Heat (LCOH)

A small (but not insignificant) potential market for nuclear heat in industry *now*



	300 MW_{th} Reactor		150 MW_{th} Reactor	
Industry	**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 U.S. sites emitting 25,000 ton-CO_2/year or more
- Considered sites needing at least 150 MW of heat
- Nuclear heat delivered at max 650°C (with nuclear battery or HTGR technology)
- Chemicals considered include ammonia, vinyl chloride, soda ash, nylon, styrene
- Heat from waste stream not accessible

In the transportation sector, hydrogen and/or electrification could create massive growth opportunities for nuclear

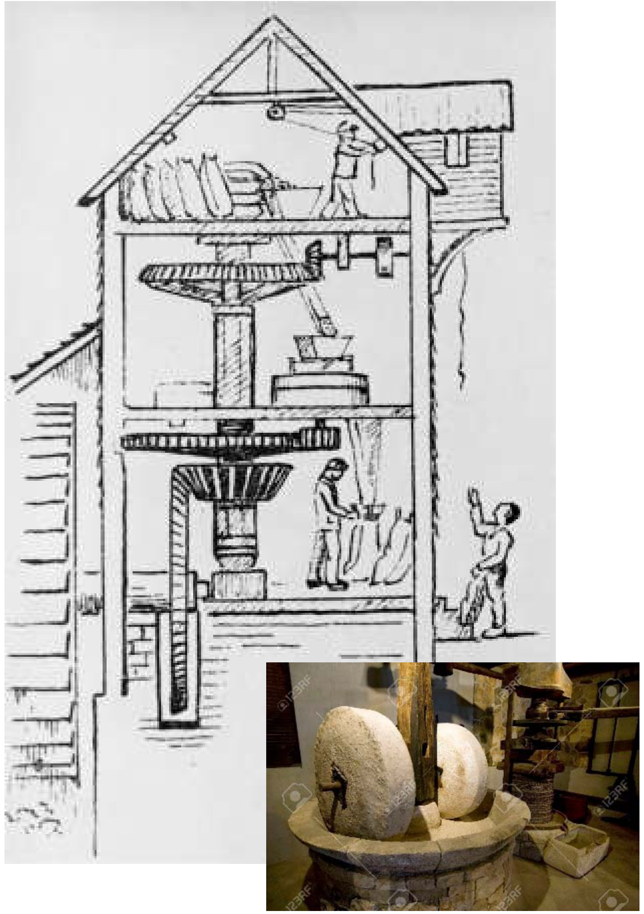
Country	**New nuclear capacity required to decarbonize the transportation sector**	
	With electrification*	With hydrogen**
U.S.	285 GW_e	342 GW_e and 111 GW_{th}
France	22 GW_e	28 GW_e and 9 GW_{th}
Japan	33 GW_e	41 GW_e and 13 GW_{th}
World	1060 GW_e	1315 GW_e and 428 GW_{th}

* Assumes that (i) the efficiency of internal combustion engines is 20%, and (ii) the efficiency of electric vehicles is 60%

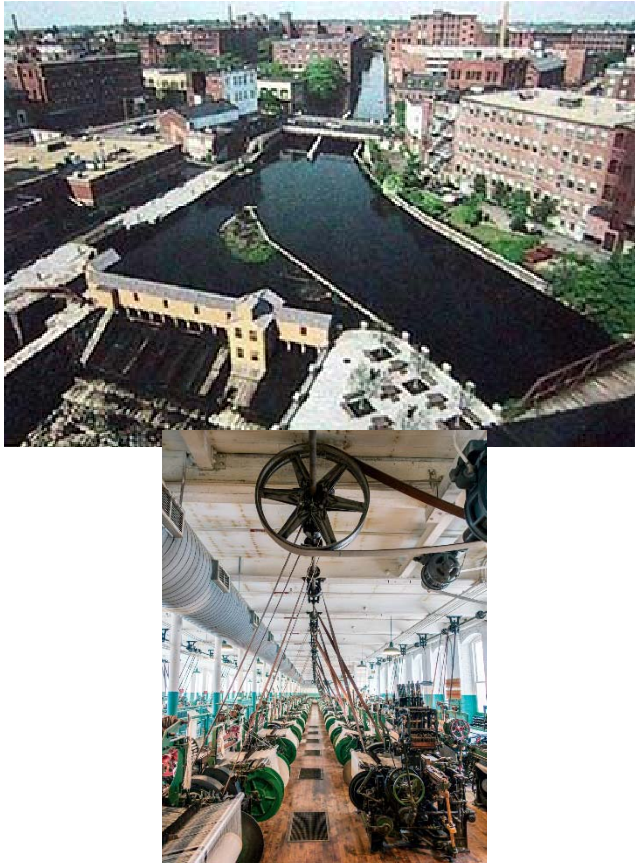
** Assumes that (i) the efficiency of internal combustion engines is 20%, (ii) the efficiency of hydrogen fuel cells is 50%, (iii) hydrogen gas has a lower heating value of approximately 121.5 MJ/kg, and (iv) the energy requirement for high-temperature electrolysis of water is 168 MJ/kg-H_2, of which 126 MJ/kg-H_2 is electrical and 41 MJ/kg-H_2 is thermal.

