Nuclear Energy: a New Beginning?

And what role it might play in Australia

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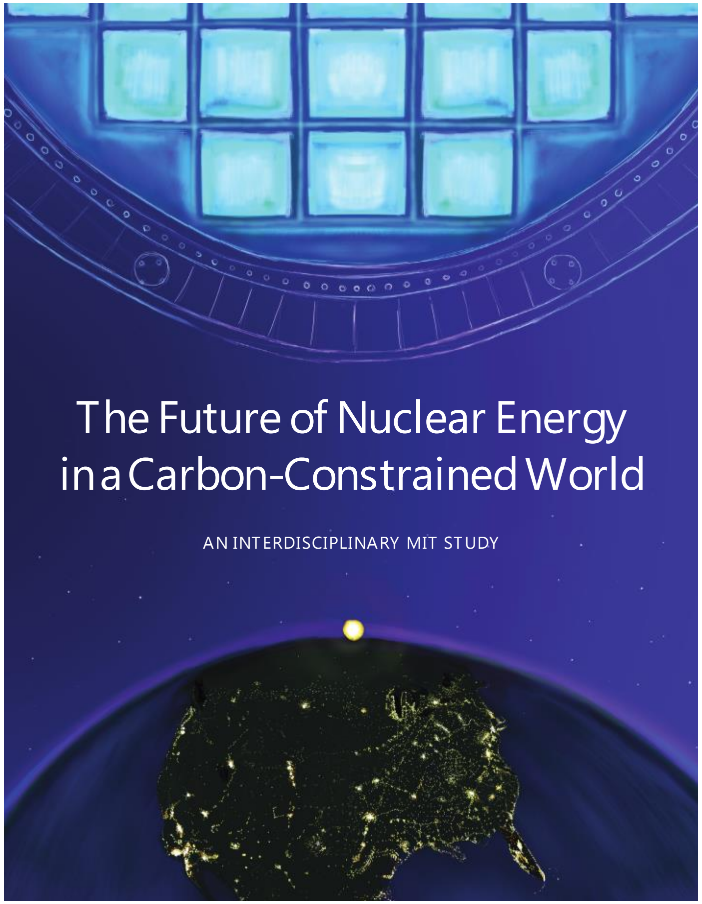
science : systems : society

2018 MIT study on the Future of Nuclear



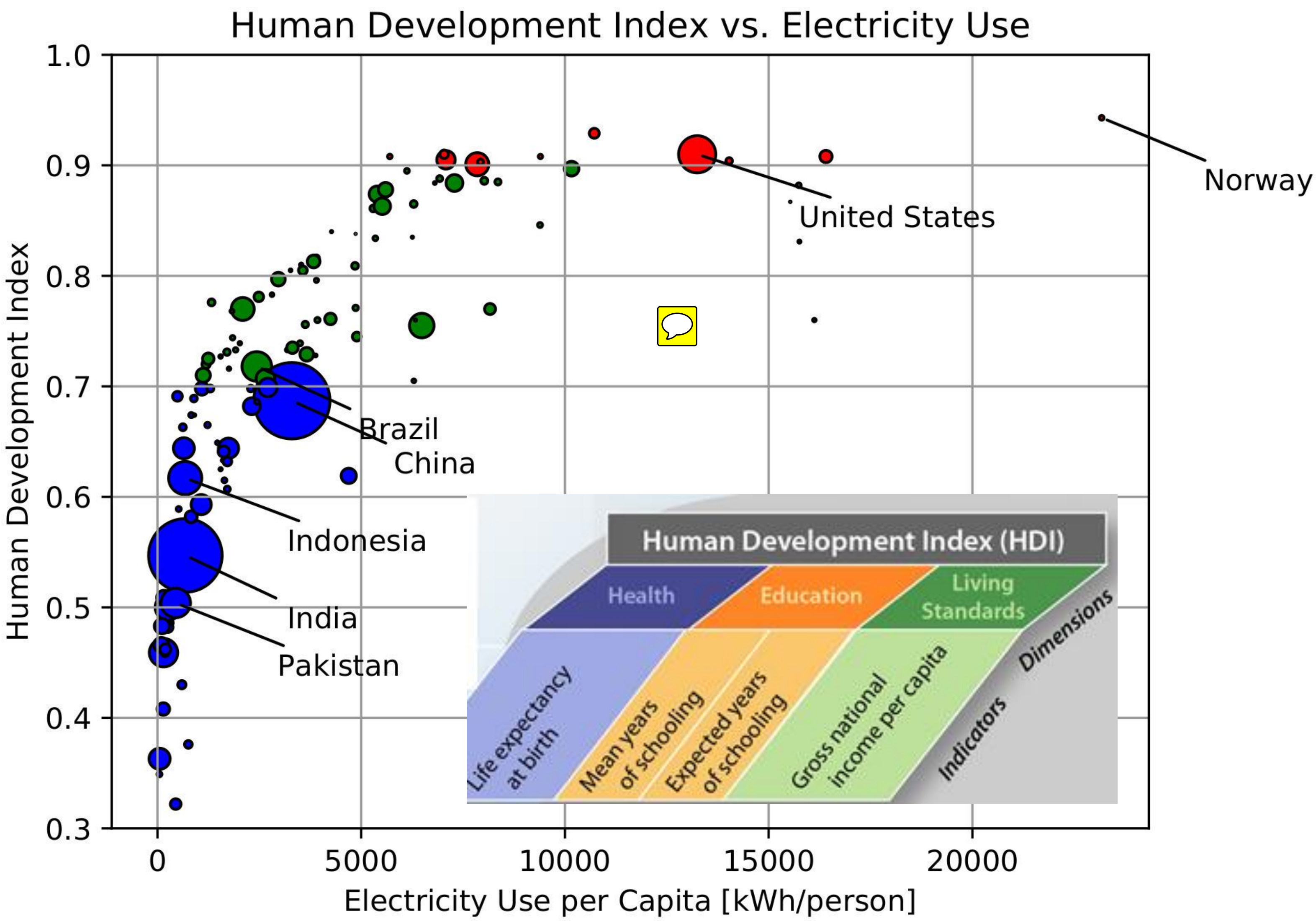
Key messages:

