Opening Address


Hon Ted O'Brien

Navigating Nuclear

UNSW Sydney - 13 May 2024

A one day opportunity to learn everything you need to know about nuclear energy and what it means for Australia's future from global experts.

Closing Address


Dr Adi Paterson

Speakers & Organising Committee


Jaz Diab - Women in Nuclear


Prof Koroush Shirvan - MIT


Prof Jacopo Buongiorno - MIT


Prof Rob Hayes - North Carolina State University


Dr Dave Collins - MIT/PhD UMelb


Prof Simon Michaux - Geological Survey of Finland/PhD UQ


Dr Sarah Lawley - PhD UAdelaide


Mark Nelson - Radiant Energy/UCambridge


Sai Prasad Balla - MIT


Steven Nowakowski - Rainforest Reserves Australia


Helen Cook - GNE Advisory


Dr Ross Koningstein - Google/PhD Stanford


Atte Harjanne - MP Finland Greens/PhD Candidate UAalto


Prof Mike Golay - MIT/PhD CornellU


Tony Irwin – ANU


Dr Mark Ho – Australian Nuclear Association


Dr John Harries – Australian Nuclear Association

WiN AUSTRALIA
WOMEN IN NUCLEAR

Australian Nuclear Association

Organising Committee

Dr Dave Collins (Chair), Dr Mark Ho (President, Australian Nuclear Association), Jasmine Diab (President, Women in Nuclear), Dr John Harries (Secretary, Australian Nuclear Association).

Acknowledgments

Sincere thanks to the following for their support and advice without whom the workshop would not have been possible: Dr Robert Barr, Connor Davies, Prof Julien Epps, Prof Stephen Foster, James Fleay, Tony Irwin, Prof Ed Obbard, Hasliza Omar, Robert Parker, Dr Adi Paterson, Chiara Scalise, Peter Sjoquist, Dr Tim Stone, Prof Peter Tyree, Darka de Vries and the speakers and organising committee.

Chatham House Rules

The Q&As and the Discussion panel were not recorded under the agreed Chatham House Rules.

Speakers & topics

No	Topic	Speakers and affiliation
1	*Opening address*	*Hon Ted O'Brien – Australian Parliament*
2	*Introduction to Navigating Nuclear*	*Jasmin Diab – Global Nuclear Security Partners*
3	*How does nuclear energy work?*	*Prof Koroush Shirvan - MIT*
4	*Nuclear energy in the 21st century*	*Professor Jacopo Buongiorno - MIT*
5	*Radiological risk in perspective*	*Professor Robert Hayes - North Carolina State University*
6	*What would the environmental impacts of nuclear energy in Australia be?*	*Dr Dave Collins - MIT*
7	*Challenges and bottlenecks to the green transition*	*Professor Simon Michaux - Geological Survey of Finland*
8	*Australia's electricity system*	*Dr Sarah Lawley - PhD University of Adelaide*
9	*What is the value of nuclear energy?*	*Mark Nelson - Radiant Energy Group*
10	*What happens inside an operating nuclear power plant?*	*Sai Prasad Balla - MIT*
11	*Environmental impacts of renewable energy in Queensland*	*Steven Nowakowski and Jeanette Kemp - Rainforest Reserves Australia*
12	*Current nuclear energy developments around the world*	*Helen Cook - GNE Advisory*
13	*A discovery that nuclear was nonpartisan in the USA*	*Dr Ross Koningstein - Google*
14	*How nuclear became green in Finland*	*Atte Harjanne - Finland Parliament*
15	*Experience and lessons from creating nuclear safety cultures*	*Professor Michael Golay - MIT*
Not recorded	*Discussion panel*	*Chair: Tony Irwin - ANU*
16	*Closing address*	*Dr Adi Paterson – ANSTO (retired)*

Nuclear Energy in the 21st Century:

Value proposition and challenges

Jacopo Buongiorno

TEPCO Professor of
Nuclear Science and Engineering

Director, Center for Advanced Nuclear
Energy Systems

MIT Energy Initiative

NSE
Nuclear Science
and Engineering

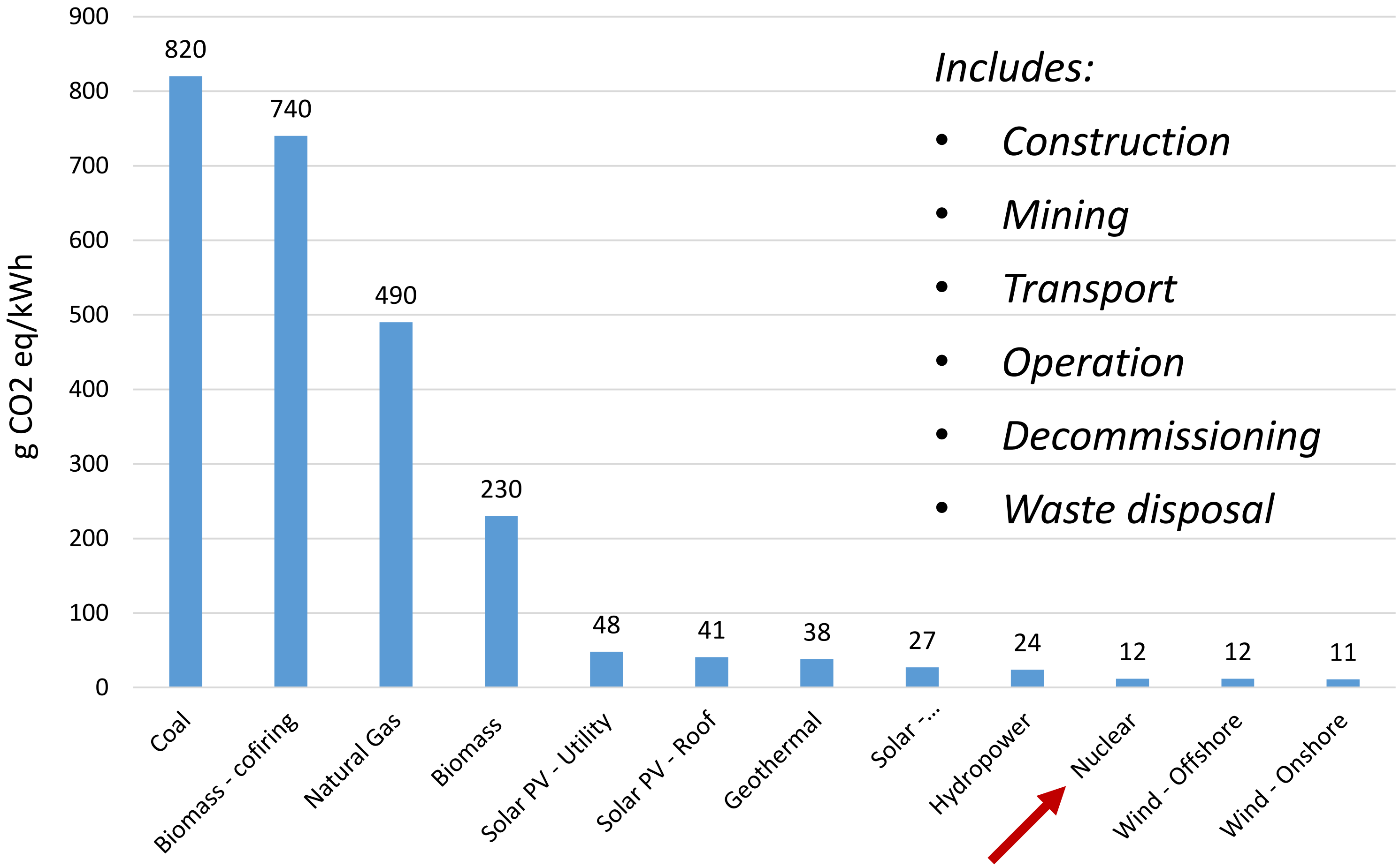
science : systems : society

ABOUT THE SPEAKER

Jacopo Buongiorno is the TEPCO Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology (MIT), the Director of Science and Technology of the MIT Nuclear Reactor Laboratory, and a member of the US national Academy of Engineering. He teaches a variety of undergraduate and graduate courses in thermo-fluids engineering and nuclear reactor engineering. Jacopo has published over 100 journal articles in the areas of reactor safety and design, two-phase flow and heat transfer, and nanofluid technology. For his research work and his teaching at MIT he won several awards, among which an ANS Presidential Citation (2022), the ANS Outstanding Teacher Award (2019), the MIT MacVicar Faculty Fellowship (2014), the ANS Landis Young Member Engineering Achievement Award (2011), the ASME Heat Transfer Best Paper Award (2008), and the ANS Mark Mills Award (2001). Jacopo is the Director of the Center for Advanced Nuclear Energy Systems (CANES). In 2016-2018 he led the MIT study on the Future of Nuclear Energy in a Carbon-Constrained World. Jacopo is a consultant for the nuclear industry in the area of reactor thermal-hydraulics and safety, and a member of the Accrediting Board of the National Academy of Nuclear Training. He is also a Fellow of the American Nuclear Society (including service on its Special Committee on Fukushima in 2011-2012), a Fellow of the NUclear Reactor Thermal Hydraulics (NURETH) conference, a member of the American Society of Mechanical Engineers, past member of the Naval Studies Board (2017-2019), past member of the Secretary of Energy Advisory Board (SEAB) Space Working Group, and a participant in the Defense Science Study Group (2014-2015).

THE VALUE PROPOSITION OF NUCLEAR IN A LOW-CARBON WORLD

LIFECYCLE GHG EMISSIONS

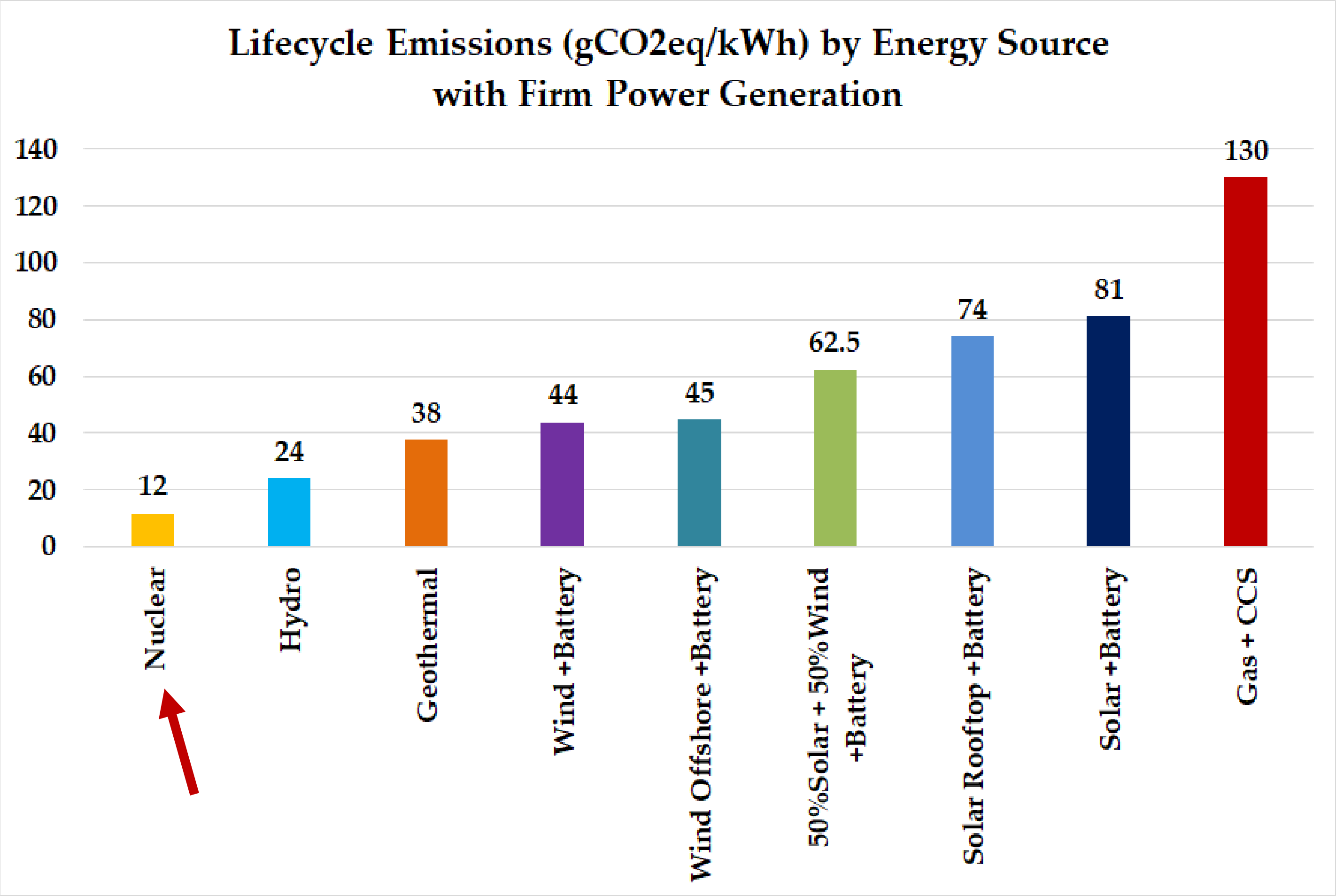


Includes:

