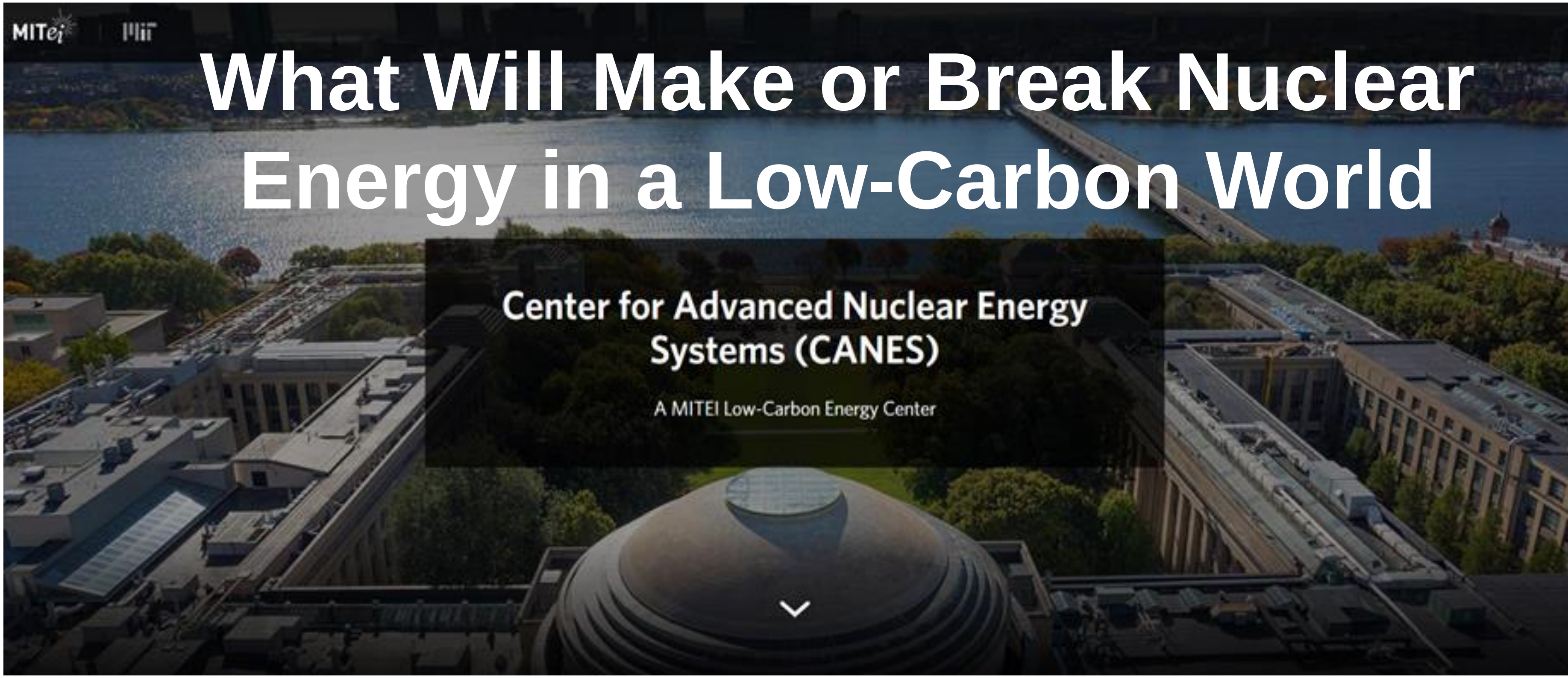
What Will Make or Break Nuclear Energy in a Low-Carbon World



Jacopo Buongiorno
TEPCO Prof. and Assoc. Dept. Head, Nuc. Sci. Eng.
Director, Center for Advanced Nuclear Energy Systems
jacopo@mit.edu, 617.253.7316

MITei
MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

About the speaker

Jacopo Buongiorno
Massachusetts Institute of Technology (MIT)

Education

Polytechnic of Milan	Nuclear Engineering	B.S.	1996
Massachusetts Institute of Technology	Nuclear Engineering	Ph.D.	2000

Professional Experience

2015-	Associate Department Head, Nuclear Science and Engineering, MIT
2015-	Director, Center for Advanced Nuclear Energy Systems (CANES)
2015-	Professor of Nuclear Science and Engineering, MIT
2011-	Accreditation Board - National Academy of Nuclear Training (NANT)
2011-2012	Special Committee on Fukushima, American Nuclear Society
2008-2015	Associate Professor of Nuclear Science and Engineering, MIT
2004-2008	Assistant Professor of Nuclear Science and Engineering, MIT
2000-2004	Research Scientist, Idaho National Laboratory

