NUCLEAR:
The Need For Radical Innovation

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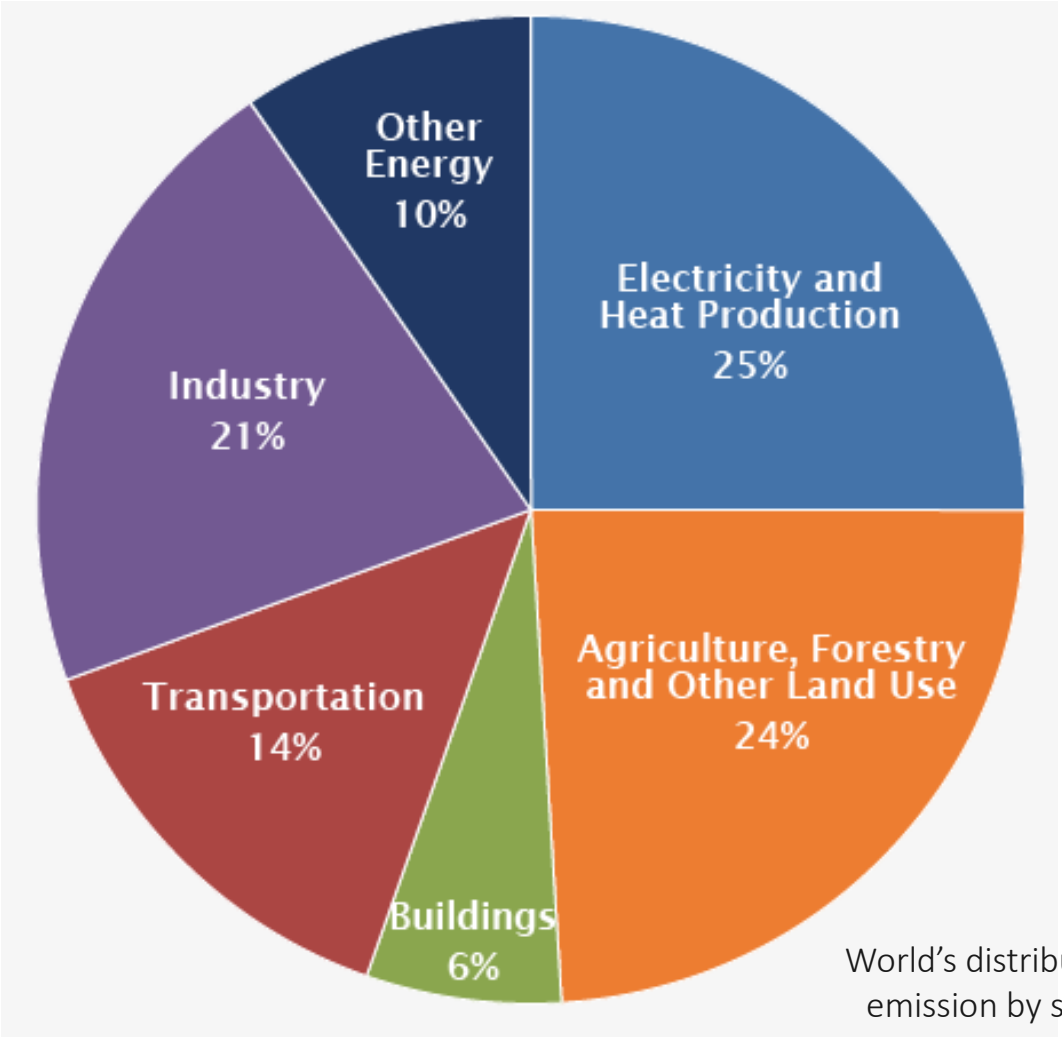
NSE
Nuclear Science and Engineering
science : systems : society

WHERE ARE THE CARBON EMISSIONS?



