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

Massachusetts Institute of Technology

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)*

How Does Nuclear Energy Work?

Koroush Shirvan
Atlantic Richfield Career Development Professor in Energy Studies
Department of Nuclear Science and Engineering

Navigating Nuclear May 13 2024
UNSW Sydney

Massachusetts Institute of Technology

How people think Nuclear Power works:

How Nuclear Power actually works:

https://www.reddit.com/r/memes/comments/w3u5z6/nuclear_power_plants_are_basically_just_big_steam/

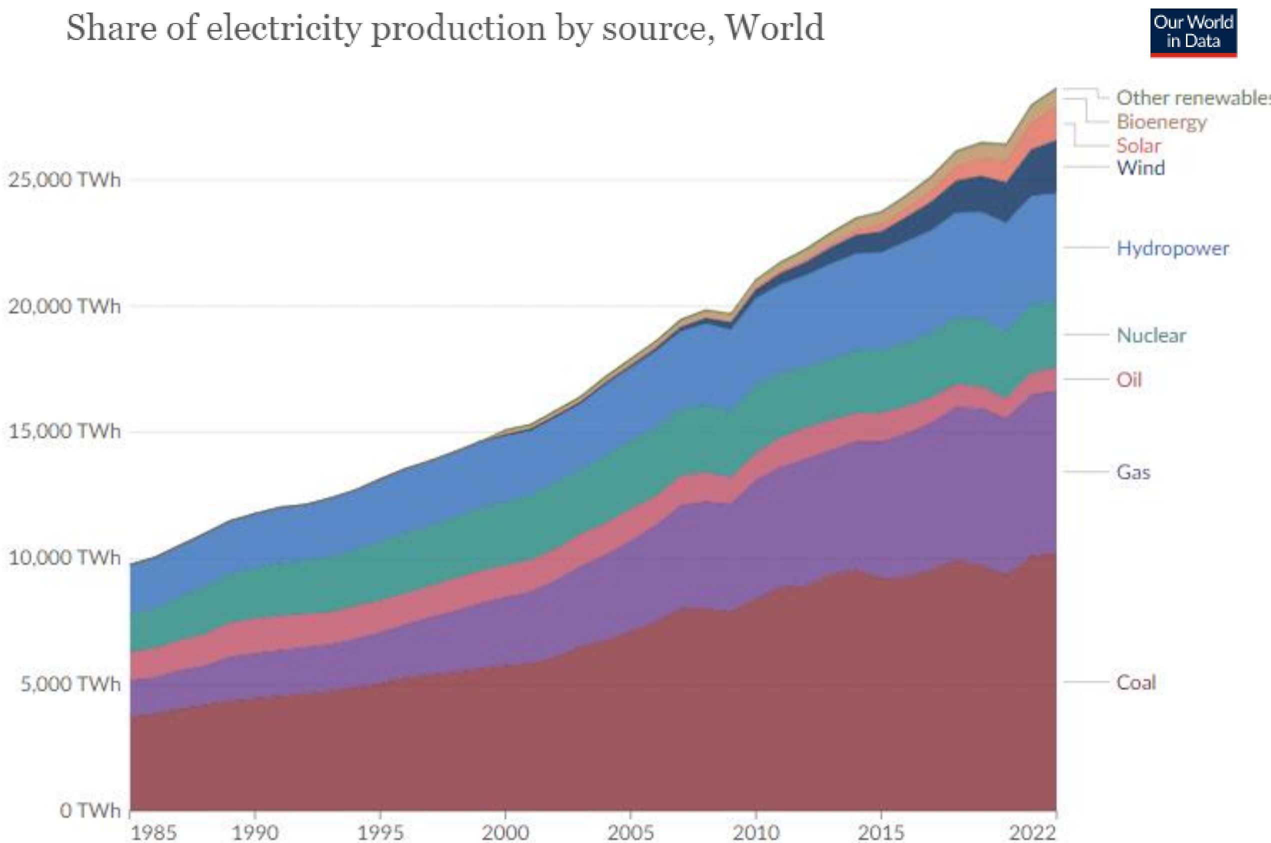
How Does Nuclear Energy Work

- Works by transferring heat to water to create steam that runs turbine-generator
  - ➢ All operating reactors today regardless of military or civilian

- Works in a very Carbon Free Manner
  - ➢ Among lowest life-cycle carbon intensive and pollution emitting energy sources (Source: IPCC)

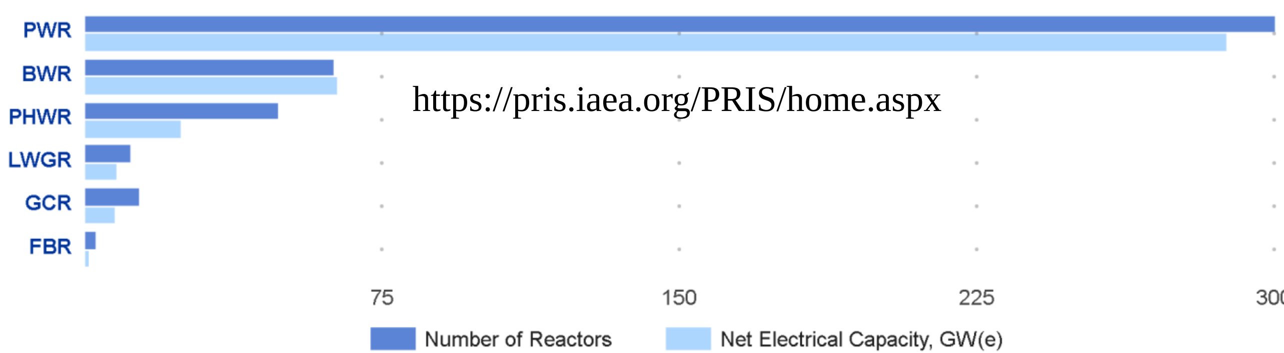
- Works in a dispatchable manner where it can meet demand
  - ➢ In France 70-80% of electricity generation is provided by Nuclear → proven to be a dispatchable energy source by powering majority of an industrialized country.

Nuclear Energy Today – Worldwide (2022)



COMMERCIAL NUCLEAR TECHNOLOGY TYPE

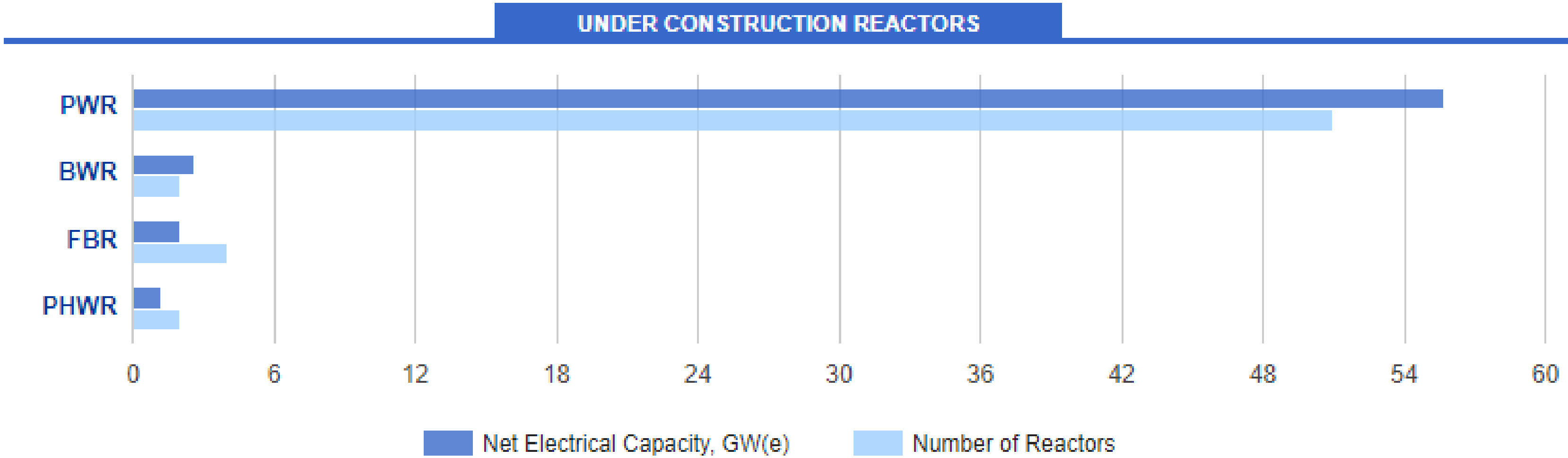
- About 440 reactors operating in over 30 countries
  - Last 20 years: roughly 100 reactors retired and 100 new reactors built
- Over 160 military Ships are Powered by over 200 Small Nuclear Reactors
- Dominant Technology: Water Cooled (**PWR** + BWR + PHWR + LWGR)
  - Dominant subset: **Pressurized Water Reactor**
  - Gas Cooled Reactors (GCR) mostly in UK
  - Few Fast Breeder Reactors (FBR) in Russia



https://pris.iaea.org/PRIS/home.aspx

Number of Reactors and Net Electrical Capacity, GW(e)

Nuclear Reactor Under Construction Today



https://pris.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByType.aspx

- *25 out of 59 from China: No, China is not building every type of reactor!*
- *All PWRs are large reactors except for 2 (1 China and 1 Argentina)*

Large Pressurized Water Reactor is the Past, Present and Future (near term)

PWR vs. Other Carbon Free Energy California, USA

Ivanpah Solar Thermal Plant (3 units)
400 MWe total (25% Capacity Factor)
37.5 m^2/kWe