- *Construction*
- *Mining*
- *Transport*
- *Operation*
- *Decommissioning*
- *Waste disposal*

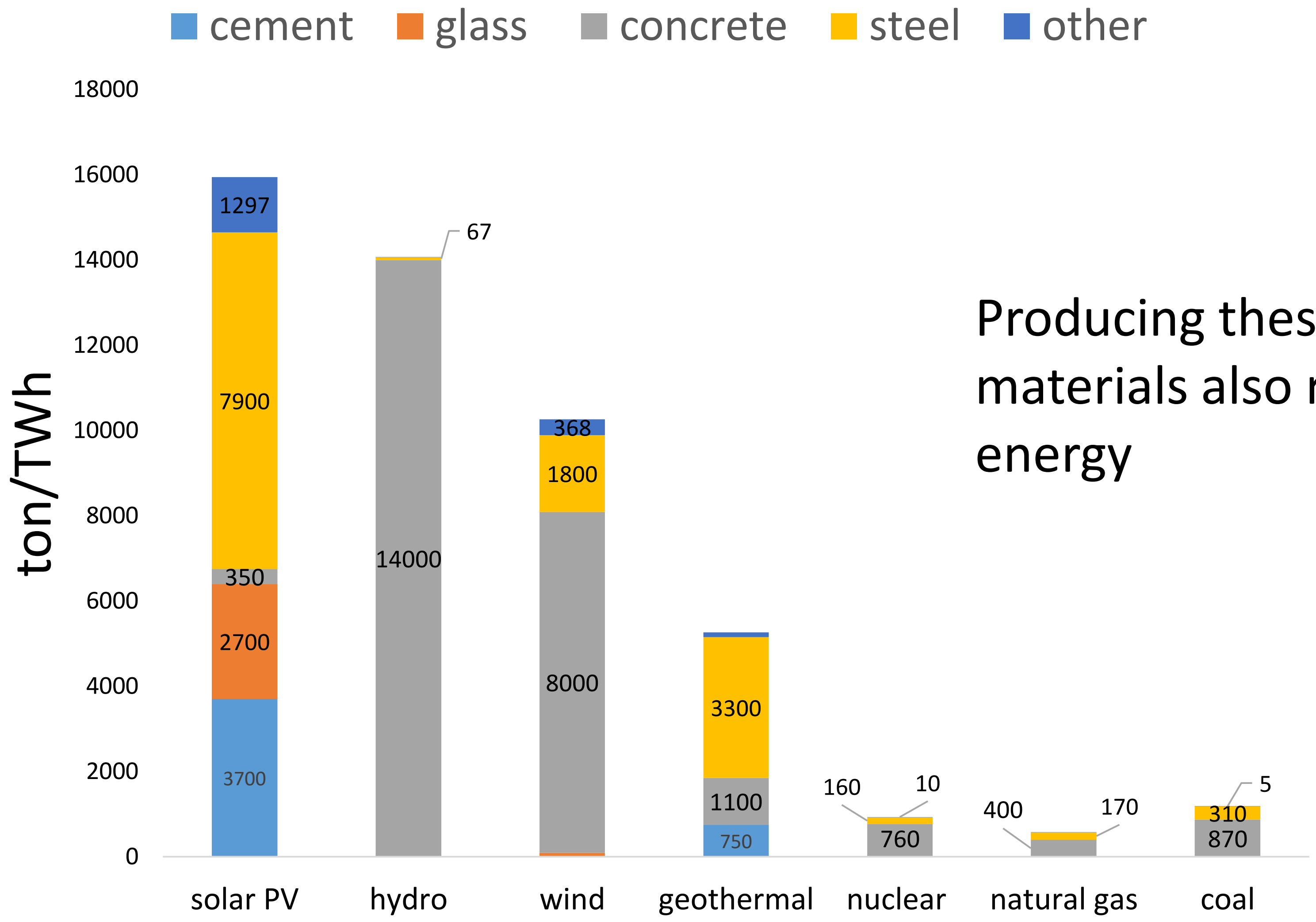
Source: IPCC

LIFECYCLE GHG EMISSIONS OF FIRM ENERGY SOURCES



Source: N. Reddy “Role of Nuclear Power in Combating Climate Change under Similar Land-use with Forest Restoration”, 2023

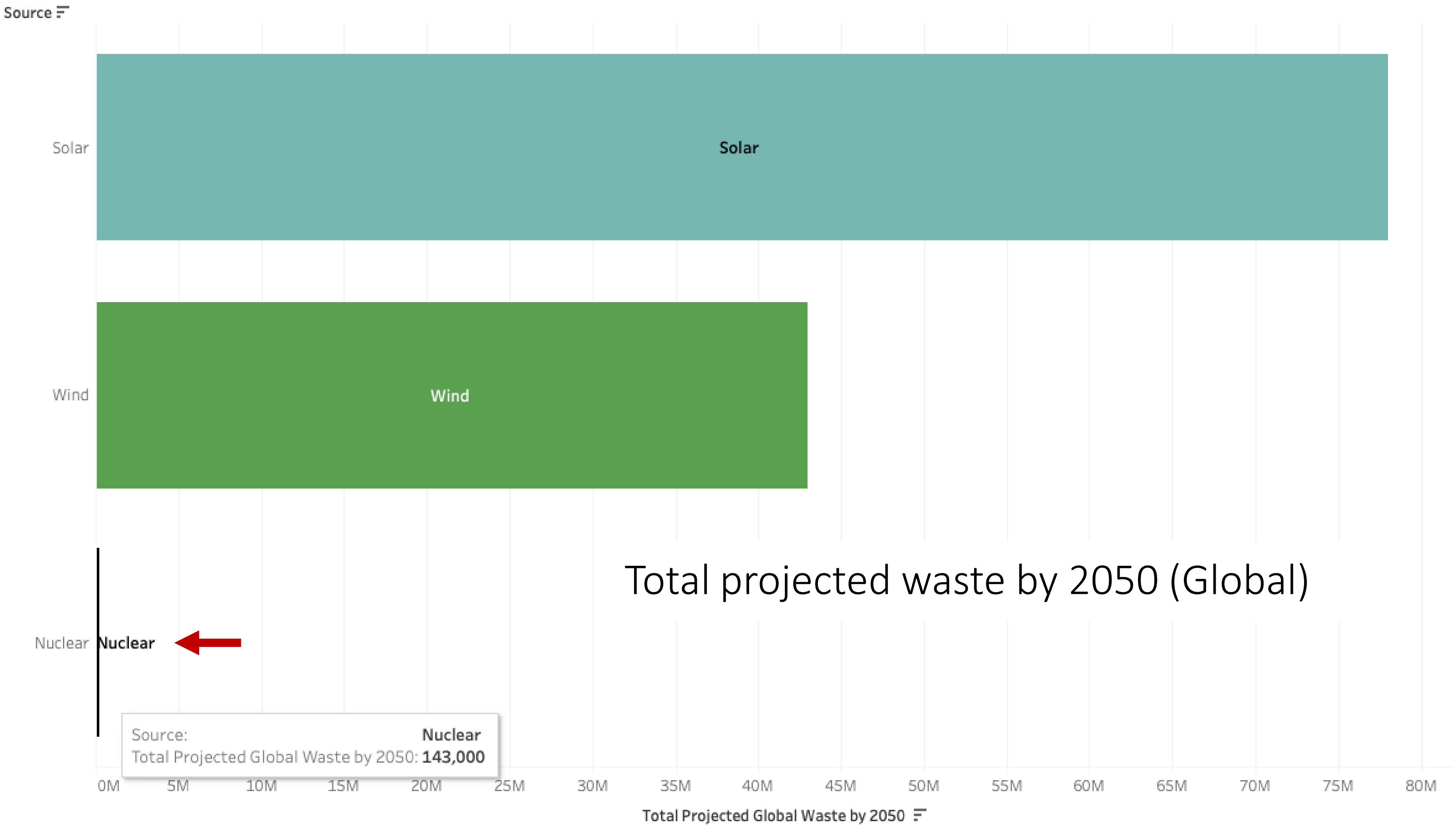
VERY LOW MATERIALS USAGE



Producing these materials also requires energy

Source: Prof. M. Dunzik-Gougar (ANS) and DOE Quadrennial technology Review, Table 10.4.

A TINY AMOUNT OF WASTE TO DISPOSE



Total projected waste by 2050 (Global)

One person's lifetime spent fuel volume if only nuclear electricity were used

Source: Prof. M. Dunzik-Gougar (ANS) and International Renewable Energy Agency

LOWEST LAND USAGE AND HIGHEST CAPACITY FACTOR OF ALL ENERGY SOURCES

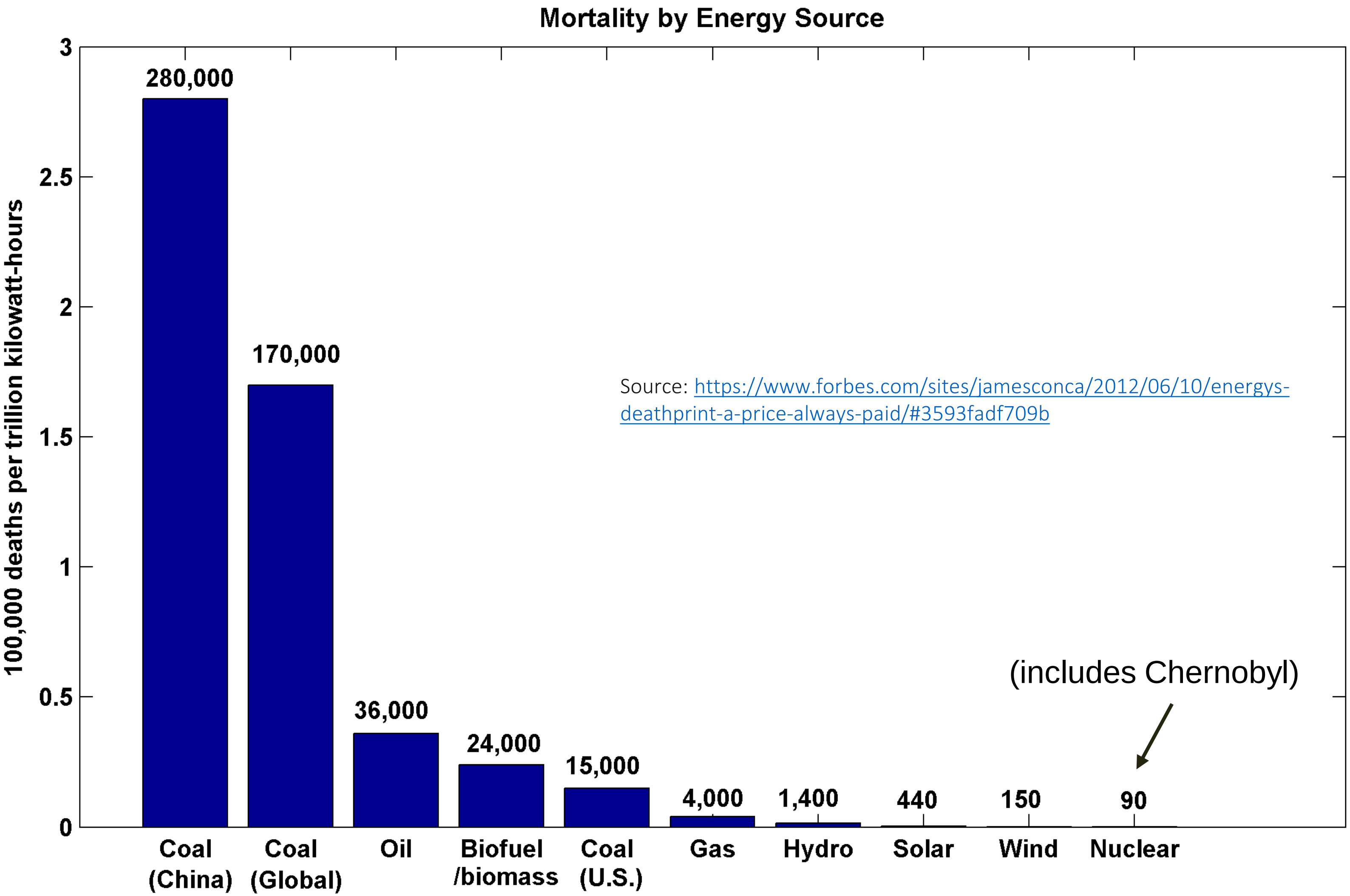
NUCLEAR: >90% capacity factor **~2260 $\mathrm{MW_e/km^2}$**