Awards and Honors

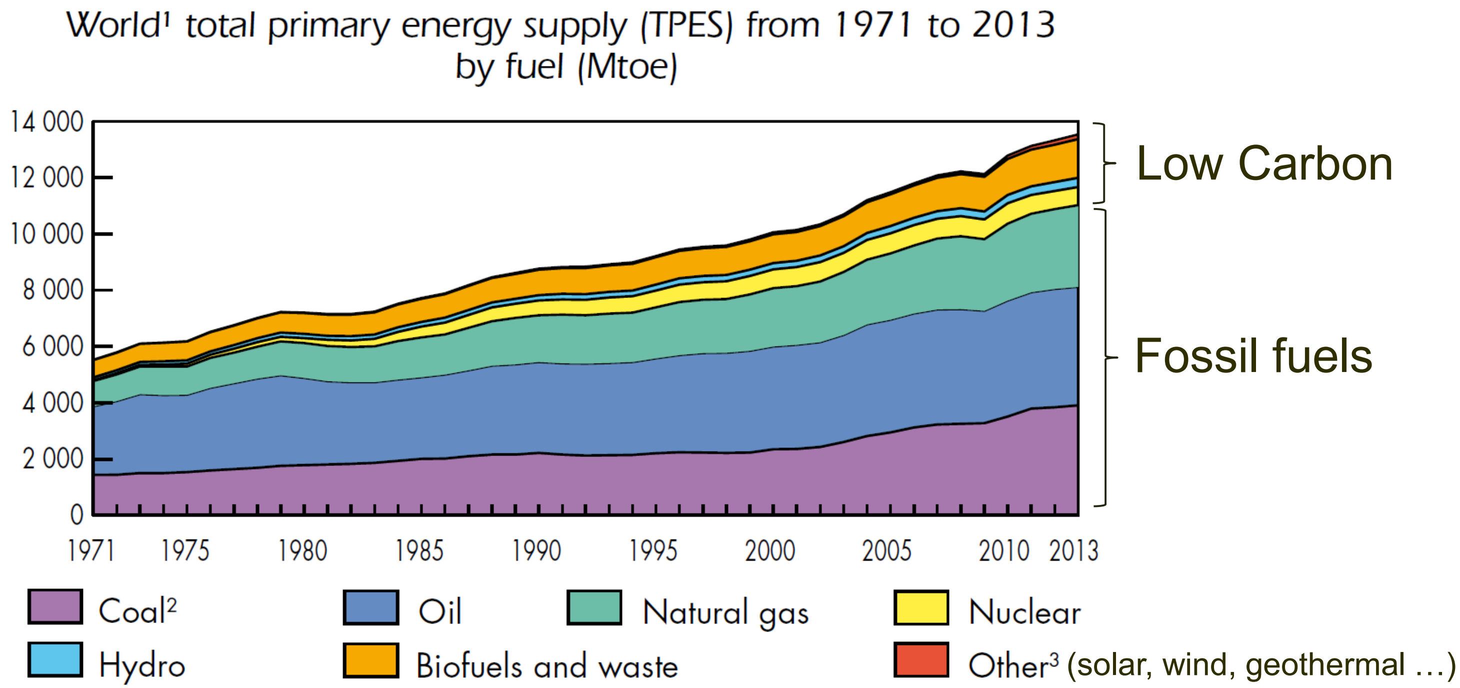
- Ruth and Joel Spira Award for Distinguished Teaching, School of Engineering, 2015, 2011 and 2006.
- MacVicar Award for Excellence in Undergraduate Teaching, MIT, 2014.
- Best Paper Award at the *9th Int. Topical Meeting on Nucl. Thermal-Hydraulics, Operation and Safety (NUTHOS-9)*, Kaohsiung, Taiwan, September 9-13, 2012.
- 2 most cited articles in Int J Heat Mass Transfer 2007-2012.
- Landis Young Member Engineering Achievement Award, American Nuclear Society, 2011.
- ASME Heat Transfer Division Best Paper, 2008.
- Best Paper Award at the 1st Micro/Nanoscale Heat Transfer Int. Conf., Tainan, Taiwan, January 6-9, 2008
- Junior Bose Award for Excellence in Teaching, MIT School of Engineering, November 2007
- Carl R. Soderberg Professor of Power Engineering Chair, MIT, July 2007-to present
- Graduate Teaching Award, MIT School of Engineering, 2005
- Norman C. Rasmussen Career Development Chair in Nuclear Engineering, MIT, 2004-2006
- Mark Mills Award for Best Nuclear Engineering Doctoral Thesis in the U.S., American Nuclear Society, 2001

Publications

>70 journal articles

WHY WE NEED NUCLEAR

Vast majority of the World's energy supply comes from CO_2 emitting fossil fuels



K. Caldeira, K. Emanuel, J. Hansen, T. Wigley (COP 21, Paris 12/3/15)

"There is no credible path to climate stabilization that does not include a substantial role for nuclear power"

"A major expansion of nuclear power is essential to avoid dangerous anthropogenic interference with the climate system this century."

"We've done the math and we can't power the world without nuclear energy."

Growth opportunities for nuclear come from the desire to decarbonize the economy

1. Dominate baseload electricity generation: 200 GWe to replace coal in the US
2. Electrify the transportation sector: 150-200 GWe to replace all US cars and light trucks with PIHVs*
3. Produce liquid fuels from biomass: 260 GWt to satisfy total US transport fuel demand*
4. Generate heat and hydrogen for oil refineries: 300 GWt to satisfy total US demand
5. Water desal is a small market: 16 GWe worldwide**

* #2 and #3 are not additive

** Assumes 100 Mm^3/day, produced with RO (3.5 kWh/m^3) and 90% capacity factor

WHY WE LIKE NUCLEAR

Nuclear plants require much less fuel than fossil plants and emit no CO_2

Fuel energy content

COAL (C): $C + O_2 \rightarrow CO_2 + 4$ eV

NATURAL GAS (CH_4): $CH_4 + O_2 \rightarrow CO_2 + 2H_2O + 8$ eV

NUCLEAR (U): $^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n + 200$ MeV

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

COAL (40% efficiency):

$10^9/(0.4 \times 4 \times 1.6 \times 10^{-19}) \approx 3.9 \times 10^{27}$ C/sec (=6750 ton/day)

NATURAL GAS (50% efficiency):

$10^9/(0.5 \times 8 \times 1.6 \times 10^{-19}) \approx 1.6 \times 10^{27}$ CH_4/sec (=64 m^3/sec)

NUCLEAR (33% efficiency):

$10^9/(0.33 \times 200 \times 1.6 \times 10^{-13}) \approx 1.0 \times 10^{20}$ ^{235}U/sec (=3 kg/day*)

1 eV = 1.6×10^{-19} J

* corresponding to about 300 kg/day of natural U

Nuclear plants require much less space and are more steady and reliable than renewables

NUCLEAR: Paluel, France, 5200 MW (24/7, year around, >90% capacity factor), 0.8 sq. miles

~ 5850 MW_e/mi^2

WIND: Alta Wind Farm, CA, 1020 MW max (only if the wind blows, <40% capacity factor), 5 sq. miles

~ 82 MW_e/mi^2

SOLAR: Ivanpah, CA, 390 MW max. (only if the sun shines, nothing at night, <30% capacity factor), 6 sq. miles

~ 20 MW_e/mi^2

Nuclear is also geographically much less constrained than renewables

Uranium is plentiful… in fact essentially infinite

▭ 100 years of uranium usage at current rate (0.067 million tonnes/year)

Resource type and size [Million tonnes U]