- 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/

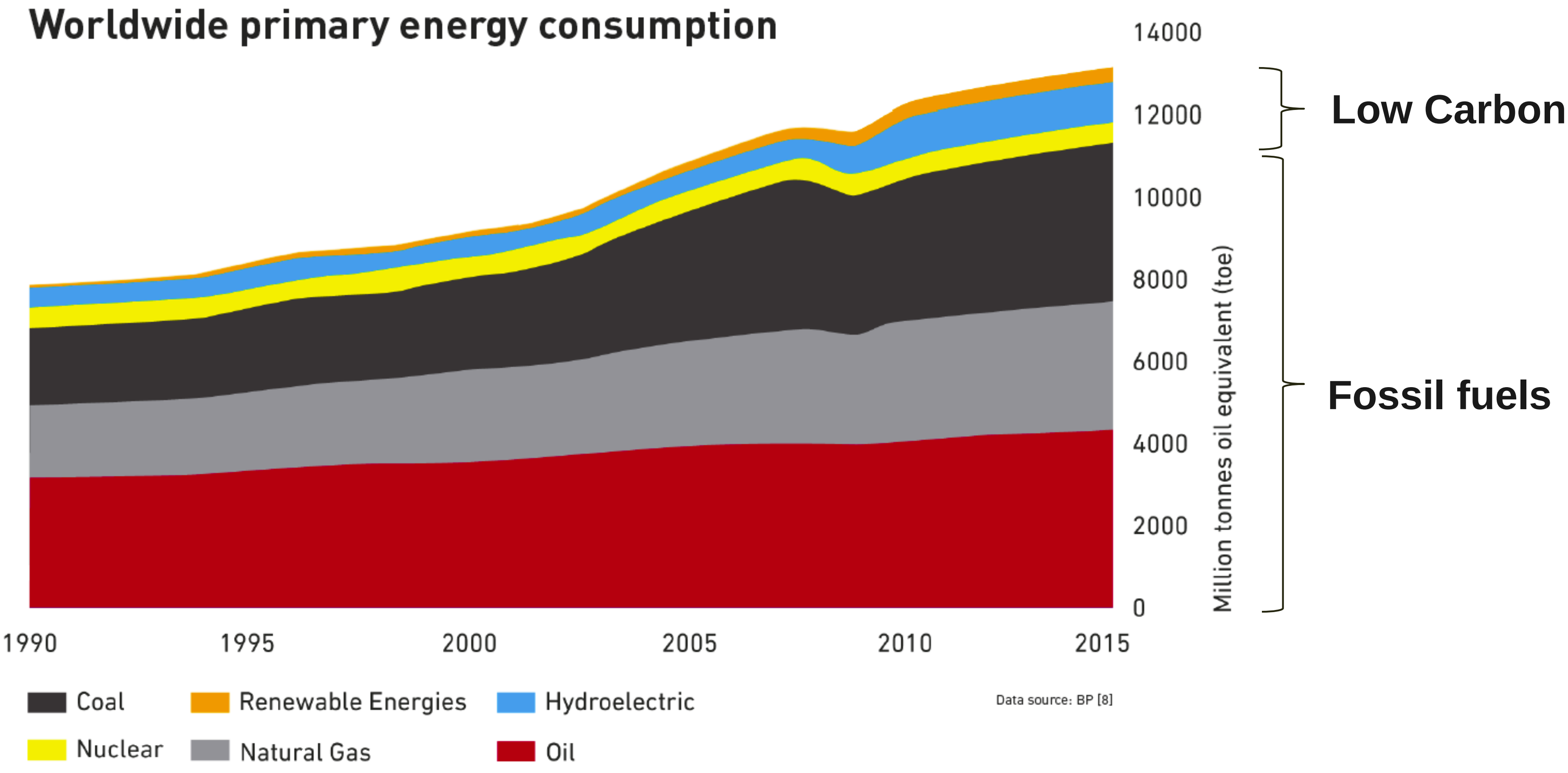
The big picture

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

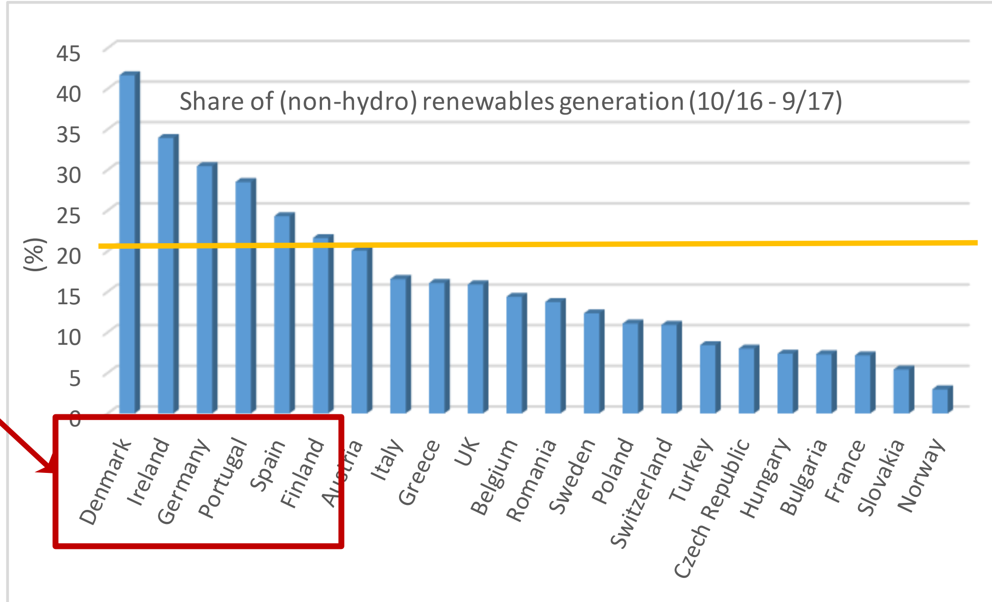


CO_2 emissions are actually rising… we are NOT winning!

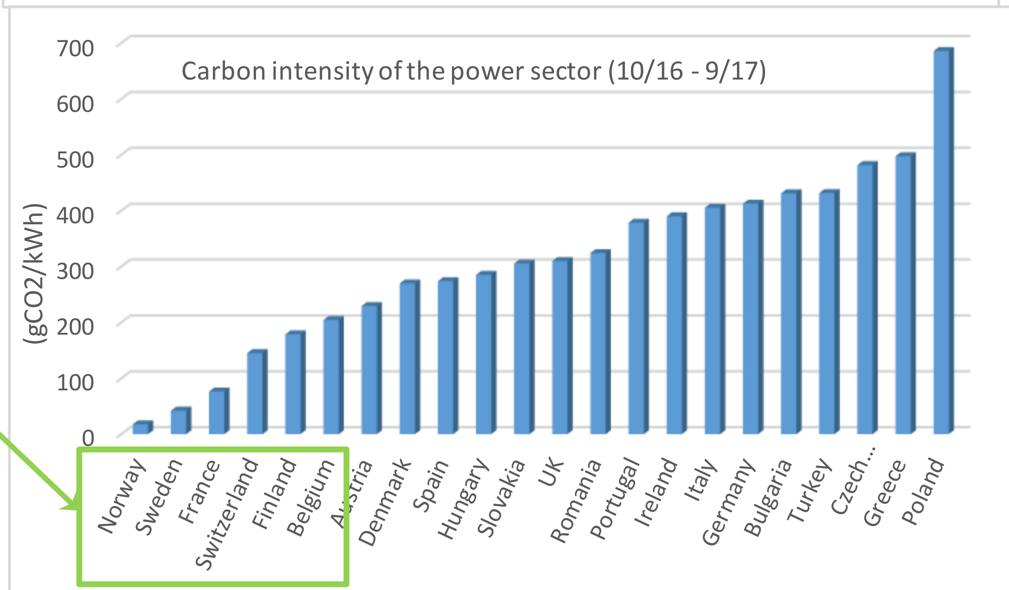
Can we decarbonize using *only* wind and solar?

Let's look at the evidence

EU countries with high capacity of solar and wind



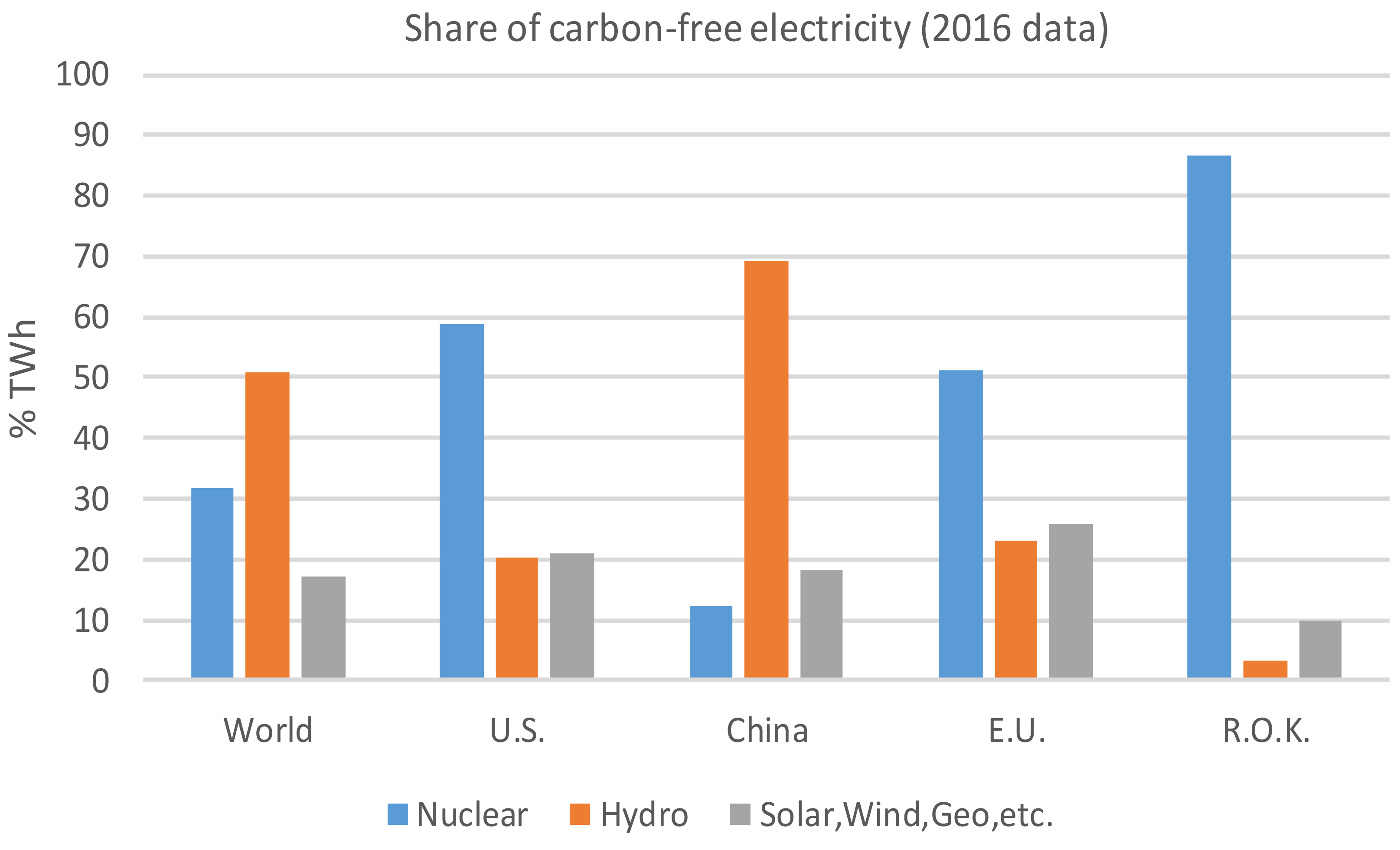
EU countries with low carbon intensity



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

Low carbon intensity in Europe correlates with nuclear and hydro

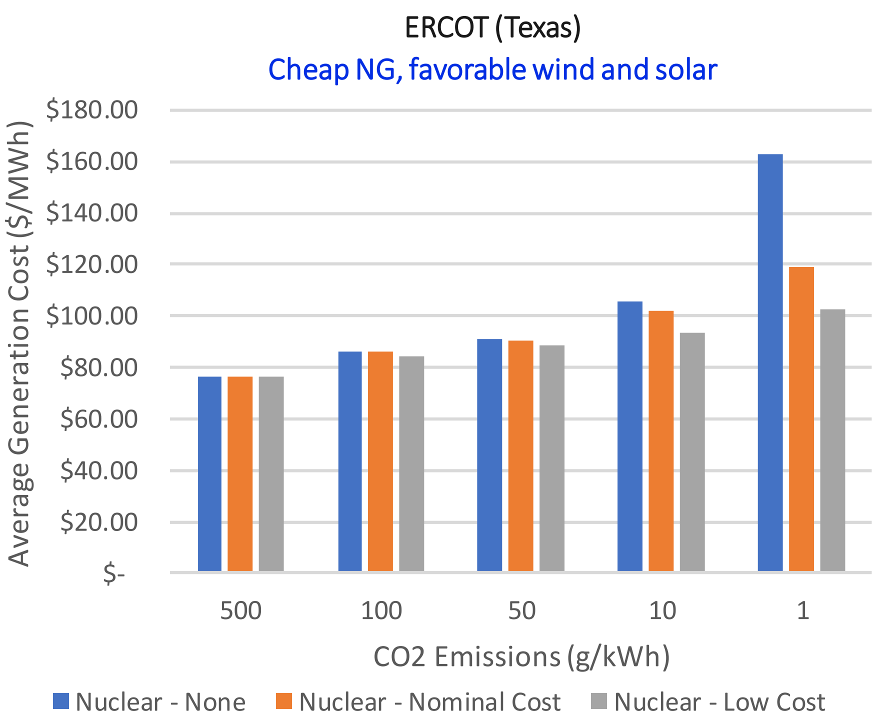
Nuclear is already the largest source of emission-free electricity in the U.S. and Europe by far