SOLAR*: <30% capacity factor **~6 $\mathrm{MW_e/km^2}$**

WIND*: <40% capacity factor **~1 $\mathrm{MW_e/km^2}$**

*L. M. Miller, D. W. Keith 2018 Environ. Res. Lett. 13 104008

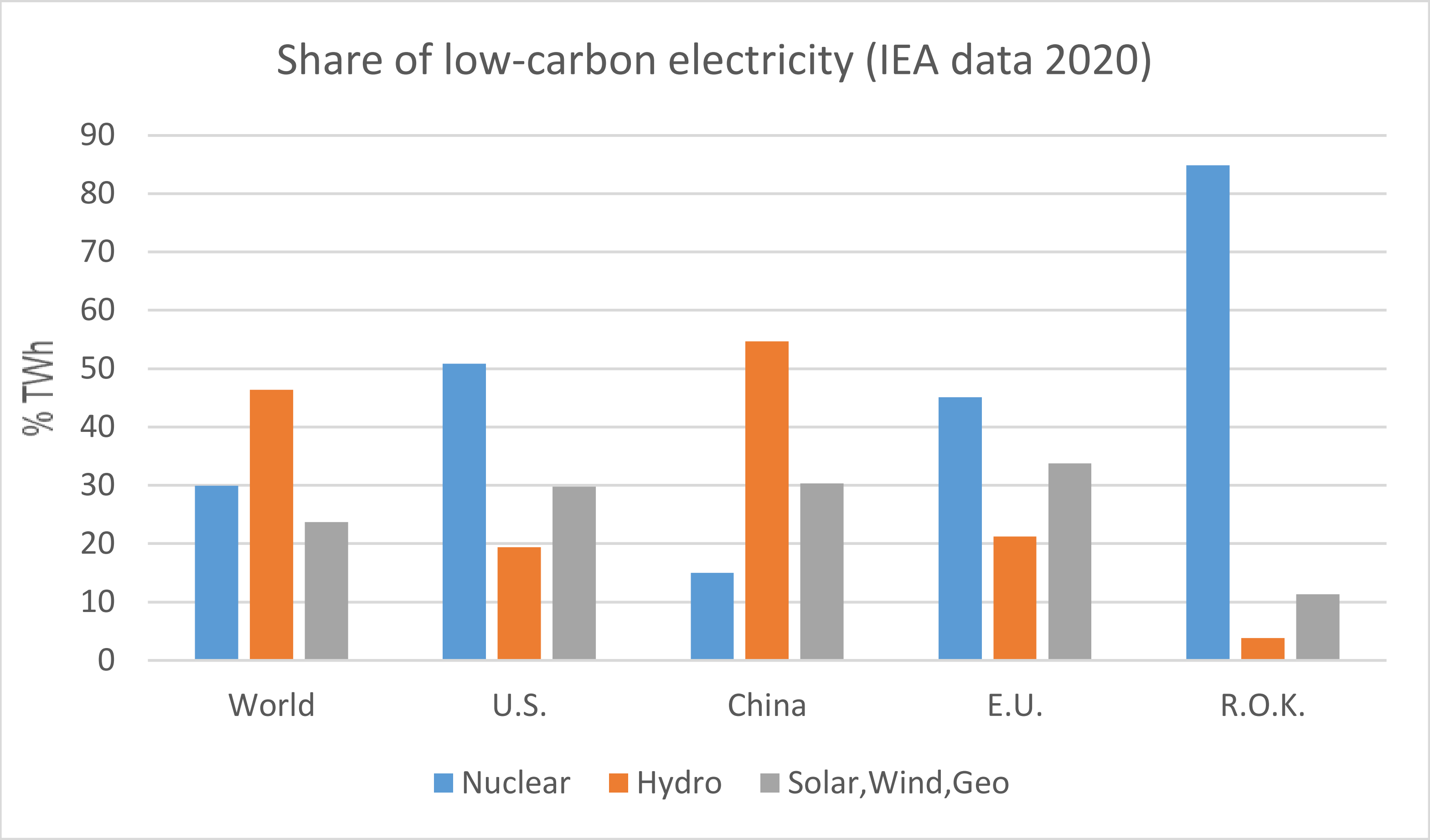
VERY LOW IMPACT ON PUBLIC HEALTH



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

(includes Chernobyl)

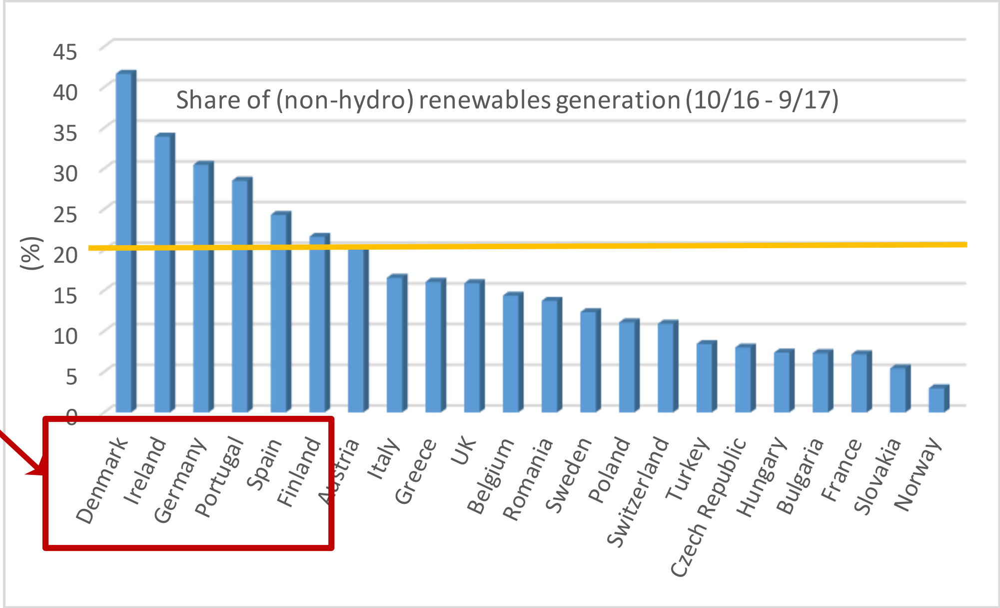
NUCLEAR IS THE LARGEST SOURCE OF EMISSION-FREE ELECTRICITY IN THE U.S. AND EUROPE BY FAR



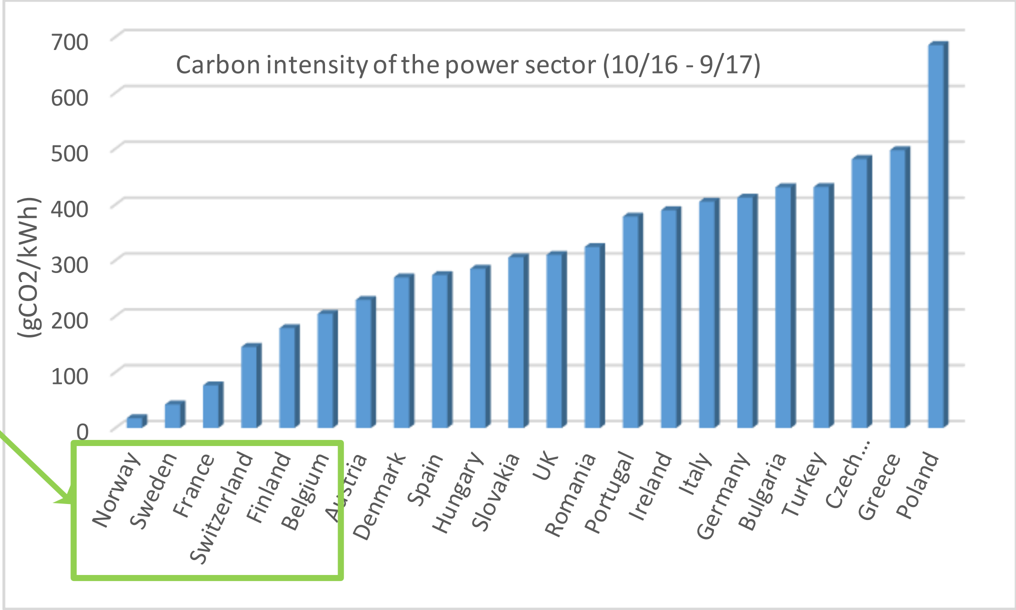
Growing in China, India, Russia, Middle-East and Eastern Europe, basically stagnant in Western Europe, Japan and the U.S.

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)

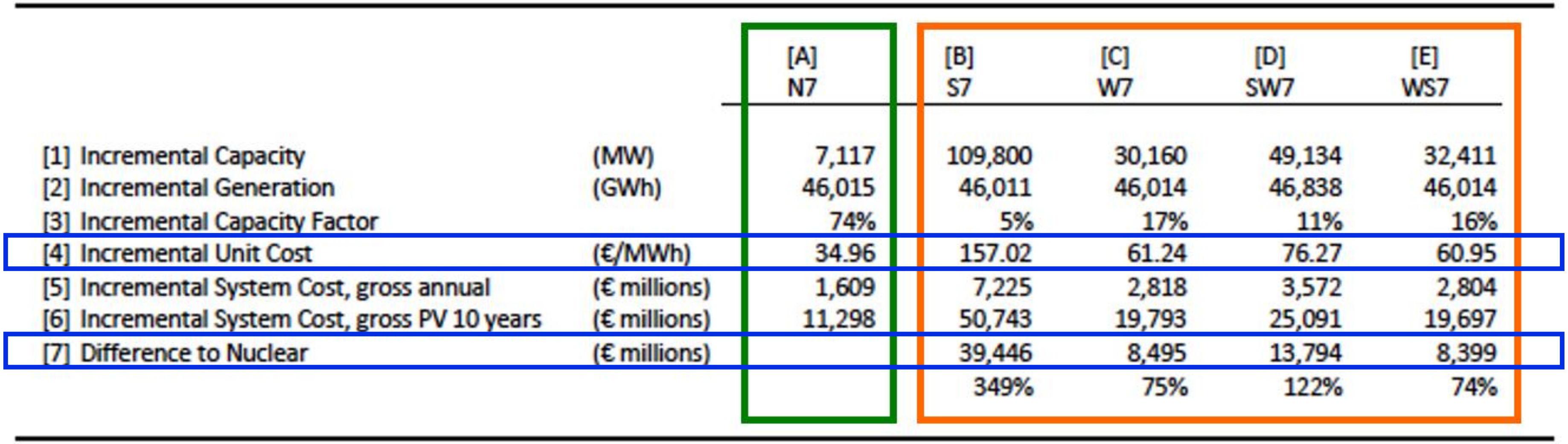
FIRST PRIORITY: DON’T SHUT DOWN EXISTING NPPs