Redbook Identified (Reasonably Assured + Inferred)	Redbook Undiscovered	Reported phosphate and shale	Estimated additional phosphate and shale	Estimated coal-lignite and monazite
7.6	6.0	10.2	18.0	7.7
7.6	**13.6**	**23.8**	**41.8**	**49.5**

Cumulative resource [Million tonnes U]

Uranium in Seawater*:

4000 (replenished from freshwater runoff and seabed)

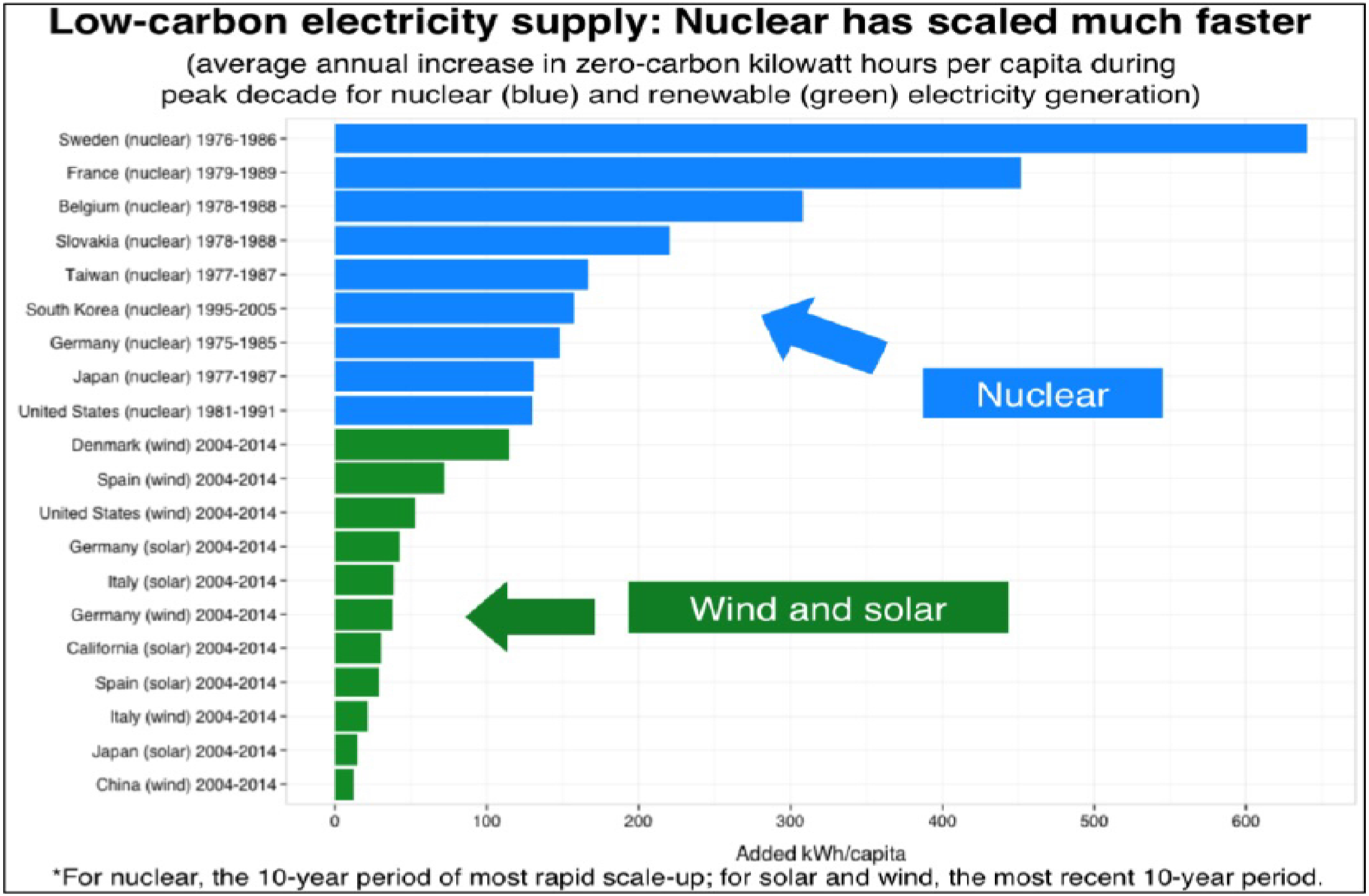
* Recoverable with braided adsorbents moored to the ocean floor.
Capacity is ~1 ton of U per km^2 of ocean floor per year

(slide courtesy of Prof. Erich Schneider, U-Texas at Austin)

