Energia Nucleare:
Tecnologie ed Applicazioni

Jacopo Buongiorno

Battelle Energy Alliance Professor of Nuclear Engineering

Member of the US National Academy of Engineering

MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

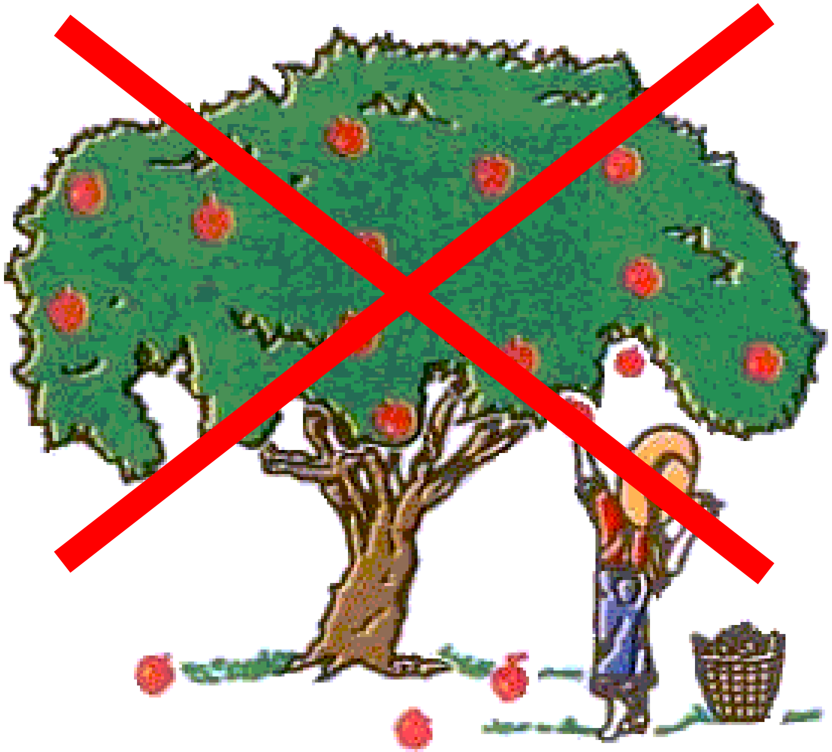
ABOUT THE SPEAKER

Jacopo Buongiorno is the Battelle Energy Alliance Professor in Nuclear 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).

NUCLEAR POWER PRIMER

WHERE DO WE GET ELECTRICITY FROM?

We don’t mine it

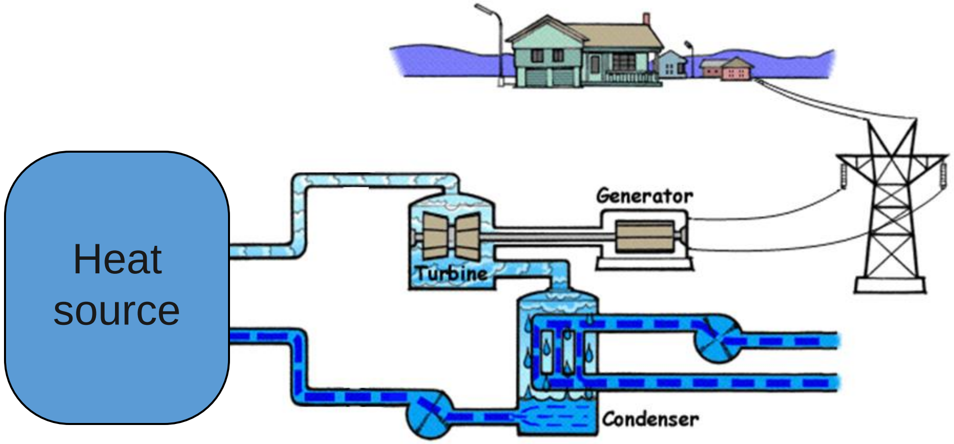


We don’t harvest it

Electricity is generated from other primary energy sources in machines that we call ‘power plants’.