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

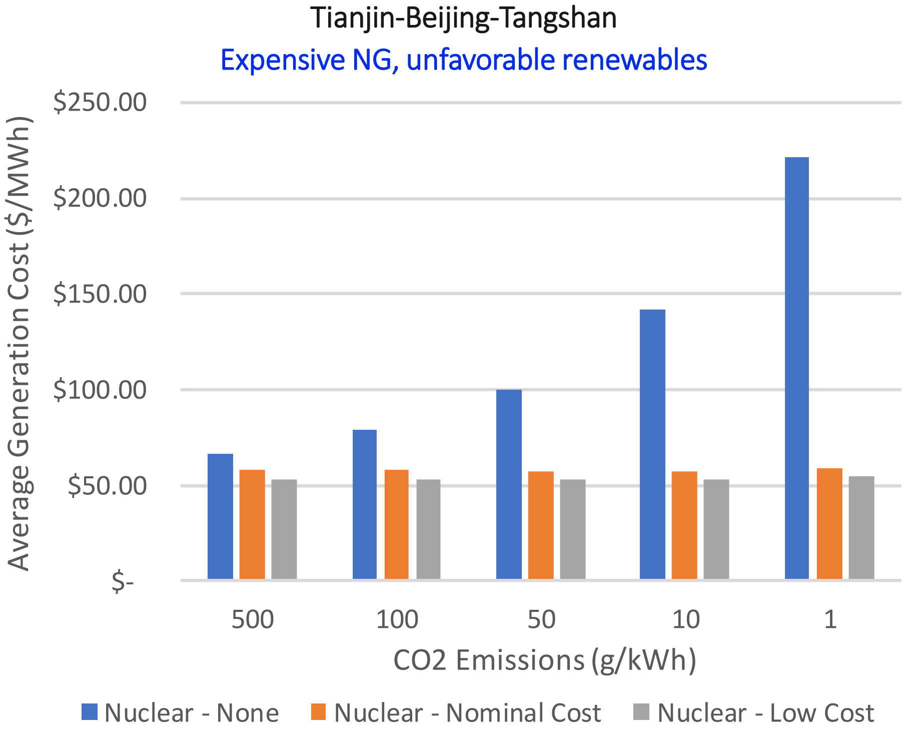
All reactors are shutdown and replaced by renewables + batteries to keep same emissions



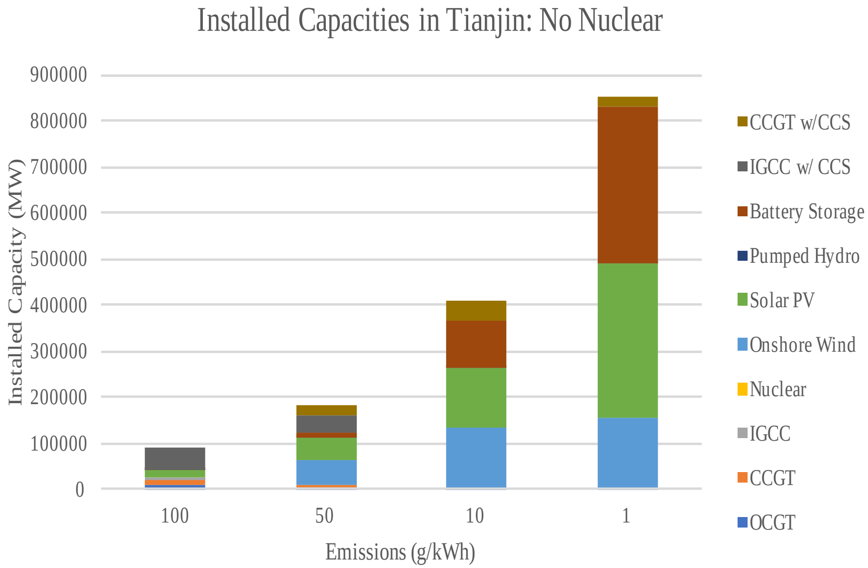
		[A]	[B]	[C]	[D]	[E]
		N7	S7	W7	SW7	WS7
[1] Incremental Capacity	(MW)	7,117	109,800	30,160	49,134	32,411
[2] Incremental Generation	(GWh)	46,015	46,011	46,014	46,838	46,014
[3] Incremental Capacity Factor		74%	5%	17%	11%	16%
[4] Incremental Unit Cost	(€/MWh)	34.96	157.02	61.24	76.27	60.95
[5] Incremental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

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

NUCLEAR CHALLENGE #1:
HIGH INITIAL CONSTRUCTION COST

THE CURRENT BUSINESS MODEL FOR NUCLEAR:

- lengthy testing/licensing

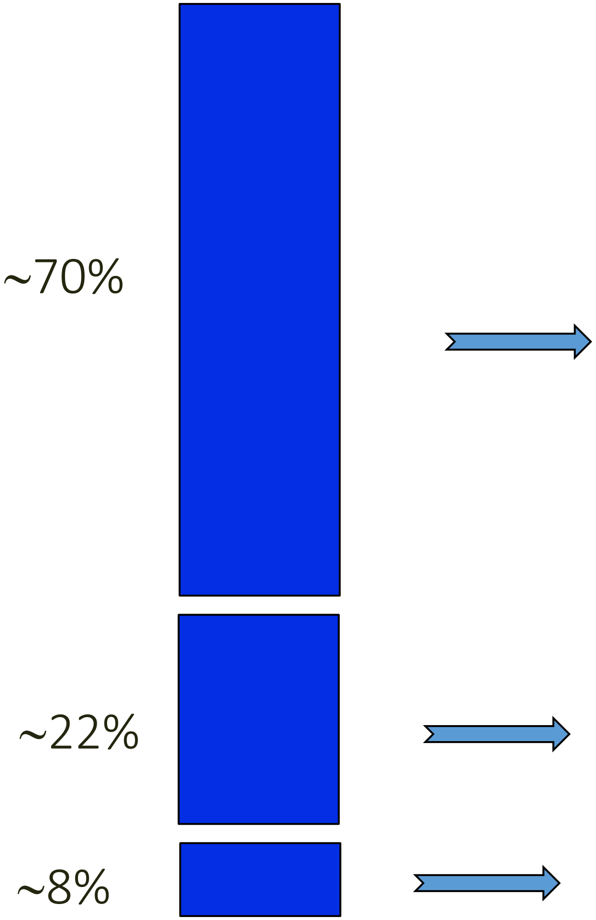
- field construction

- very large plant

- selling a commodity (electrons to the grid)

IS ECONOMICALLY PROBLEMATIC IN THE US AND EUROPE
THE SITUATION IS DIFFERENT IN ASIA

LEVELIZED COST OF ELECTRICITY (LCOE) FOR A NEW NUCLEAR PLANT IS DOMINATED BY THE CAPITAL COST



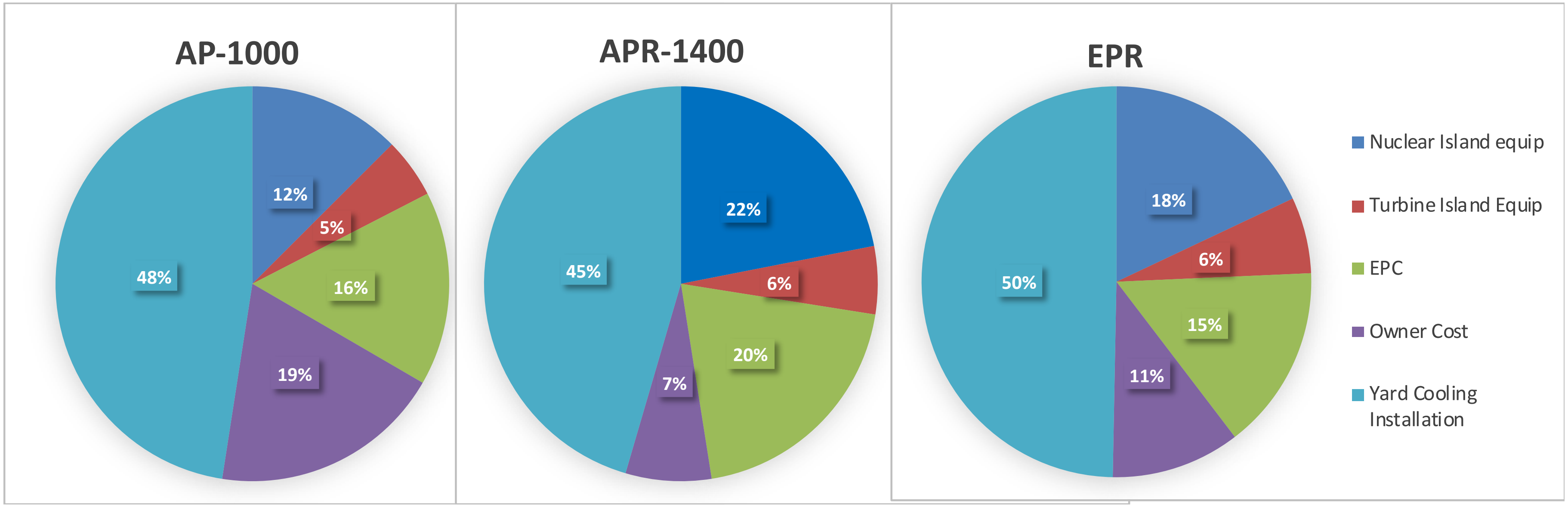
Build the plant, including financing

Operate and maintain the plant, including security

Pay for the fuel

LCOE for NG is mostly fuel, little capital and O&M
LCOE for wind/solar is almost all capital and some O&M, no fuel

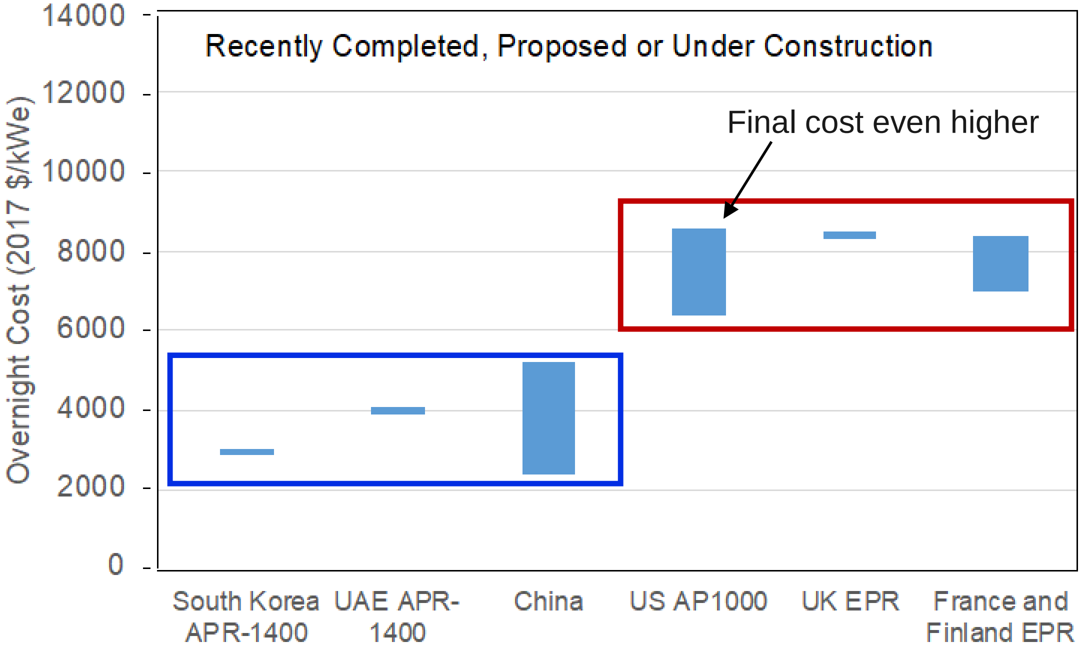
BREAKDOWN OF CAPITAL COST



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

WHY HAVE NEW NPPs IN THE WEST BEEN SO EXPENSIVE AND DIFFICULT TO BUILD?