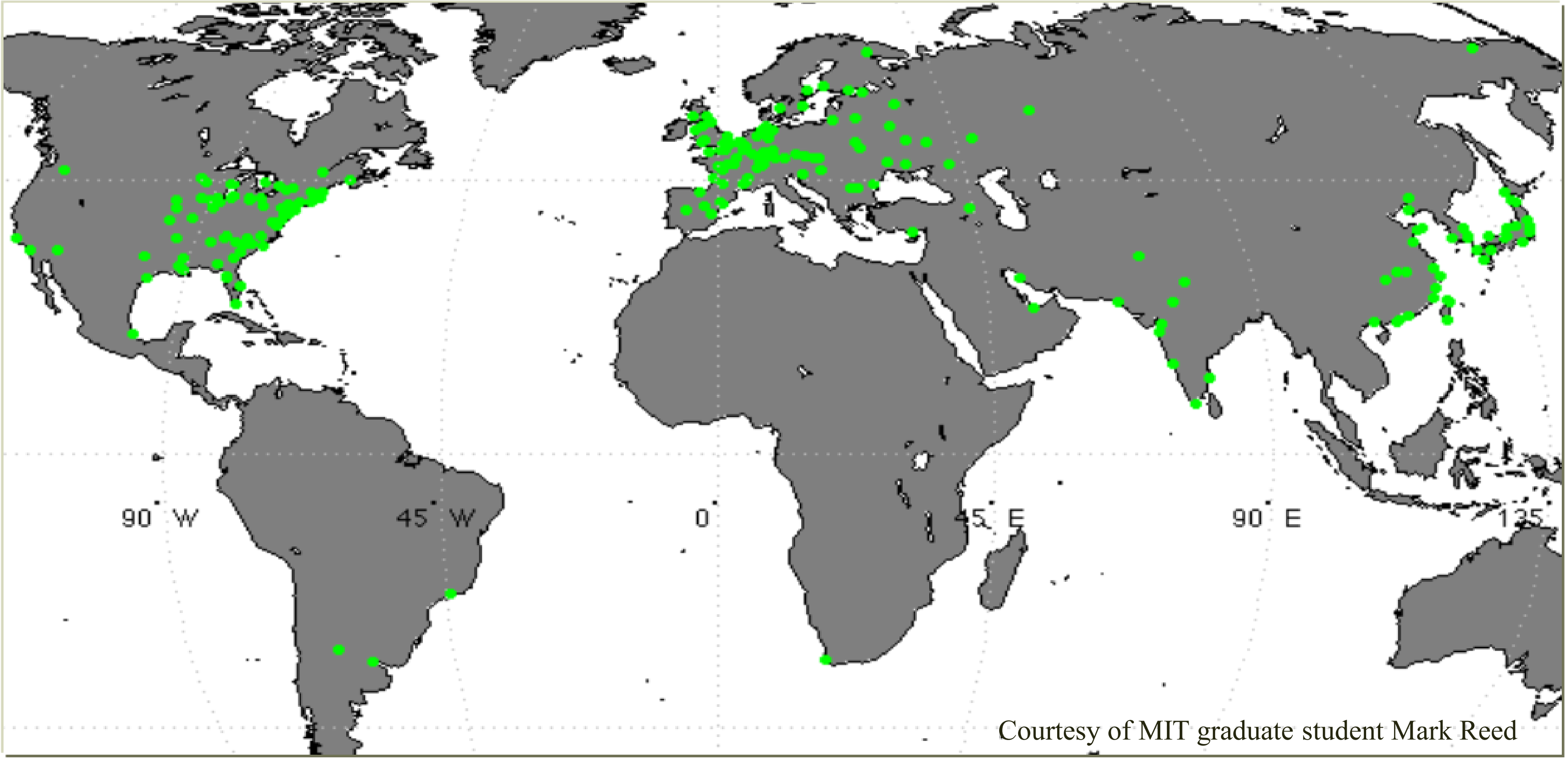
Uranium prices are set by stable, friendly countries

vs.