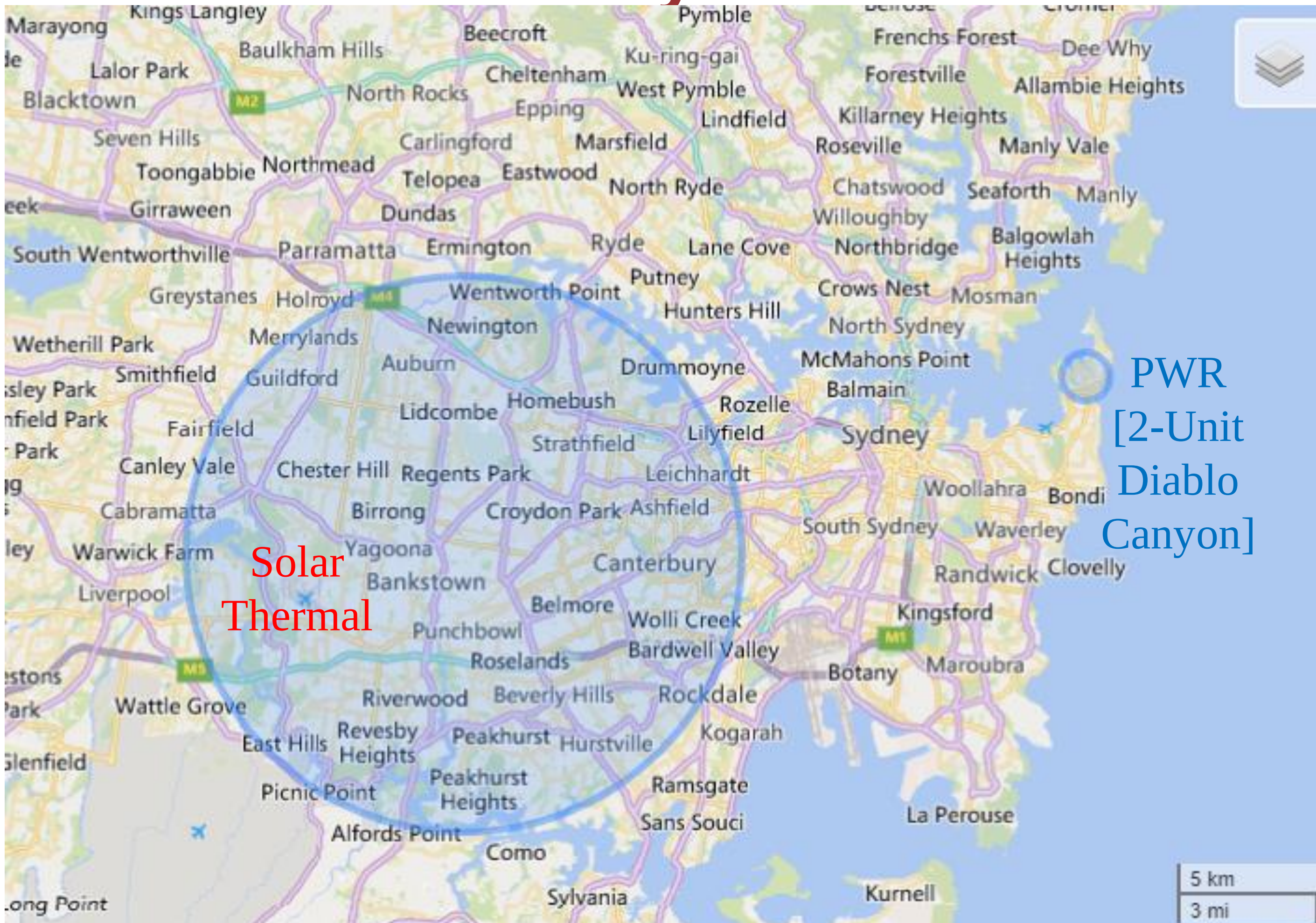
Diablo Canyon Nuclear Power Plants (2 units)
2256 MWe total (90% Capacity Factor)
1.3 m^2/kWe

>100 times less land for the same generation (kWe-hr)

*Generic Capacity Factors

6% of AUS Electricity Generation

But the Solar Plant can be moved to the desert area on the west away from the fish!



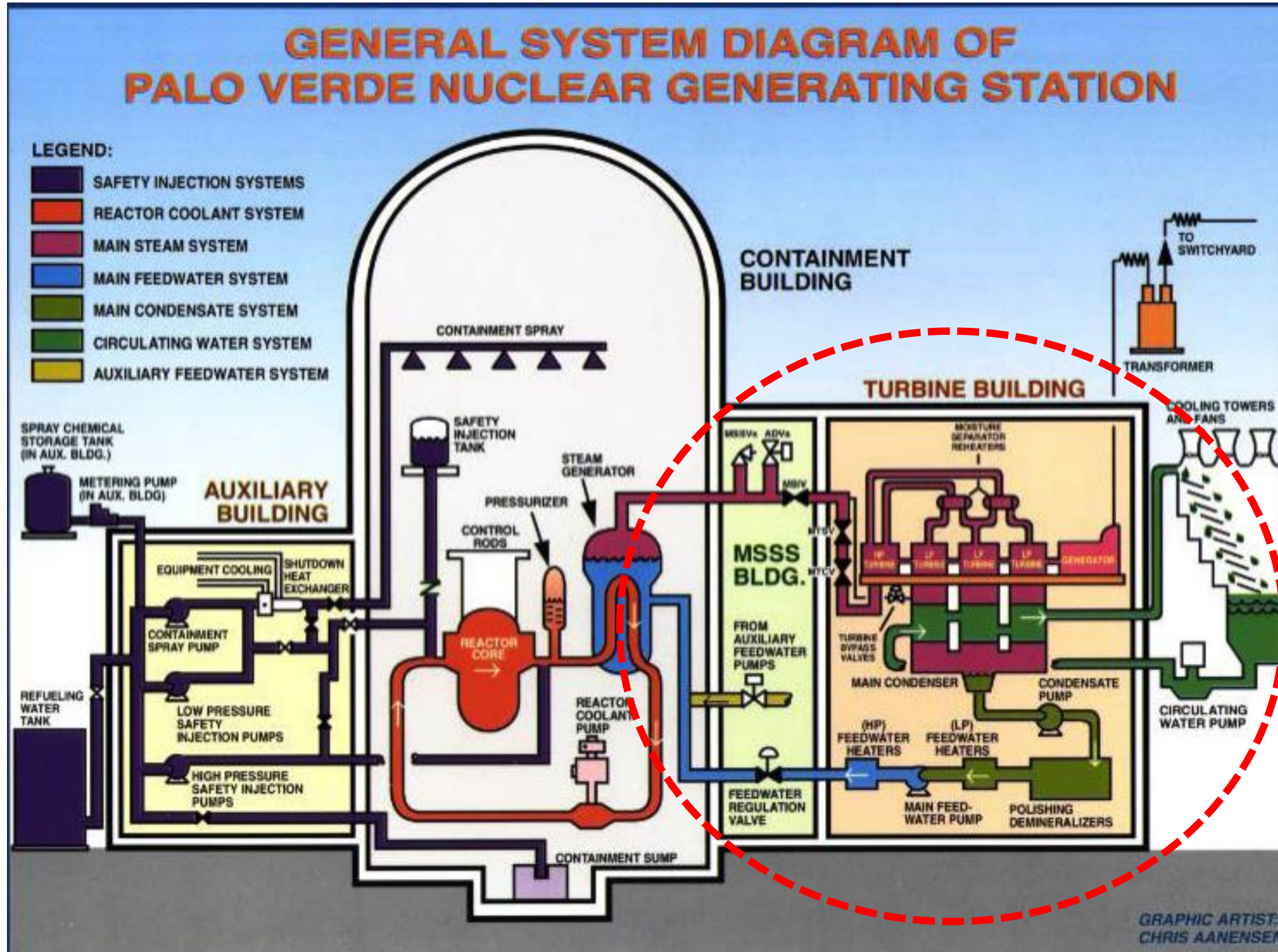
Waste Water!!!

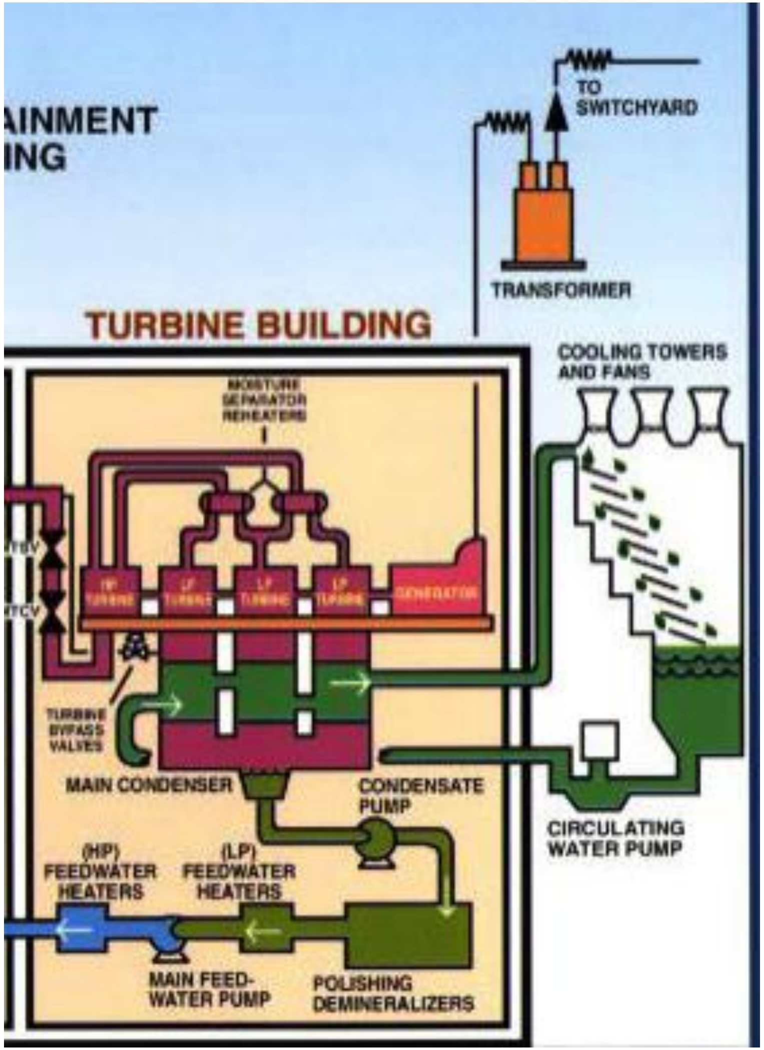
4,000 acres
16 Mm^2
4 m^2/kWe

Pale Verde Nuclear Station in Arizona US

Nuclear Energy in Desert

- NamePlate Capacity: 3937 MWe (3 reactors)
- 93% Capacity Factor and ~32,000 GWh production in past 10 years
- >10% of Australia Grid (similar to total wind or solar generation in Australia)
- 10 years to construct

