# New Nuclear Needs a DD&D Paradigm and Market Inversion

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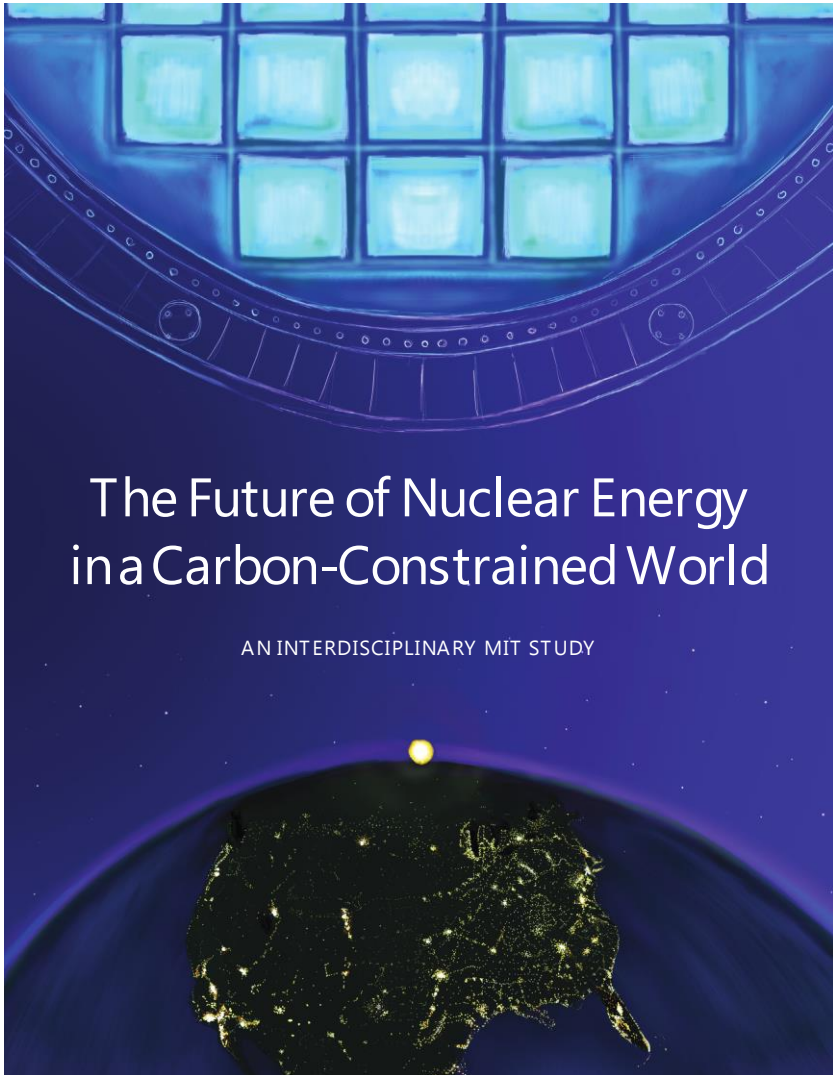
science : systems : society




**Download the report at**
**http://energy.mit.edu/studies-reports/**

# 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**

# DD&D paradigm needs to shift to:

- *smaller, serial-manufactured* systems,

- with *accelerated testing/licensing,*

- producing *high added-value* energy products.

# SMALLER SYSTEMS PUT LESS CAPITAL AT RISK

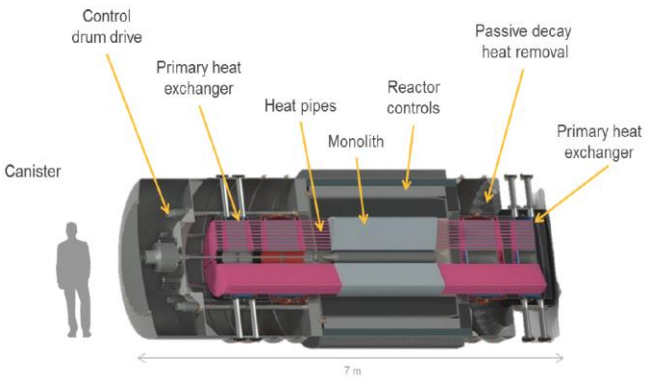
*Small Modular Reactors*

[ 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

*Micro-Reactors*

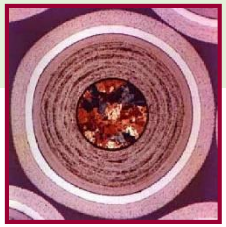



[ Westinghouse's eVinci ]
<20 MWe
Block core with heat pipes, self-regulating operations, Stirling engine or air-Brayton