Nuclear capacity can be scaled up much quicker than renewables



There are >440 nuclear power plants worldwide



mostly built in a period of only 25 years

67 new reactors are in various stages of construction

Olkiluoto – Finland

Lungmen – Taiwan

Kudankulam – India

Flamanville – France

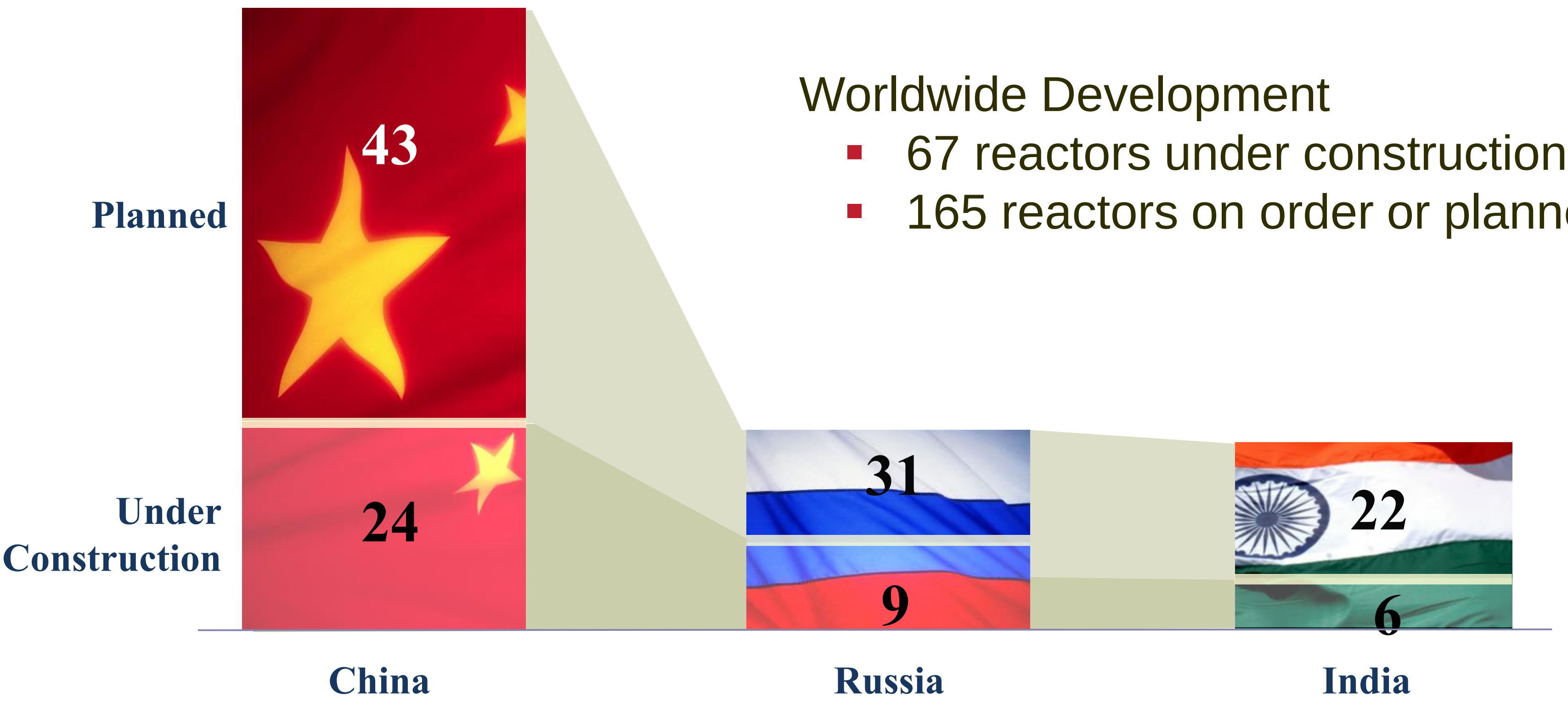
Rostov – Russia

Shin kori – S. Korea

Shimane – Japan

Taishan – China

Nuclear constitutes a large near-term business opportunity



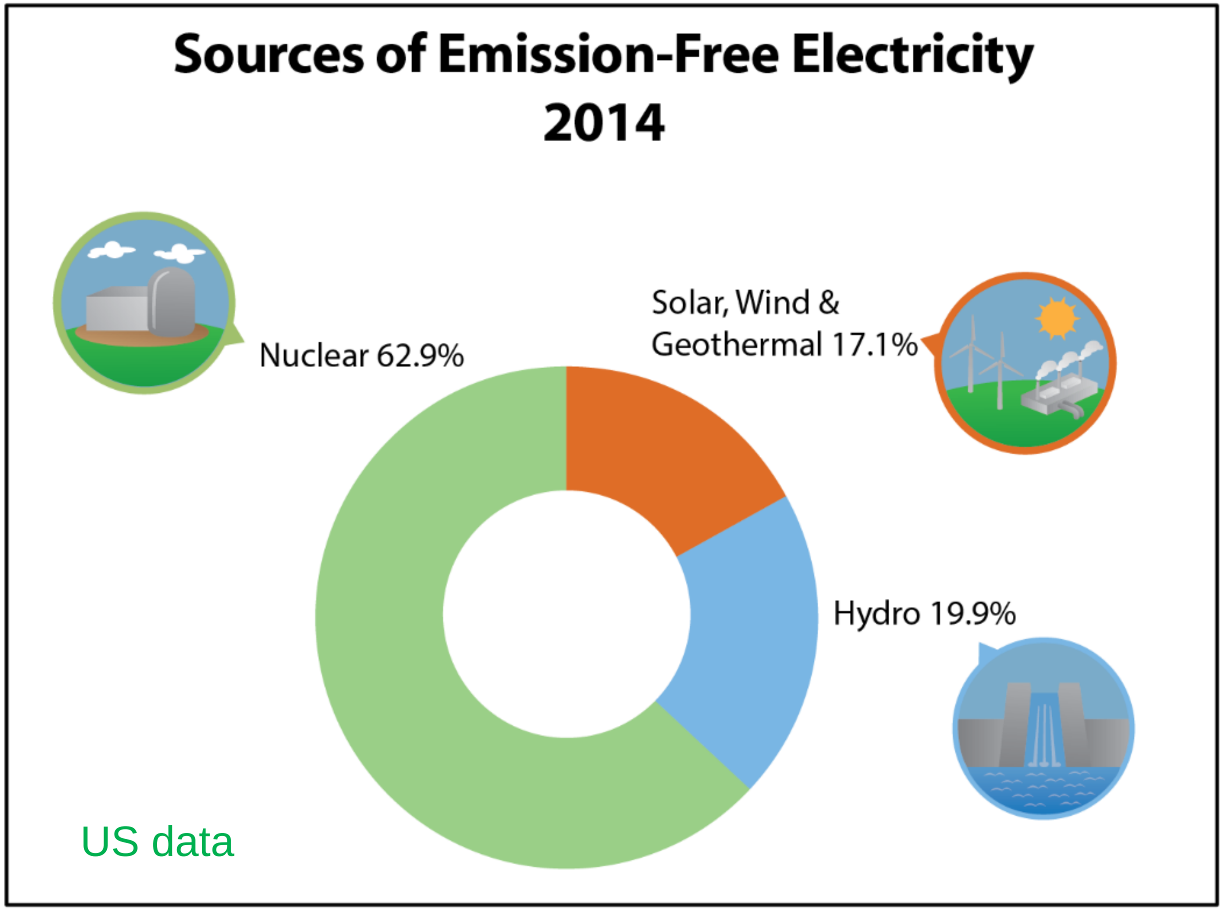
Worldwide Development

- 67 reactors under construction
- 165 reactors on order or planned

Sources: International Atomic Energy Agency; World Nuclear Association; U.S. Department of Commerce

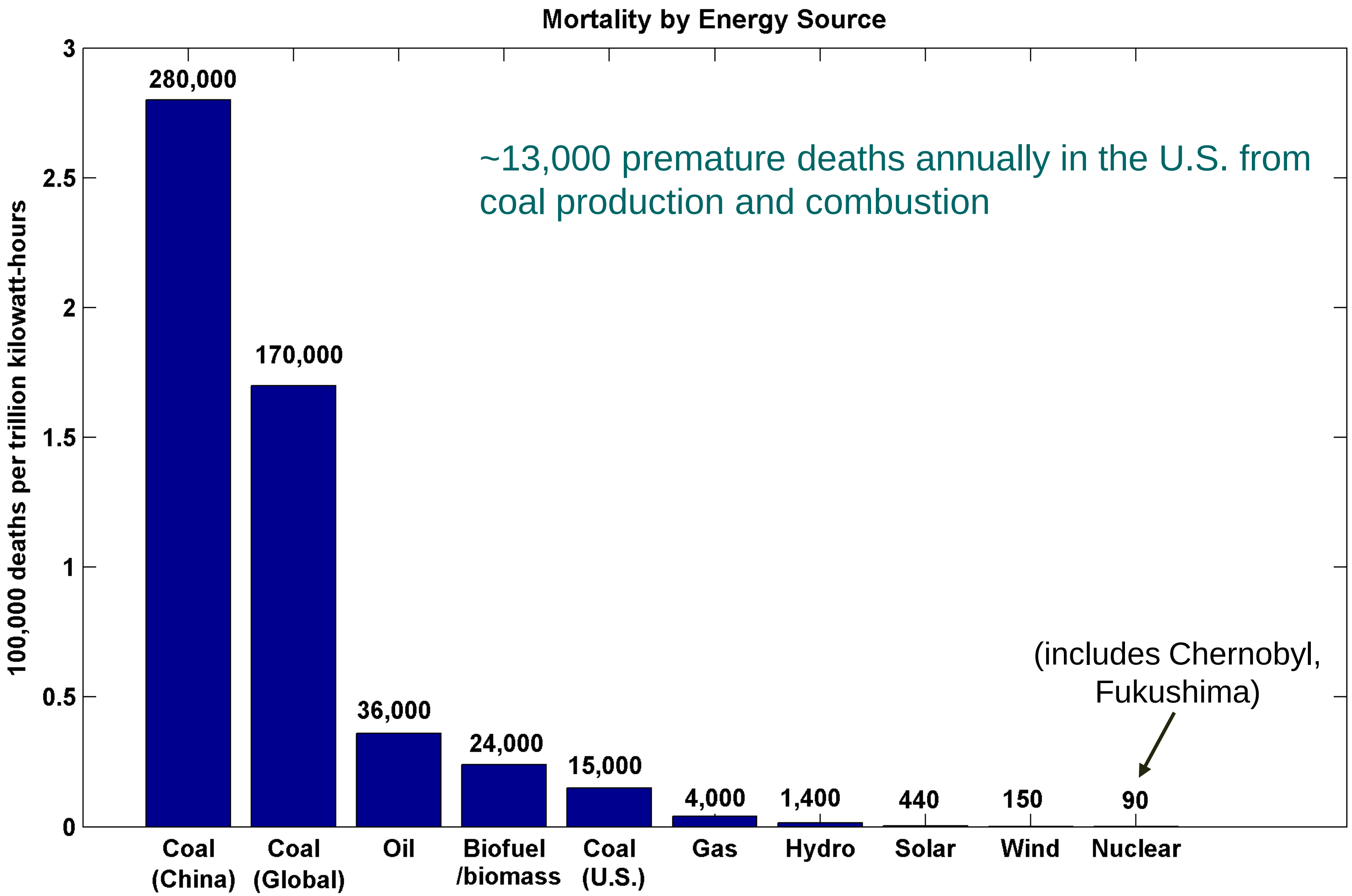
$740 Billion Global Nuclear Energy Market Over Next 10 Years