World's distribution of CO_2-equivalent emission by sector, from IPCC 2014

Much more than the power grid

GROWING CONSENSUS THAT NUCLEAR CAN PLAY A BIG ROLE

BUT THE CURRENT ECONOMIC MODEL FOR NUCLEAR:

- **lengthy testing/licensing**

- **field construction**

- **GW-scale plant**

- **connected to the electric grid**

IS BROKEN

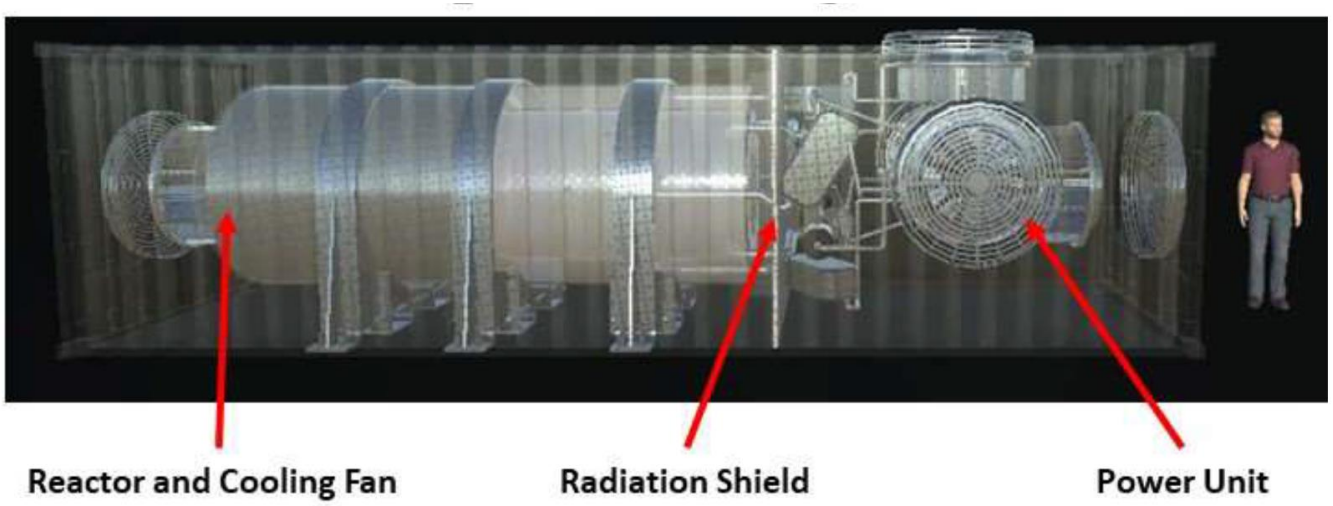
NUCLEAR DEPLOYMENT PARADIGM NEEDS TO SHIFT TO:

- *smaller, serial-manufactured* systems,

- with *accelerated testing/licensing,*

- producing *higher added-value* energy products than electricity for the grid.

THE NUCLEAR BATTERY CONCEPT



- 1 to 10 MW micro-reactor generating heat and/or electricity
- Carbon free
- Dry cooling (no water needed)

Fabrication and Installation

- Standardized reactor design
- Factory built
- Mobile deployment (ISO 20’ container)
- Modular energy conversion (e.g., air Brayton or small Rankine)