CO-LOCATED SUPPLY AND DEMAND

Co-located supply and demand has always been the most efficient approach



Watermill for production of flour and olive oil (since Roman times)



Hydro electricity and textile factories (industrial revolution)

Back to the future

Off-grid, mobile, containerized production and processing (agro, aqua, pharma, 3D-printing, data centers, etc.)

Nuclear battery

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Energy source	Stable output	Carbon-free	Geographically unconstrained	Suitable for mobile deployment	Predictable generation cost
Nuclear (traditional)	Yes	Yes	No	No	Yes
Nuclear (micro-reactors)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Natural gas	Yes	No	Yes	Yes	No
Coal	Yes	No	No	No	No
Hydro	No	Yes	No	No	No
Solar/Wind	No	Yes	No	No	No

Multi-trillion markets: foods, pharmaceuticals, fuels, manufacturing, consumer goods

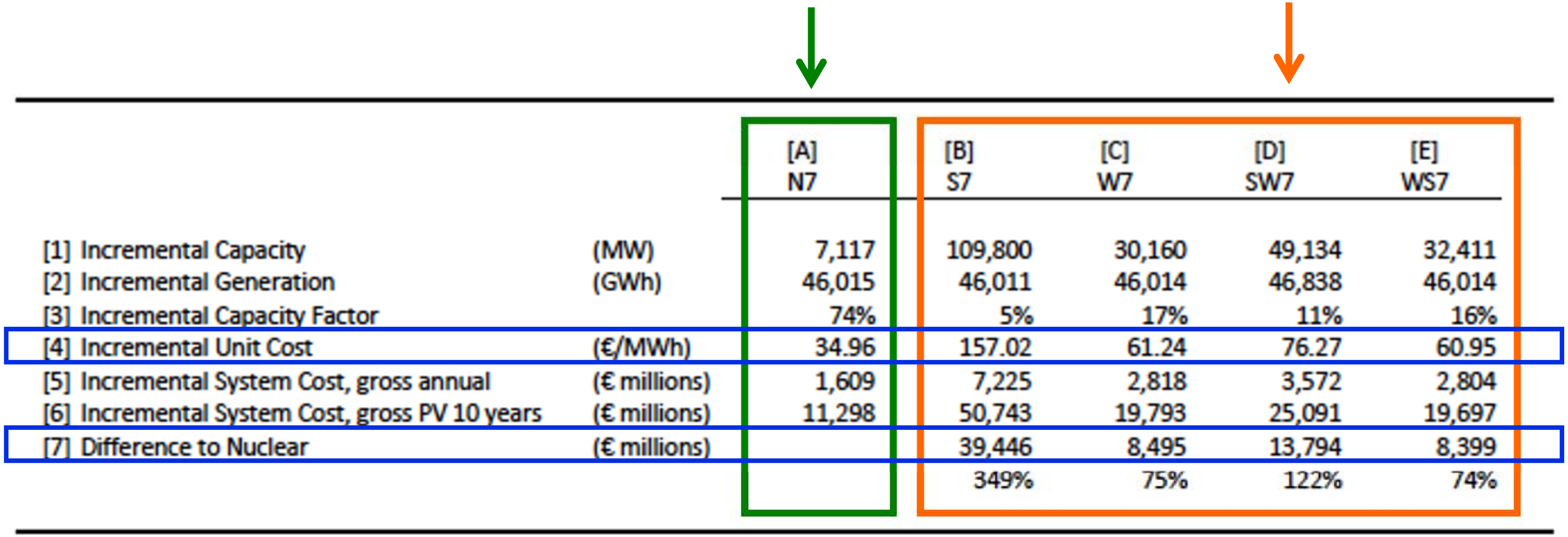
The future of nuclear?

Back-up slides

First priority: don’t shut down existing NPPs

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

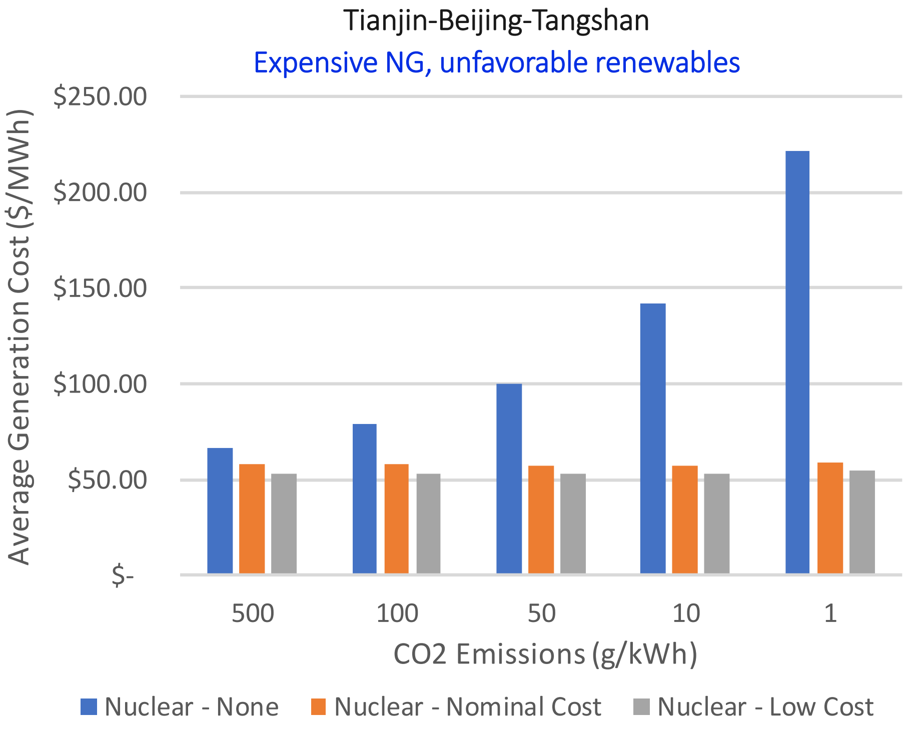
All reactors are shutdown and replaced by renewables + batteries to keep same emissions

