Nuclear Energy: a New Beginning?

- Findings from a recent MIT study -

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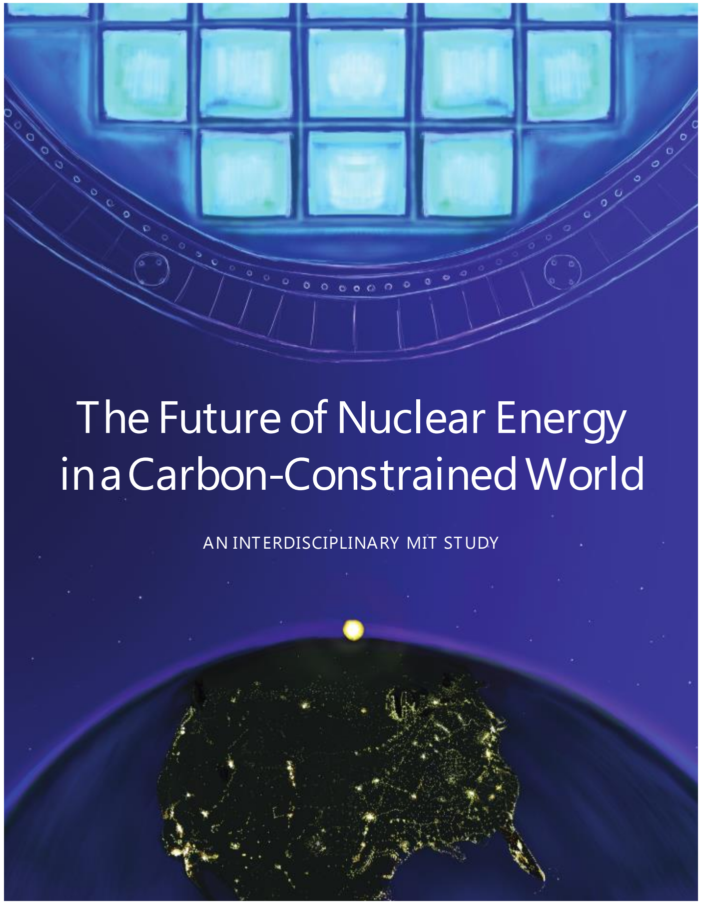
science : systems : society

2018 MIT study on the Future of Nuclear



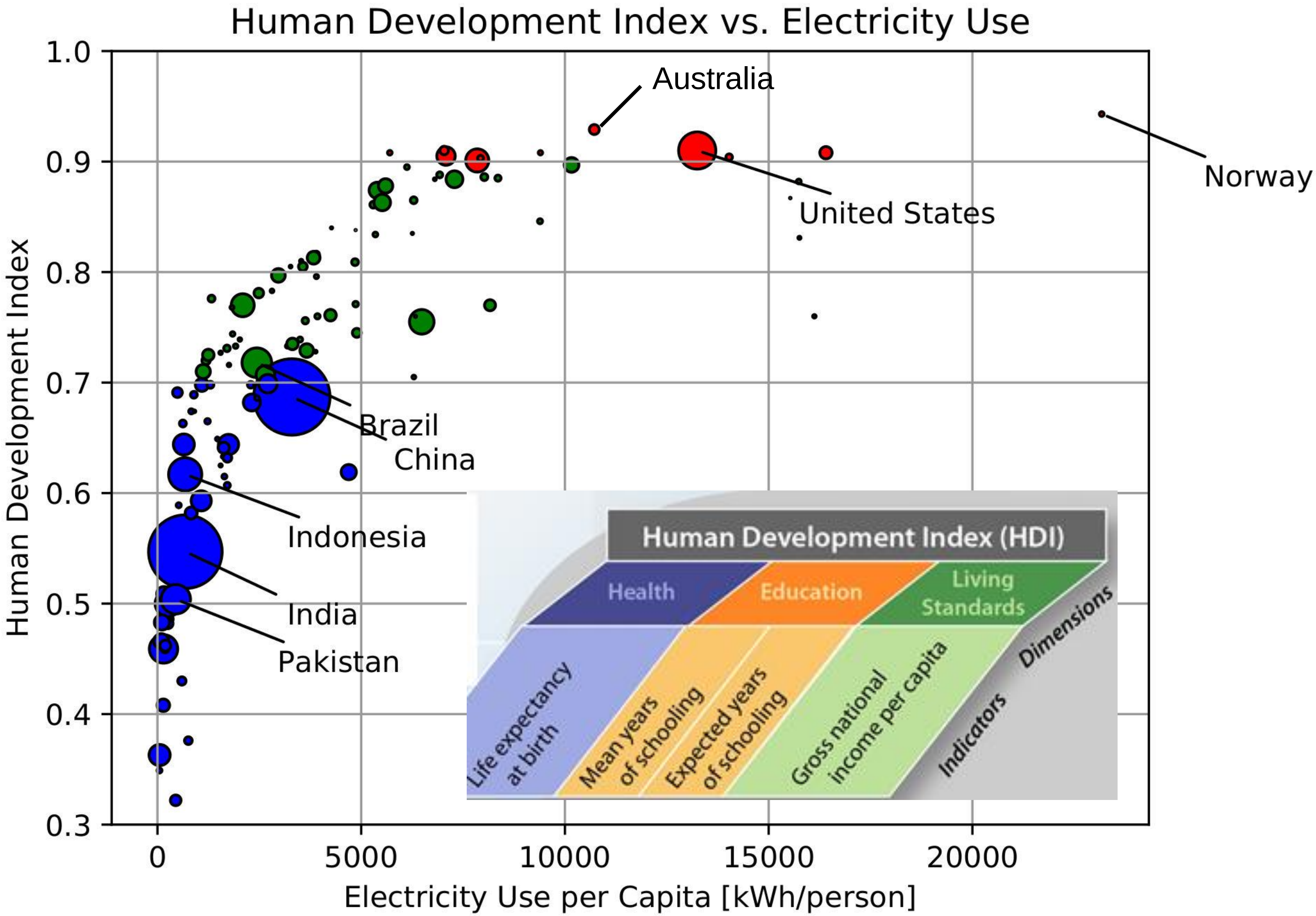
Key messages:

- When deployed efficiently, nuclear can prevent electricity cost escalations in a decarbonized grid
- The cost of new nuclear builds in the West has been too high
- There are ways to reduce the cost of new nuclear
- Government's help is needed to make it happen