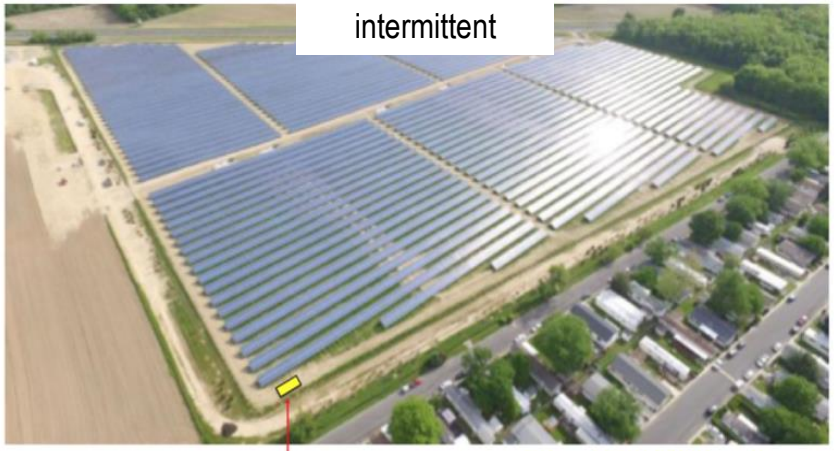
Operation

- Plug-and-Play standardized connections
- Semi-autonomous operation
- Offsite refuelling every 3-5 years
- No onsite handling or storage of radioactive material

NUCLEAR BATTERIES ARE:

- uniquely compact and reliable

Vestas 10 MW

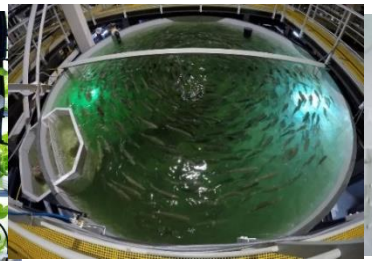


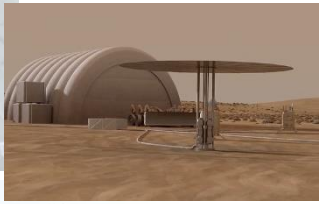
Altus 10 MW New Jersey

10 MW Nuclear Battery (24/7)

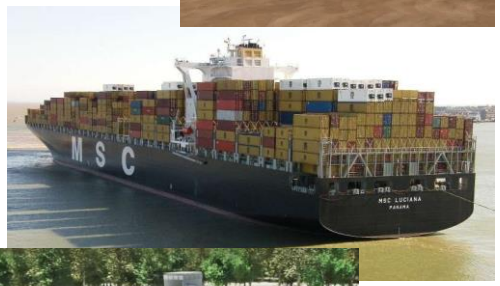
- geographically unconstrained
- suitable for mobile deployment
- predictable generation cost over lifetime of the asset
- ultra-safe and robust

WHAT ARE THE POTENTIAL MARKETS?





- Process heat = factories
- Charging stations = e-trucks, hydrogen vehicles
- District heating = home heating
- Desalination = fresh water
- Micro-grids = towns, islands, military bases
- Large pumps = flood protection
- Propulsion = freight ships
- Portable data centers = support local businesses
- Portable farms = fresh produce
- Indoor aquaculture = fresh fish
- Portable biopharma = synthetic insulin, vaccines
- Portable 3D printers = manufacturing
- Space = surface power and propulsion



Heat, electricity and much more

NEW MARKETS - U.S. EXAMPLES

Potential heat applications in the state of Washington

Site Name and Location	Business type	Non-biogenic CO_2 emissions (tons/year)	Average heat load (MW_t)
Darigold Sunnyside	cheese manufacturing	38,000	24
Darigold Lynden	dry, condensed, and evaporated dairy product manufacturing	17,900	11
Darigold Chehalis	dry, condensed, and evaporated dairy product manufacturing	11,800	8
J.R. Simplot Company Othello	potato processing plant	47,000	30
McCain Foods Othello	potato processing plant	37,000	23
Lamb Weston, Inc. Pasco	potato processing plant	44,000	28
Lamb Weston, Inc. Quincy	potato processing plant	32,000	20
Lamb Weston, Inc. Connell	potato processing plant	35,000	22
Lamb Weston, Inc. Richland	potato processing plant	60,000	38
Lamb Weston, Inc. Warden	potato processing plant	18,000	11
Basic American Foods Moses Lake	dried and dehydrated food manufacturing	24,000	15
Univ. of Washington Seattle	university campus	92,000*	58
Univ. of Washington Pullman	university campus	62,000	39
Univ. of Washington Ellensburg	university campus	19,000	12
CertainTeed Gypsum Seattle	gypsum products manufacturing	50,000	32
Georgia/Pacific Gypsum LLC Tacoma	gypsum products manufacturing	50,000	32
Longview Fibre Paper and Packaging, Inc. Longview Mill	paperboard mills	150,000**	95
Nippon Dynawave Longview	paperboard mills	280,000**	177
WestRock CP, LLC Tacoma	paperboard mills	122,000**	77
Boise Paper Wallula	paperboard mills	111,000**	70
Georgia/Pacific Consumer Products LLC Camas	paperboard mills	124,000**	78
Sonoco Products Company Sumner	paperboard mills	11,000**	7
North Pacific Paper Company, LLC Longview	newsprint mill	37,000	23
Inland Empire Paper Company Spokane	newsprint mill	10,000	6
Michelsen Packaging Yakima	other converted paper products	11,000	7
Cosmo Specialty Fibers Inc. Cosmopolis	sulfite mills pulp	20,000	13
Tyson Fresh Meats, Inc. Wallula	animal slaughtering	22,000	14
Darling Ingredients Inc. Tacoma	rendering and meat products	10,000	6