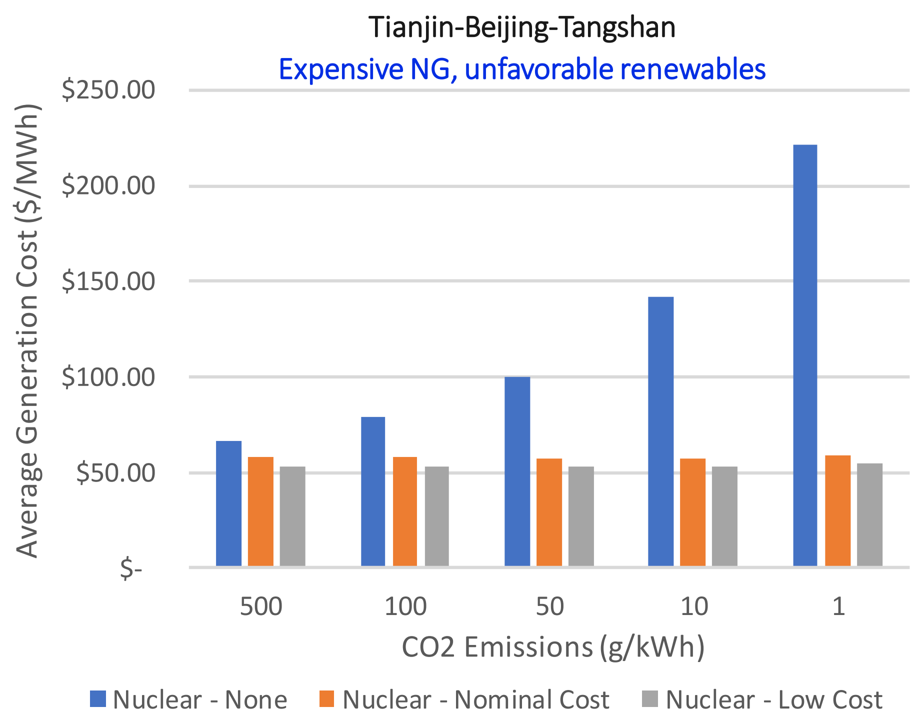


Do we need nuclear to *deeply* decarbonize the power sector?

The economic argument

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

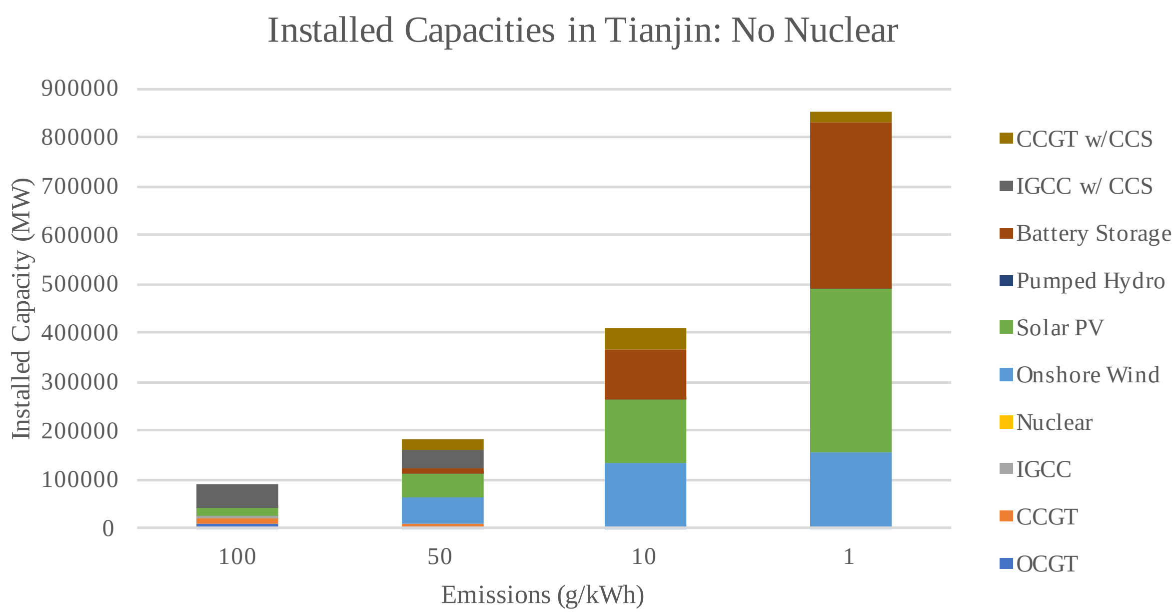




Simulation of optimal generation mix in power markets

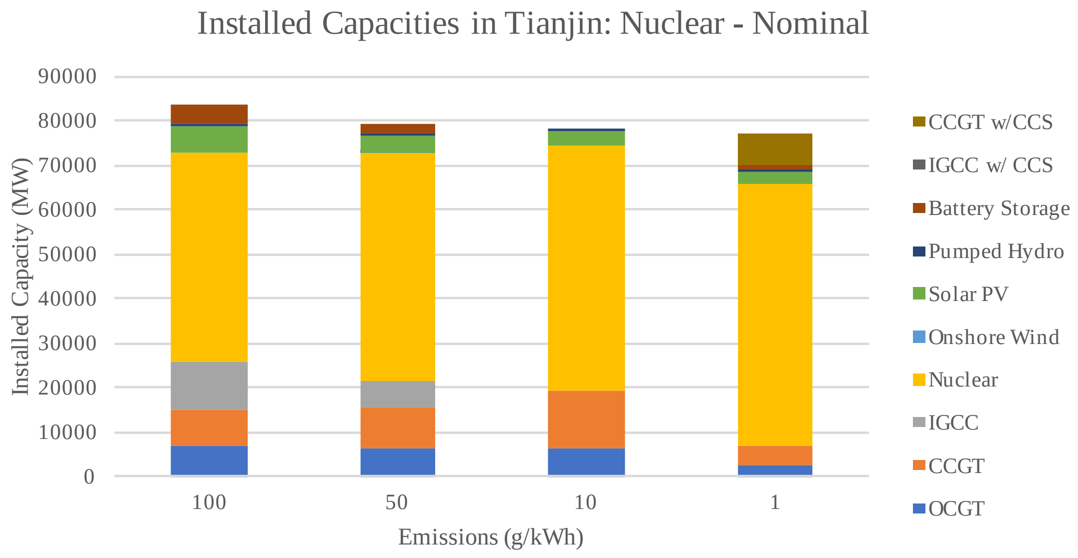
MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates

The problem with the no-nuclear scenarios
(Tianjin-Beijing-Tangshan example)