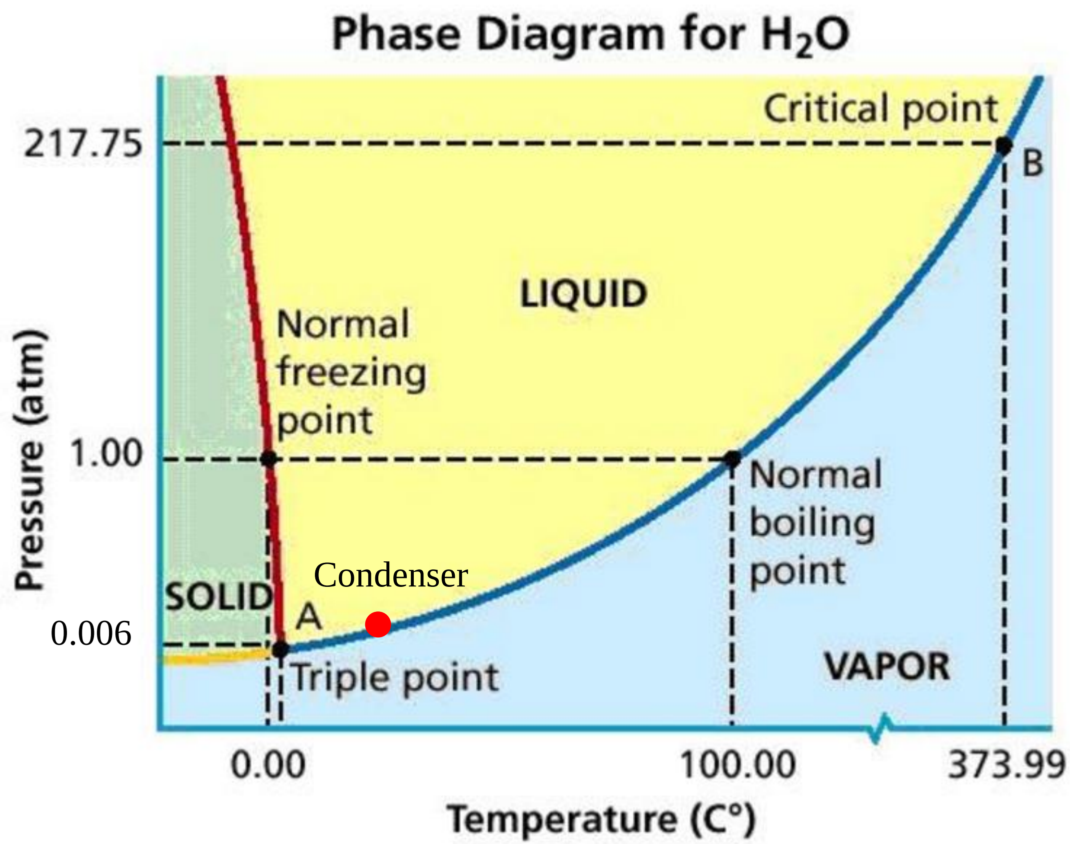




Turbine "Island"

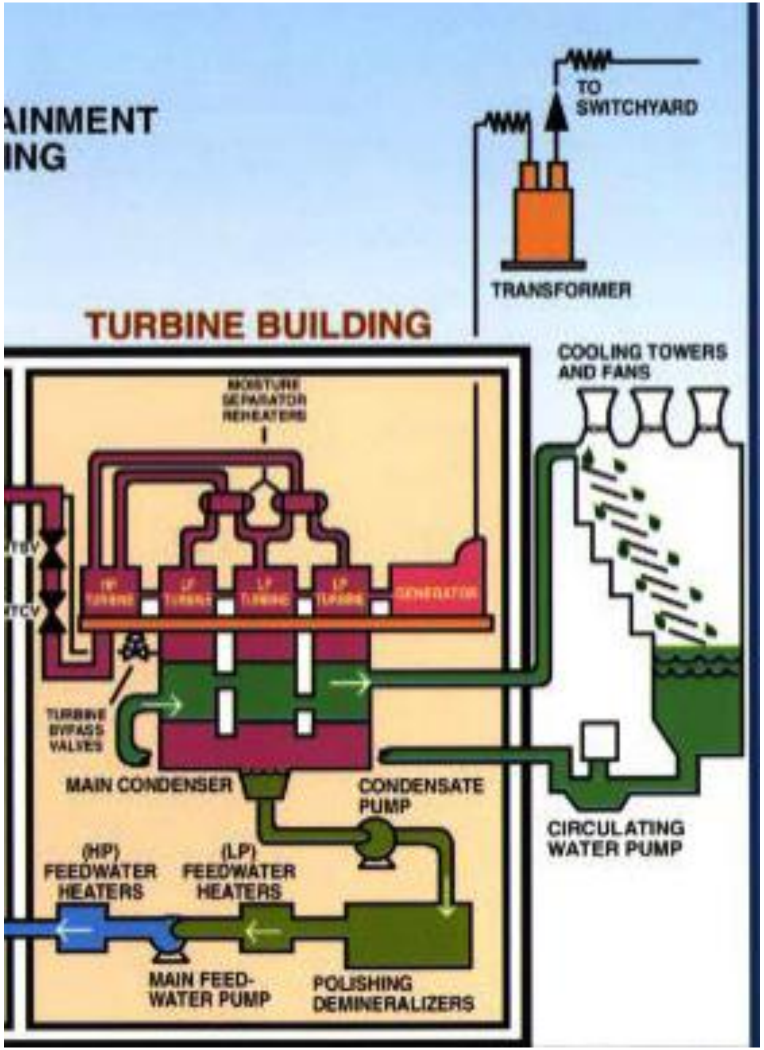
- Pressurized steam to rotate turbine (~70x atmosphere at ~300 ^{o}C)
  - In order to maintain liquid water in PWR reactor we have to pressurized water such that its boiling point is > 300 ^{o}C → reactor pressure is ~150x atmosphere

TYPICAL TEMPERATURE-PRESSURE RELATION FOR WATER



https://craigssenseofwonder.wordpress.com/tag/phase-diagram/

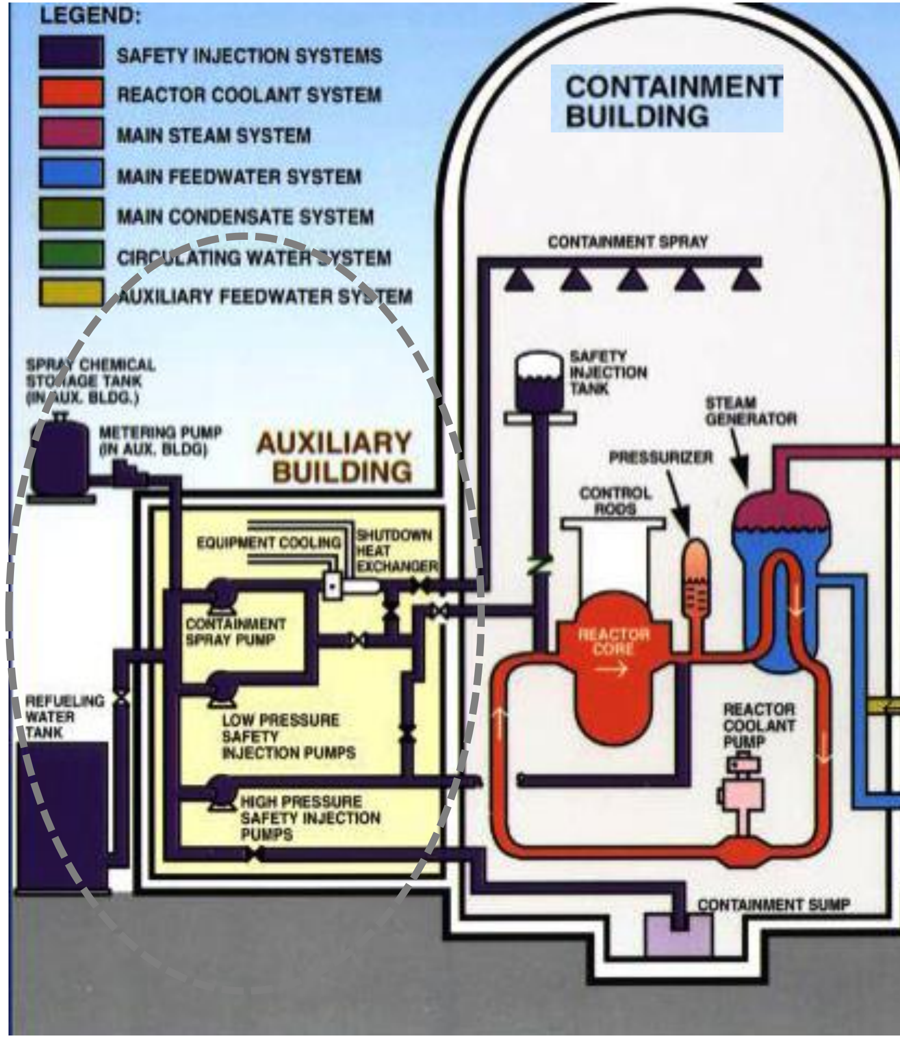
Turbine "Island"