# 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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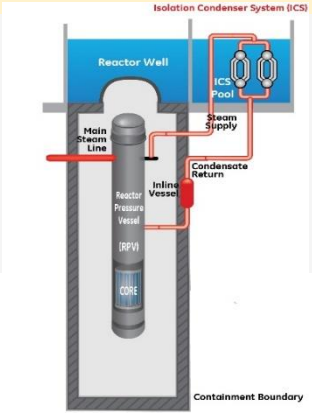
**Engineered passive safety systems:**

- Heat removal
- Shutdown

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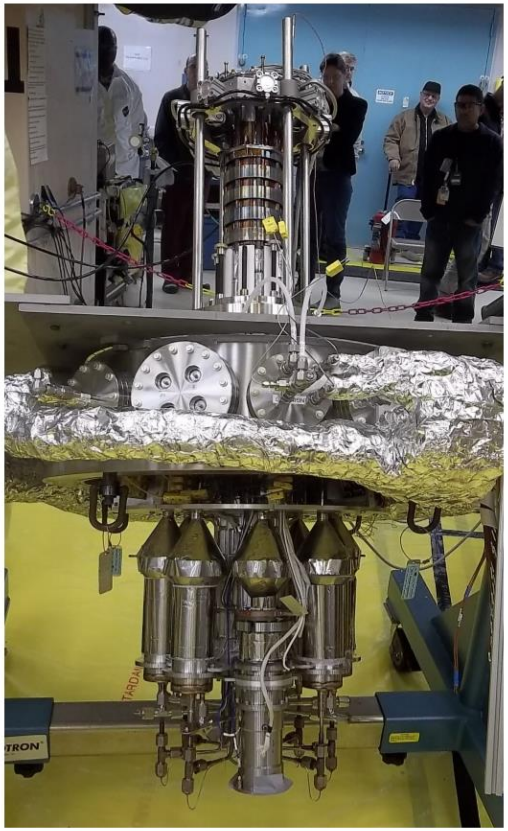
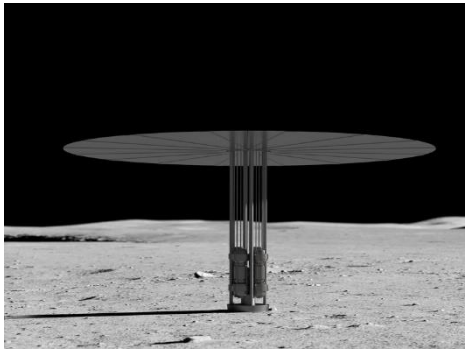
- ✓ No need for emergency AC power
- ✓ Long coping times
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary

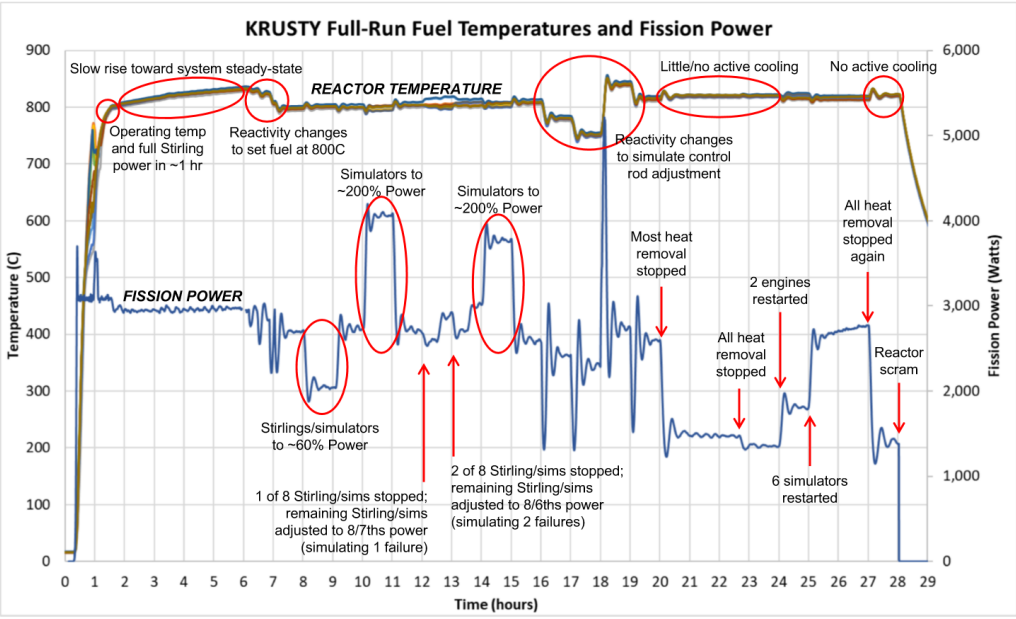
Design certification of NuScale is showing U.S. NRC's willingness to value new safety attributes