Download the report at
http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/

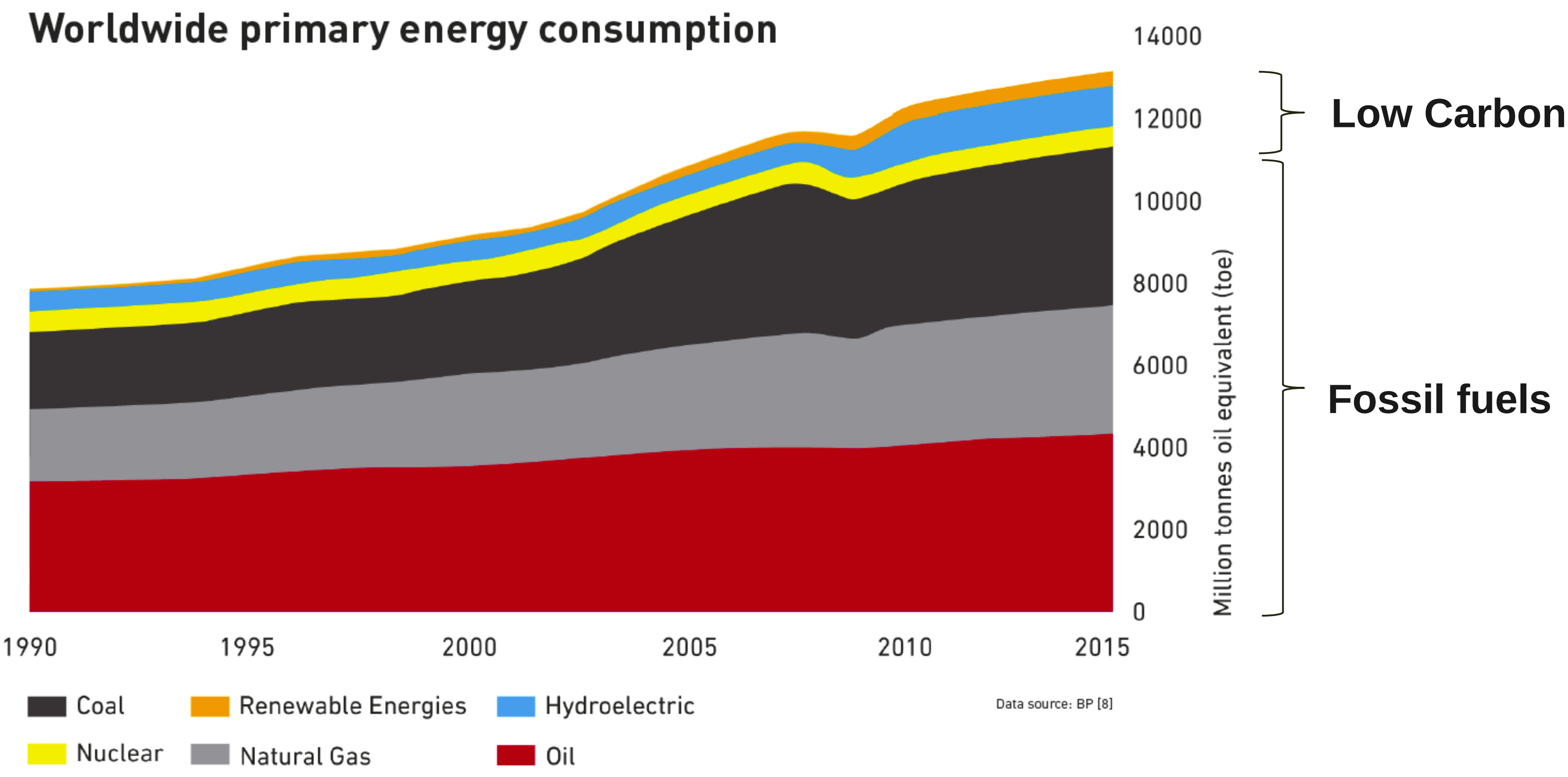
The big picture

The World needs a lot more energy



Global electricity consumption is projected to grow 45% by 2040

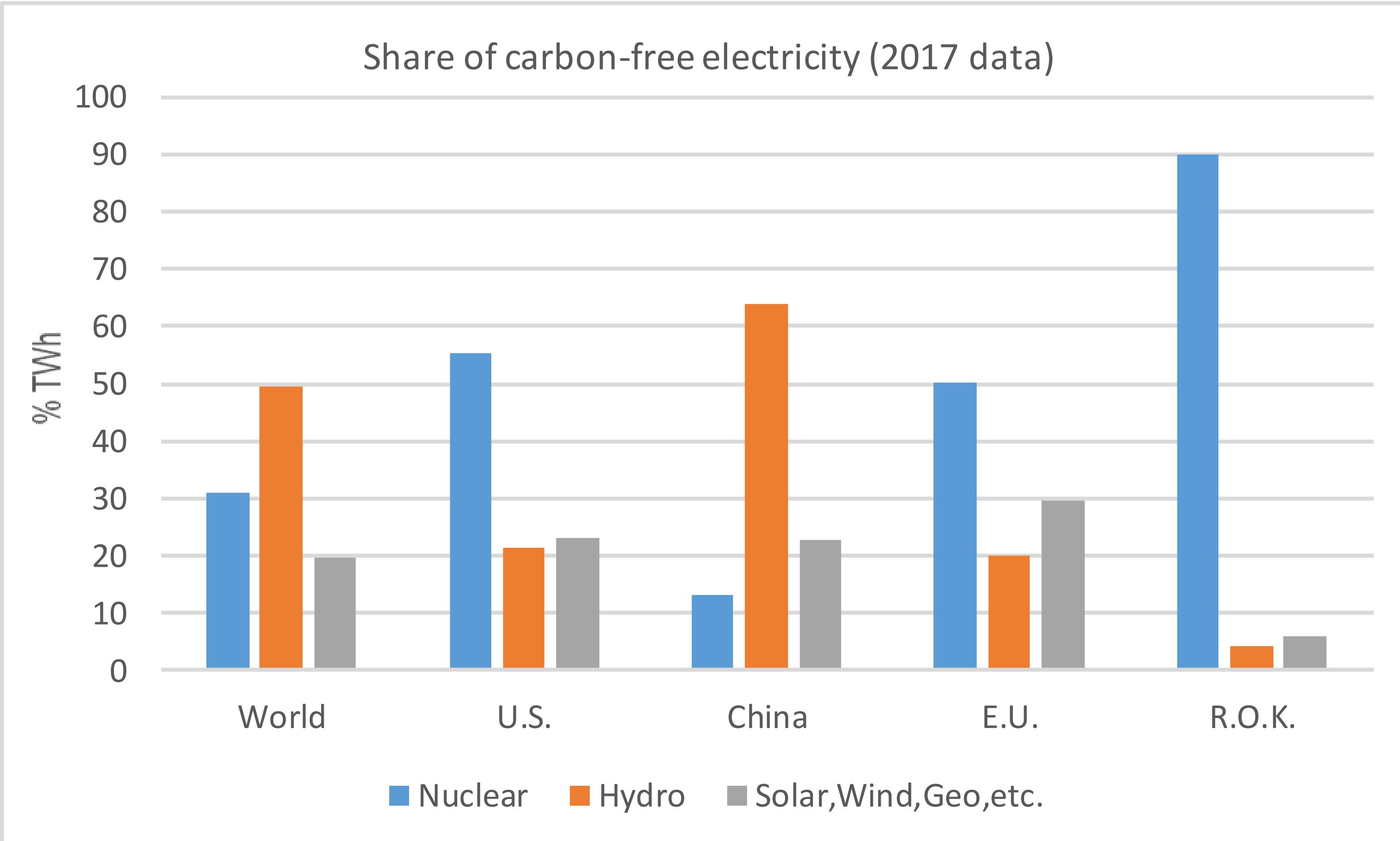
The key dilemma is how to increase energy generation while limiting global warming