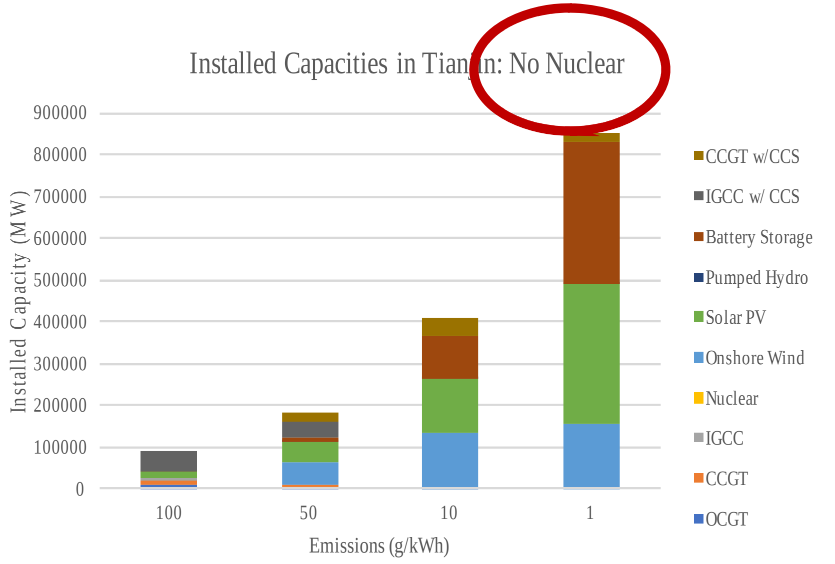
		[A] N7	[B] S7	[C] W7	[D] SW7	[E] WS7
[1] Incremental Capacity	(MW)	7,117	109,800	30,160	49,134	32,411
[2] Incremental Generation	(GWh)	46,015	46,011	46,014	46,838	46,014
[3] Incremental Capacity Factor		74%	5%	17%	11%	16%
[4] Incremental Unit Cost	(€/MWh)	34.96	157.02	61.24	76.27	60.95
[5] Incremental 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%

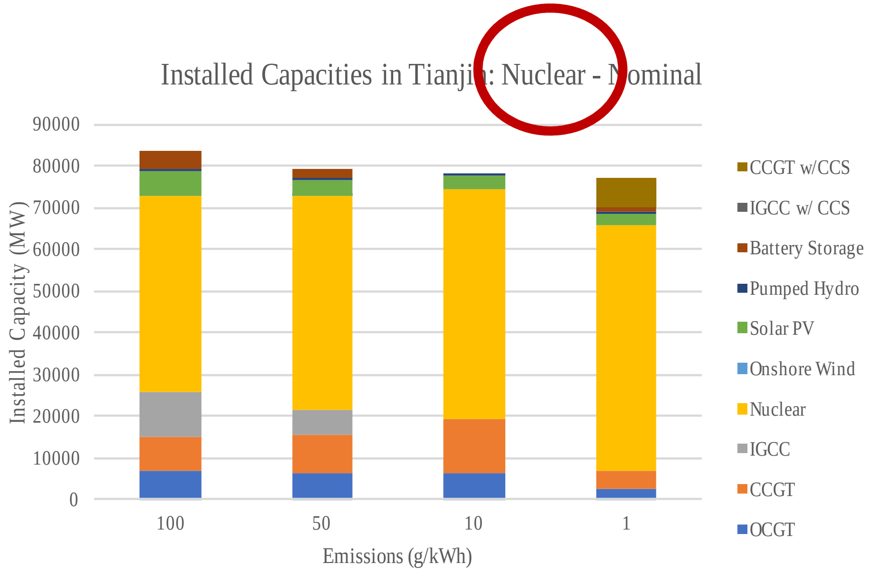
The Climate and Economic Rationale for Investment in Life Extension of Spanish Nuclear Plants, by A. Fratto-Oyler and J. Parsons, MIT Center for Energy and Environmental Policy Research Working Paper 2018-016, November 19, 2018. http://ssrn.com/abstract=3290828