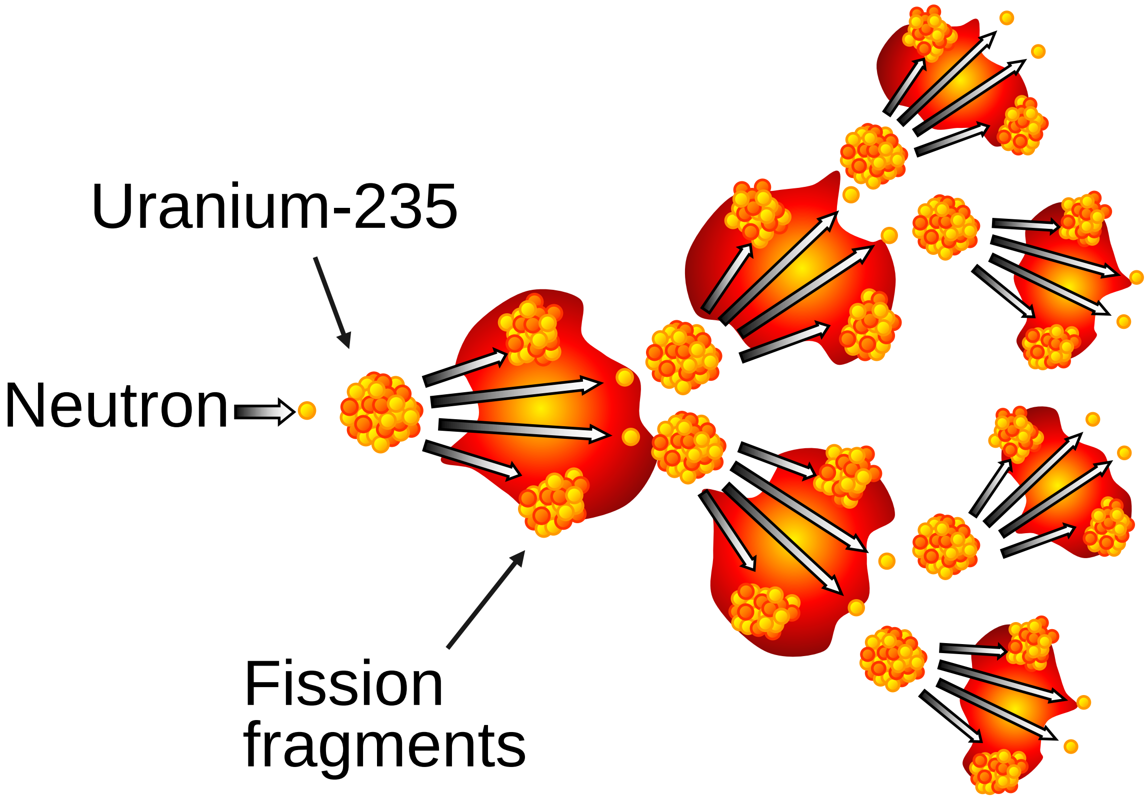
Primary energy sources of interest include:

- Coal
- Natural Gas
- Hydro
- Wind
- Solar
- Geothermal
- Nuclear



Nuclear power is the generation of electricity by a nuclear reactor, i.e., a machine that realizes a self-sustained, stable nuclear fission chain reaction

THE NUCLEAR FISSION PROCESS



Uranium-235

Neutron

Fission fragments

- In a nuclear reactor the neutron-driven chain reaction is controlled and stable, producing heat at steady rate (vs. a nuclear weapon in which the chain reaction diverges rapidly and explosively)
- Uses ^{235}U as fuel. Only 0.7% of natural uranium is ^{235}U. It must be enriched to at least 5%.

A NUCLEAR REACTOR USES URANIUM WITHIN FABRICATED FUEL ASSEMBLIES

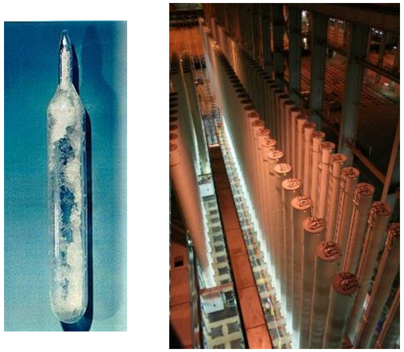
Natural U ore

→

Yellow cake (U_3O_8)

→

Conversion and Enrichment (UF_6)



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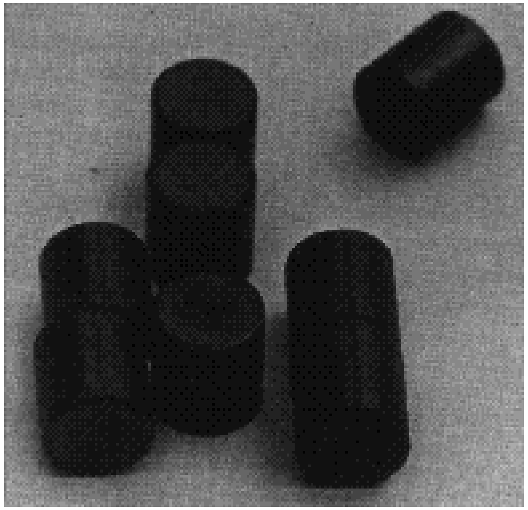
Enriched uranium dioxide (UO_2) pellets