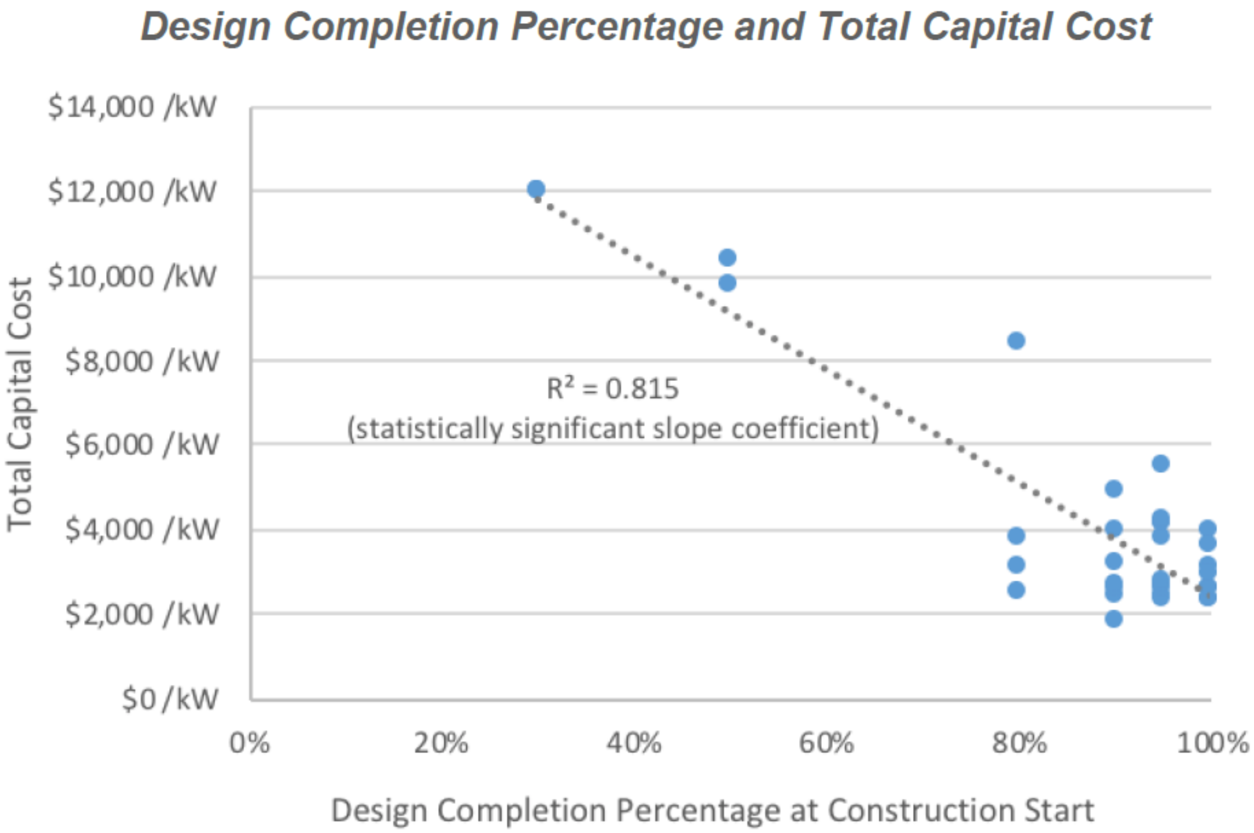
ASIA

- >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
- Government financing

US / Europe

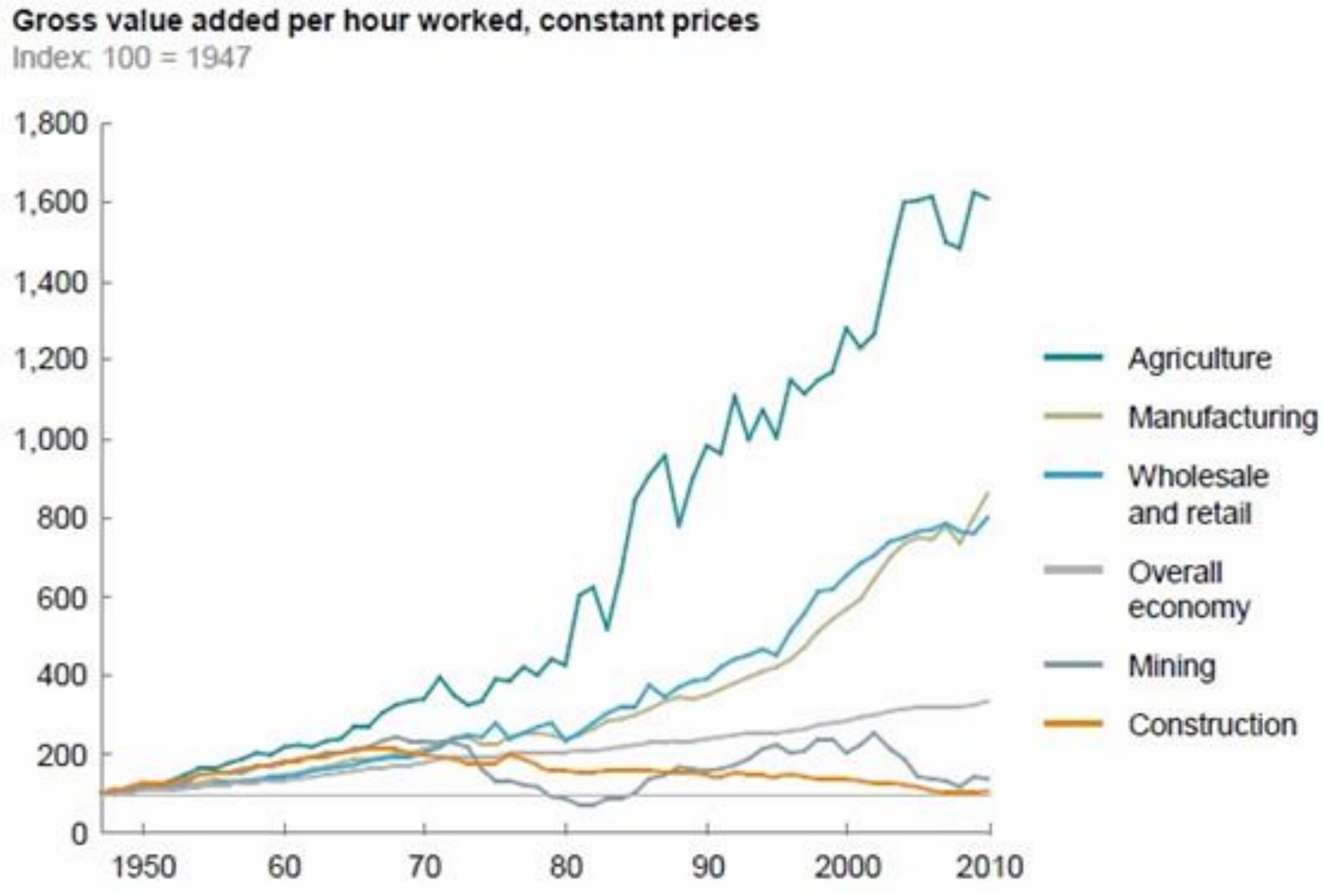
- Started construction with <50% design completed
- Atrophied supply chain, inexperienced workforce
- Litigious construction teams
- Regulatory process averse to design changes during construction
- Often private equity and debt

THE IMPORTANCE OF FINISHING DETAILED DESIGN BEFORE BREAKING GROUND AT A SITE



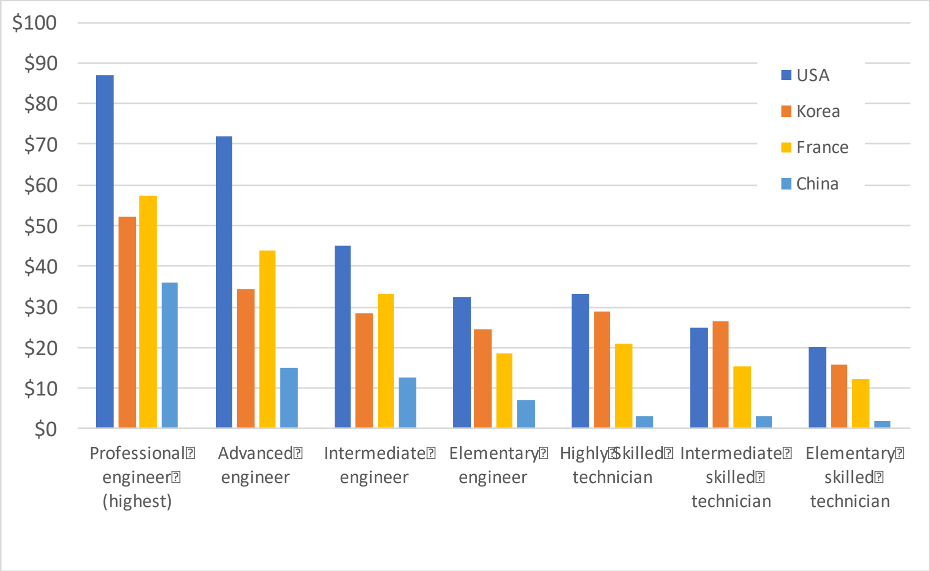
Source: “The ETI Nuclear Cost Drivers Project,” Energy Technologies Institute (2018)

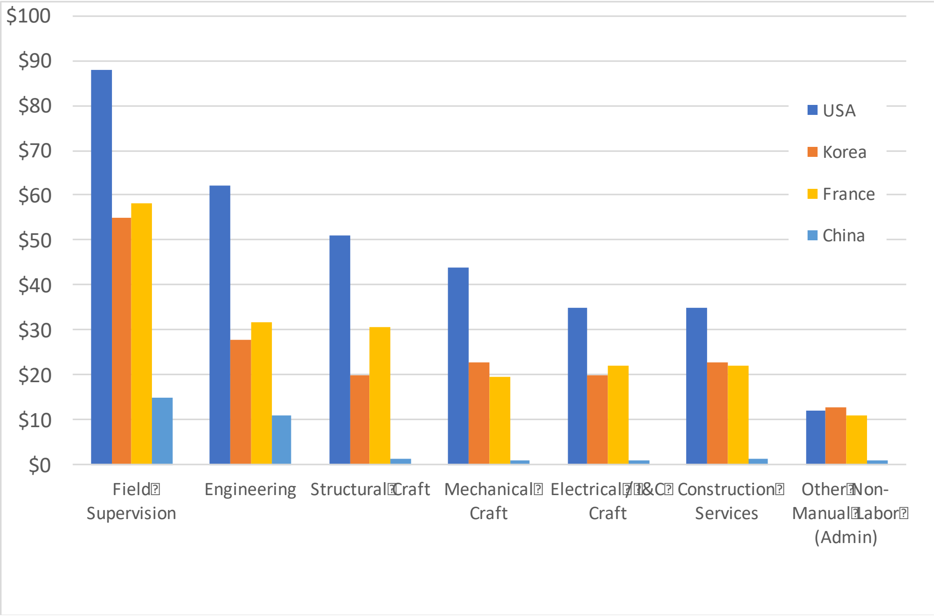
Aggravating factors



Construction labor productivity has decreased in the US

Aggravating factors (2)





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

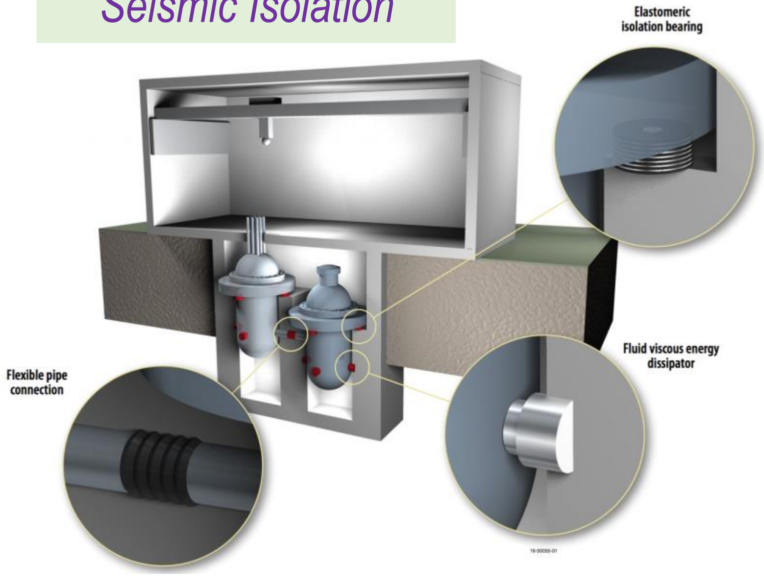
Estimated effect of construction labor on overnight construction cost (wrt US):
-$900/kWe (China)
-$400/kWe (Korea)

Source: Bob Varrin, Dominion Engineering Inc.

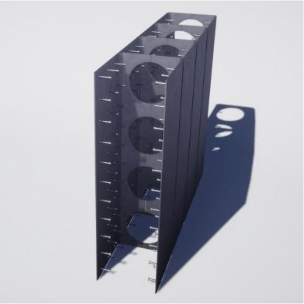
WHAT INNOVATIONS COULD MAKE A DIFFERENCE ON COST?