Nuclear is already the largest emission-free electricity source in the US and the EU by far



~595,000,000 ton of CO_2 emissions (equivalent to 135 million cars) avoided in the US in 2014

Nuclear has a very low environmental impact



Nuclear power, by replacing fossil fuels, has prevented an estimated 1.84 million air-pollution related deaths worldwide

NUCLEAR HAS ITS CHALLENGES

- Capital cost and construction schedule of new nuclear plants are too high
- Significant changes in local market conditions can cause premature shutdown
- Design certification and licensing of new plants is too lengthy and expensive (especially in the US)

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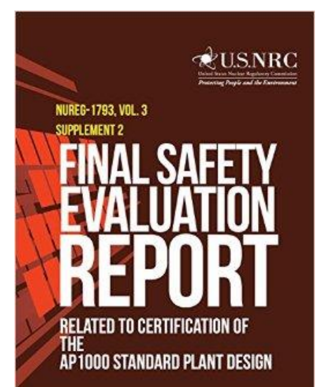
BUSINESS

Entergy Plans to Shut Down Pilgrim Nuclear Plant

Cites poor market conditions, lower revenue and higher operating costs



- Severe accidents can result in land contamination and long-term evacuation of local population
- Disposal of spent fuel in traditional geological repositories has proven politically challenging
- Diversion of fissile material can lead to development of nuclear weapons

Challenge 1: Reduce Capital Cost

LCOE for new nuclear is high because of the high cost of the plant

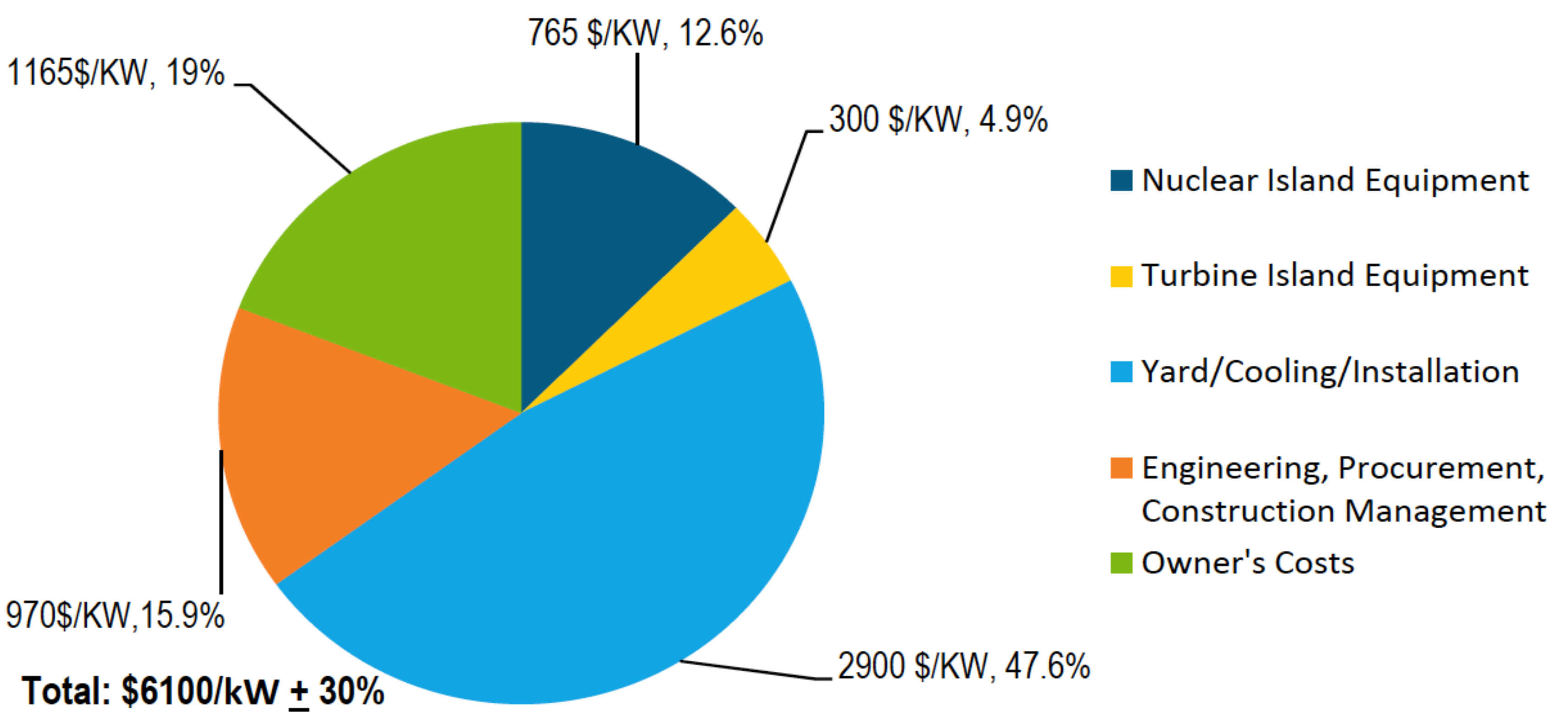
Technology	Capacity Factor (%)	Range of Levelized Costs (2013 $/MWh)		
		Minimum	Average	Maximum
Dispatchable				
Gas Combined Cycle	87	68.6	72.6	81.7
New Nuclear	90	91.8	95.2*	101
Advanced Coal (IGCC with CCS)	85	132.9	144.4	160.4
Intermittent				
Onshore Wind	35	65.6	73.6	81.6
Utility-Scale Solar PV	25	97.8	125.3	193.3