THE ELECTRIC GRID

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

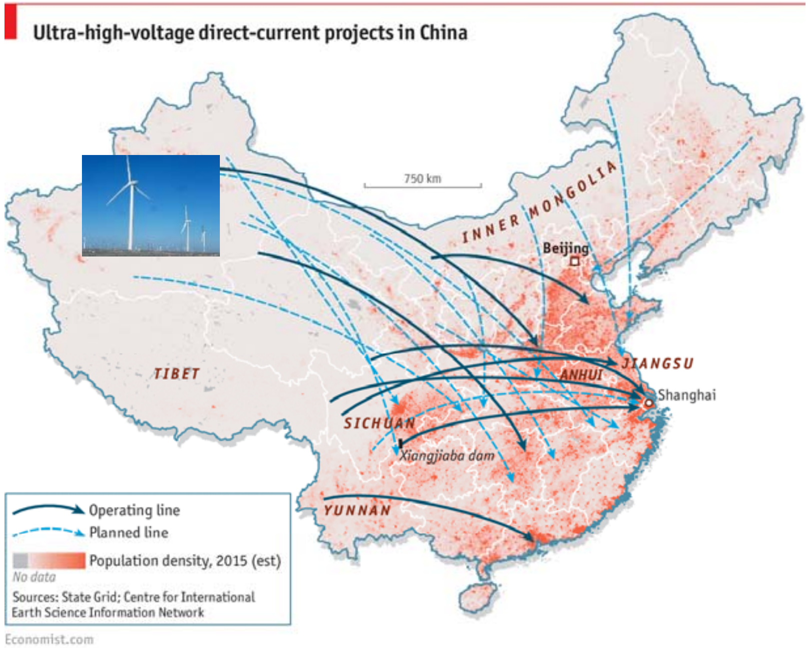






A rational decarbonized grid would include a lot of nuclear (or equivalent low-carbon dispatchable tech)

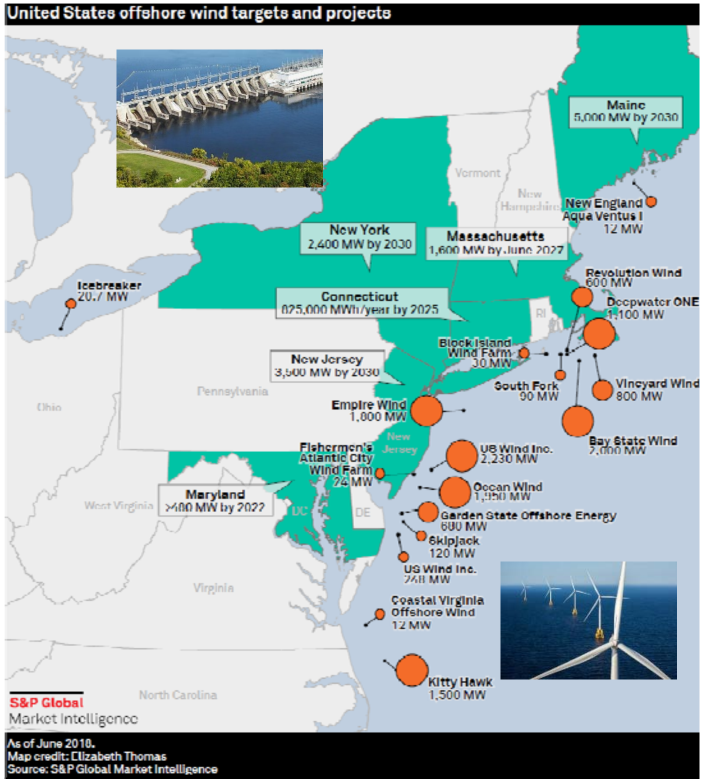
Instead, the grid is becoming more complicated, overbuilt, inefficient and expensive… and emissions are only marginally being reduced