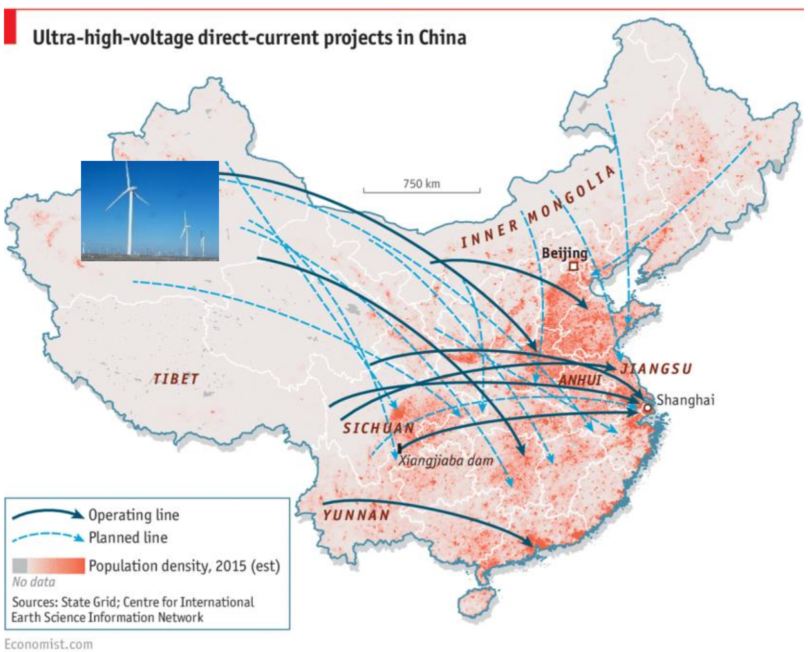


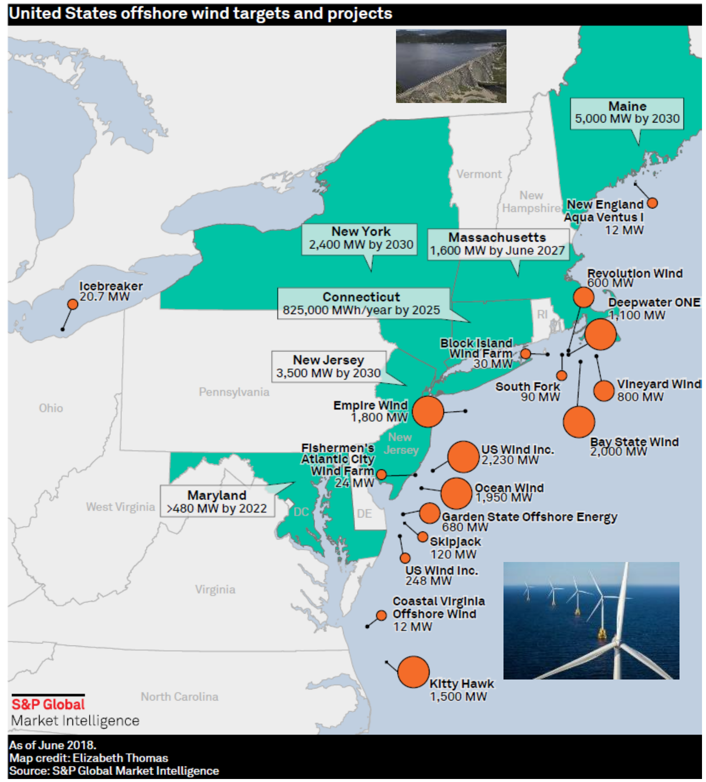
To meet constraint without nuclear requires significant overbuild of renewables and storage

By contrast, installed capacity is relatively constant with nuclear allowed



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 (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)
- Germany and California have spent over half a trillion dollars on intermittent renewables and have not seen a significant decrease in emissions

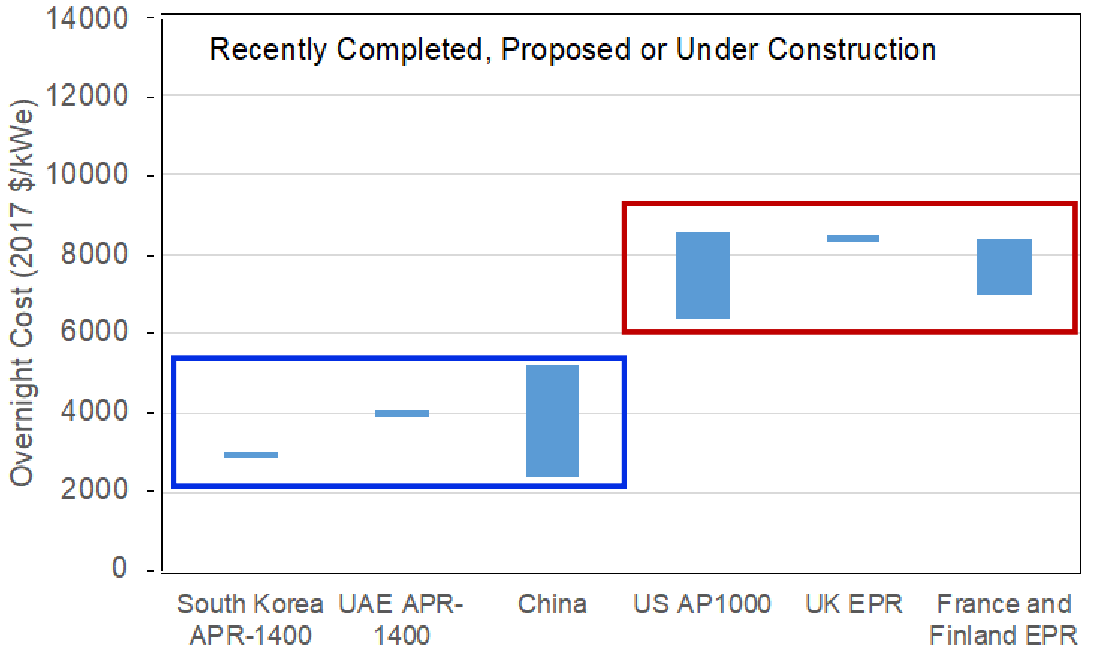







Build new NPPs
…but what about cost?

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



ASIA

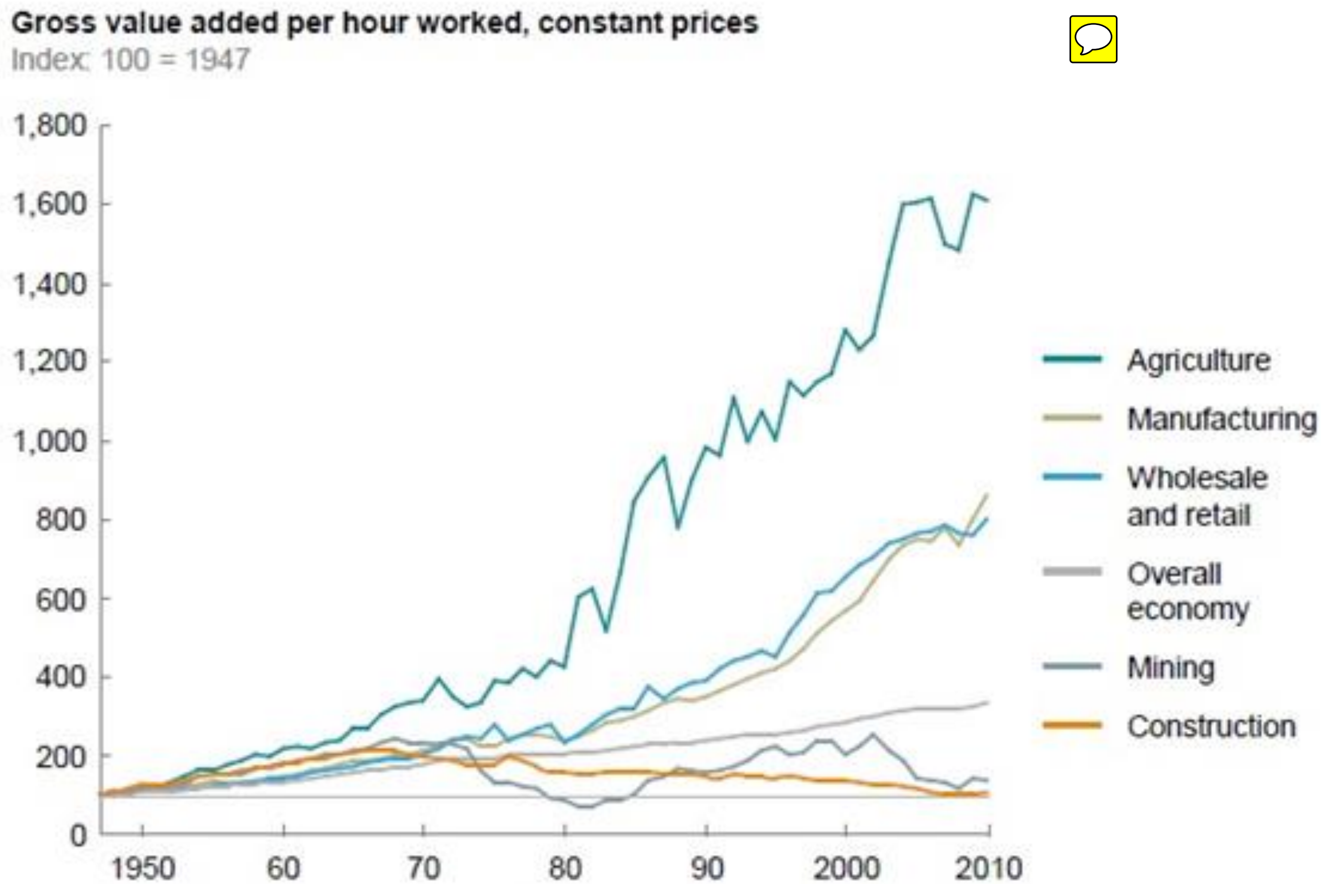
- >90% detailed design completed before starting construction
- Proven NSSS supply chain and skilled labor workforce
- Fabricators/constructors included in the design team
- A single primary contract manager
- Flexible regulator can accommodate changes in design and construction in a timely fashion