CO_2 emissions are actually rising… we are NOT winning!

The current role of nuclear

Nuclear is the largest source of emission-free electricity in the U.S. and Europe by far



Growing in China, India, Russia and the Middle-East, declining in Western Europe, Japan and the U.S.

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

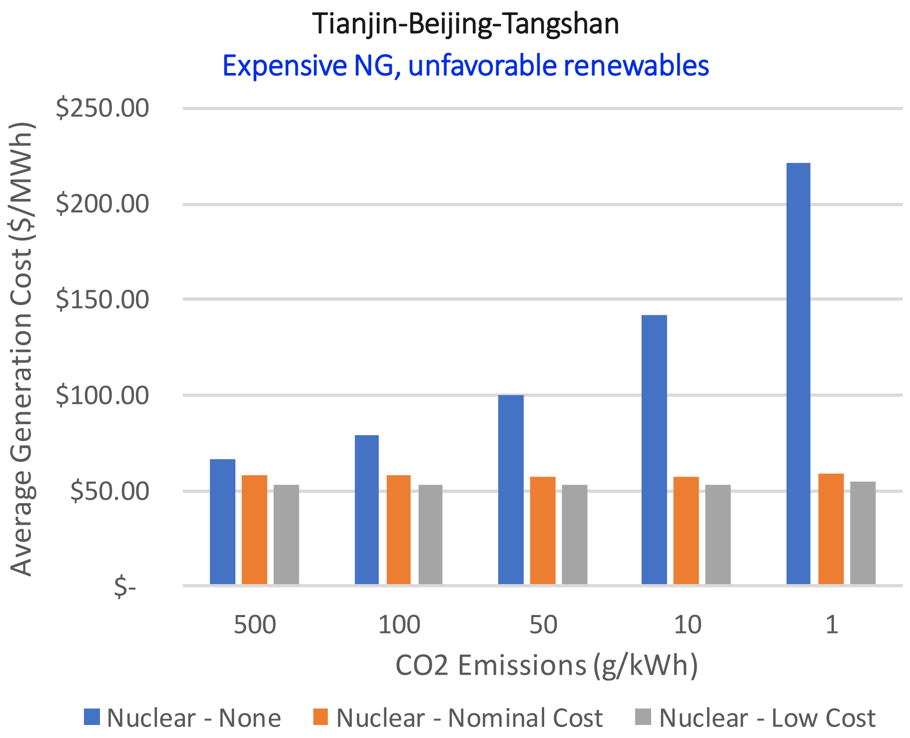
		[A] N7	[B] S7	[C] W7	[D] SW7	[E] WS7
[1] Incremental Capacity	(MW)	7,117	109,800	30,160	49,134	32,411
[2] Incremental Generation	(GWh)	46,015	46,011	46,014	46,838	46,014
[3] Incremental Capacity Factor		74%	5%	17%	11%	16%
[4] Incremental Unit Cost	(€/MWh)	34.96	157.02	61.24	76.27	60.95
[5] Incremental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

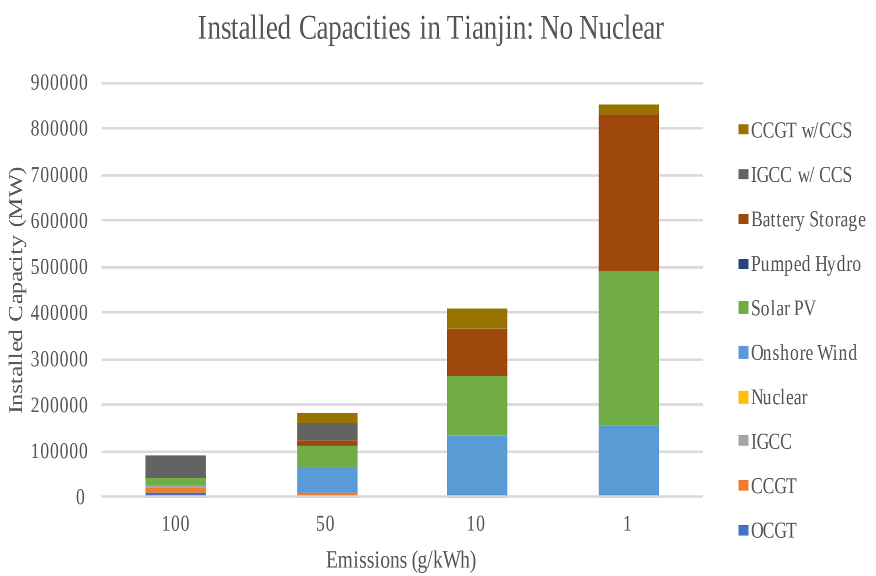
Do we need nuclear to *deeply* decarbonize the power sector?