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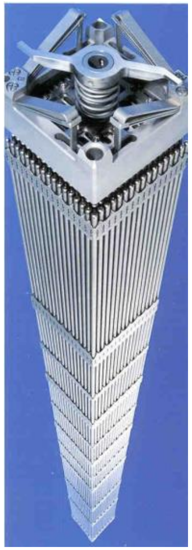
Fuel pin

←

Fuel assembly



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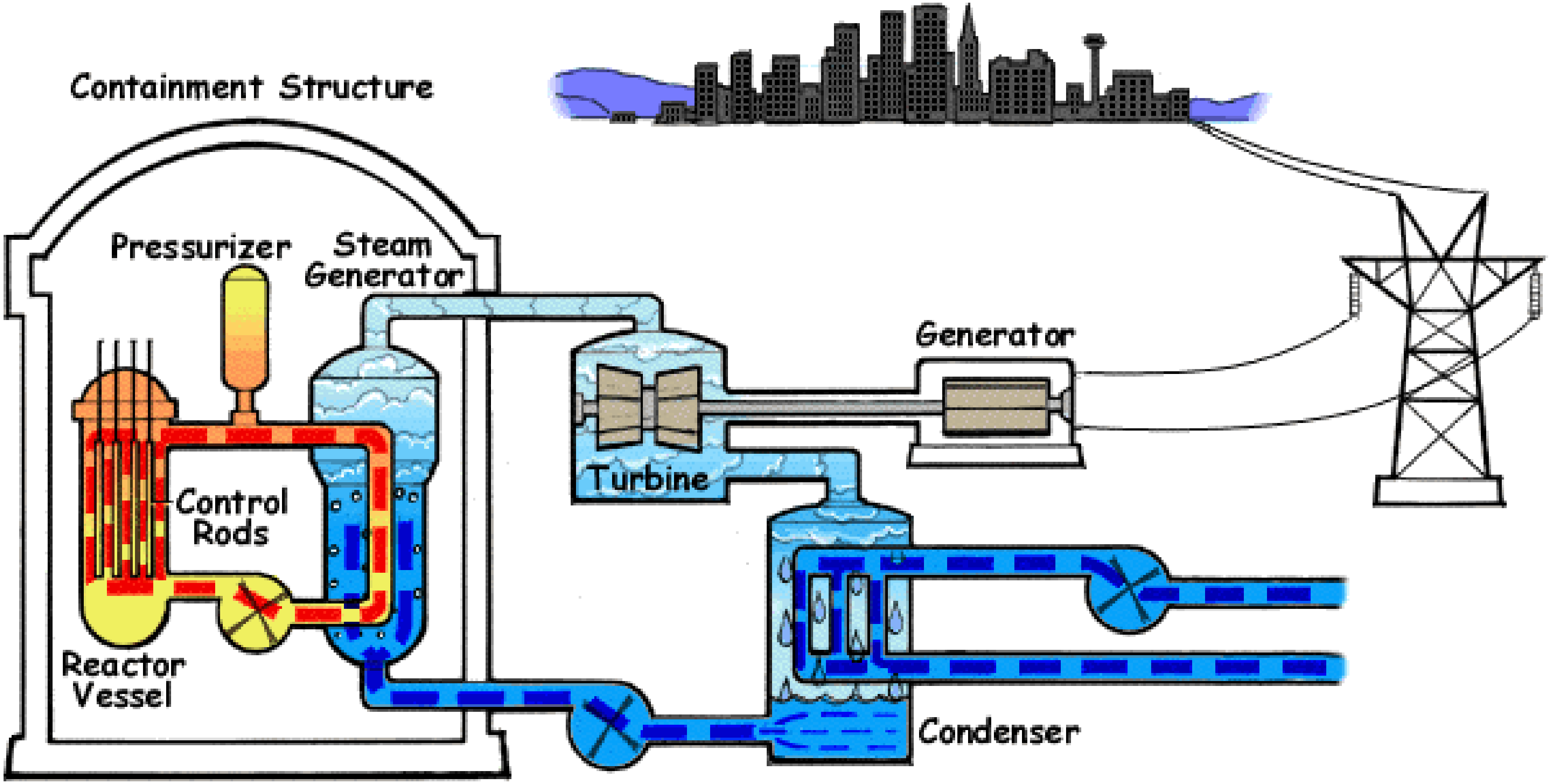
Into the reactor