US/Europe

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

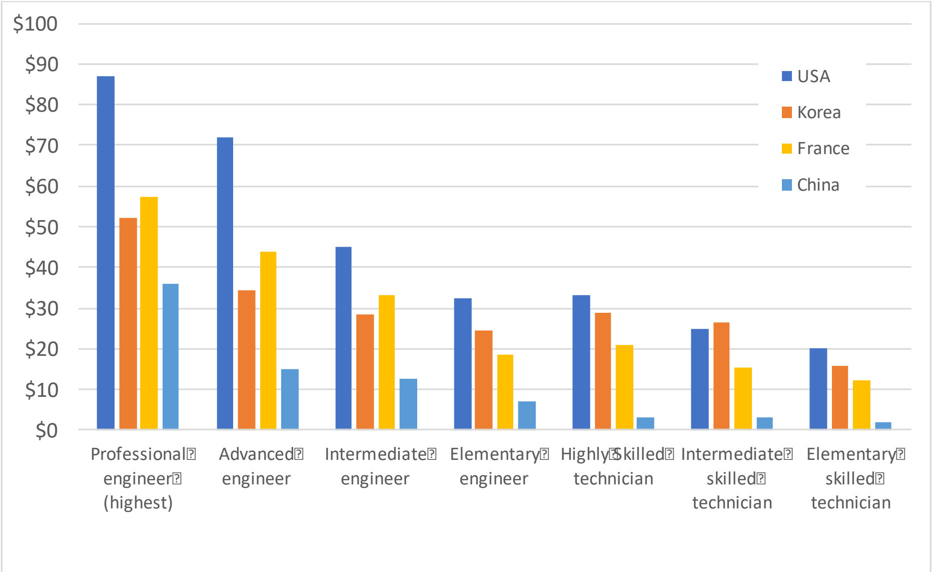
Aggravating factors

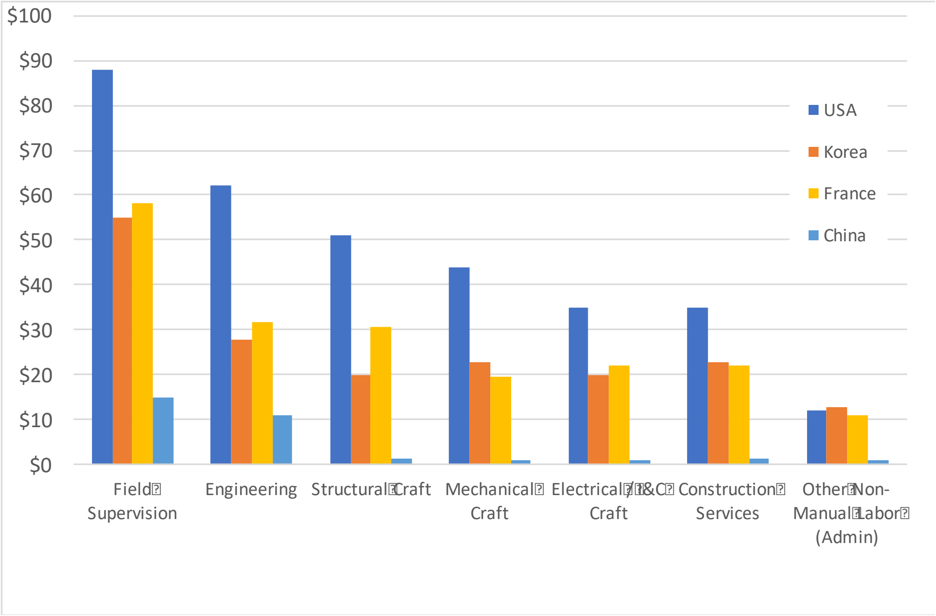
From Nuclear Power in an Age of Uncertainty 1984			
US	19,160	mhs/MW	
W Germany	13,280	mhs/MW	
Sweden	12,190	mhs/MW	
Japan	13,280	mhs/MW	
France	9,670	mhs/MW	
All 900 to 1000 MW plants			



Construction labor productivity has decreased in the West

Aggravating factors (2)



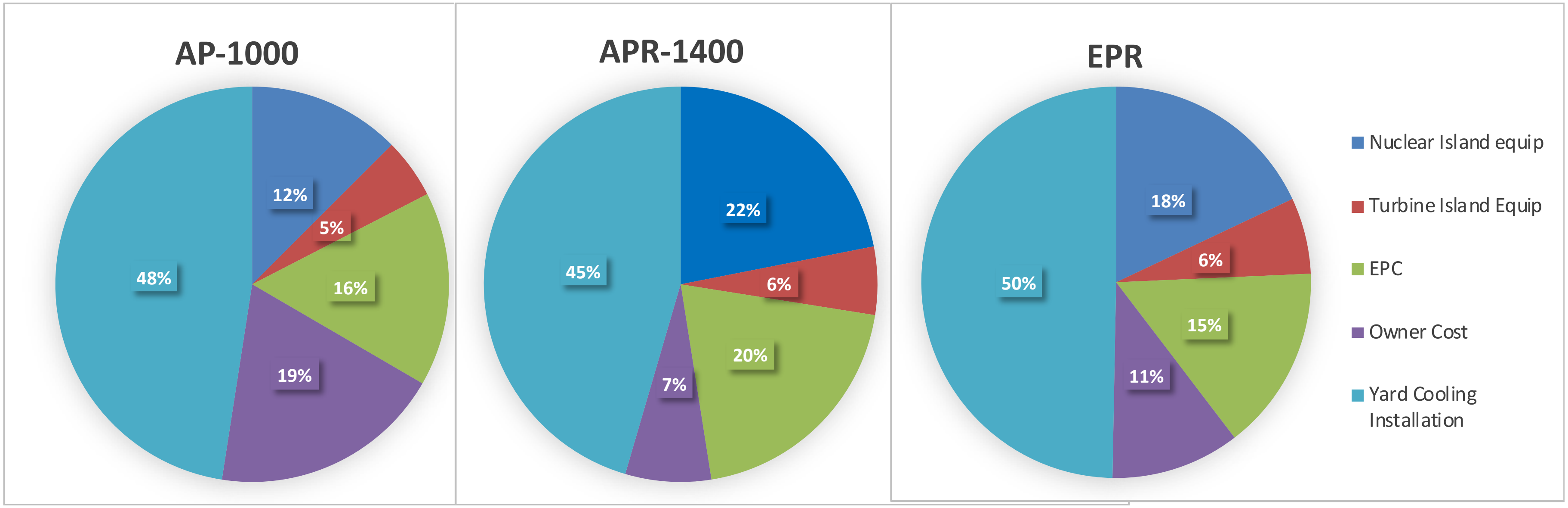


Construction and engineering wages are much higher in the US than China and Korea

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?



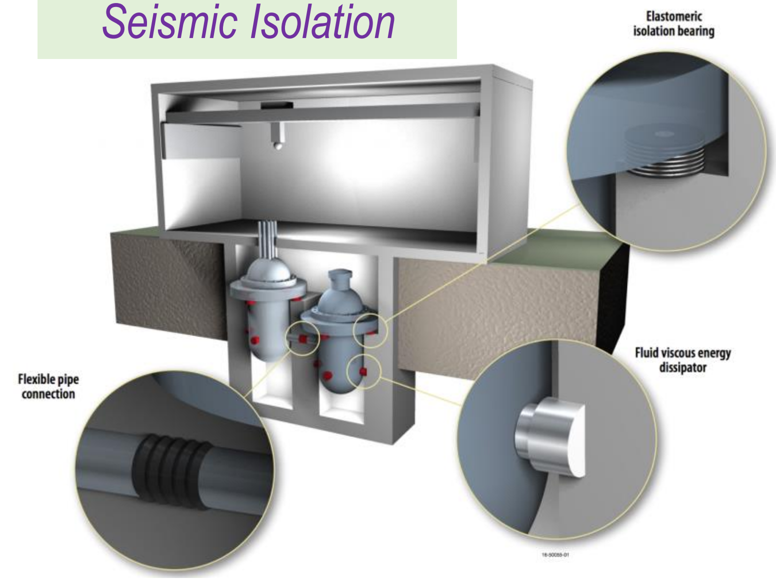
Sources:
AP1000: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11
APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication,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

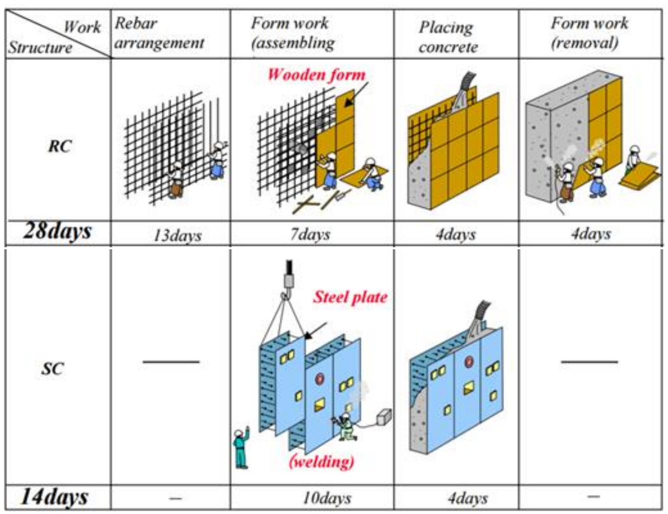
What innovations could make a difference?