# BYPASSING NRC FOR EARLY DEMONSTRATION CAN SAVE A DECADE AND A BILLION DOLLARS

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








Actual test data from Kilopower nuclear test performed Mar 20-21, 2018 – reactor temperature is measured by thermocouples on fuel perimeter, fission power is directly scaled from neutron flux.

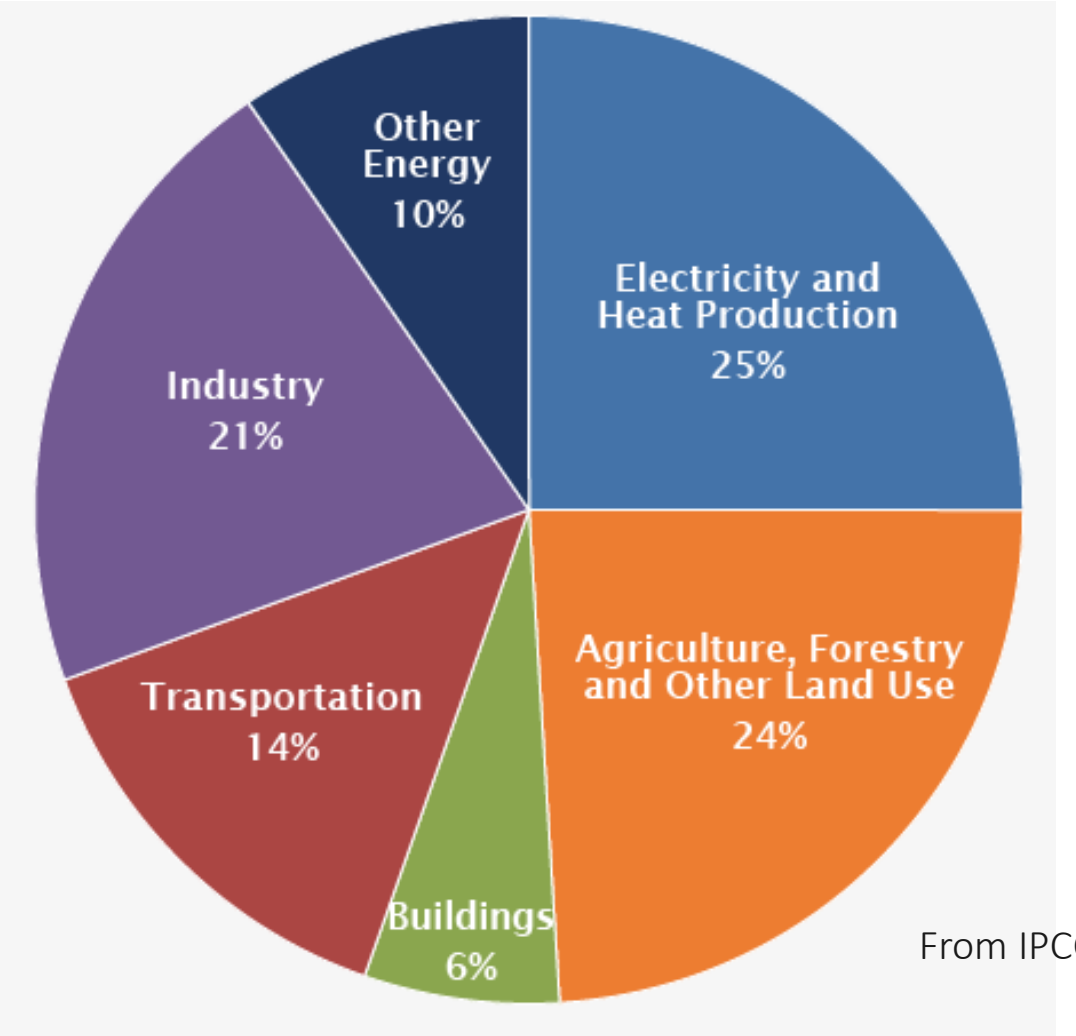
## HIGHER ADDED VALUE FOR NUCLEAR CAN COME FROM