- Pressurized steam to rotate turbine (~70x atmosphere at ~300 ^{o}C)
  - In order to maintain liquid water in PWR reactor we have to pressurized water such that its boiling point is > 300 ^{o}C → reactor pressure is ~150x atmosphere
- Heat-to-Electric Efficiency (est.)
  - PWR 33% vs. Combined Cycle Natural Gas 66% (includes both gas and steam turbines)
- *Modern PWR Turbine Island serves to no nuclear safety role*

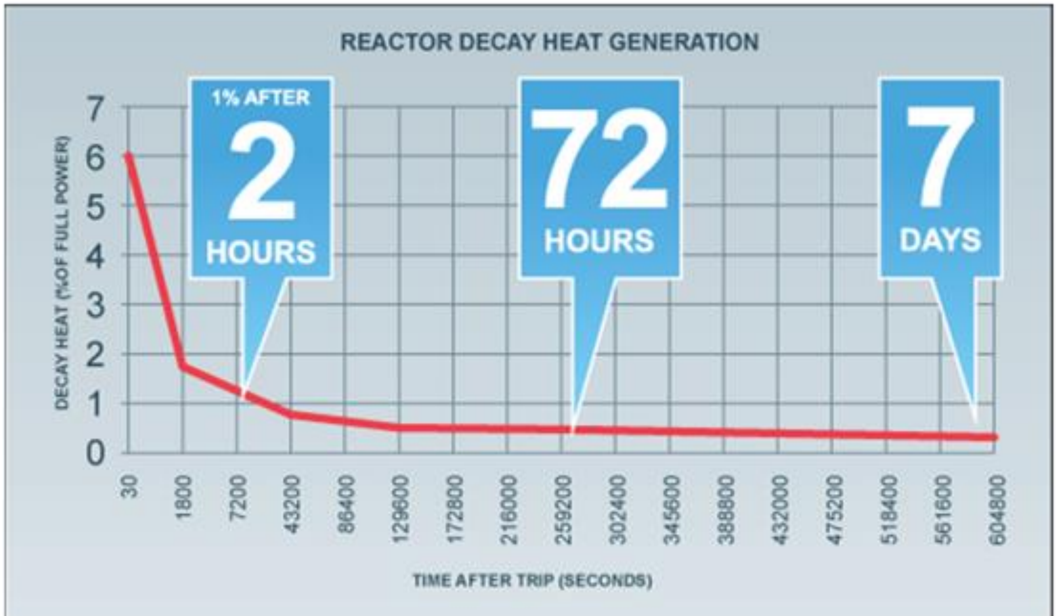
Nuclear "Island"

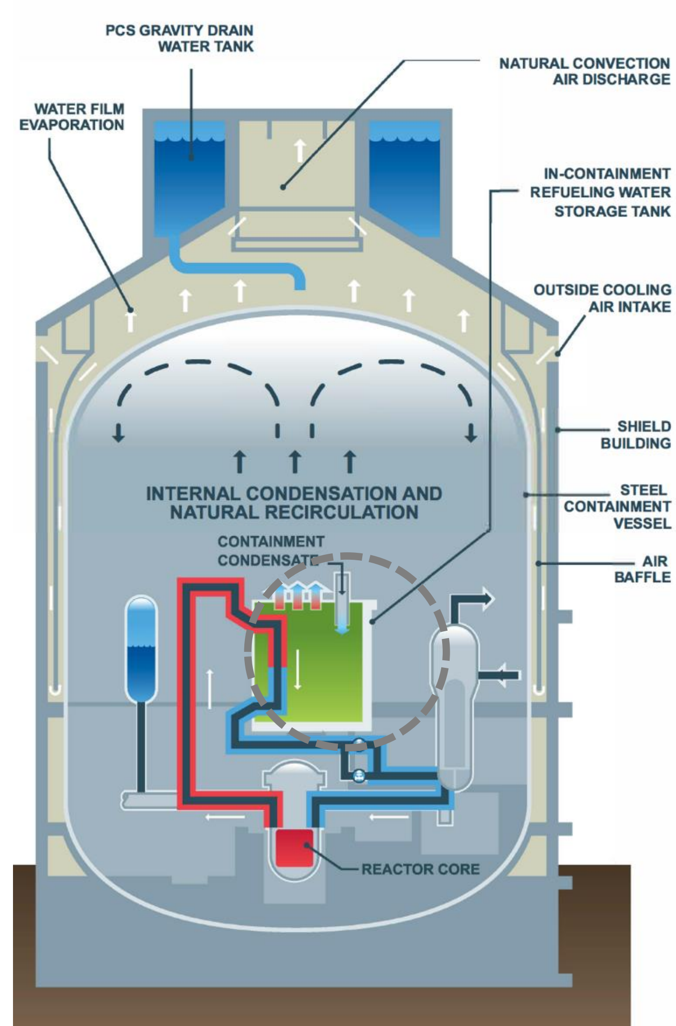
- Highly Regulated Industry
  - Nuclear Hazard: Reactor is never shutdown → engineering safety systems to remove decay heat
  - Pumps driven by diesel generators to provide long term cooling
  - Fukushima: these systems were flooded and resulted in core partial meltdown contained in the containment building



Modern PWR – AP1000

- Water is moved by Gravity toward the reactor vessel → Eliminating pumps, diesel generators, valves,

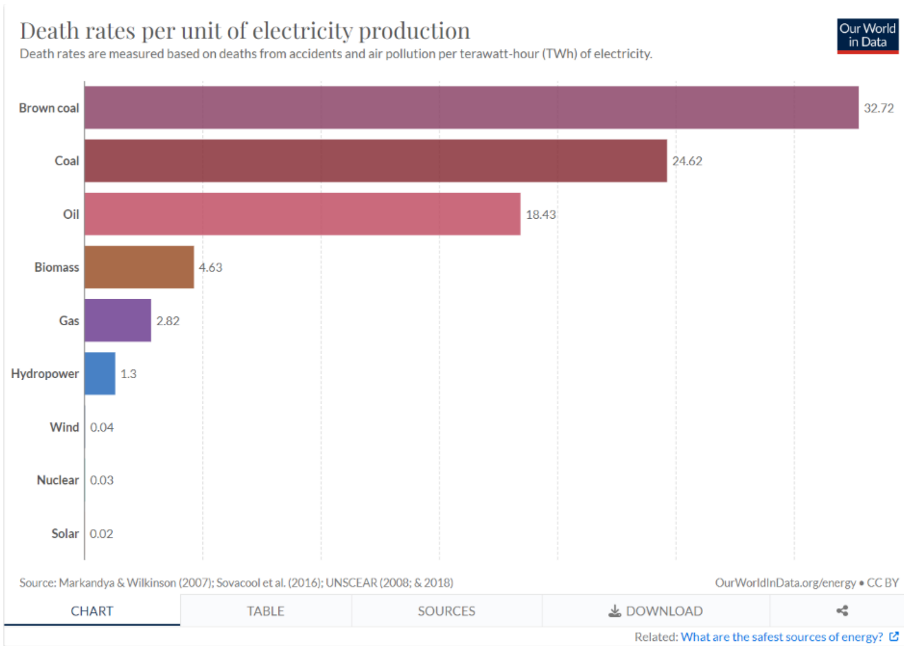




80% taller building and $teel containment

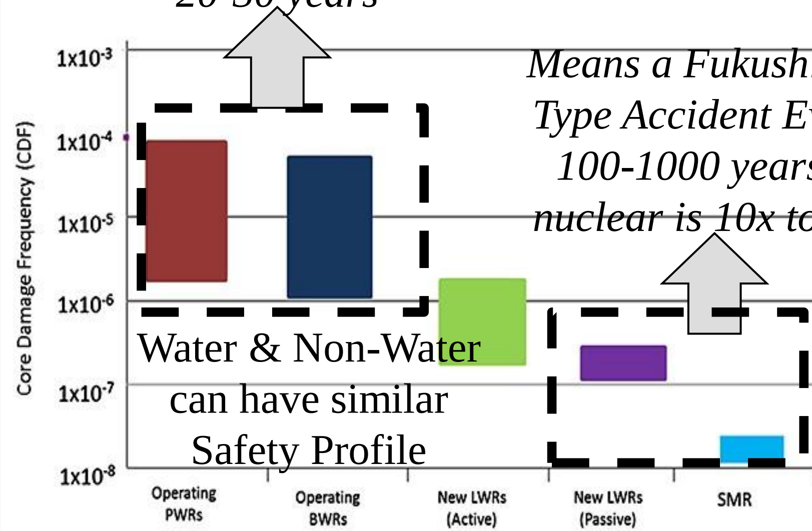
Addressing Safety through >1990 Designs

- Existing Nuclear is the safest energy source and the upcoming generation will reduce environmental impact such that we will not have every 20-30 years an accident.