Pressurized Water Reactor (PWR)

NUCLEAR PLANTS EMIT NO CO_2 OR CRITERIA POLLUTANTS, AND DO NOT REQUIRE A CONTINUOUS FUEL SUPPLY

Fuel energy content

COAL (C): $C + O_2 \rightarrow CO_2$ + *1 unit of energy*

NATURAL GAS (CH_4): $CH_4 + O_2 \rightarrow CO_2 + 2H_2O$ + *2 units of energy*

NUCLEAR (U): $^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n$ + *50 million units of energy*

Fuel Consumption, 1000 MWe Power Plant (~740,000 homes)

COAL: 6750 ton/day of coal

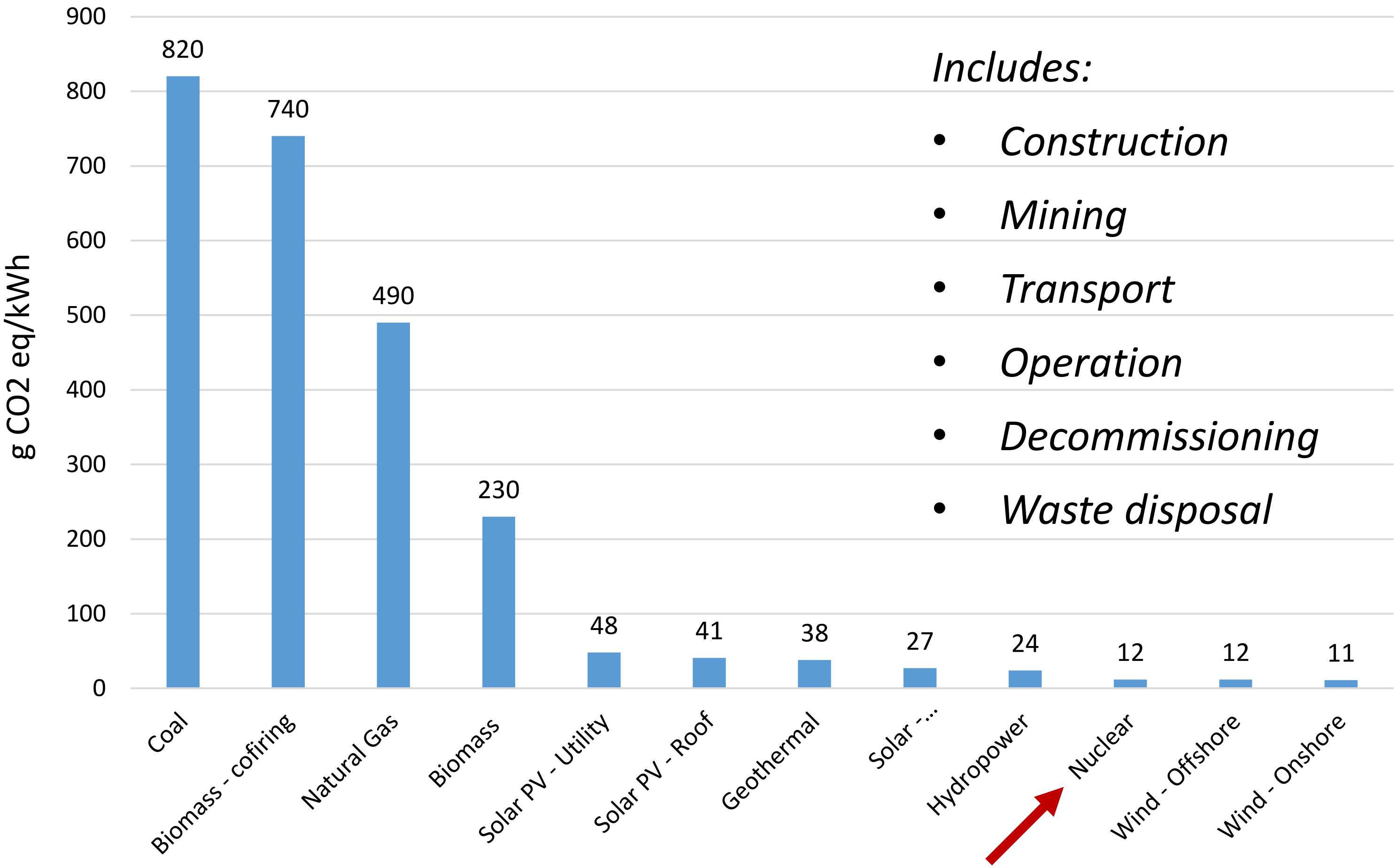
NATURAL GAS: 64 m^3/sec of gas

Need for continuous fueling can impact reliability of electricity supply (e.g., polar vortex, wild fires)