The economic argument

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



The problem with the no-nuclear scenarios

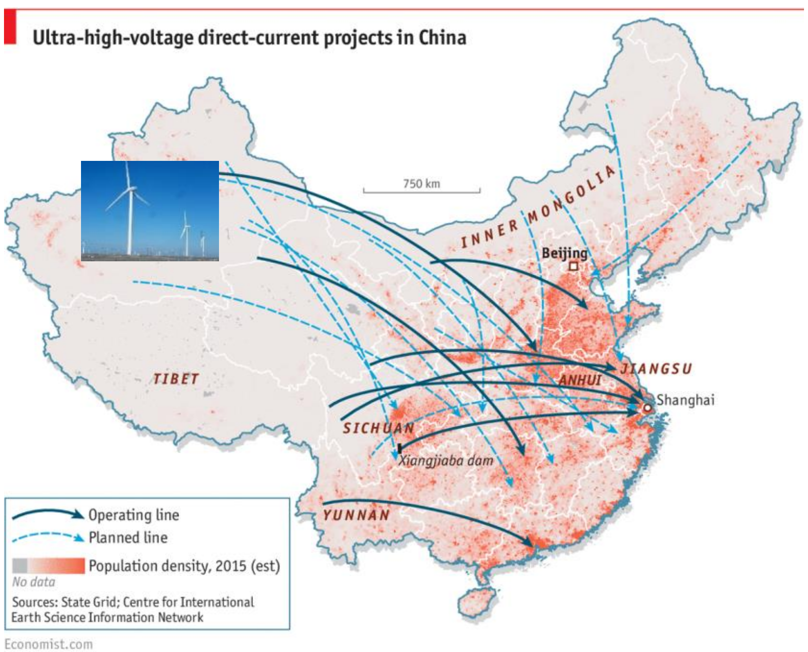


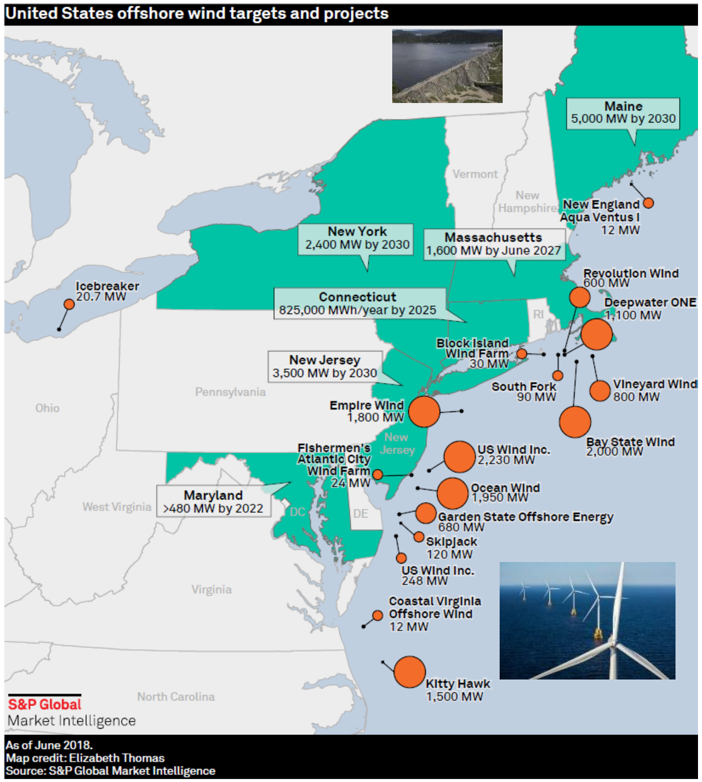
Simulation of optimal generation mix in power markets

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

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

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





- Supply (generators) and demand (end users) are geographically separated and static, requiring massive transmission infrastructure
- 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)
- Germany and California have spent over half a trillion dollars on intermittent renewables and have not seen a significant decrease in emissions