Standardization on multi-unit sites

Seismic Isolation



Advanced Concrete Solutions



Modular Construction Techniques and Factory/Shipyard Fabrication

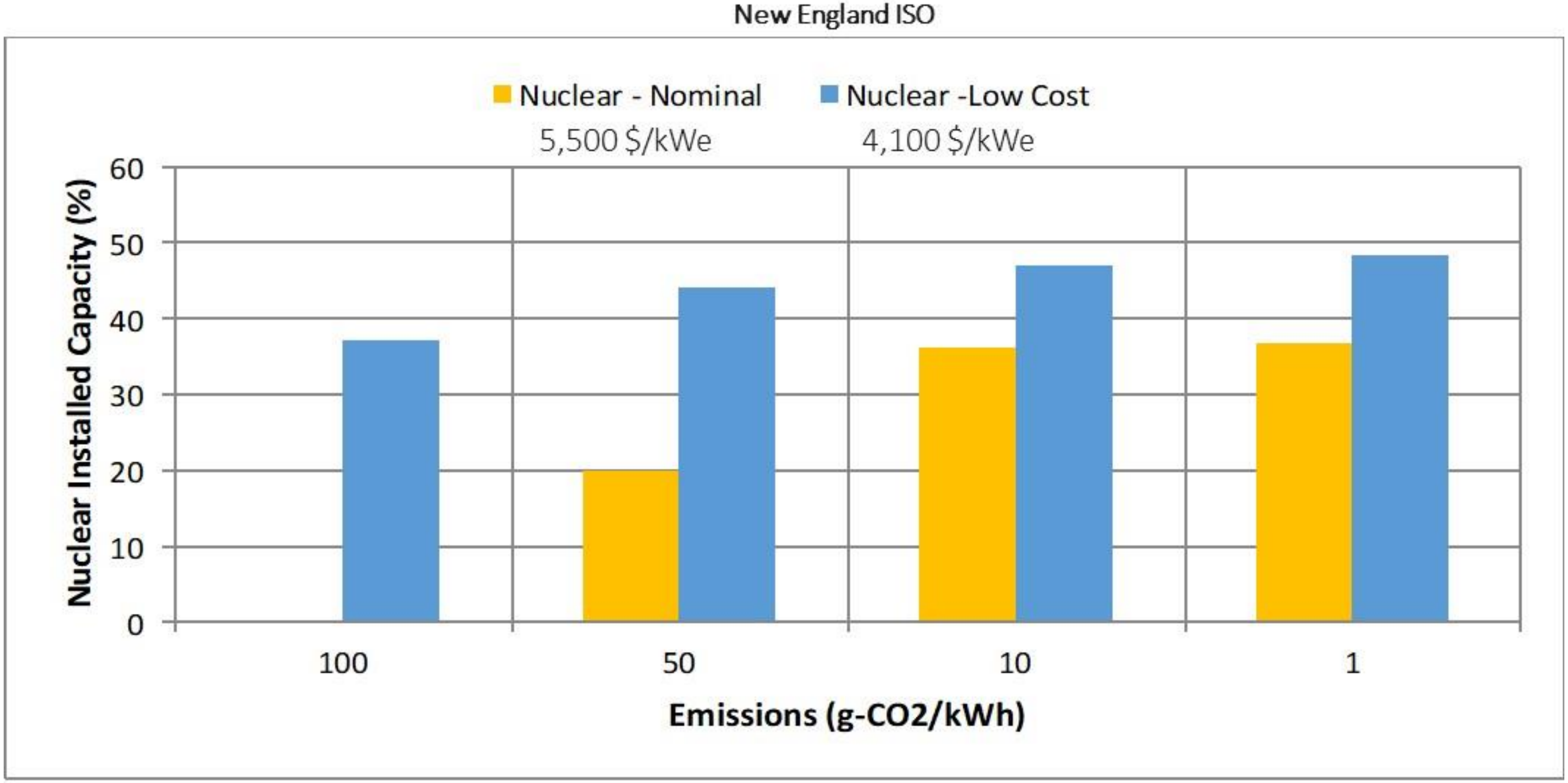
Applicable to all new reactor technologies

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

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

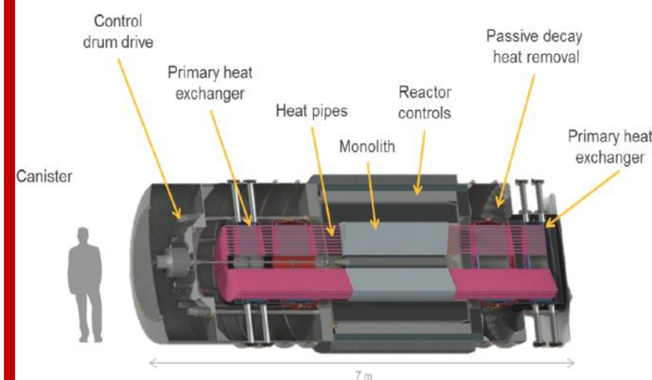
Small Modular Reactors

[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



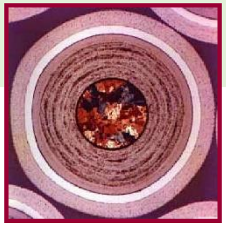
[Westinghouse's eVinci]
<20 MWe
Block core with heat pipes, self-regulating operations, Stirling engine or air-Brayton

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

A SUPERIOR SAFETY PROFILE 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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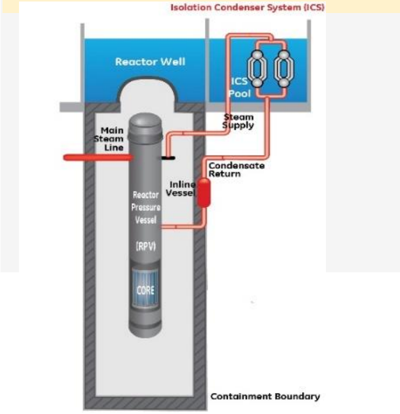
Engineered passive safety systems:

– 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

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

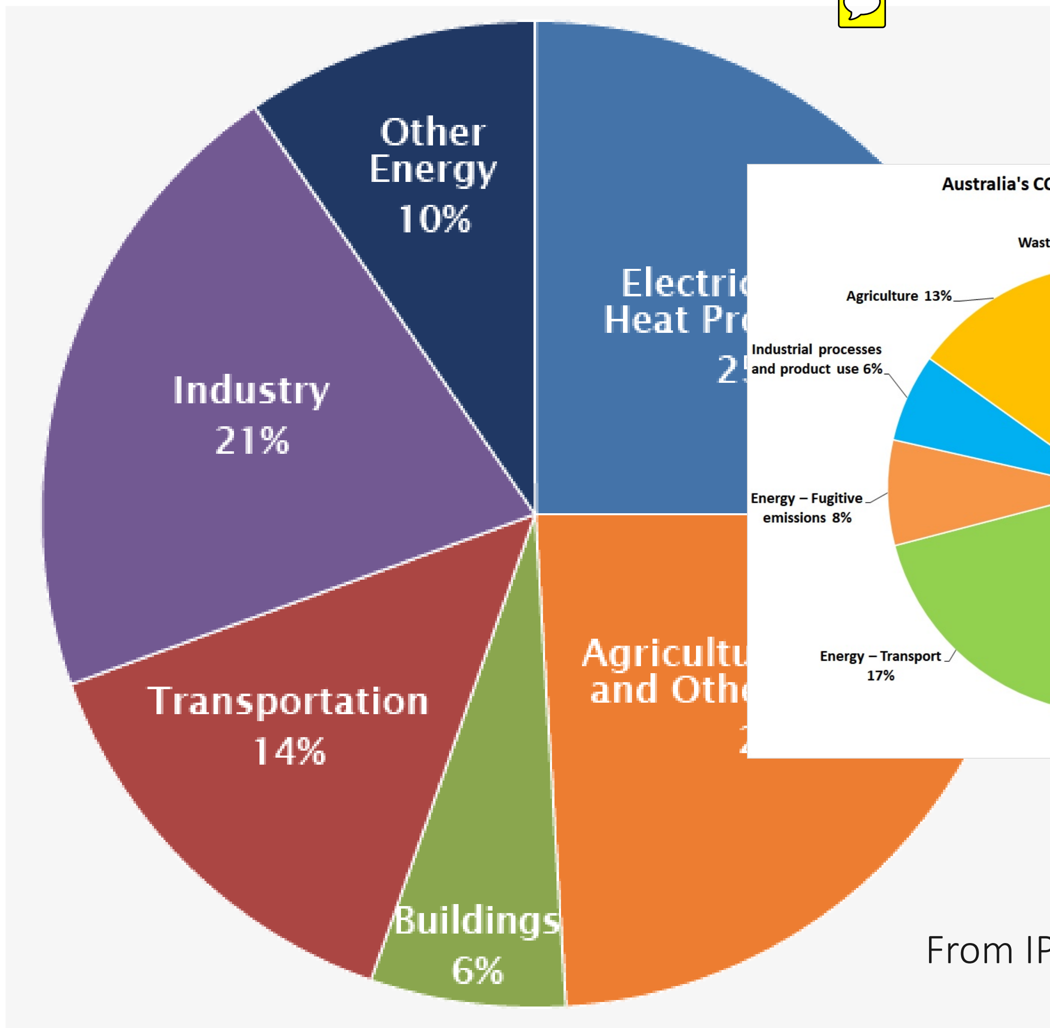
AND/OR

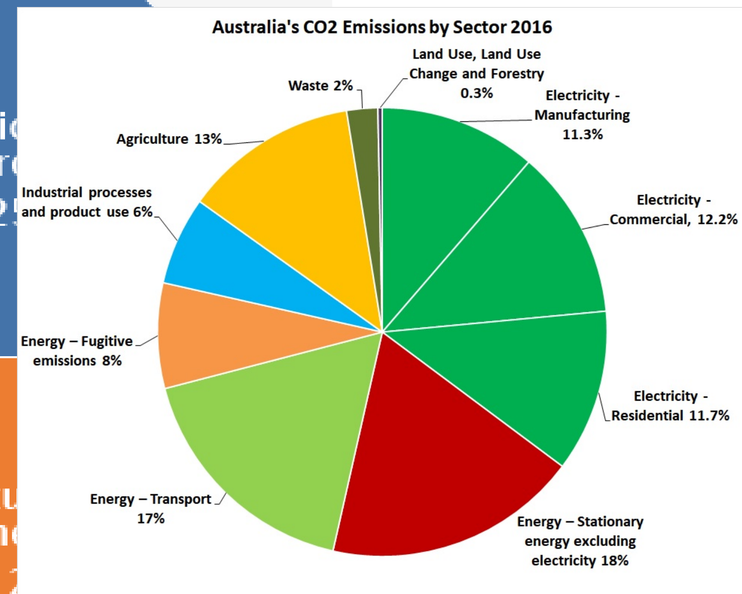
- Capture of new markets (heat, hydrogen, syn fuels, water desal, propulsion, etc.) in which nuclear products could sell at a premium