Sources: New generating capacity costs from Energy Information Administration, *Annual Energy Outlook 2015*; existing nuclear costs are 2013 total generation costs (fuel, O&M, capital) from Electric Utility Cost Group for US.

*Compare to average production cost of nuclear electricity from current U.S. fleet: 24 $/MWh

Most of the cost is in installation and financing, not equipment

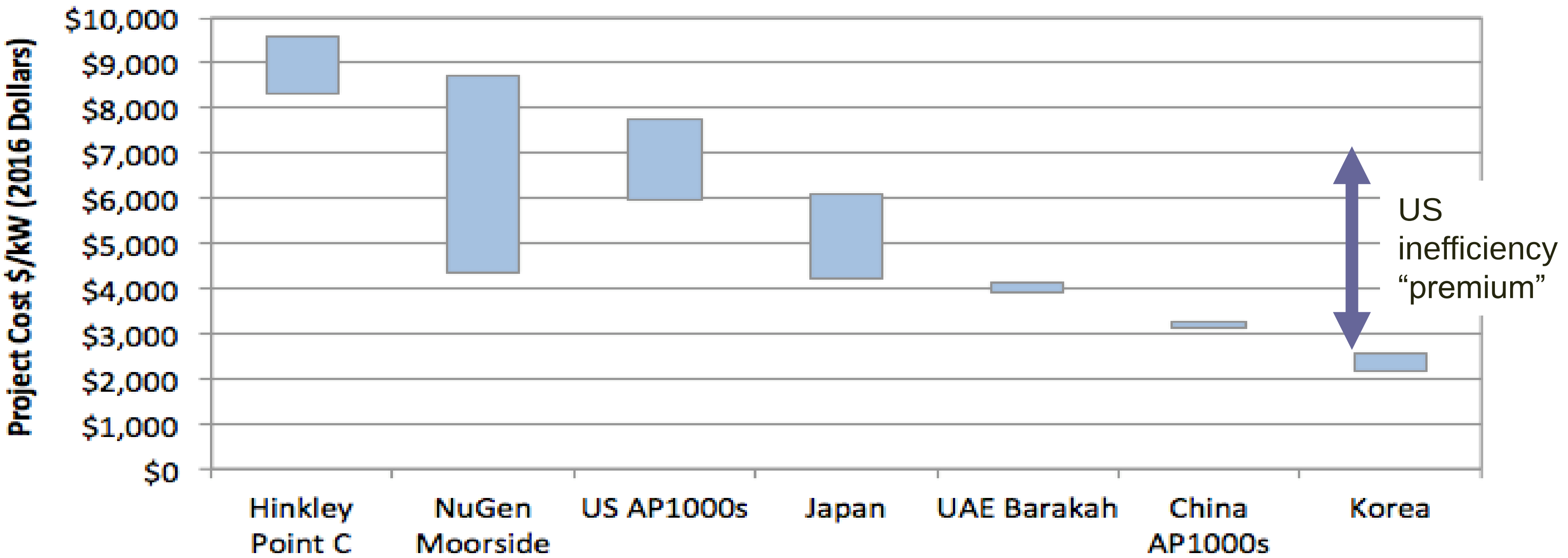
Construction Cost Estimates for Generic US AP1000 Project



Total: $6100/kW ± 30%

Source: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11

Standardization, tight project management and efficient construction can make a huge difference



Project cost range (2016 $/kW)	$8,300 - $9,600	$4,400 - $8,700	$6,000 - $7,800	$4,200 - $6,100	~ $3,900	~$3,100	$2,200 - $2,600
Time range	Proposed	Proposed	2013 -	1998 - 2009	2012 -	2009 -	1997 - 2016
Units included	2	3	4	5	4	4	9

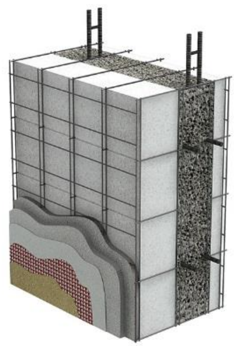
Note: Project costs are "all-in" (overnight + financing); Sources: See backup slides. (Data collected and organized by Eric Ingersoll)