Ultra-high-voltage direct-current projects in China

Sources: State Grid; Centre for International Earth Science Information Network

Economist.com



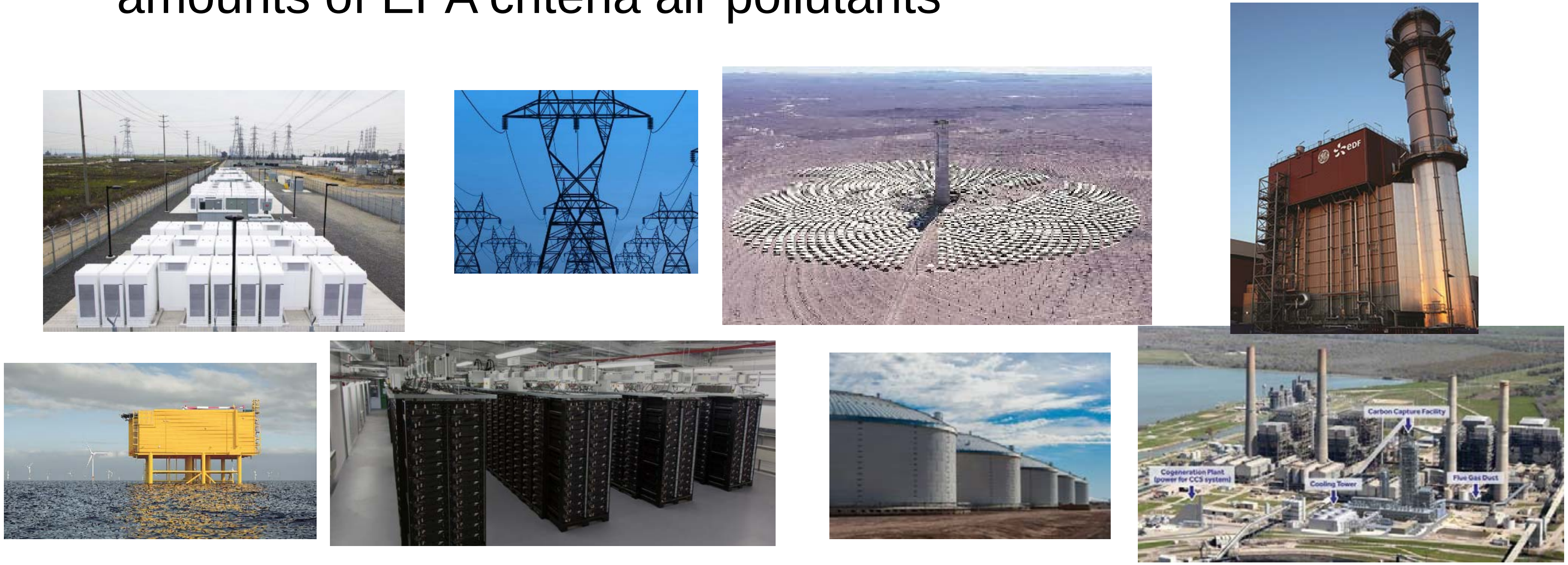
United States offshore wind targets and projects

As of June 2018.
Map credit: Elizabeth Thomas
Source: S&P Global Market Intelligence

- Supply (generators) and demand (end users) are geographically separated and static, requiring massive transmission infrastructure (supply-to-demand model)
- Complex interconnected system is vulnerable to external perturbations (e.g., extreme weather, malicious attacks)

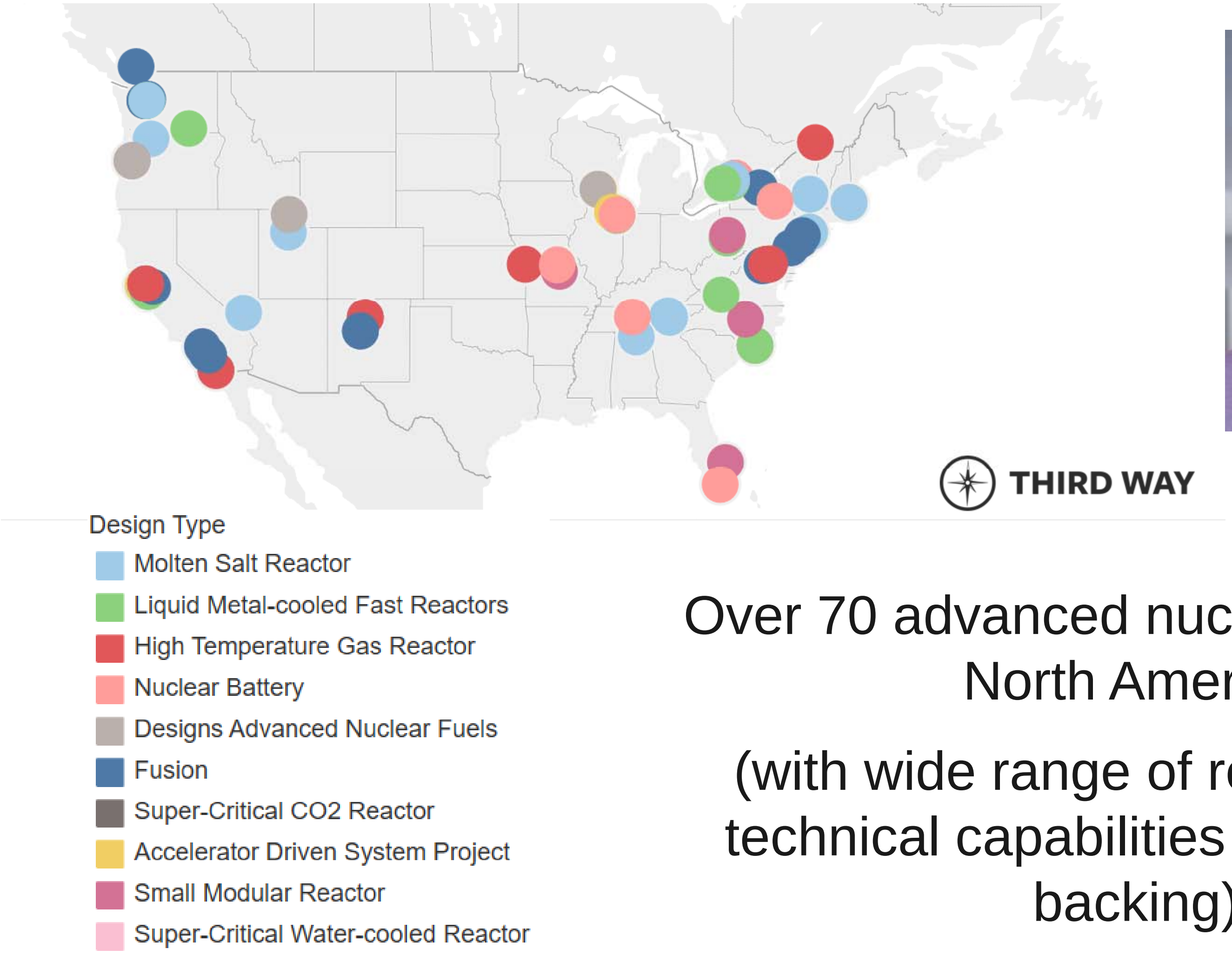
(Cont.)