NUCLEAR: 300 kg/day of natural U

Refuel every 18-24 months

LIFECYCLE CO_2 EMISSIONS



Includes:

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

Source: IPCC

LOWEST LAND USAGE AND HIGHEST CAPACITY FACTOR OF ALL ENERGY SOURCES

NUCLEAR: >90% capacity factor **~2260 MW_e/km^2**

SOLAR*: <30% capacity factor **~6 MW_e/km^2**

WIND*: <40% capacity factor **~1 MW_e/km^2**

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

TECHNOLOGIES

CLASSES OF NUCLEAR REACTORS

Electric output
Construction cost
Construction duration
Vendors

Large Light Water Reactors (LWRs)

~1000-1600 MW_e
~\$3-10B
5-10 yrs

Westinghouse, KHNP, Rosatom, CNNC, CGN, EDF, GEH

Small Modular Reactors (SMRs)

~70-300 MW_e
~\$1-3B
3-5 yrs

GEH, Westinghouse, Rolls Royce, EDF, Holtec, Nuscale, X-energy, Kairos, Terrapower, KHNP

Microreactors (Nuclear Batteries)

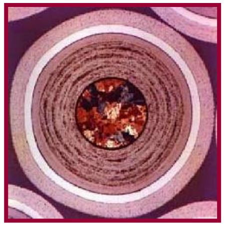
~1-10 MW_e
<\$0.2B
<1 yr

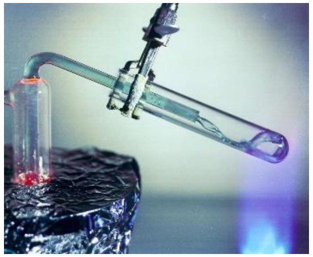
Westinghouse, BWXT, X-energy, Oklo, USNC, Radiant Nuclear

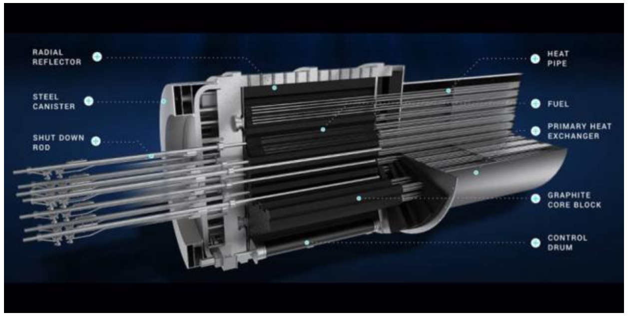
THE NEW REACTORS' EXCEPTIONAL SAFETY PROFILE IS A GAME CHANGER

Inherent features

- Coolant does not boil off
- Ceramic fuel fully retains radioactivity at up to very high temperatures
- High thermal capacity prevents sudden temperature escalation
- Passive cooling requires no external intervention to cope with accidents





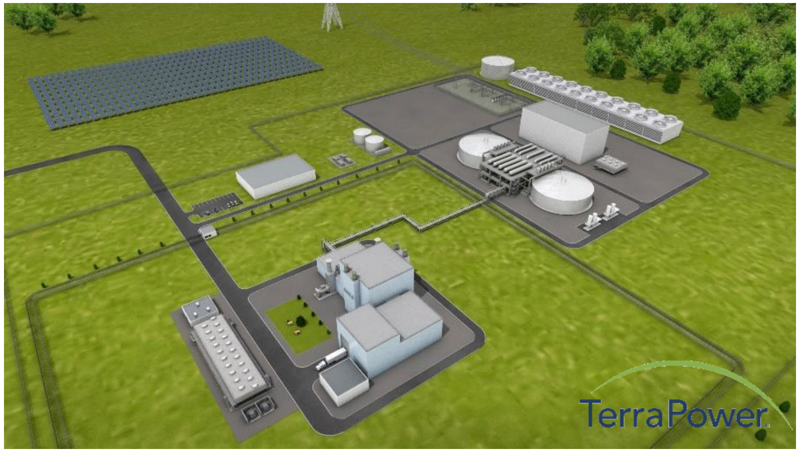


- Accidents like TMI, Chernobyl and Fukushima are eliminated by design
- Emergency planning zone is limited to site boundary (no evacuation needed)