COST TARGET (ELECTRICITY)

- For electricity the main competition is the grid, but NB are NOT on the grid.

- NB obviate the need for transmission and distribution charges, thus must be compared to retail prices (not generation cost).

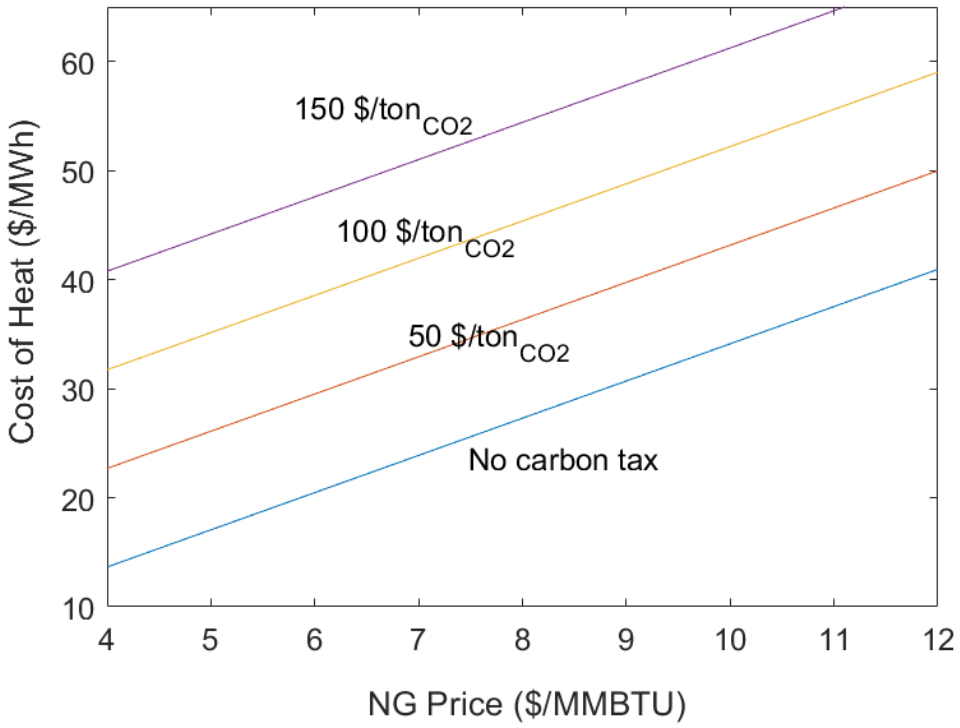
US Electricity Retail Prices 2019 ($/MWh) (includes generation, transmission, distribution)

Region	Residential	Commercial	Industrial	Transportation	All Sectors
New England	210	163	131	92	178
Middle Atlantic	158	122	66	112	123
East North Central	134	102	69	71	101
West North Central	119	97	73	87	97
South Atlantic	119	94	65	79	100
East South Central	114	107	58	--	94
West South Central	112	82	54	66	84
Mountain	118	96	63	93	94
Pacific Contiguous	156	144	97	90	138
Pacific Noncontiguous	283	245	235	--	255
U.S. Total	130	107	68	97	105