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

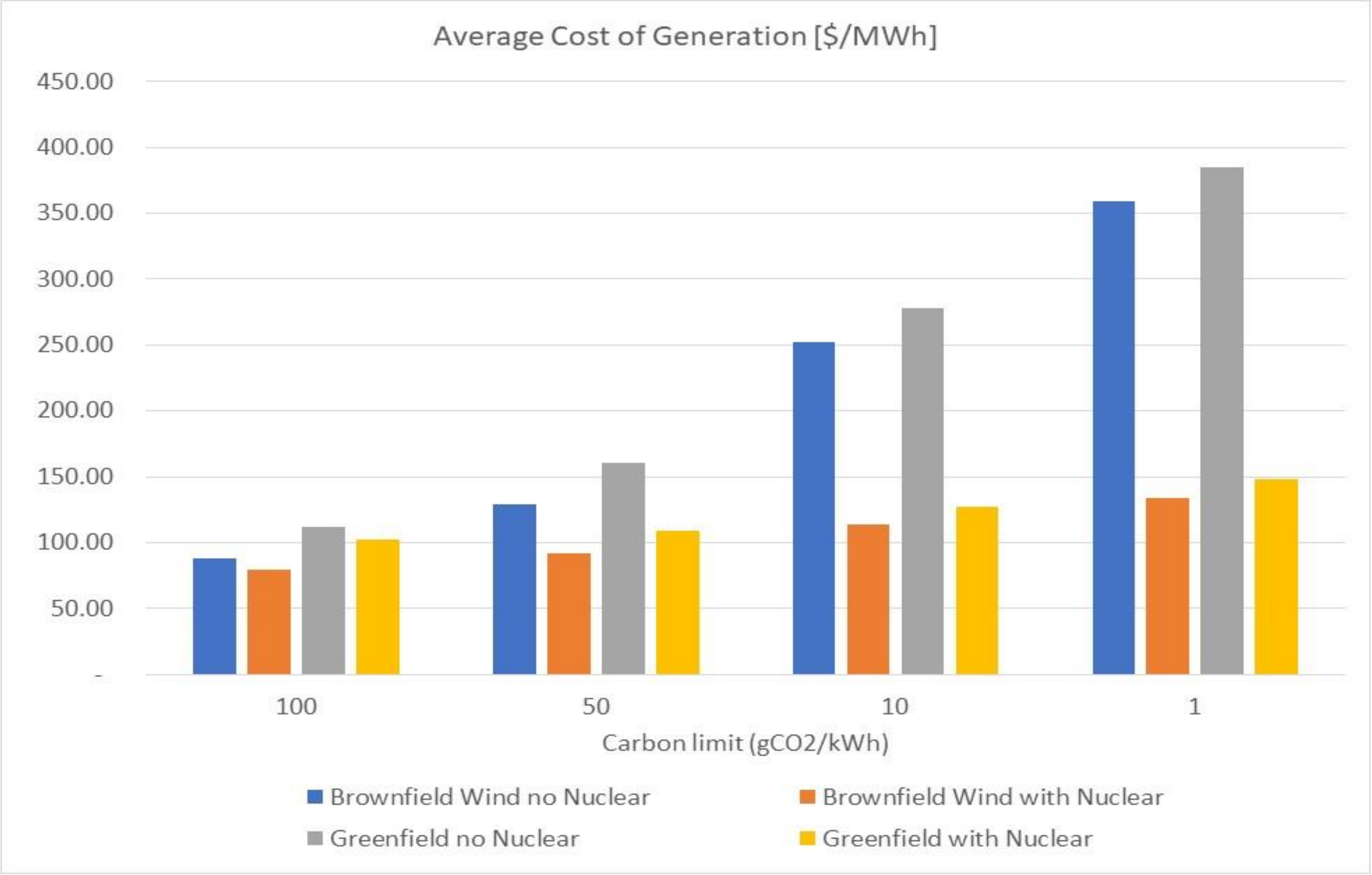
Country	New nuclear capacity required to decarbonize the transportation sector	
	With electrification*	With hydrogen**
U.S.	285 GW_e	342 GW_e and 111 GW_{th}
France	22 GW_e	28 GW_e and 9 GW_{th}
Japan	33 GW_e	41 GW_e and 13 GW_{th}
Australia	18 GW_e	22 GW_e and 7 GW_{th}
World	1060 GW_e	1315 GW_e and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

What’s in for Australia?

Decarbonize the grid at reasonable cost



MIT calculations for the South Australia electric grid. Average system cost of electricity is in USD $/MWh. “Brownfield Wind” refers to scenarios in which existing SA wind generation is included (and treated as fully-amortized). “Greenfield Wind” allows for an unconstrained optimal mix, in which the capital cost of wind has to be recovered.

Freshwater for everyone

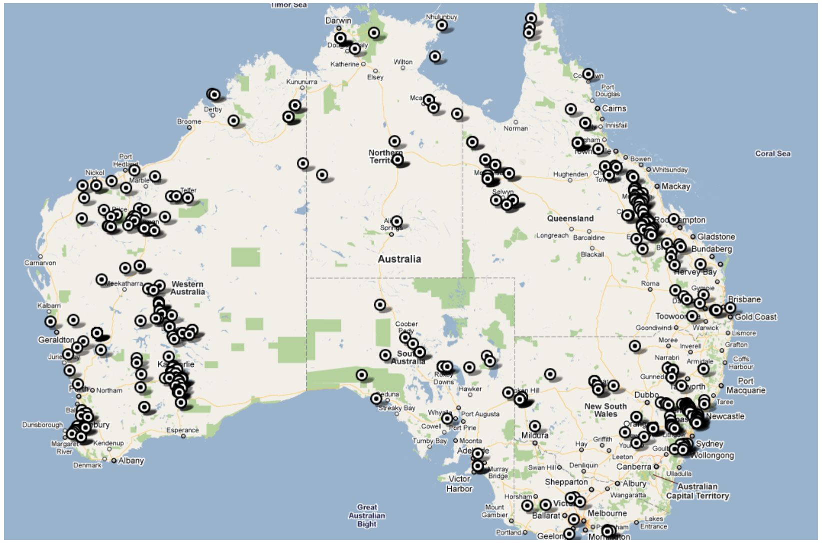
A 300 MWe nuclear reactor (such as BWRX-300) would be able to produce ~2 Mm^3/day (or 730 Mm^3/day) of desalinated water*, enough to render a semi-arid area of ~5000 km^2 suitable for agriculture

Israel's Sorek Desalination Plant (left) produces ~0.63 Mm^3/day, most of which is used for agriculture in arid land in the Negev Desert (right)

Nuclear-powered water desalination has a low carbon footprint of ~50 gCO_2/m^3 vs. World's average ~2000 gCO_2/m^3