Standardization on multi-unit sites

Seismic Isolation



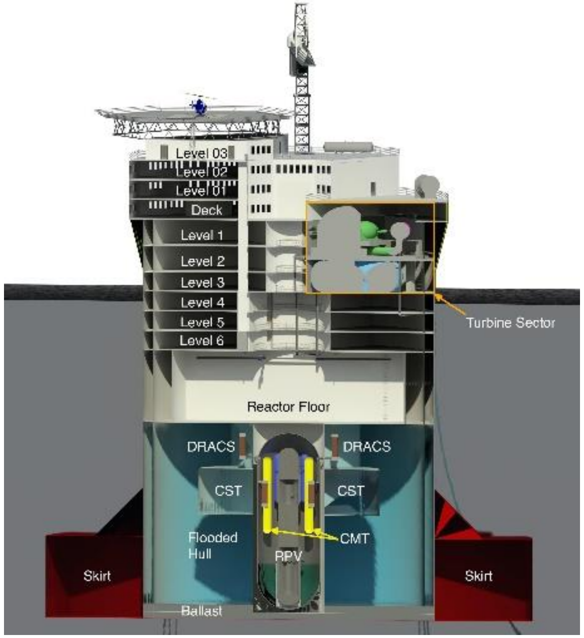
Advanced Concrete Solutions



Applicable to all new reactor technologies

WHAT INNOVATIONS COULD MAKE A DIFFERENCE ON COST? (2)

Integration in floating platform/barge



Modular Construction Techniques and Factory/Shipyard Fabrication

Applicable to all new reactor technologies

WITH THESE INNOVATIONS IT SHOULD BE POSSIBLE TO:

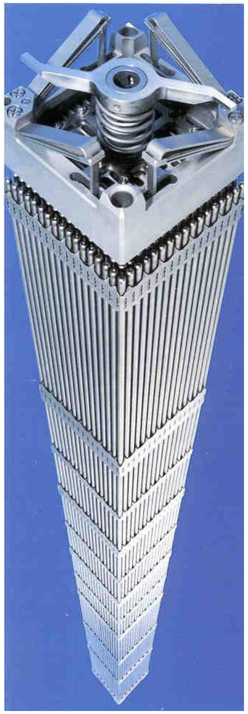
- Shift labor from site to factories/shipyards ⇒ reduce construction cost and indirect cost
- Standardize design ⇒ reduce licensing and engineering costs + maximize learning
- Shorten construction schedule ⇒ reduce interest during construction

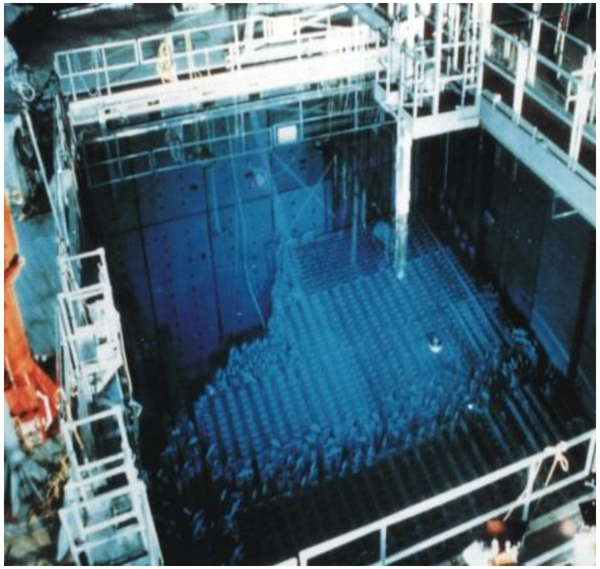
In other industries (e.g., chemical plants, nuclear submarines) the capital cost reduction from such approaches has been in the 10-50% range

NUCLEAR CHALLENGE #2:
HIGH LEVEL WASTE DISPOSAL

NUCLEAR WASTE: CURRENT PRACTICE IN THE US

- The spent fuel is the waste
- Spent fuel in storage pools for 3-5 years
- Then transferred to sealed dry casks: 80 casks needed for all spent fuel produced by a 1000-MW reactor in 60 years (very small volumes)
- Dry casks are completely safe to handle and last for decades with minimal maintenance





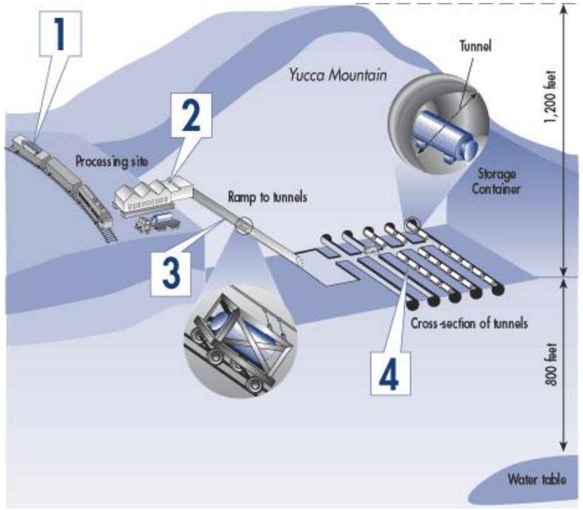
STORAGE OF SPENT NUCLEAR FUEL IN DRY CASKS IS A MATURE TECHNOLOGY USED AT 60 SITES THROUGHOUT THE US

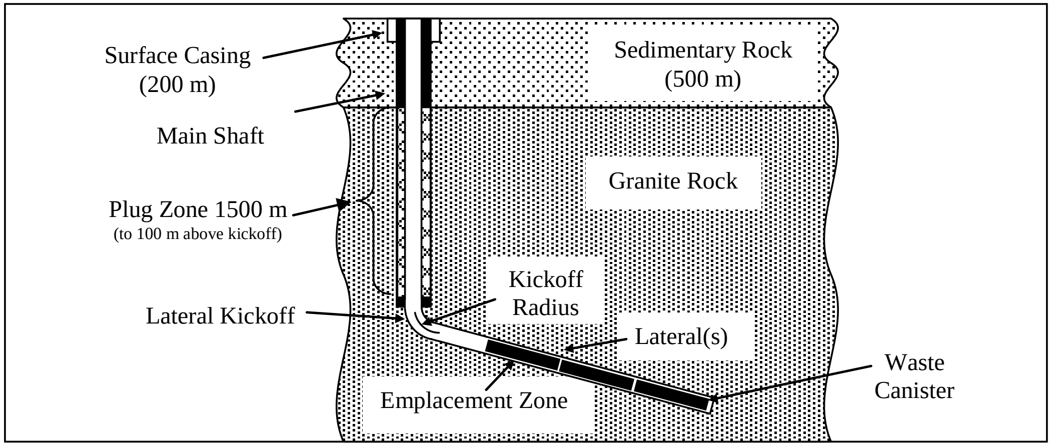
MIT Nuclear Science and Engineering faculty and students visiting the spent fuel dry-cask storage facility at the Pilgrim nuclear power plant in Plymouth, Massachusetts.

Dry-cask storage facility at now-decommissioned Maine Yankee nuclear power plant in Wiscasset, Maine.

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.)





TECHNOLOGIES AND MARKETS

CLASSES OF REACTORS

Electric output
Construction cost
Construction duration

Large Light Water Reactors (LWRs)

~1000-1600 MW$_e$
~$2-10B
5-10 yrs

Small Modular Reactors (SMRs)

~70-300 MW$_e$
~$1-3B
3-5 yrs

Microreactors (Nuclear Batteries)

~1-10 MW$_e$
<$0.1B
<1 yr

Korean, Russian and Chinese suppliers (KHNP, Rosatom, CNNC, CGN) are in the lead over Western suppliers (EDF, Westinghouse, GEH)

Western suppliers are in the lead for LWR-based designs (GEH, Nuscale, Westinghouse, Rolls Royce, EDF, Holtec), reasonably positioned for non-LWR designs (X-energy, Kairos, Terrapower)

US suppliers are in the lead (BWXT, X-energy, Westinghouse)

ECONOMY OF SCALE MATTERS

$$\mathrm{LCOE}\left[\frac{\$}{\mathrm{MWh}}\right]=\frac{\mathrm{ICC}\cdot(A/P,i,N)+\mathrm{DC}\cdot(A/F,i,N)}{W_e\cdot \mathrm{CF}\cdot 8760}+\frac{\text{Fixed O\&M}}{W_e\cdot \mathrm{CF}\cdot 8760}+\frac{\text{Variable O\&M}}{W_e\cdot \mathrm{CF}\cdot 8760}+\frac{\mathrm{FC}\cdot(A/P,i,N_{\mathrm{Fuel}})}{24\cdot \mathrm{BU}}$$

LCOE = levelized cost of electricity; W_e = electric output; ICC = initial construction cost; DC = decommissioning cost; CF = capacity factor; N = lifetime; O&M = operations & maintenance; FC = fuel cost; BU = fuel burnup; $(A/P,i,N)$ and $(A/F,i,N)$ = capital recovery factors; i = discount rate

Best-in-class experience with modern large LWRs

- W_e = 1000-1400 MW, built in 48 months (South Korea, China)
- ICC = $2.5-4.0 billion (South Korea, China)
- ICC / W_e = 2500-3500 $/kW (South Korea, China)
- CF = 90-93% (US)
- N = 60-80 years (US)
- Fixed O&M / W_e = 0.5-0.6 FTE/MW (US)
- FC = 3800 $/kg$_U$ (5% enriched UO_2 fuel)
- BU = 50 MWd/ kg$_U$ (US)

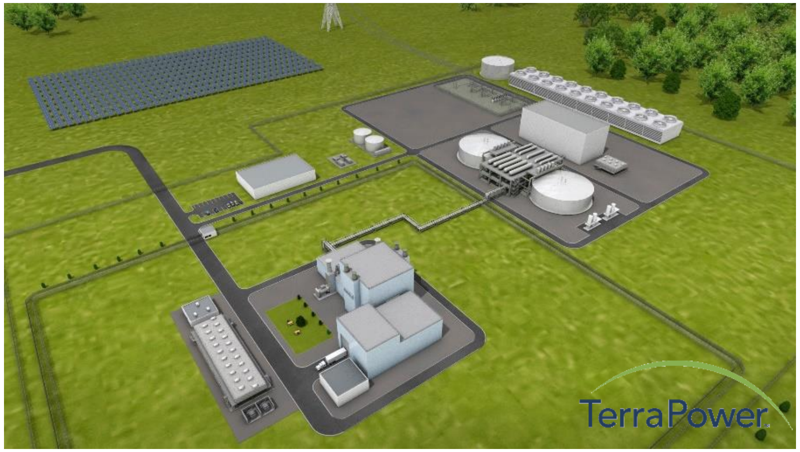
Small reactors (qualitative)

- W_e: 1-300 MW
- ICC: smaller plant, simplified design, shorter schedule
- ICC / W_e = ??
- CF: no operating experience
- N = 20 (micro) to 60-80 years (all others)
- O&M: more automation
- FC: same (5% enriched UO_2) or higher (HALEU + TRISO)
- BU: all over the place

The effect of W_e (3-1400x less than large LWRs) at the denominator of the LCOE equation is very challenging to overcome *even with* aggressive design simplification, factory fabrication, learning and automation.