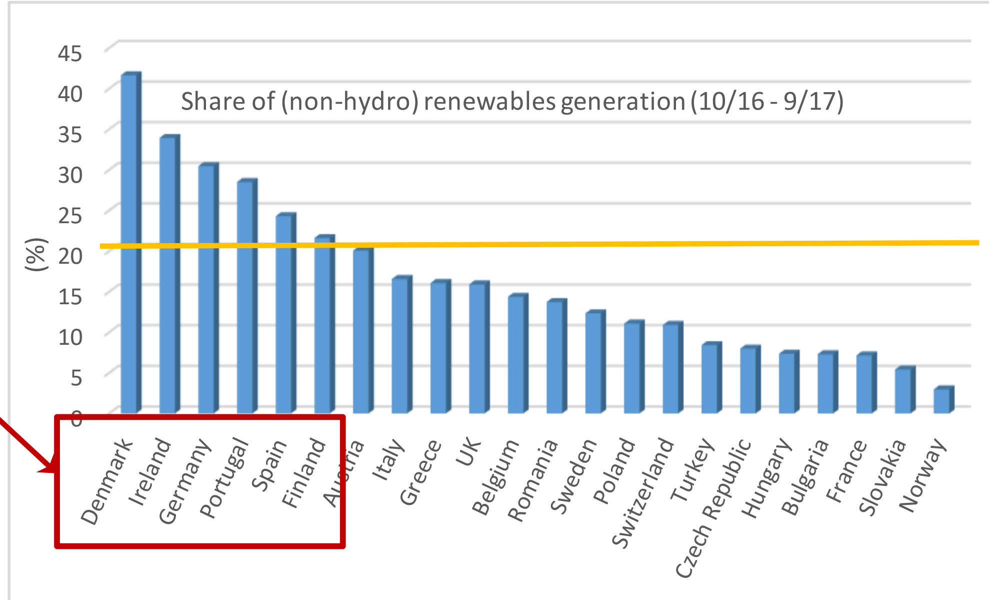




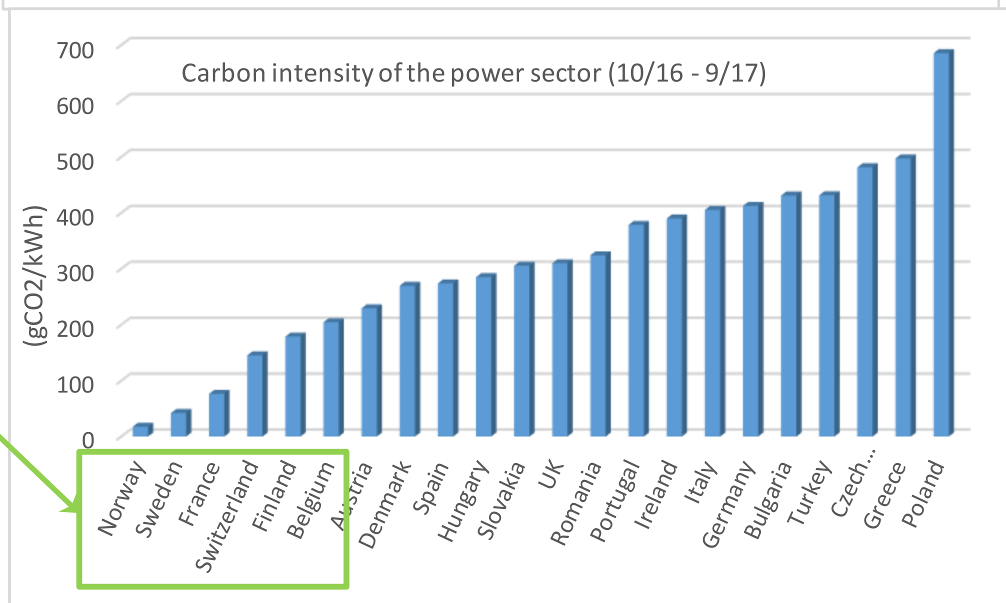



Low carbon intensity in Europe correlates with nuclear and hydro

EU countries with high capacity of solar and wind



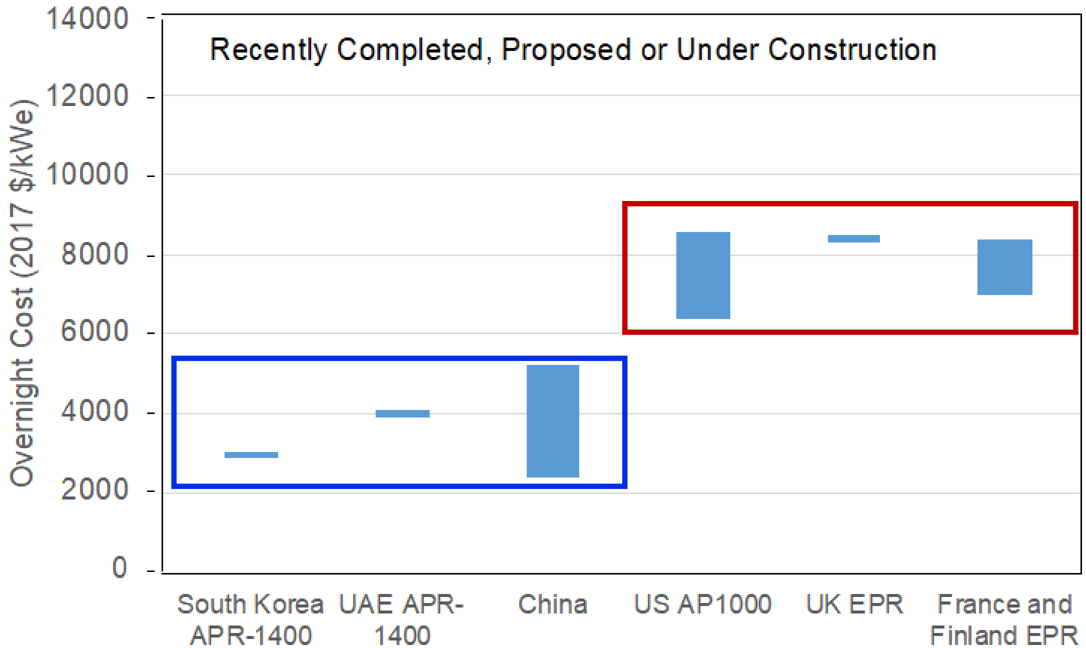
EU countries with low carbon intensity



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

Second priority: build new NPPs …but what about cost?

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



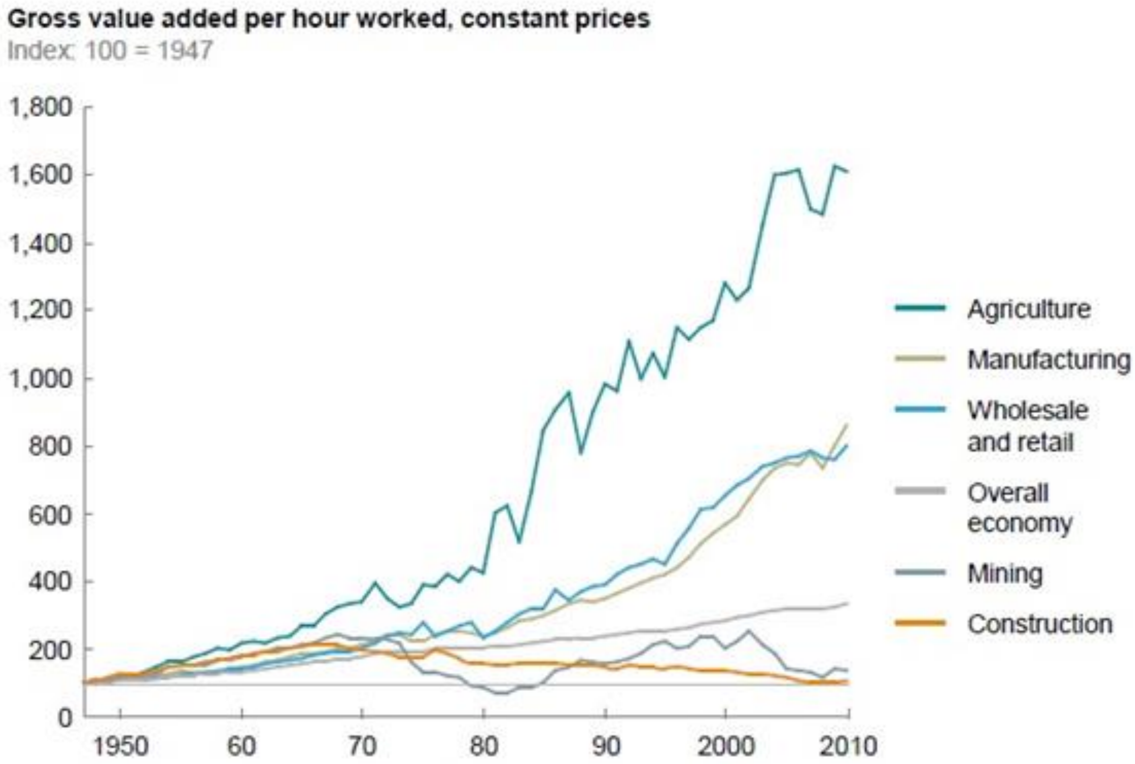
ASIA

- >90% detailed design completed before starting construction
- Proven NSSS supply chain and skilled labor workforce
- Fabricators/constructors 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