- Capital-intensive equipment has low utilization factor because of high variability in demand and intermittency in supply (e.g., back-up, storage, solar/wind overcapacity)
- Market is muddied by subsidies (e.g., renewables, nuclear) and un-accounted costs (e.g., social cost of carbon)
- Still responsible for ¼ of global CO_2 emissions and large amounts of EPA criteria air pollutants



Why continue to play on natural gas' and renewables' home turf?

Robust interest in new reactor technologies with support from private capital (>$2B) and influential advocates



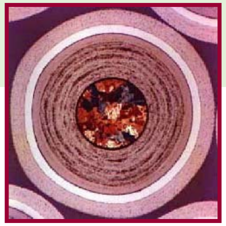
Over 70 advanced nuclear projects in North America

(with wide range of reactor types, technical capabilities and financial backing)

A SUPERIOR SAFETY PROFILE CAN REDUCE TIME AND COST TO LICENSING

Demonstrated inherent safety attributes:

- No coolant boiling (HTGR, microreactors)
- Strong fission product retention in robust fuel (HTGR)
- High thermal capacity (SMRs & HTGR)
- Strong negative temperature/power coefficients (all concepts)
- Low chemical reactivity (HTGR)



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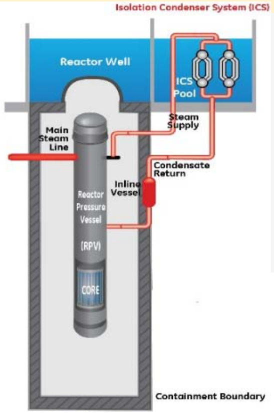
Engineered passive safety systems:

- Heat removal
- Shutdown



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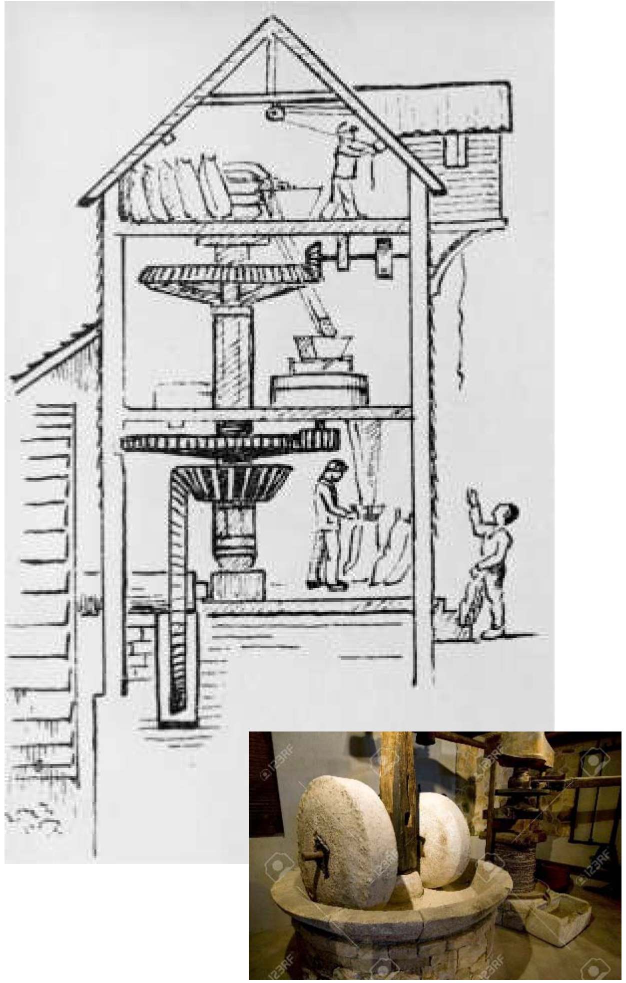
- ✓ No need for emergency AC power
- ✓ Long coping times
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary

Design certification of NuScale is showing U.S. NRC’s willingness to value new safety attributes