Means a Fukushima-Type Accident Every 20-30 years

Means a Fukushima-Type Accident Every 100-1000 years if nuclear is 10x today

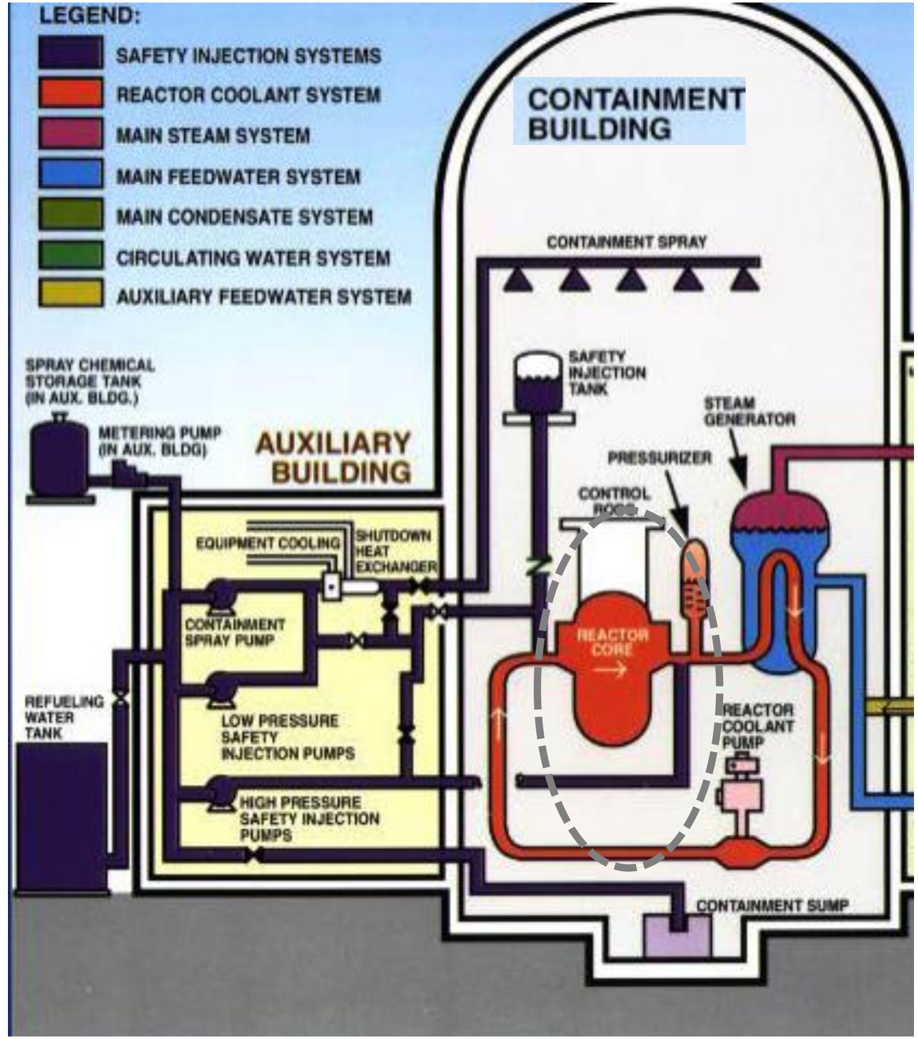


Water & Non-Water can have similar Safety Profile

Example of Large LWR Designs that can Withstand Fukushima Accident: AP1000, HI-ABWR, APR1400+, EPR

Nuclear "Island"

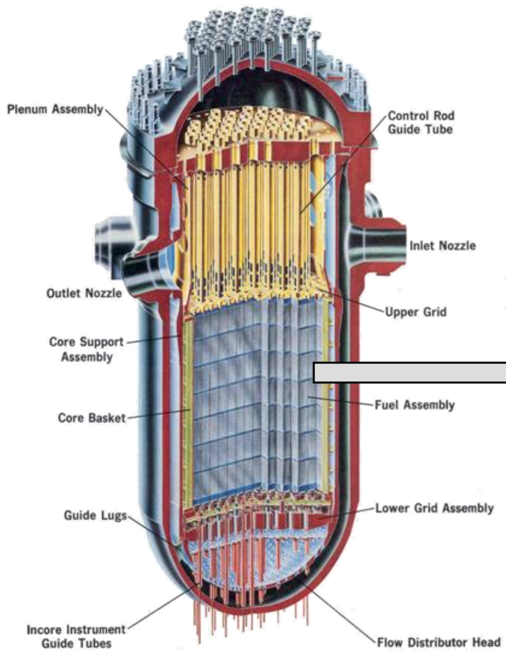
- Highly Regulated Industry
  - Nuclear Hazard: Reactor is never shutdown → engineering safety systems to remove decay heat
  - Pumps driven by diesel generators to provide long term cooling
  - Fukushima: these systems were flooded and resulted in core partial meltdown contained in the containment building

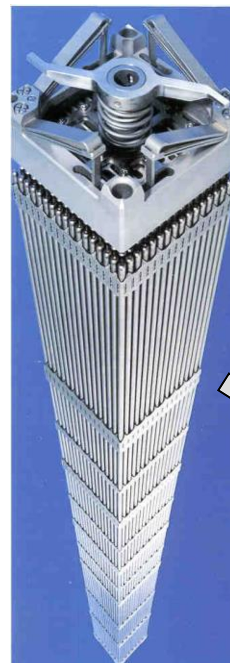


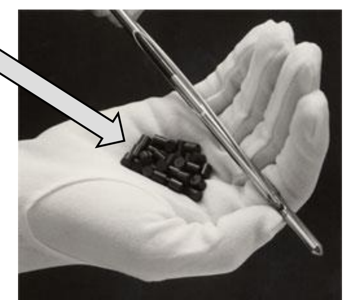
Reactor Vessel, Fuel Assembly and Pellets

About 50% of U.S. Carbon-Free Electricity from 93 Fission Reactors at 54 sites

- Reactor Pressure Vessel
  - 12.5 m Height
  - 4.3 m Inner Diameter
  - 18 Million Fuel Pellets
- Fuel Assemblies (~200)
  - 4 m Height
  - 20 cm Width







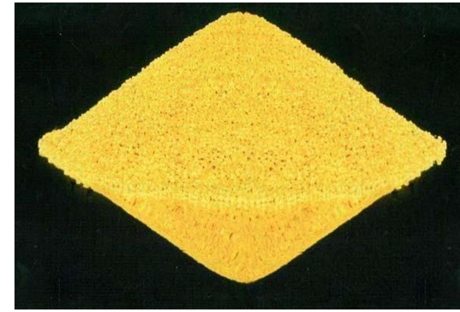
1 pellet is ~200 gallons of oil or 20,000 cubic feet of natural gas

Pellet

Mine Uranium (Australia)

Conversion

Yellow Cake (U_3O_8)



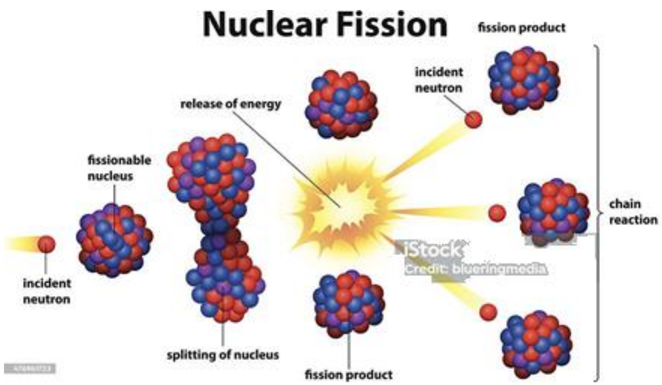
UF_6 Cylinders

Enrichment (Centrifuge)

Fabrication (UO_2)

UO_2 ~ 3-5% enriched U-235

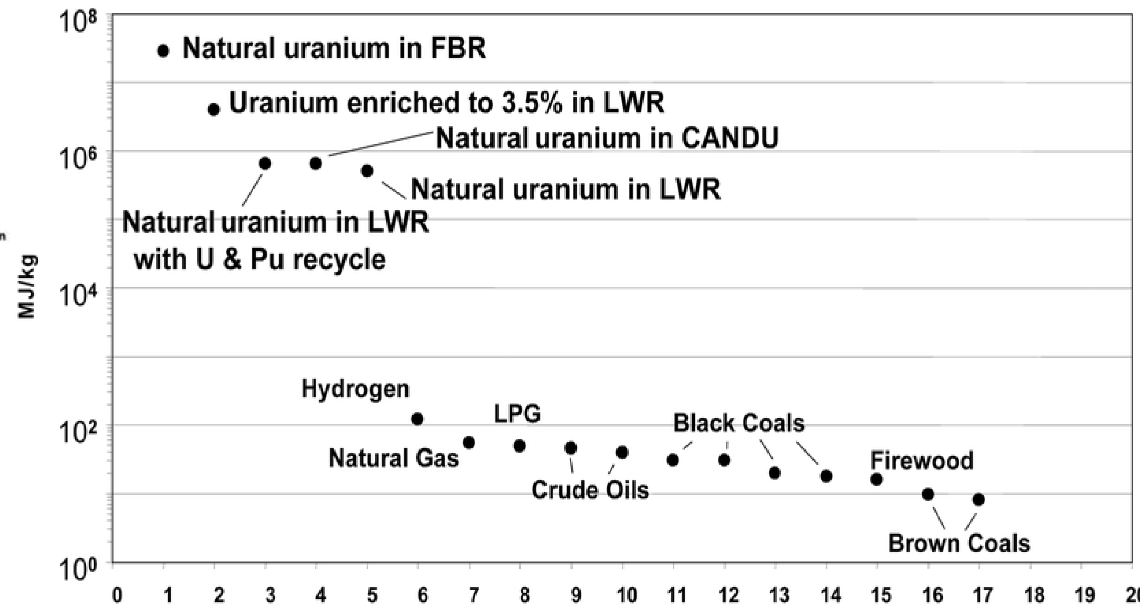
- Large power density means very low fuel use and material input.
  - ➢ 70,000 times more dense than natural gas on energy per mass basis