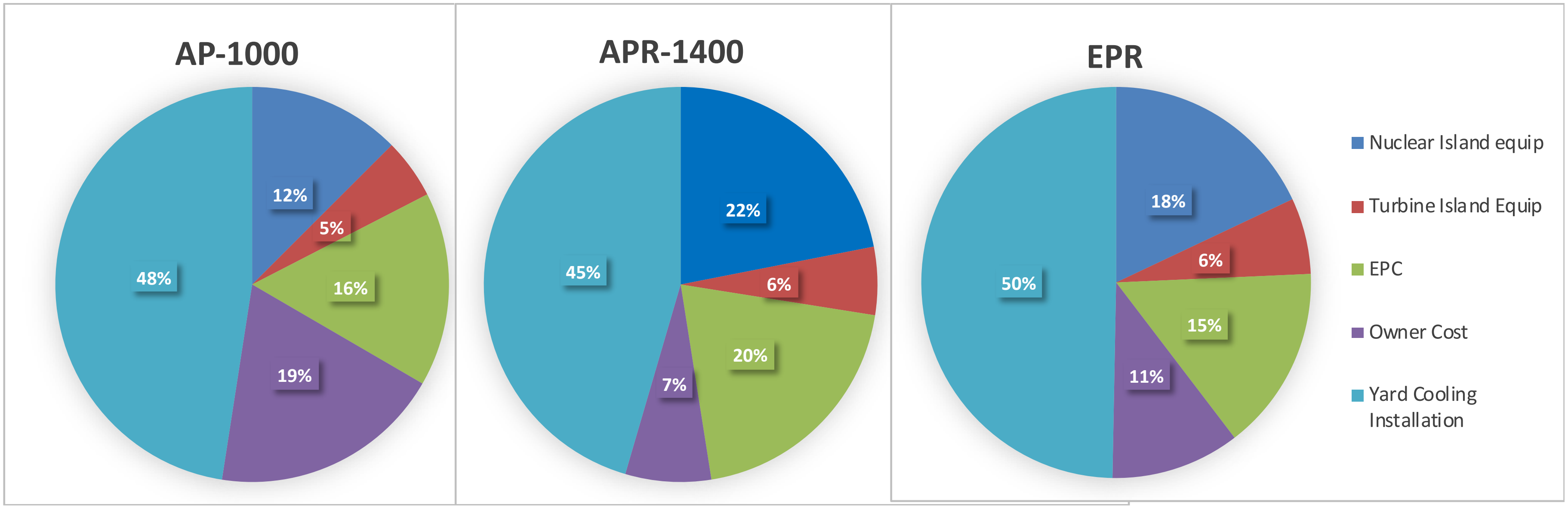


Construction labor productivity has decreased in the West

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)

Where is the cost of a new NPP?



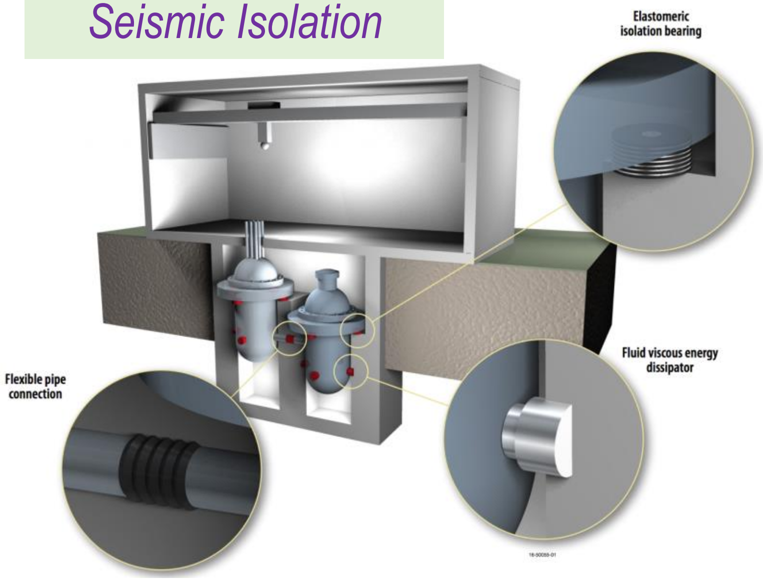
Sources:
AP1000: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11
APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication,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

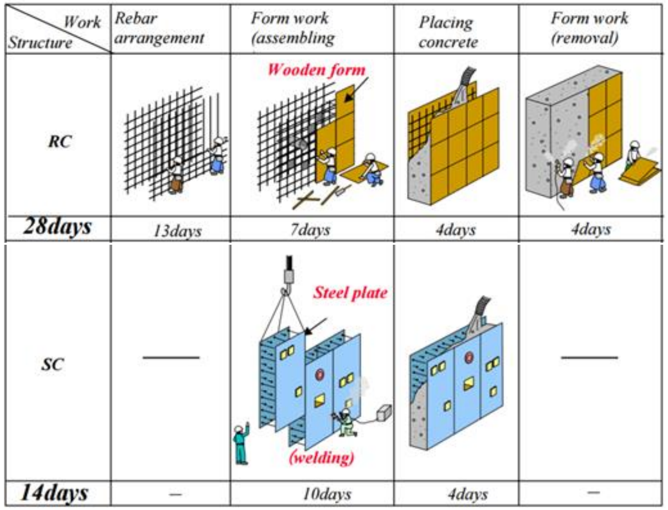
What innovations could make a difference?