1. New policies that fully recognize the non-emitting nature, local economic impact, and contribution to energy security and grid stability of nuclear *electricity*

**AND/OR**

2. Capture of new energy markets:
   - *Process heat* for industry (e.g., ammonia, vinyl chloride, soda ash, nylon, styrene)
   - Production of *hydrogen* or synthetic fuels for transportation
   - *Power and heat* for remote islands and communities, mining operations, military bases, disaster relief activities, data centers, etc.
   - *Propulsion* for transoceanic commercial ships
   - *District heating*
   - *Water desalination*

# 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*

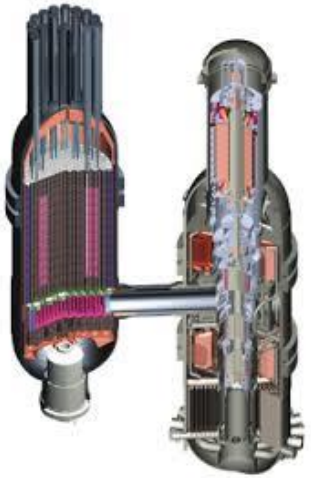
| | 300 $MW_{th}$ Reactor | | 150 $MW_{th}$ Reactor | |
|---|---|---|---|---|
| Industry | U.S. Capacity ($MW_{th}$ Installed) (%) | Global Capacity ($MW_{th}$ Installed) (%) | U.S. Capacity ($MW_{th}$ Installed) (%) | Worldwide Capacity ($MW_{th}$ Installed) (%) |
| Co-Generation Facilities | 82,800 (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)

~1/5 of global heat demand in industry

Methodology:

- EPA database for U.S. sites emitting 25,000 ton-$CO_2$/year or more
- Site must need at least 150 $MW_{th}$ of heat
- Nuclear heat delivered at max 650°C (with HTGR technology)
- Heat from waste stream not accessible
- Extrapolated U.S. data to World based on GDP and refinery capacity



# 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 $GW_{th}$ |
| 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, 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 more radical market inversion

# The evils of the electric grid

- 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)
- Capital-intensive equipment has low utilization factor because of variability in demand and intermittency in supply (e.g., back-up and storage, solar/wind overcapacity)
- Market is muddied by subsidies (e.g., renewables, nuclear) and un-accounted costs (e.g., social cost of carbon)
- Responsible for ¼ of global $CO_2$ emissions and large amounts of EPA criteria air pollutants

Why continue to play on natural gas' and renewables' home turf?

# Co-located supply-and-demand
## (the wildcard opportunity)

Mobile containerized production and processing
(agro, aqua, pharma, 3D-printing, data centers, etc.)

Nuclear ‘battery’

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| Energy source | Stable output | Carbon-free | Geographically unconstrained | Suitable for mobile deployment | Predictable generation cost |
|---|---|---|---|---|---|
| Nuclear (traditional) | Yes | Yes | No | No | Yes |
| Nuclear (micro-reactors) | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |
| Natural gas | Yes | No | Yes | Yes | No |
| Coal | Yes | No | No | No | No |
| Hydro | No | Yes | No | No | No |
| Solar/Wind | No | Yes | No | No | No |

Can defeat the NG/renewables/grid stranglehold on economy and open new, enormous markets for nuclear

**The opportunities for new nuclear are vast.**
**There is hope after all!**