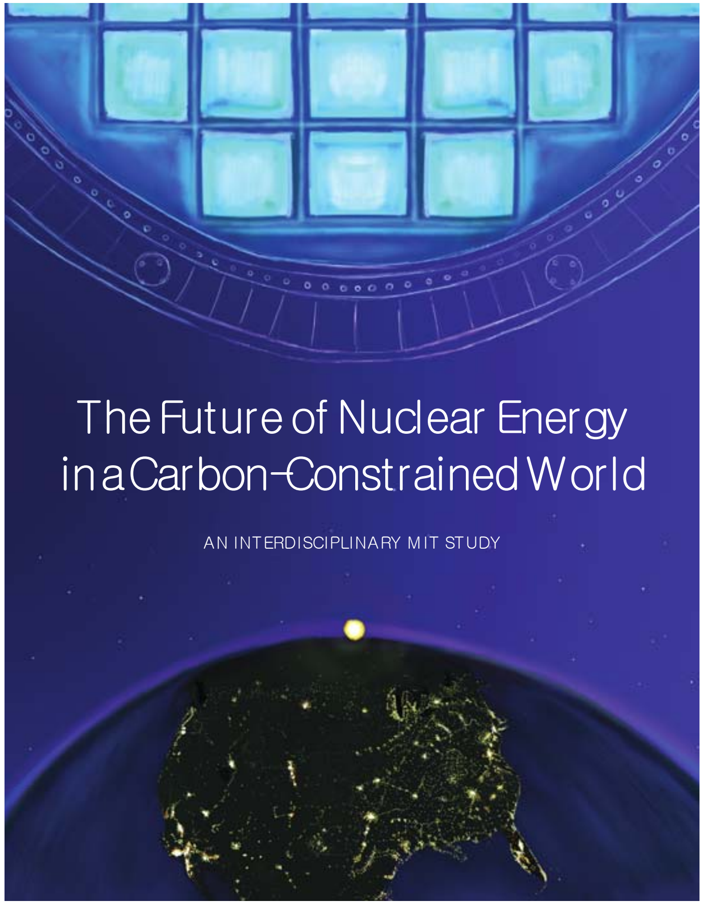
Co-located supply-and-demand is where we started

Water mill for flour and olive oil production



Hydro electricity + textile factory (industrial revolution)

2018 MIT study on the Future of Nuclear

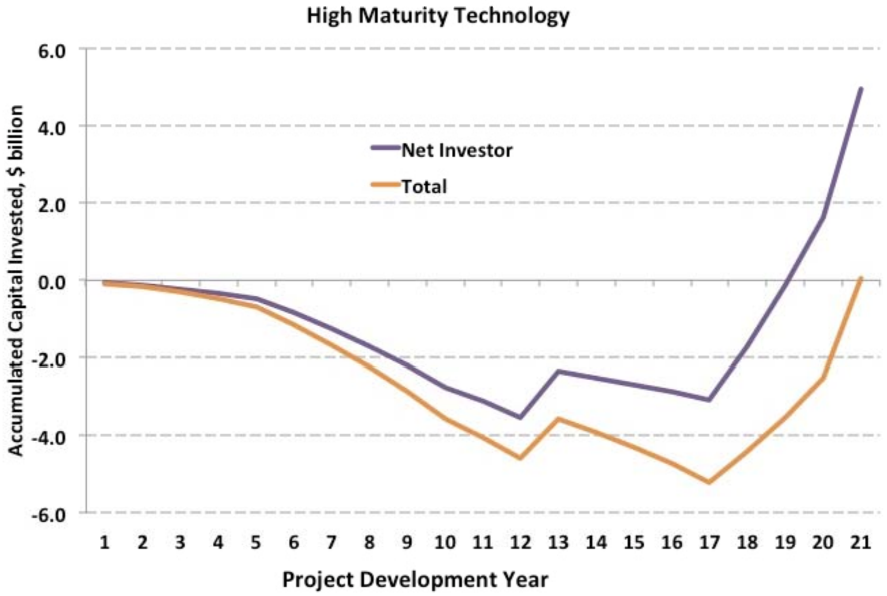


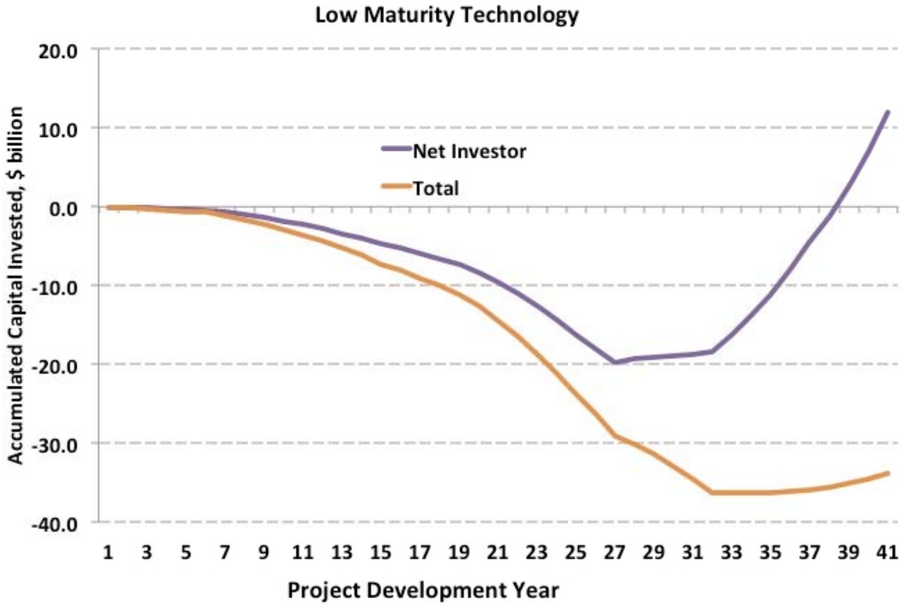
Key messages:

- 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/research/future-nuclear-energy-carbon-constrained-world/

Government can help to mitigate project risks for new technologies





Early government support is needed.

Four “levers”:

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

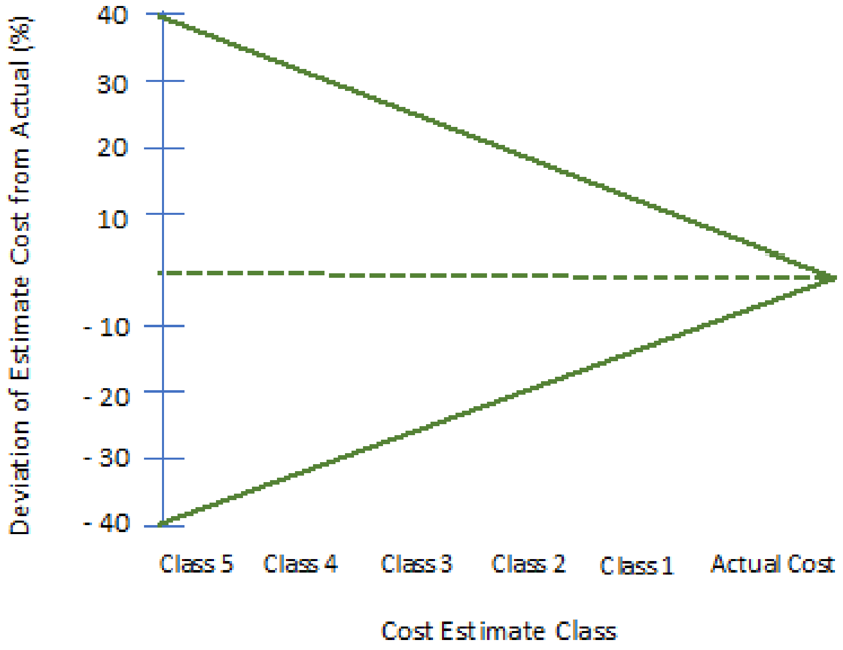
The jury is still (very much) out on the economic potential of advanced reactors

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

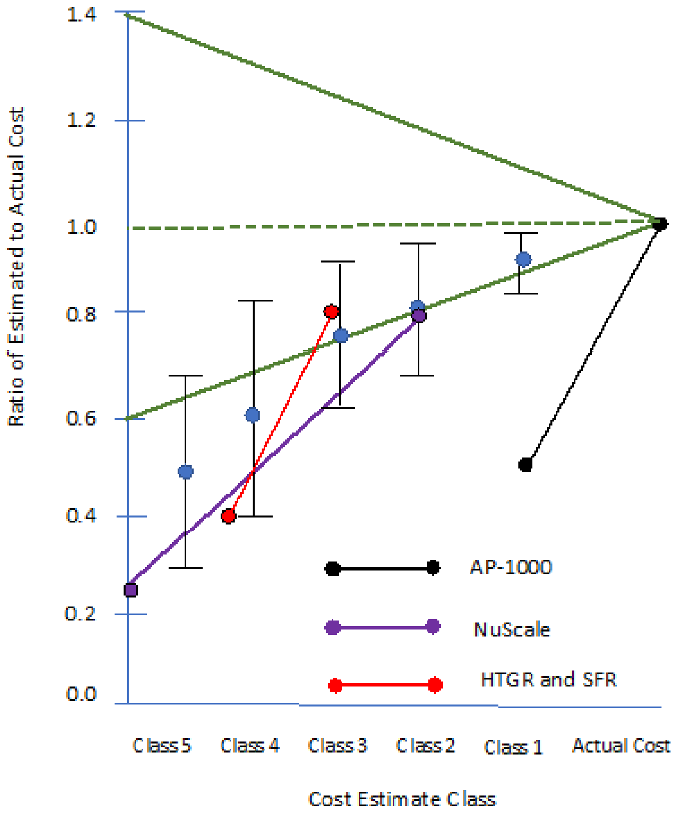
1. E. Ingersoll, "International Nuclear Project Costs, Proprietary and Confidential
2. F. Ganda et al., "Reactor Caital Costs Breakdown and Statistical Analysis of Historical US Construction Costs," ICAPP 206
3. A. M. Gandrik, "Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating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