Standardization on multi-unit sites

Seismic Isolation



Advanced Concrete Solutions



Work / Structure	Rebar arrangement	Form work (assembling	Placing concrete	Form work (removal)
RC				
28days	13days	7days	4days	4days
SC	—			—
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 ⇒ reduce installation cost
- Standardize design ⇒ reduce licensing and engineering costs + maximize learning
- Shorten construction schedule ⇒ 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

Why advanced reactors

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

Nuclear DD&D paradigm needs to shift to:

- ❑ *smaller, serial-manufactured* systems,

- ❑ with *accelerated testing/licensing,*

- ❑ producing *high added-value* energy products.

SMALLER SYSTEMS

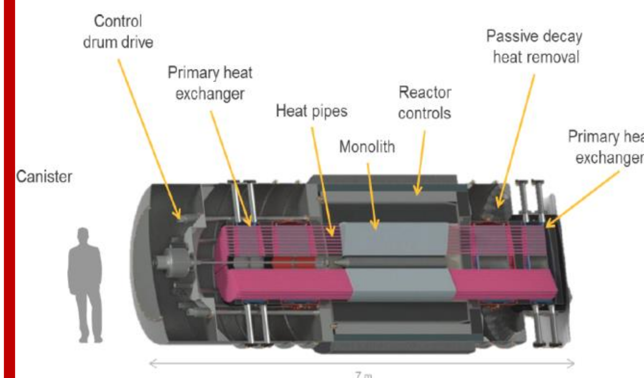
Small Modular Reactors

[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



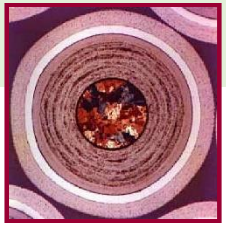
[Westinghouse's eVinci]
<20 MWe
Block core with heat pipes, self-regulating operations, Stirling engine or air-Brayton

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

A SUPERIOR SAFETY PROFILE ENABLED BY INHERENT FEATURES AND ENGINEERED SYSTEMS

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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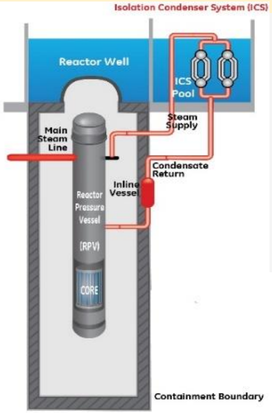
Engineered passive safety systems:

– Heat removal

– Shutdown



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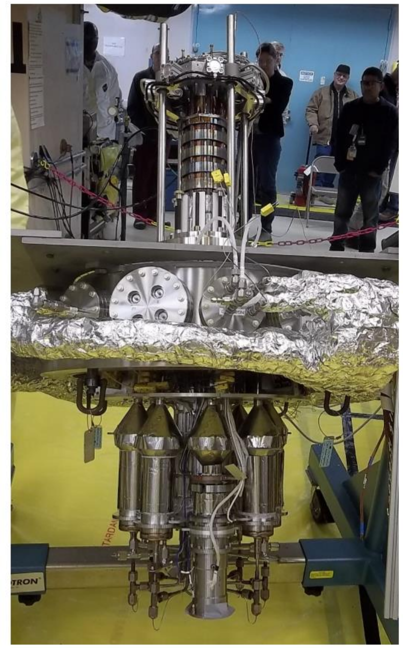
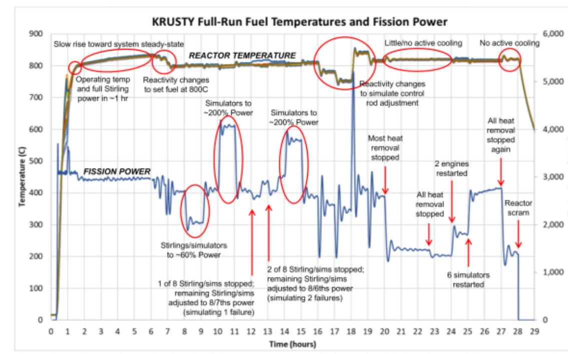
- ✓ No need for emergency AC power
- ✓ Long coping times
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary

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

ACCELERATED TESTING/LICENSING
ENABLED BY SUPERIOR SAFETY PROFILE

- ✓ No need for emergency AC power
- ✓ No need for operator intervention
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary





NASA designed, fabricated and tested a nuclear battery (<1MW) for space applications at a total cost of <$20M, in less than 3 years (2015-2018)