MARKETS

LARGE AND INTERMEDIATE SIZE REACTORS COULD GROW NUCLEAR'S SHARE ON THE GRID

Coal plant replacement for
baseload generation



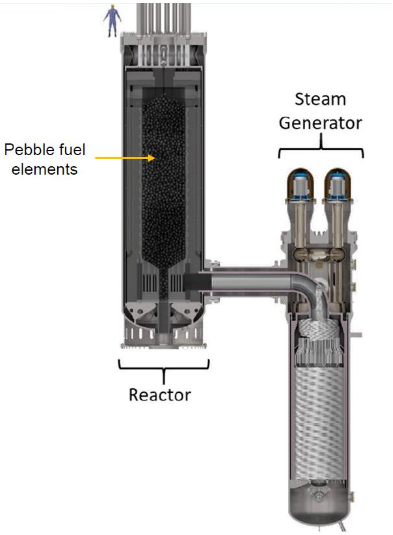
with flexible generation
(for NG plant replacement)

perhaps even re-using the
existing plant BOP

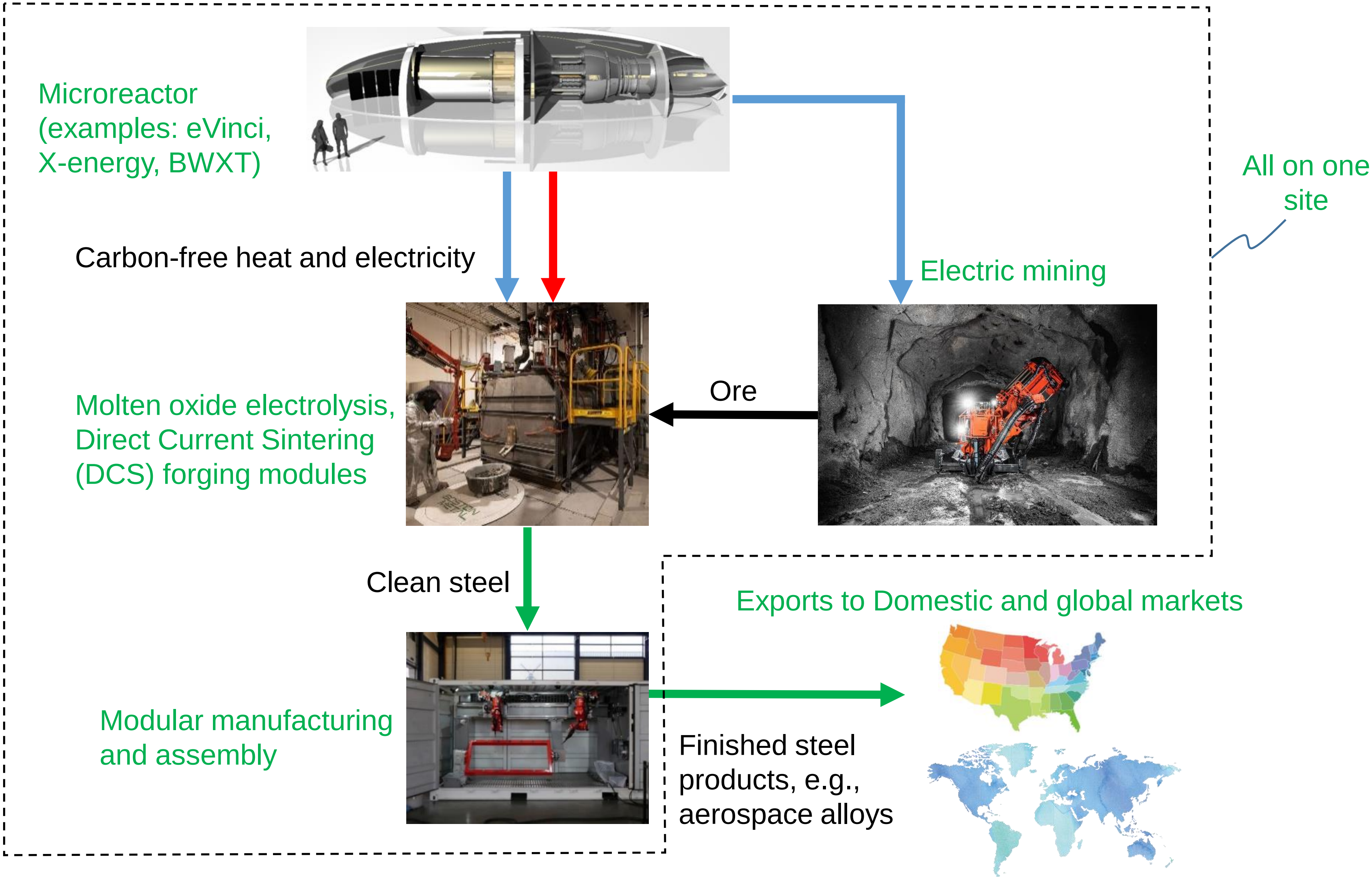
CAPTURE A SIGNIFICANT SHARE OF THE NASCENT MARKET FOR HYDROGEN AND SYNTHETIC FUELS