Cost target for electricity 70-100 $/MWh

COST TARGET (HEAT)

- For heat the main competition is NG-fired boilers.
- NG boilers are too small for CCS*, so burning NG will incur a carbon tax in a carbon-constrained world



*The cost of CO_2 capture from a large NG-fired boiler at around 10%mol concentration in the flue gas and 99% efficiency could be up to 100 $/$t_{CO2}$, including compression, but excluding transport and storage, which might add 3-30 $/$t_{CO2}$ depending on location.
(Int. J. Greenhouse Gas Control 105, 2021, 103239)

NG price does not include the cost of the boiler

Cost target for heat 20-50 $/MWh (6-15 $/MMBTU)

ECONOMIC IMPERATIVES

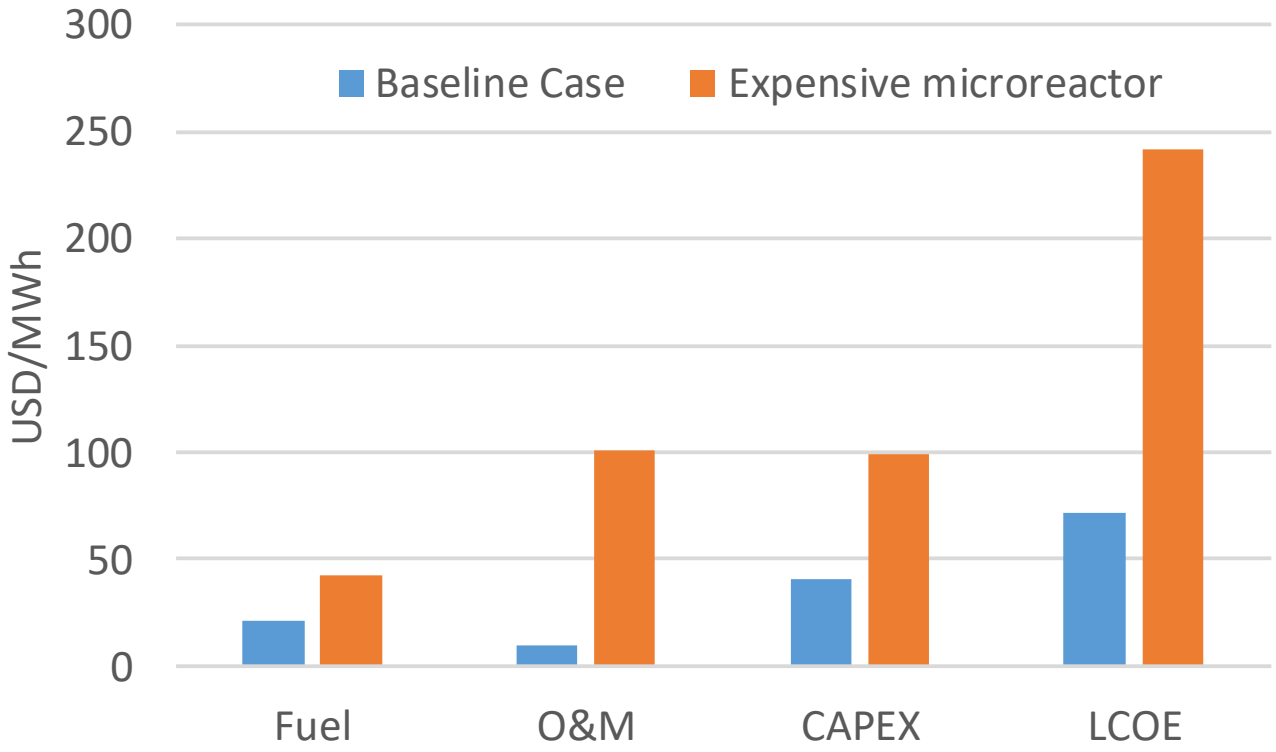
- To access large markets, the NB must be licensable for deployment in population centers