Fission vs. **Carbon**
200,000,000 eV **Few eV**

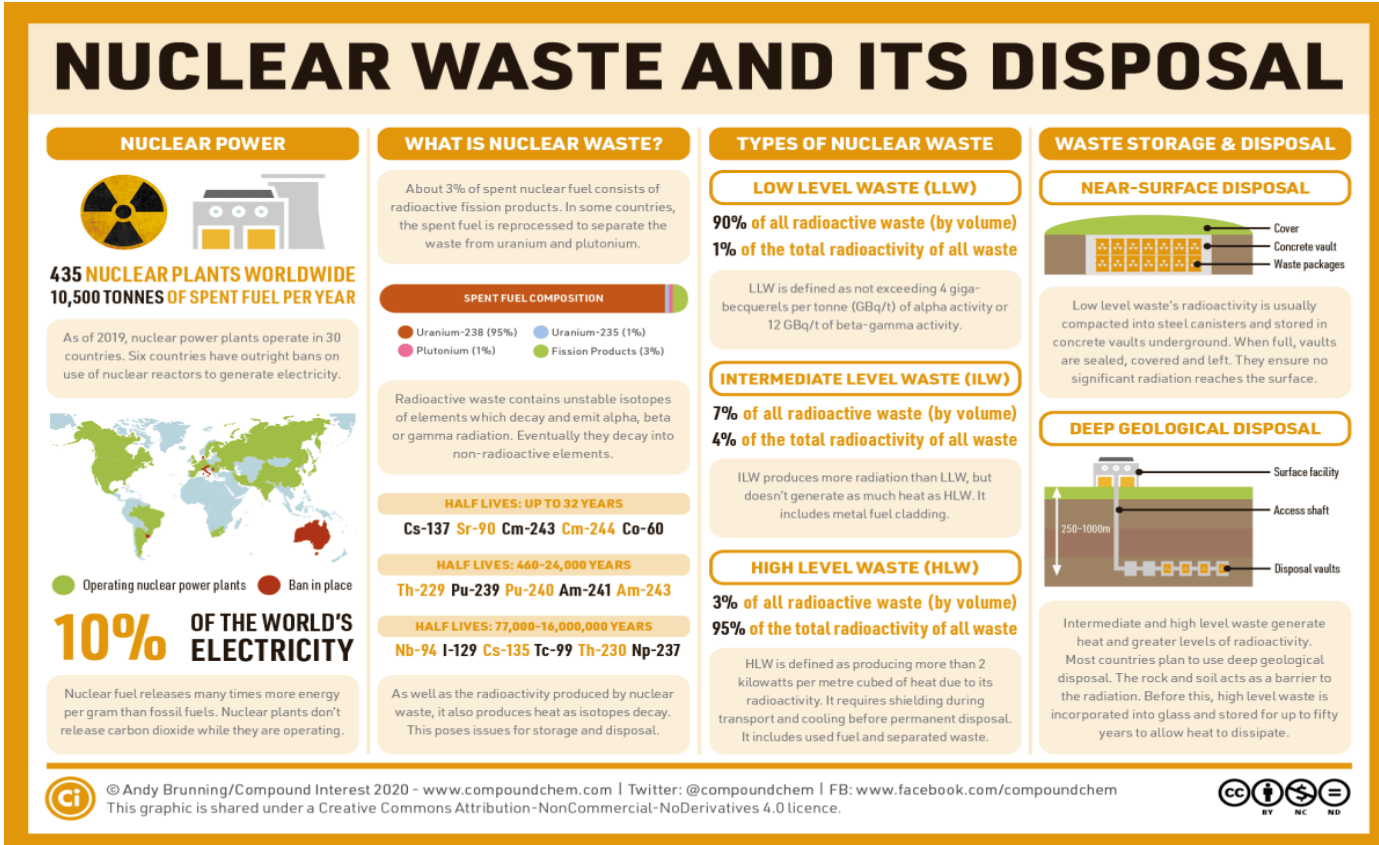
<u>>80% of Fission Energy Resides <50 µm of Fuel (<hair thickness)</u>

Major fuels ranked by heat value



What about the "Waste"→ Spent Fuel

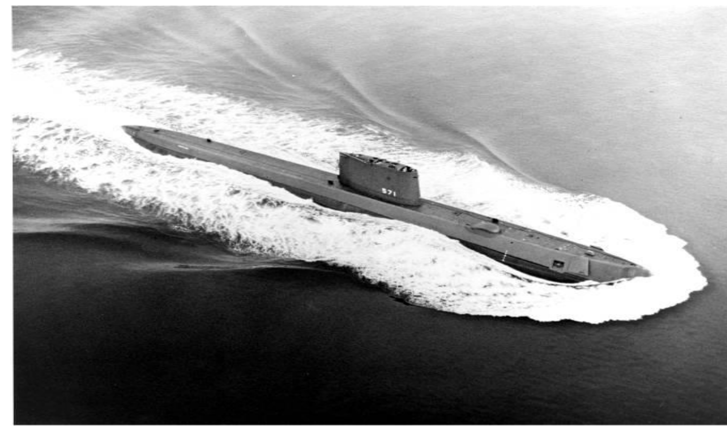
Each Ton takes 0.3 m³ of volume → ~5m high Football field every 10 years



- Above numbers are derived from Water-Cooled Technology

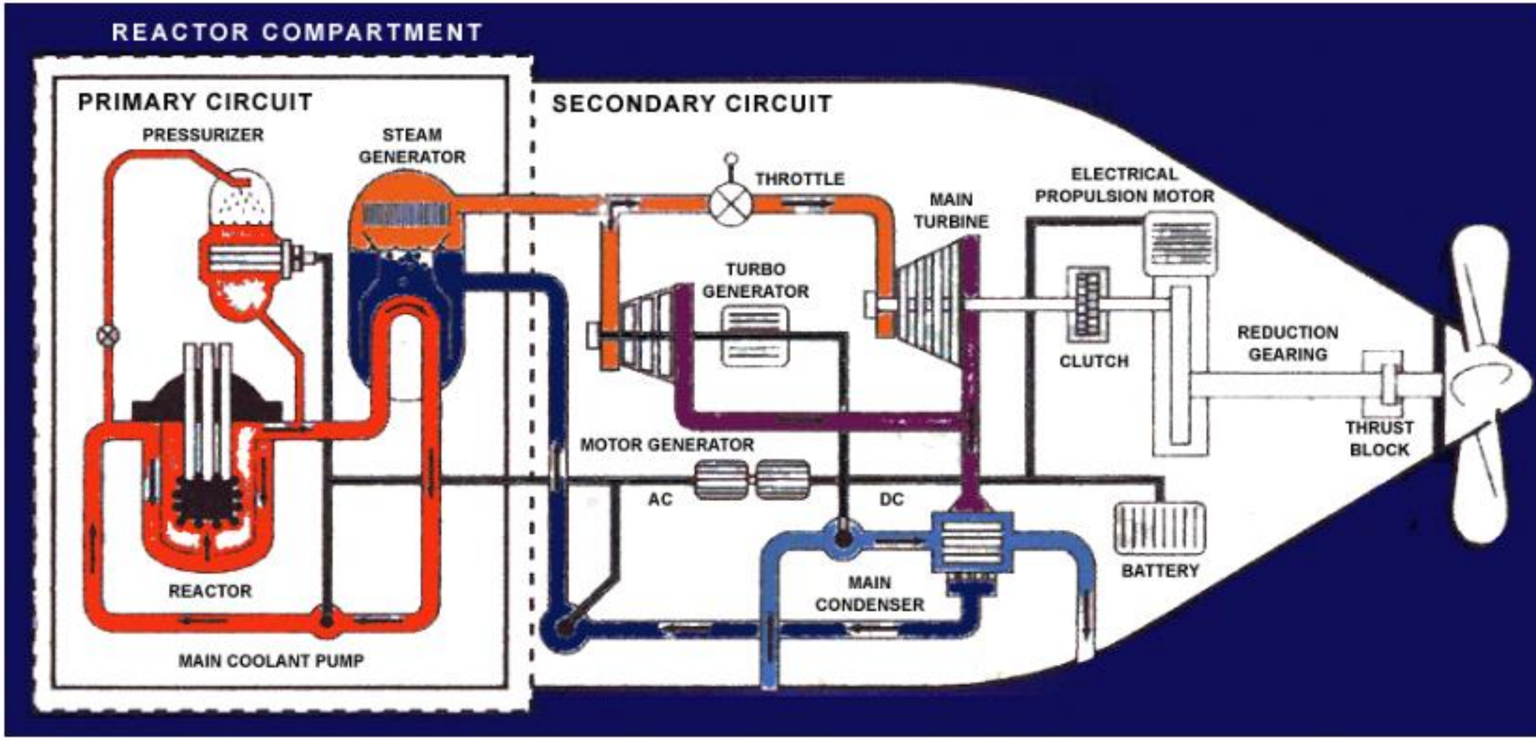
Development of PWR

- Pressurized Water Reactors have been developed for "submarine" propulsion *(Westinghouse)*
- First "full-scale" prototype STR Mark-1, 1953.
- First Nuclear submarine "NAUTILUS", 1955.