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

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

Ore

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) Shortened markup chains; (3) Allows for incremental provisioning; (4) Carbon-free products

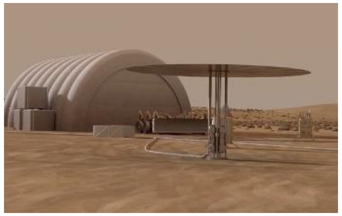
THIS APPROACH COULD APPLY ACROSS EVERY SECTOR OF THE ECONOMY


military bases


microgrids (remote communities, islands)

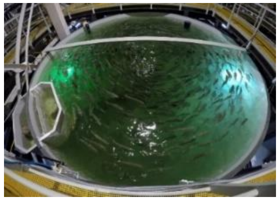

mining sites


indoor farming

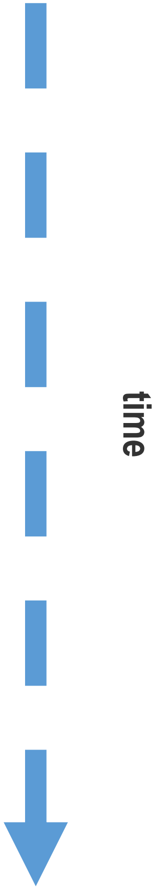

space installations


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

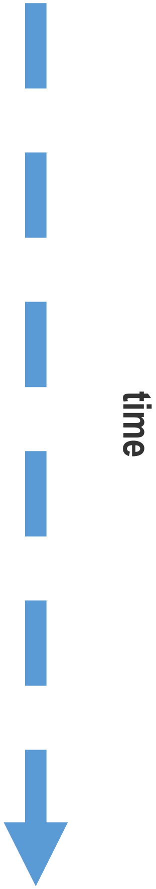

freight ship propulsion


e-vehicle charging stations


hydrogen electrolyzers

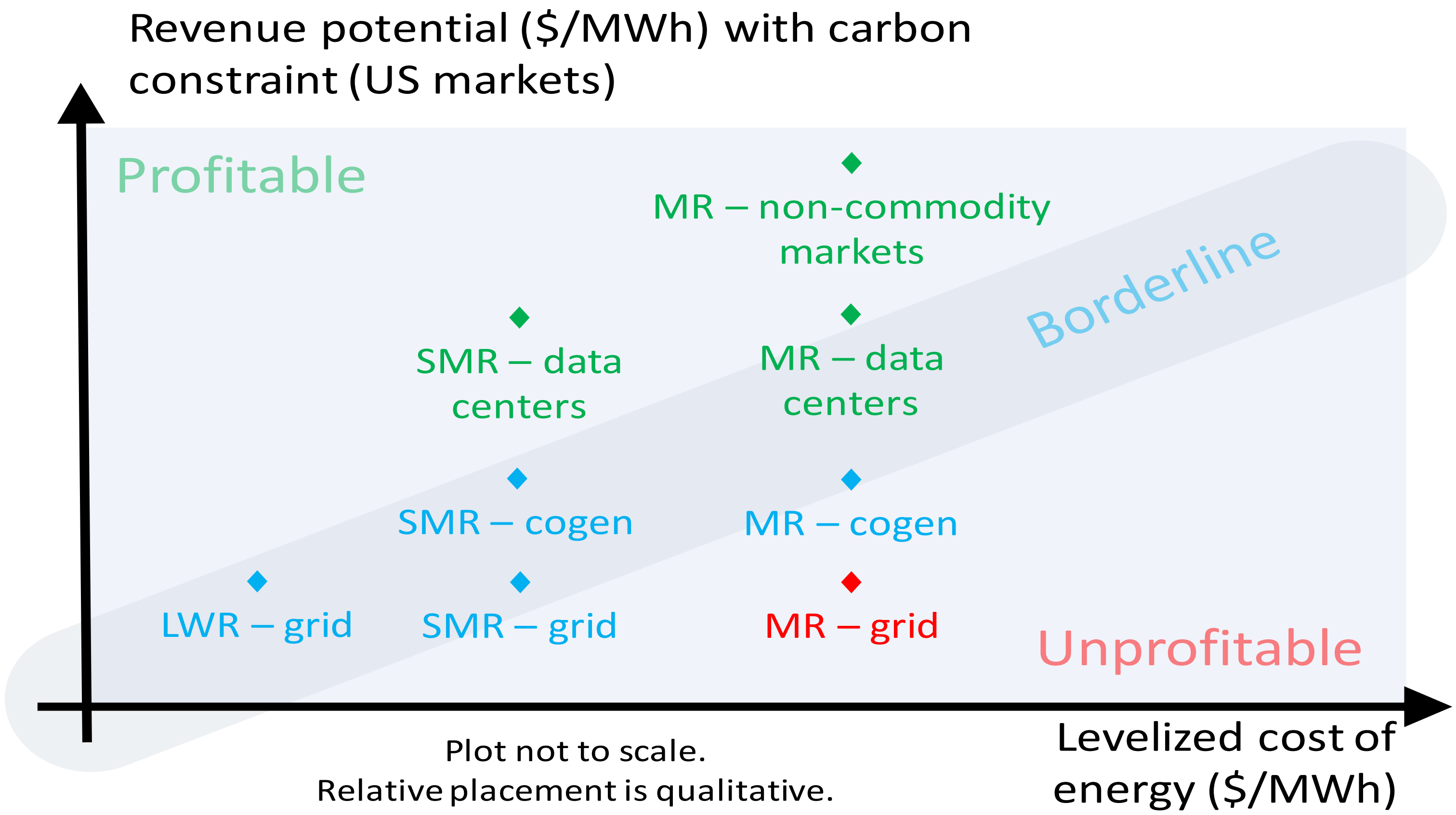

existing factories and chemical plants


biofuels



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

MARKET POTENTIAL



Plot not to scale.
Relative placement is qualitative.

(LWR = Large LWR; SMR = Small Modular Reactor; MR = Microreactor)

Higher LCOE (levelized cost of electricity) does not necessarily mean unprofitable, but focus on right markets is essential

IS ADVANCED NUCLEAR HAPPENING?

NEW REACTOR PROJECTS IN NORTH AMERICA

LWR-based SMRs

- BWRX-300 (GEH): 300 MWe, OPG Darlington, 2029