- LCOE and LCOH analysis suggests that NB can meet the heat and electricity cost targets, if:

  - Power output is maximized, within NB constraints (e.g., truck transportability, passive decay heat removal)
  - Staff is in the 0.5-1.5 FTE/MW range
  - Enrichment <10% and burnup >20 MWd/kg_U
  - NB fabrication cost (excluding fuel) <5000 $/kW
  - Discount rate <10 %/yr

COST CAN EASILY GET OUT OF HAND FOR A SMALL REACTOR

	Baseline design	**Example of "expensive design"**
Electric output:	10 MW	2 MW
NB fabrication:	3000 $/kW	7000 $/kW
Fuel:	500 $/kg$_U$	2500 $/kg$_U$
Enrichment:	5%	15%
Burnup:	20 MWd/kg$_U$	50 MWd/kg$_U$
Refueling interval:	5 yrs	20 yrs
# of FTEs:	5	10



NUCLEAR BATTERIES BUILD ON MATURE 20TH AND 21ST CENTURY TECHNOLOGIES

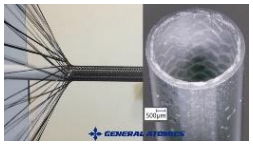
US Army's ML-1 (400 kW)

1960s

US Army's PM-2 (2 MW)

Early Army experience with small mobile reactors

Advanced power conversion



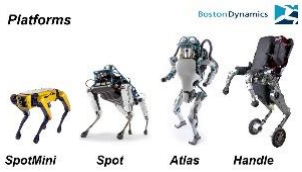
Additive manufacturing

New materials and sensors

Smart architectures

Innovation models, energy policy and economics

Robotics



AI / machine learning

Synergistic US government efforts

NASA's Krusty* (<100 kW) 2018

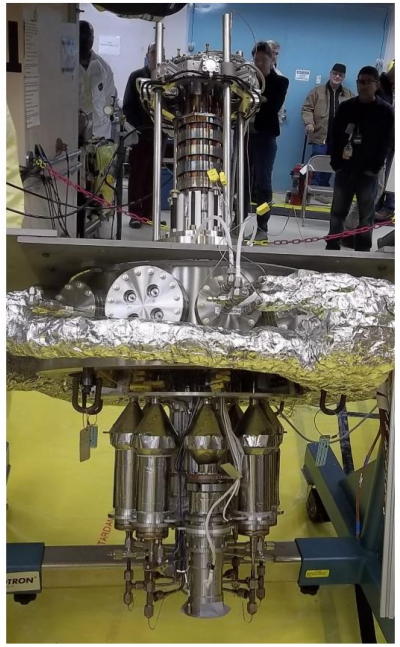
Today

- DOE's program for advanced nuclear reactor demo
- Army's program for micro-reactor development
- NASA's program for space nuclear power and propulsion

**Designed, fabricated and tested at a total cost of <$20M, in less than 3 years*

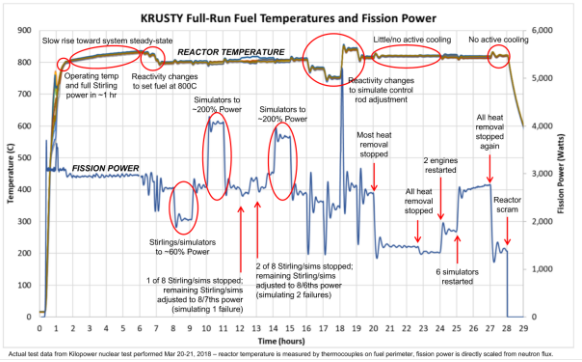
ACCELERATED TESTING/LICENSING ENABLED BY SUPERIOR SAFETY PROFILE

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



NASA

Los Alamos NATIONAL LABORATORY EST.1943



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

CAN SAVE A DECADE AND AN EARLY BILLION DOLLARS

PRESENT

FUTURE?