LARGE LWRs AND SMRs COULD GROW NUCLEAR'S FOOTPRINT ON THE GRID

Coal plant replacement for baseload generation



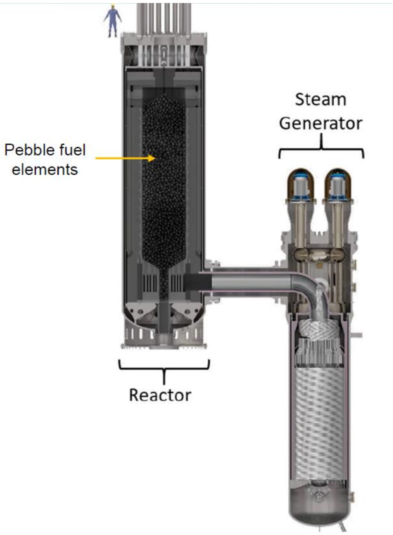
with flexible generation (for NG plant replacement)

perhaps even re-using the existing plant BOP

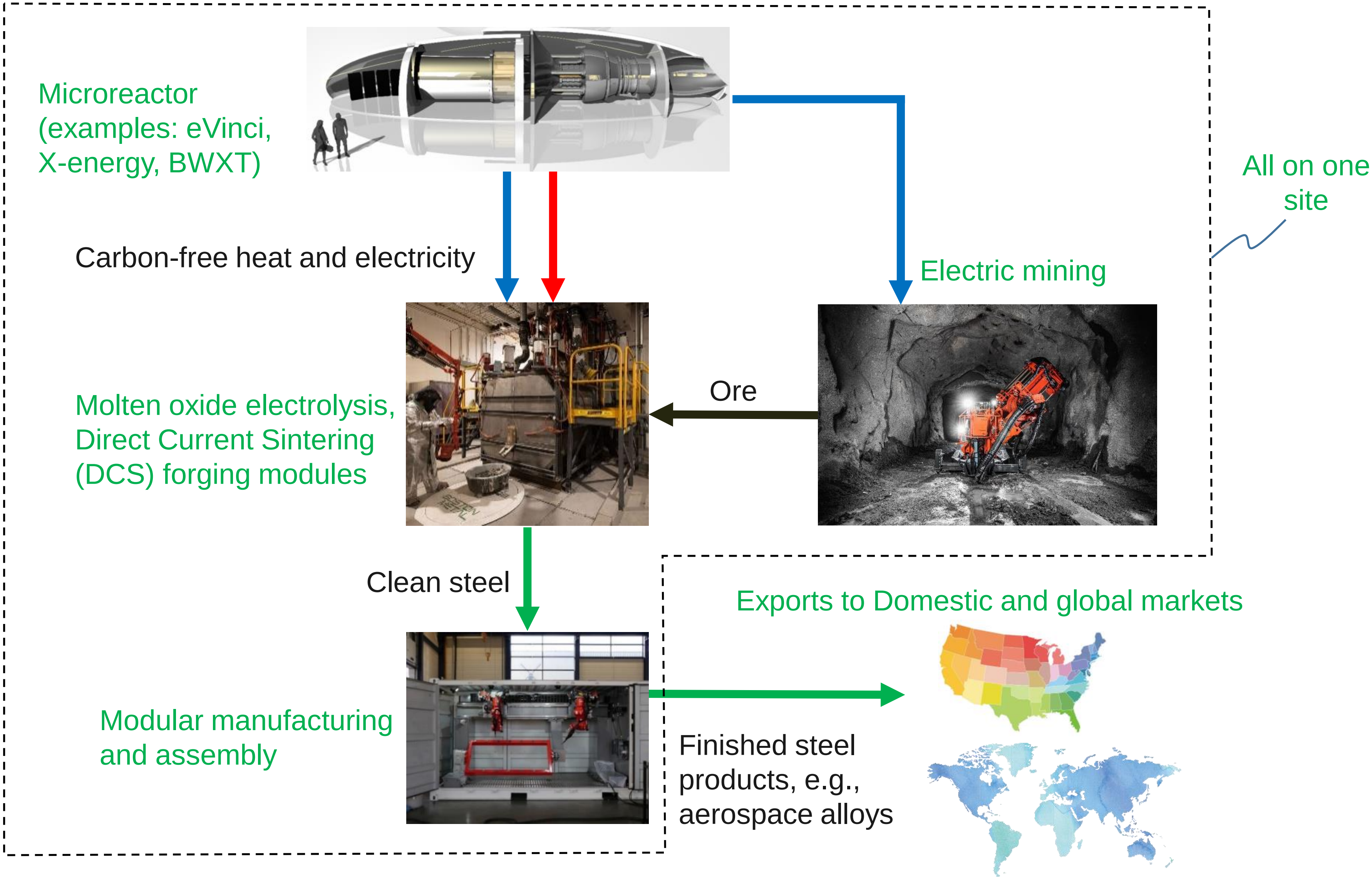
CAPTURE A SIGNIFICANT SHARE OF THE NASCENT MARKET FOR HYDROGEN AND SYNTHETIC FUELS

Centralized hydrogen/fuel generation on a grand scale

or co-located with hydrogen industrial users



MICROREACTORS COULD PENETRATE NON-COMMODITY MARKETS WHERE THEY CAN ENJOY A SIGNIFICANT COMPETITIVE ADVANTAGE



Microreactor (examples: eVinci, X-energy, BWXT)

Carbon-free heat and electricity

Electric mining

All on one site

Ore

Molten oxide electrolysis, Direct Current Sintering (DCS) forging modules

Clean steel

Exports to Domestic and global markets

Modular manufacturing and assembly

Finished steel products, e.g., aerospace alloys

Systems features: (1) No grids or pipelines needed; (2) Carbon-free products; (3) Shortened markup chains; (3) Allows for incremental provisioning → Spectacular cashflow

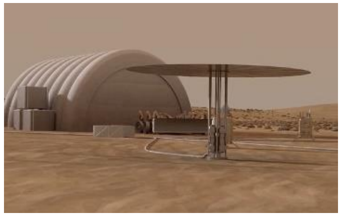
THIS APPROACH COULD APPLY ACROSS EVERY SECTOR OF THE ECONOMY


military bases


microgrids (remote communities, islands)

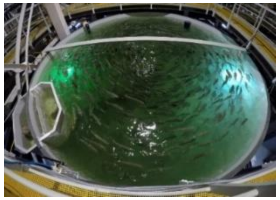

mining sites


indoor farming

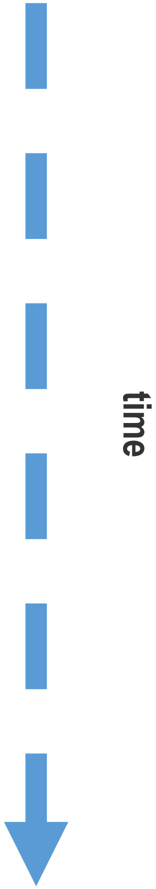

space installations


high-end metals, ceramics and glass


data centers


indoor aquaculture


portable pharma



Largest margin or early need determines relative order of deployment

(CONTINUED)

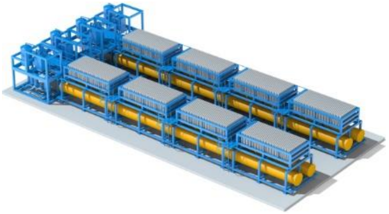

district heating


flood protection


desalination

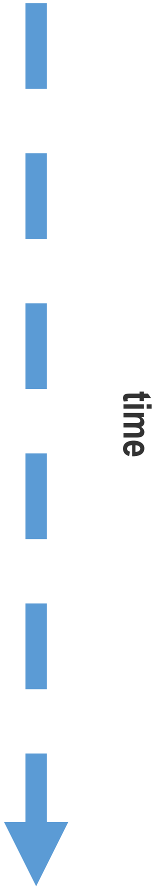

freight ship propulsion


e-vehicle charging stations


hydrogen electrolyzers


existing factories and
chemical plants

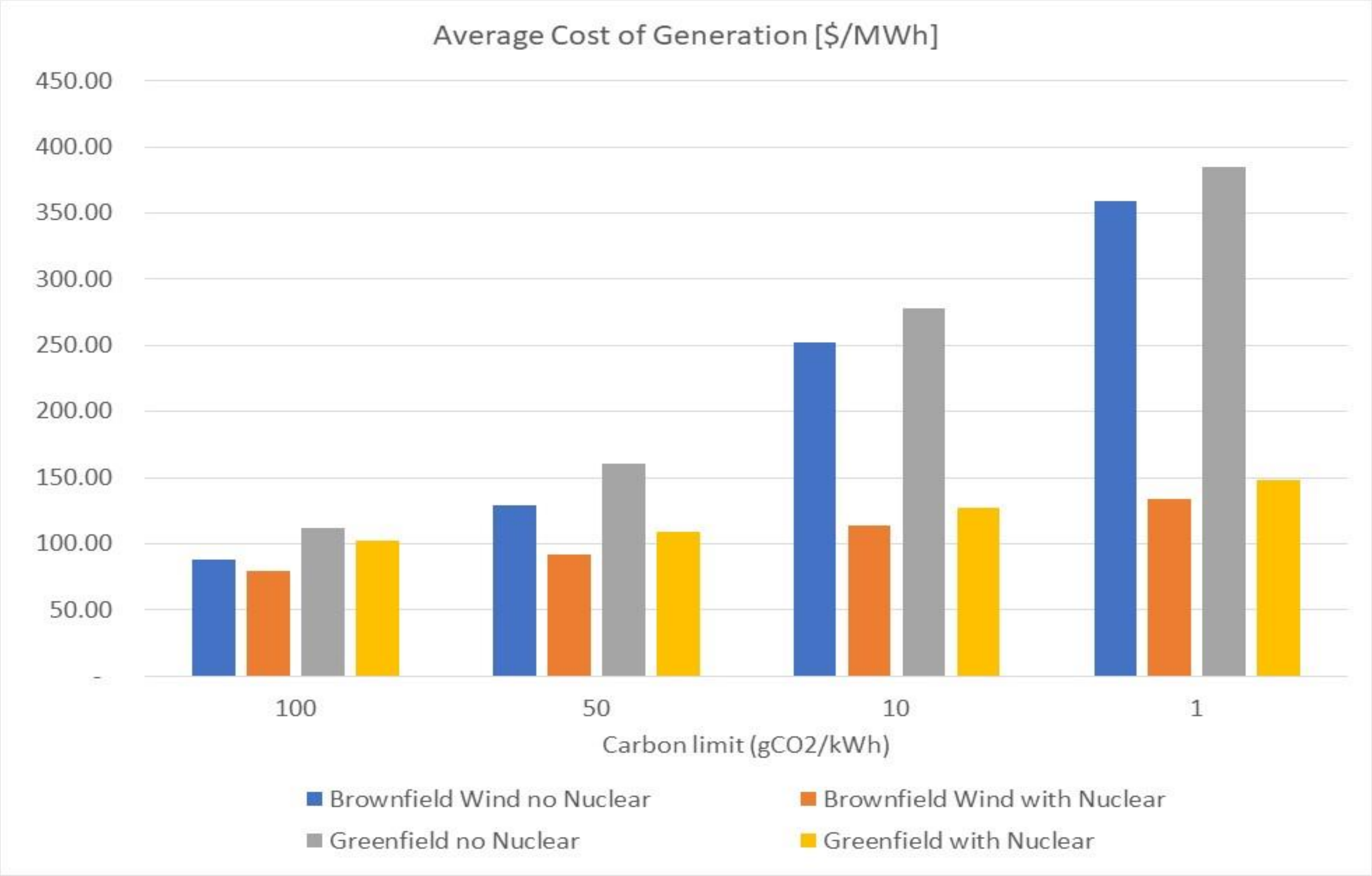

biofuels



This goes way beyond the electric grid, which represents only ¼ of global GHG emissions

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. Conservative assumption: transmission costs not included.

FRESHWATER FOR ARID AREAS

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

Israel's Sorek Desalination Plant (left) produces ~0.63 Mm^3/day. Israel uses desalinated and reclaimed water 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 RELIABLE, AFFORDABLE AND CLEAN ELECTRICITY TO REMOTE MINING OPERATIONS