CAN SAVE A DECADE AND AN EARLY BILLION DOLLARS

HIGHER ADDED VALUE
CAN COME FROM

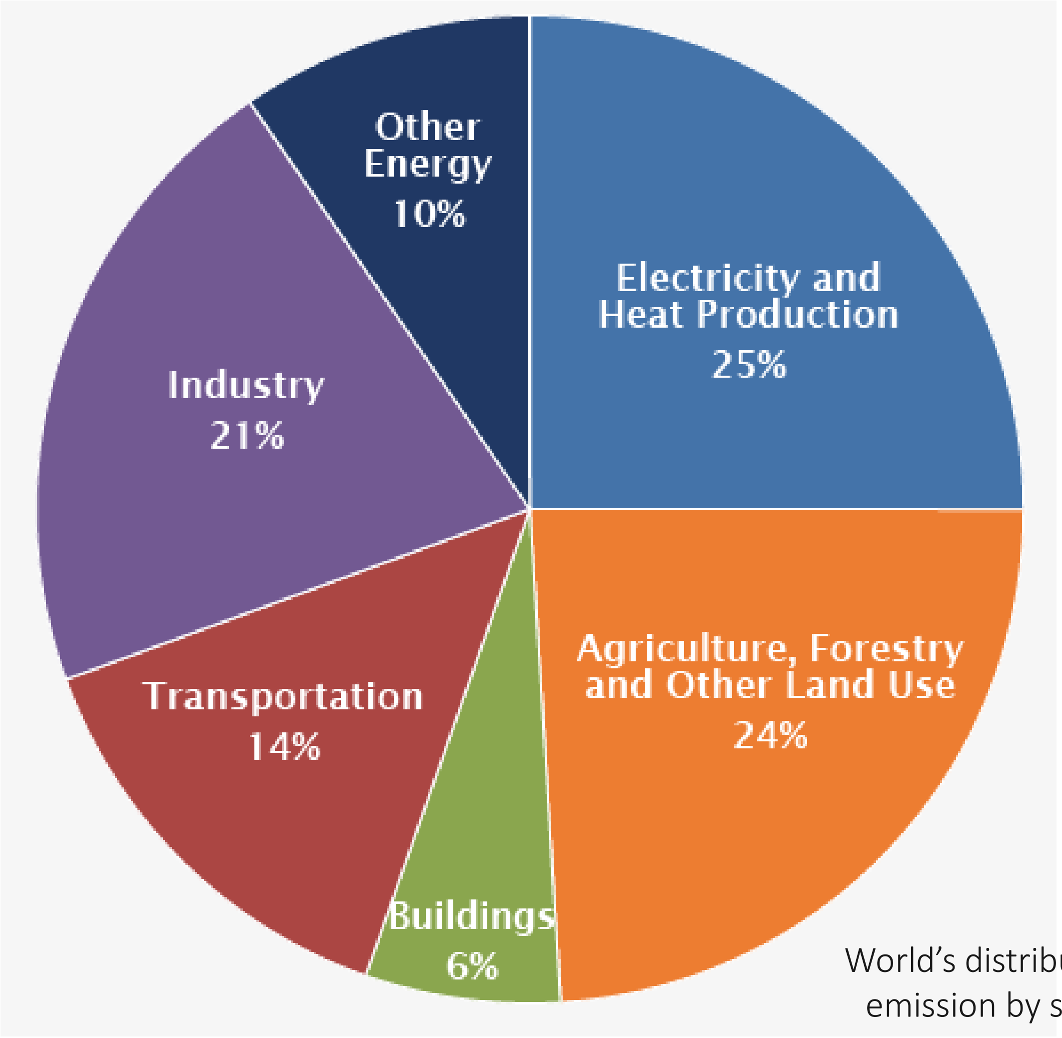
- A strong policy signal recognizing the non-emitting nature, economic impact, and contribution to energy security of nuclear *electricity* on the grid

AND/OR

- Capture of new markets (heat, hydrogen, syn fuels, water desal, remote communities, mining operations, propulsion, etc.) in which nuclear products could sell at a premium

Beyond the grid

Where are the carbon emissions?



World's distribution of CO_2-equivalent emission by sector, 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

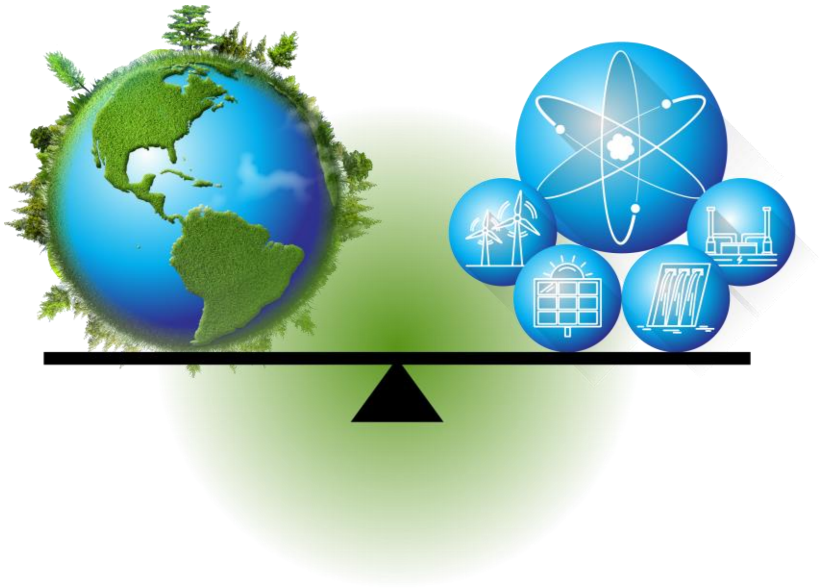
Country	New nuclear capacity required to decarbonize the transportation sector	
	With electrification*	With hydrogen**
U.S.	285 GW_e	342 GW_e and 111 GW_{th}
France	22 GW_e	28 GW_e and 9 GW_{th}
Japan	33 GW_e	41 GW_e and 13 GW_{th}
Australia	18 GW_e	22 GW_e and 7 GW_{th}
World	1060 GW_e	1315 GW_e and 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-H_2, 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.

"A doomsday future is not inevitable! But without immediate drastic action our prospects are poor. We must act collectively. We need strong, determined leadership in government, in business and in our communities to ensure a sustainable future for humankind."

Admiral Chris Barrie, AC RAN Retired, May 2019



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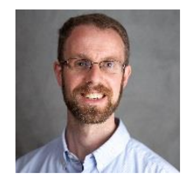

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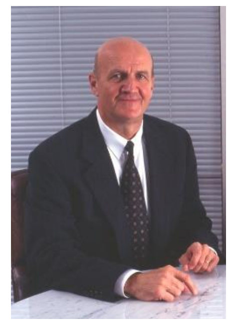

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and in-kind contributions from

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Dissemination

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

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

>70 presentations at universities, industry and government organizations, 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), 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 (Nuclear Radiation Science Board) Dec 2018 (Corradini), Zurich December 2018 (Petti), AGH Univ Science Cracow Jan 2019 (JB), Poland Ministry of Energy Jan 2019 (JB), Swedish Energiforsk Nuclear Seminar Jan 2019 (JB), Energy Foretagen Stockholm Jan 2019 (JB), Idaho State Univ Jan 2019 (Petti), Massachusetts Department of Energy Resources Jan 2019 (Parsons), UT-Austin Feb 2019 (Petti), ETH Feb 2019 (JB), NEA Feb 2019 (Petti), NARUC DC Feb 2019 (Parsons), Colorado School of Mines Mar 2019 (JB), European Nuclear Society Mar 2019 (JB), Conservation Law Foundation Apr 2019 (JB and Parsons), Seminar on Energy Options and Economic Opportunities for Decarbonization Apr 2019 (JB), ICAPP May 2019 (JB), PPPL May 2019 (JB), Applied Energy Conf MIT May 2019 (JB), EPRI Jun 2019 (JB), NEI Sep 2019 (JB), NCSU Sep 2019 (JB), ARPA-E Oct 2019 (JB), Madrid Oct 2019 (JB), Nei Legal Nov 2019 (JB), Total S.A. at MIT Nov 2019 (JB), Yale Nov 2019 (JB)

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