- Shippingport – 1957 (68 MWe) first commercial PWR

SCHEMATIC OF A NUCLEAR SUBMARINE



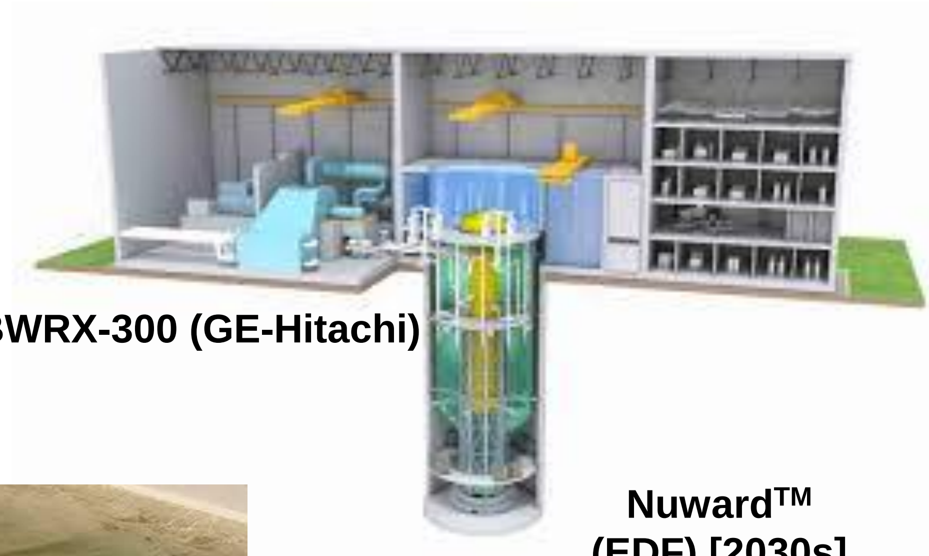
UK nuclear submarine layout

https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx

Small Modular Reactor Designs: All PWRs except for One (BWRX-300 by GE-Hitachi)

Leading US SMRs: Natural Circulation **& Forced**

NuScale (Fluor)



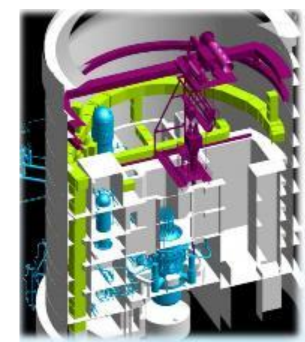
BWRX-300 (GE-Hitachi)

SMR-300 (Holtec) AP300 (Westinghouse) Are Forced Circulation

Leading International SMRs: Forced Circulation

UK SMR (ROLLS ROYCE) [2030s]

Nuward™ (EDF) [2030s]

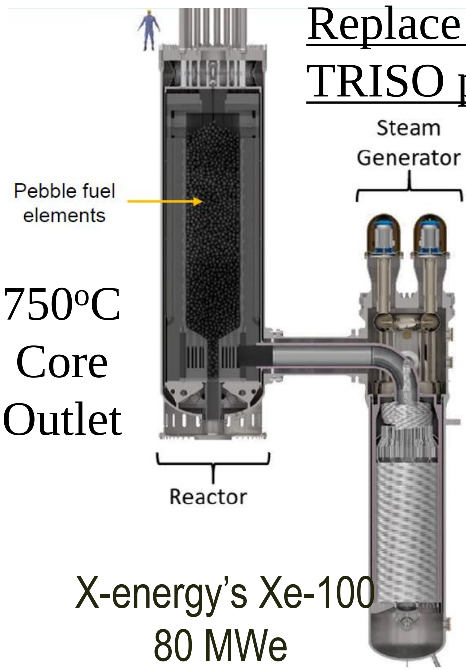


ACP100 (CNNC) [late 2020s]

Advanced (non-Water) Reactors

Technologies that were demonstrated in the past and are being revisiting due to rise in interest and support to nuclear → Fundamentally no innovation

<u>Replace water with Helium</u>
<u>Replace UO2 pellets with TRISO particles</u>



750°C Core Outlet

550°C Steam Outlet

X-energy's Xe-100
80 MWe
High-Temperature Gas Reactor
Part of U.S. Planned Demonstrations

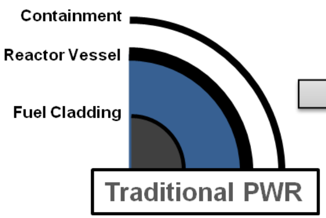
<u>Replace water with lead (Pb)</u>
<u>Replace UO2 with UN pellets</u>

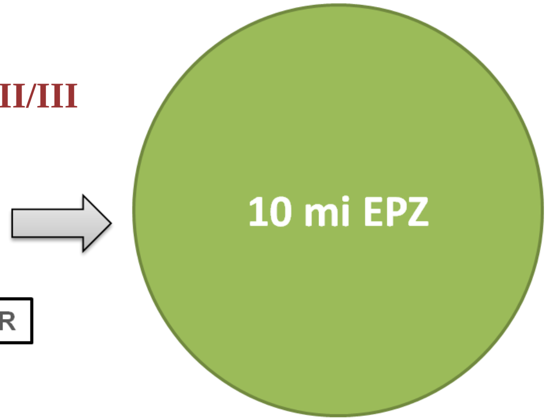
500°C Steam Outlet

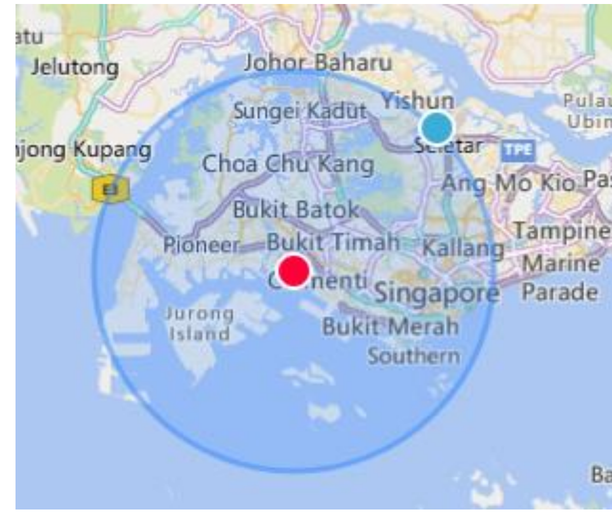
BREST300 (Lead Cooled Fast Reactor) construction started June 2021 and scheduled for 2026 start to support fuel recycling.

Gen III+ and Gen IV vs. Gen II/III

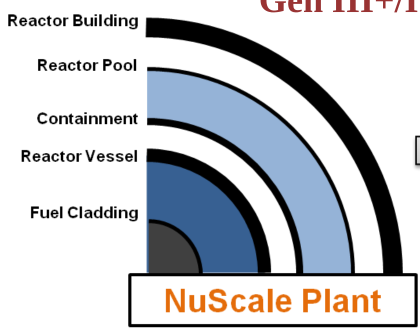
Gen II/III

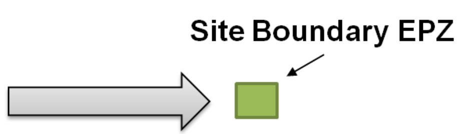






Gen III+/IV





- *Passive Safety*
- *Additional Fission Product Barriers*
- *SignificantlDelay in Release of Radiation*

<u>Applicable</u> to all mature GENIII+ and GENIV Reactors

Methodology to Reduce EPZ is Approved by U.S. Nuclear Regulatory Commission for NuScale (Water-Cooled SMR)

Why No "Advanced" Reactors

- New Fuels Qualification Timeline ~20-30 years
- New Nuclear Structural Materials Qualification Time line ~10-20 years
- Energy Market demands new nuclear now to next 10 years
  - Vendors have to pivot to what has worked in the past (Terrapower, Oklo, X-Energy, Westinghouse, GE-Hitachi are recent examples)

- Solution:
  - Alternative technologies to advanced reactors: Focus on Large LWRs by replicating Korean, Chinese and Japanese Construction Experience
  - Establish performance based Regulation - Understand the value of nuclear to energy market and society
  - Establish R&D capability for component testing and qualification.

How Does Nuclear Energy Work

- Works by transferring heat to water to create steam that runs turbine-generator
  - All operating reactors today regardless of military or civilian

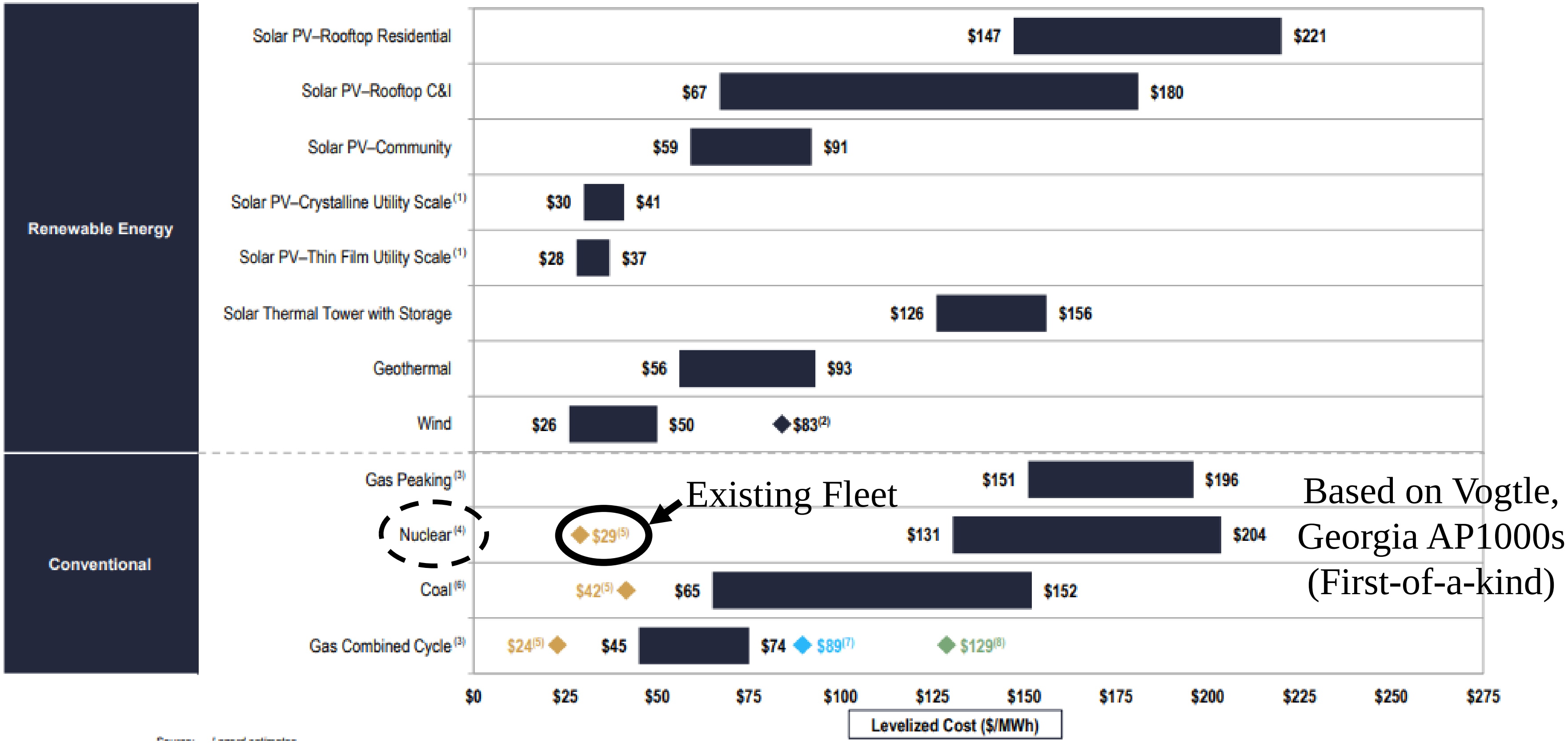
- Works in a very Carbon Free Manner
  - Among lowest life-cycle carbon intensive and pollution emitting energy sources (Source: IPCC)