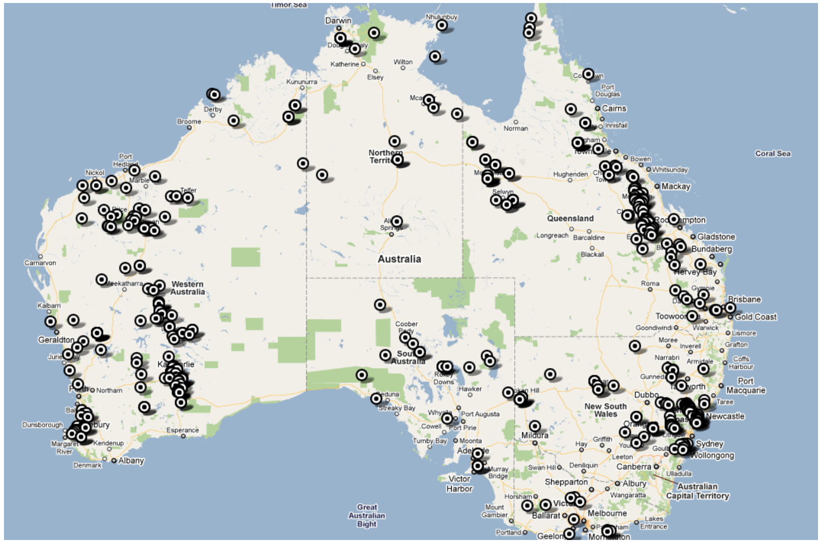


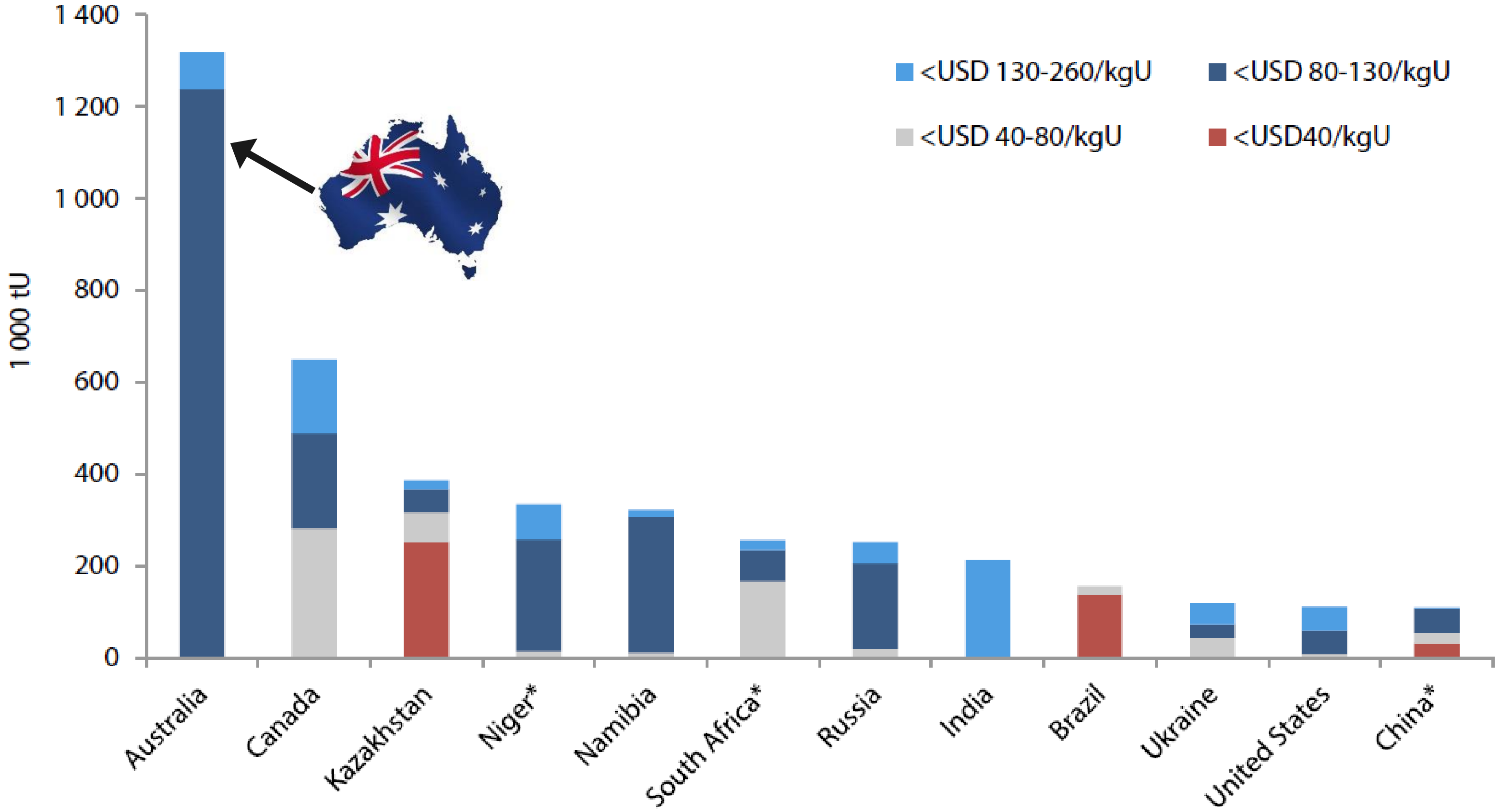

Image courtesy: BHP Billiton

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

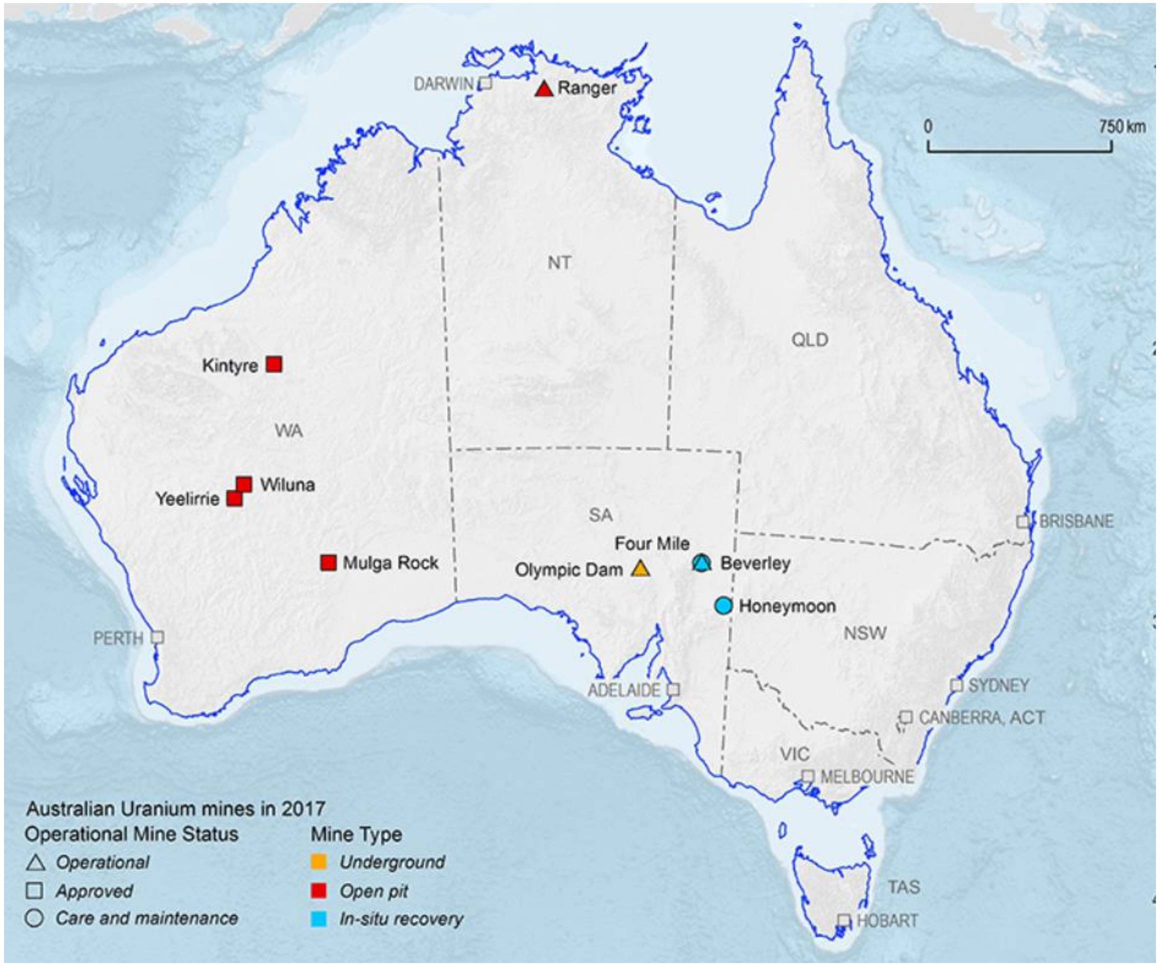
SUPPLY NUCLEAR FUEL TO THE WORLD

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



Reasonably Assured U Resources (from IAEA “redbook” 2022)

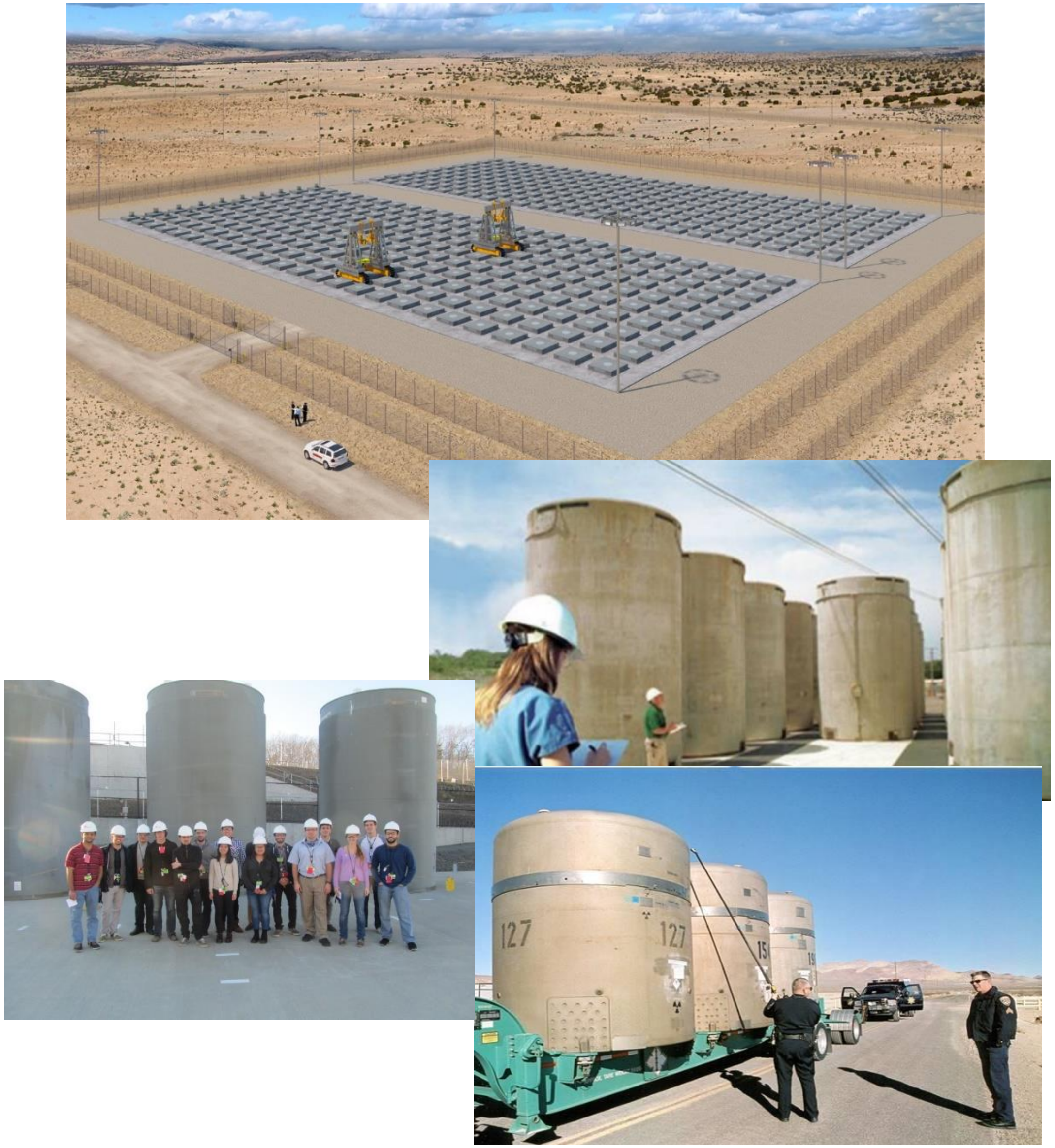
SUPPLY NUCLEAR FUEL TO THE WORLD (CONT.)



- In 2022 produced about 10% of world’s Uranium (all for power plants)
- ~1 billion AUD export value in 2022
- ~3000 jobs*

* Source: Uranium Resources, Production and Demand, IAEA “redbook”, 2022

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

LEVERAGE AUKUS TO KICK START THE CIVILIAN NUCLEAR ENERGY INDUSTRY

- Synergies in education and human resources development
- Post-service job opportunities for RAN submariners
- Infuse RAN rigor and safety culture into civilian nuclear sector
- Business opportunities in the nuclear supply chain for Australian manufacturing sector

EXTRAORDINARY RESURGENCE OF INTEREST IN NUCLEAR IN 2021-2023

- Invasion of Ukraine → energy security epiphany
- COP-26, -27 and -28, EU taxonomy → climate policies allow inclusion of nuclear
- China’s commitment to massive nuclear expansion (150 GW in 15 yrs)
- South Korea’s and Sweden’s elections → cancellation of nuclear phaseout
- Japan’s new government committed to restart idle NPPs
- France, Finland, Sweden, Netherlands, UK, Poland, Czech Republic, Hungary and Romania committed to new NPP builds
- Through Inflation Reduction Act and Infrastructure Bill the US Government committed substantial $$ to existing and new NPPs
- New nuclear build projects launched in the US and Canada
- Dow Chemical’s project to use nuclear heat for chemical plants
- CA legislature’s decision about Diablo Canyon extension
- Signs of attention in pop culture, e.g., Oliver Stone’s movie “Nuclear Now”

WILL AUSTRALIA RECONSIDER?