- ~~VOYGR (Nuscale): 6x77 MWe units, INL site, 2029~~

Non-LWR SMRs

- Natrium (Terrapower-GEH): 840 MWt, former coal power plant site in Kemmerer (Wyoming), 2030
- Xe-100 (X-energy): 4x100 MWe units, Dow's site in Seadrift (Texas), 2030

Nuclear Batteries and Microreactors

- BWXT: 5 MWe, INL site, 2026
- MARVEL: 20 kWe, INL site, 2027
- eVinci (Westinghouse): 5 MWe, INL site, 2027
- Hermes (Kairos): 35 MWt, Oak Ridge, 2026

Longer-term:

- SMR-160, AP300
- Terrestrial, ARC
- Oklo, USNC, Xenith

EXTRAORDINARY RESURGENCE OF INTEREST IN 2021-2025

- Invasion of Ukraine → energy security epiphany
- COP-26, -27, -28 and -29, EU taxonomy → climate policies allow inclusion of nuclear
- Tripling nuclear capacity statement with support from 14 leading financial institutions
- China's ongoing massive nuclear expansion (150 GW in 15 yrs) is on track
- 63 new reactors under construction worldwide. 440 already in operation.
- South Korea's and Sweden's elections → cancellation of nuclear phaseout
- 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
- TMI and Palisades NPP restart; Diablo Canyon extension
- Microsoft, Google and Amazon PPAs to use nuclear power for new data centers
- Signs of attention in pop culture, e.g., Oliver Stone's movie "Nuclear Now"

WILL ITALY FINALLY RECOMMIT?