- Works in a dispatchable manner where it can meet demand
  - In France 70-80% of electricity generation is provided by Nuclear → proven to be a dispatchable energy source by powering majority of an industrialized country.

Backup Slide Cost

Levelized Cost of Energy Comparison—Unsubsidized Analysis

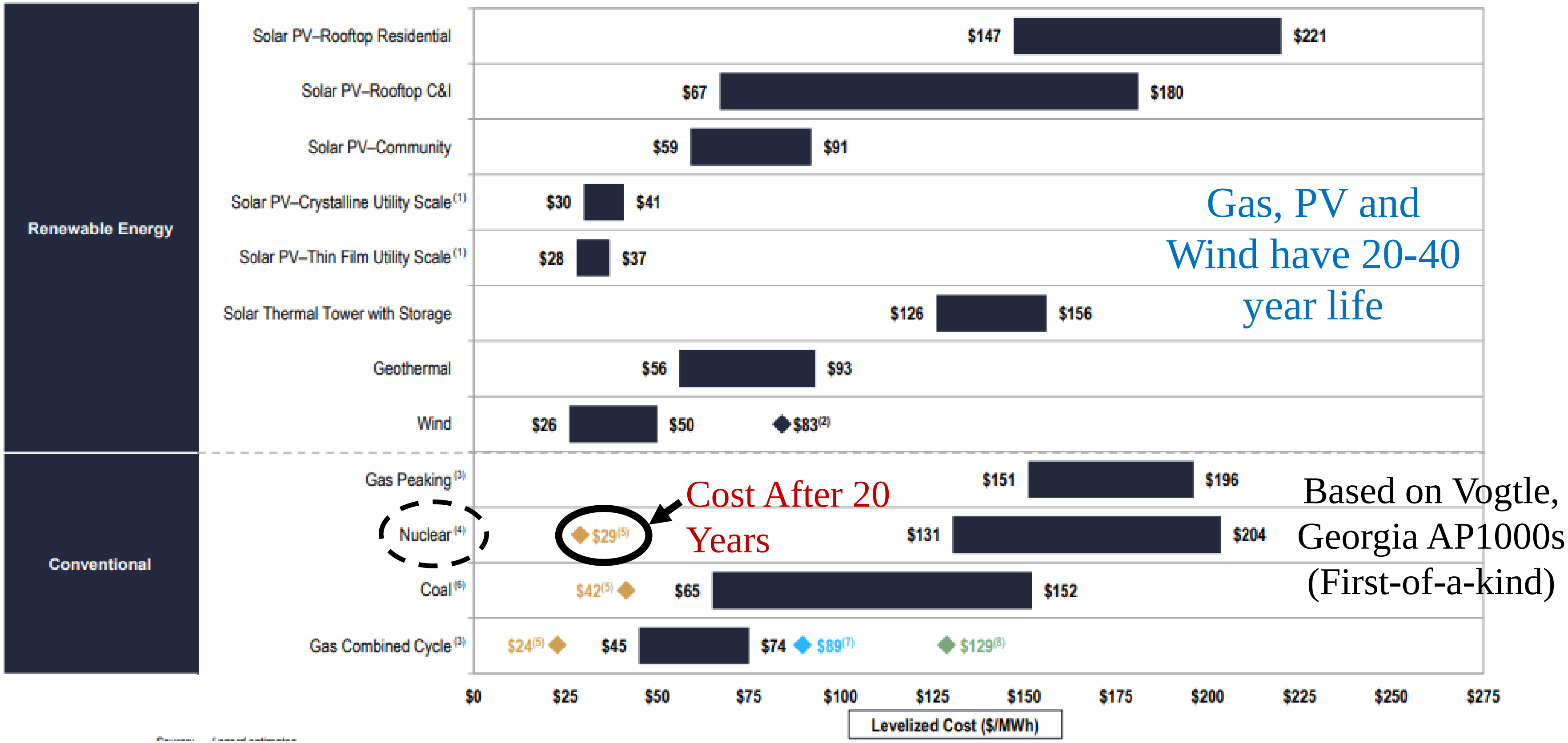
Selected renewable energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances



Gas, Solar PV (Utility Scale), Geothermal and Wind are all Cheaper than Nuclear

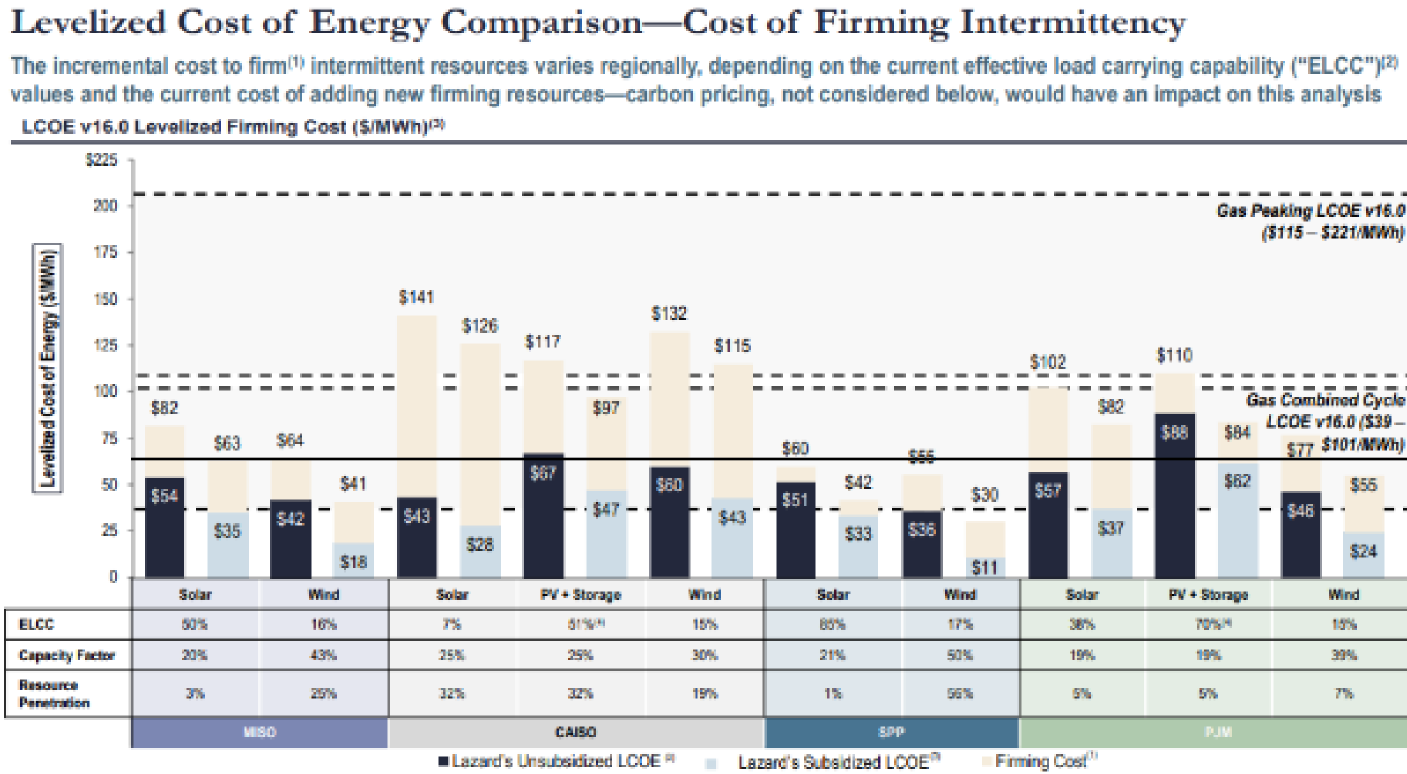
Levelized Cost of Energy Comparison—Unsubsidized Analysis

Selected renewable energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances



Over 75 Years: FOAK Nuclear $65/Mwhre (Starting to be competitive)

Will Value of Intermittency Be Considered



	MISO		CAISO			SPP		PJM		
	Solar	Wind	Solar	PV + Storage	Wind	Solar	Wind	Solar	PV + Storage	Wind
ELCC	60%	16%	7%	51%(4)	15%	65%	17%	38%	70%(4)	15%
Capacity Factor	20%	43%	25%	25%	30%	21%	50%	19%	19%	39%
Resource Penetration	3%	25%	32%	32%	19%	1%	56%	5%	5%	7%

$65/MWhre (Even FOAK Nuclear can be competitive in the long run with access to financing)

- MISO, CAISO, SPP, PJM are different regions of U.S.