*Assumes Reverse Osmosis (RO) plant with electricity consumption of 3.5 kWh/m^3

Supply affordable and clean electricity to remote mining operations

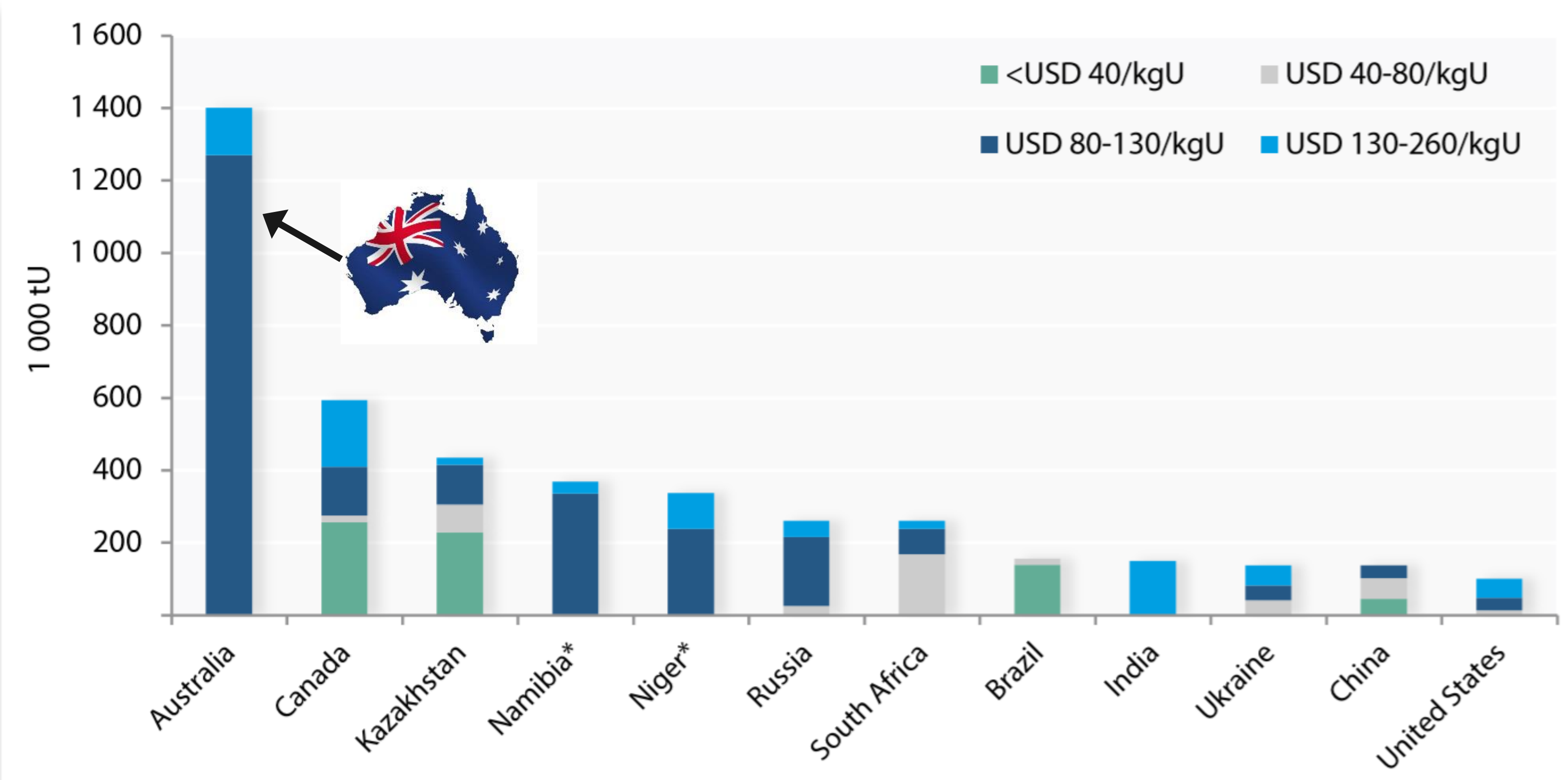


- Requires nuclear reactors with dry cooling technology (available)
- Expansion of Olympic Dam alone could require an additional ~640 MW of electricity*

* https://www.bhp.com/-/media/bhp/regulatory-information-media/copper/olympic-dam/0000/information-sheets/olympic-dam-eis-energy-and-greenhouse-gases.pdf

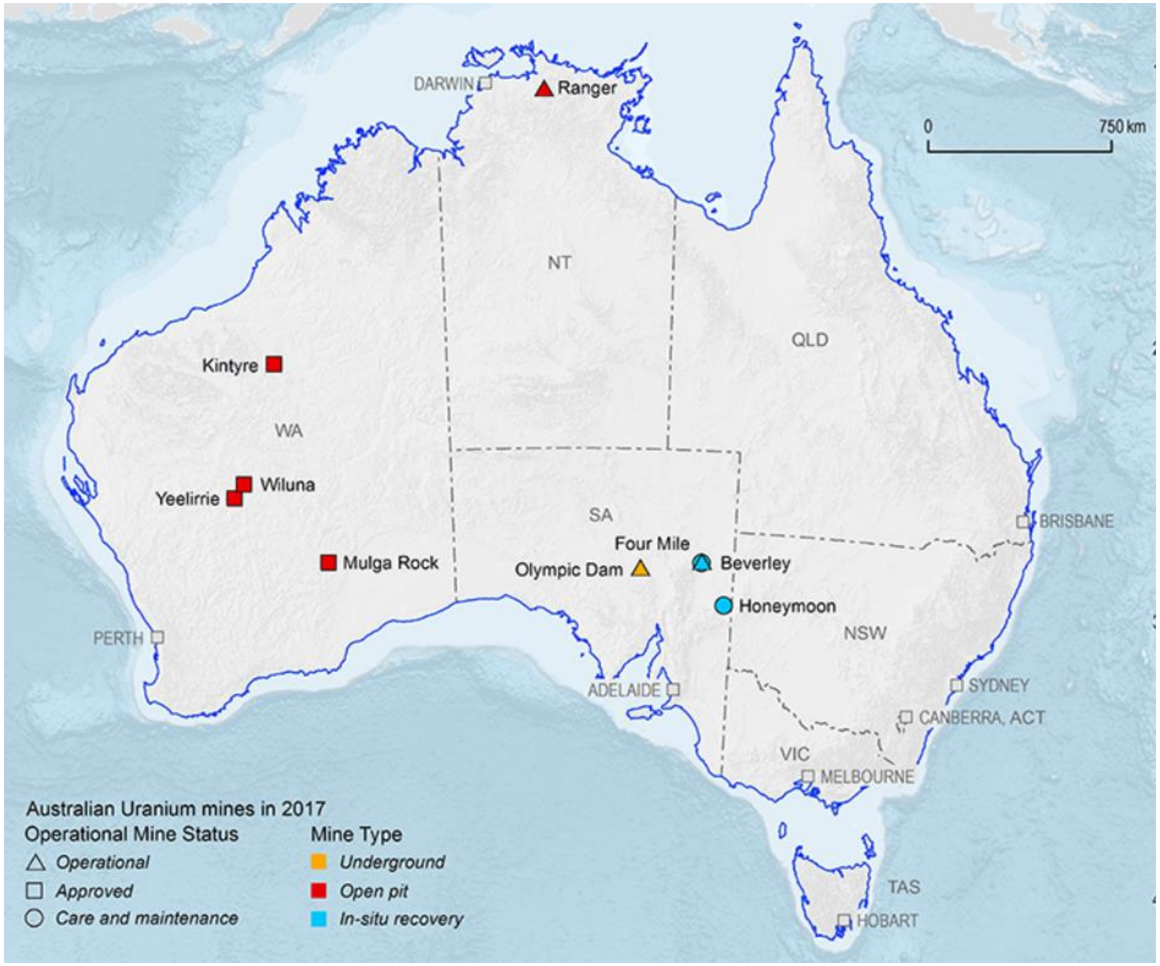
Supply nuclear fuel to the world

Australia has the largest reserves of uranium in the world by far



Reasonably Assured U Resources (from IAEA “redbook” 2018)

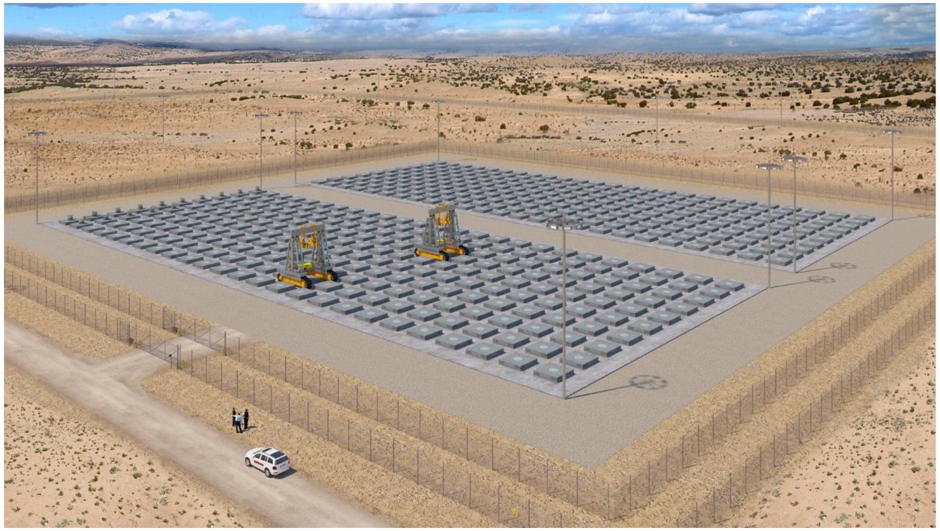
Supply nuclear fuel to the world (cont.)



- Currently produces about 10% of world's Uranium (all for power plants)
- AUD 500 million export value in 2017
- ~6300 jobs*

* Source: Uranium Resources, Production and Demand, IAEA "redbook", 2018

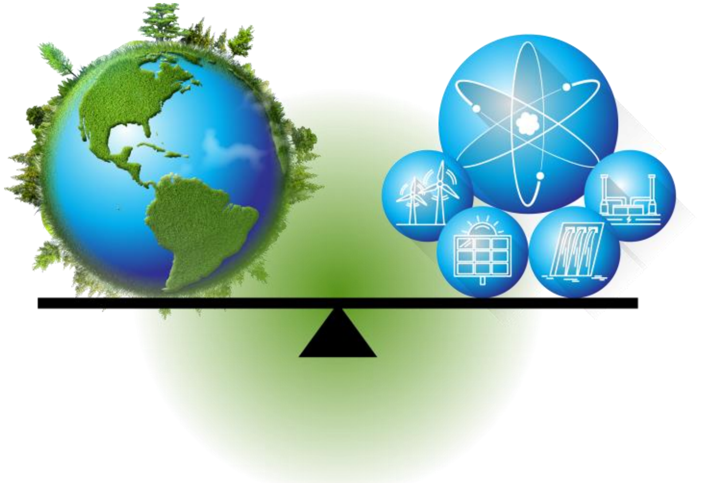
Securing spent fuel for the world may be a major economic opportunity for Australia



- Ideal arid climate
- Remote locations, far from population centers:
  - Superior physical security at site
  - Ease of transportation to site
- Signee of NPT
- Technically sophisticated, politically stable country (and not an international ‘bully’)
- Market size: U.S. alone accumulates ~$1B worth of spent nuclear fuel every year
- May enhance economic value of aboriginal land in the deep outback

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



MIT