Opportunities for innovation in NPP cost reduction

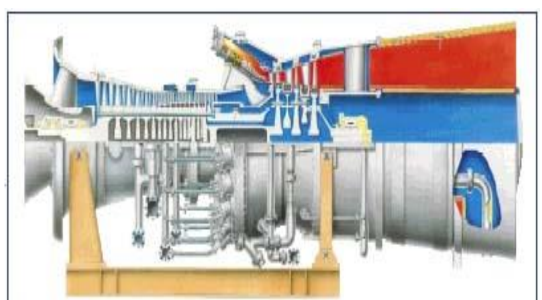


Shipyard / factory construction + new methods for transportation to site

Advanced robotics to reduce # of operators and guards



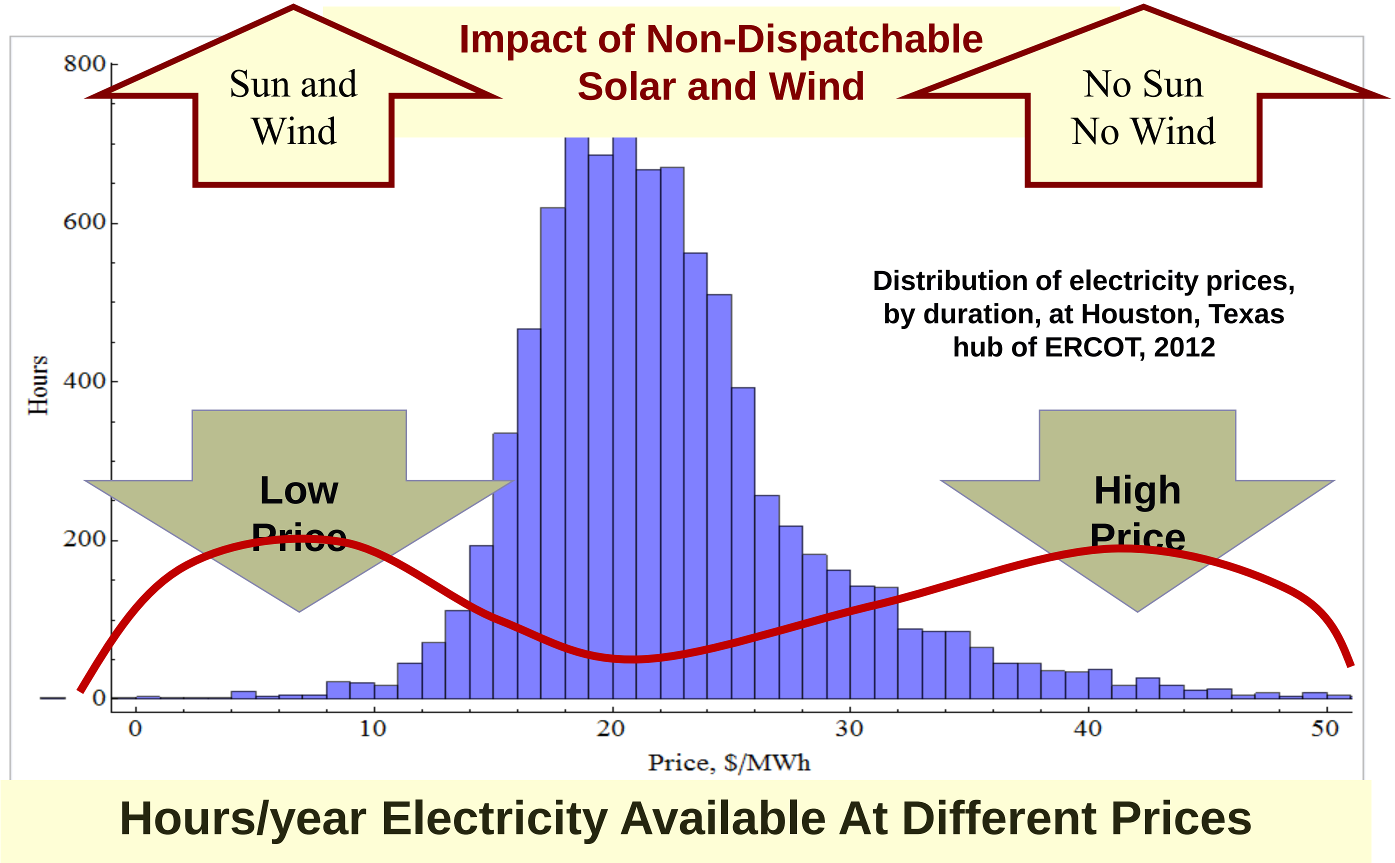
Prefab reinforced concrete



High thermal efficiency lowers direct and indirect costs

Additive manufacturing for nuclear components with complex geometry

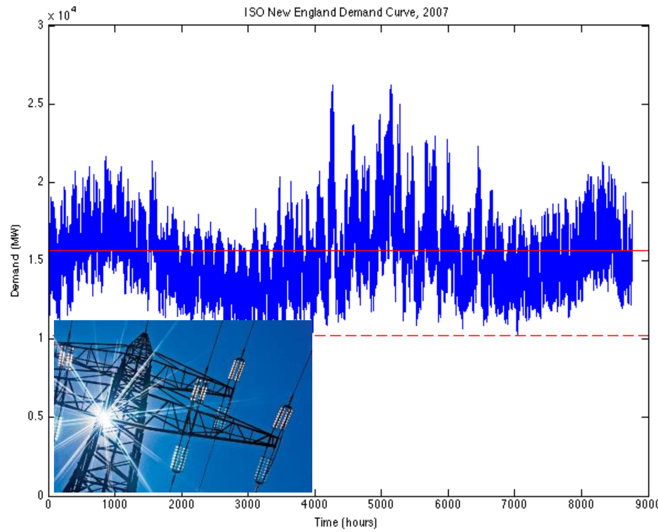
Challenge 2: Achieve Profitability in Renewable Intensive Markets



Low electricity prices erase the profits of baseload generators like nuclear power plants

Opportunities for innovation in NPP operation modes

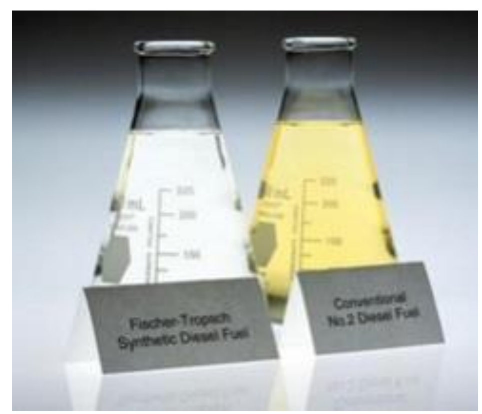
Couple to inexpensive energy storage



Load following

Hydrogen generation

Water desalination



Syn fuels

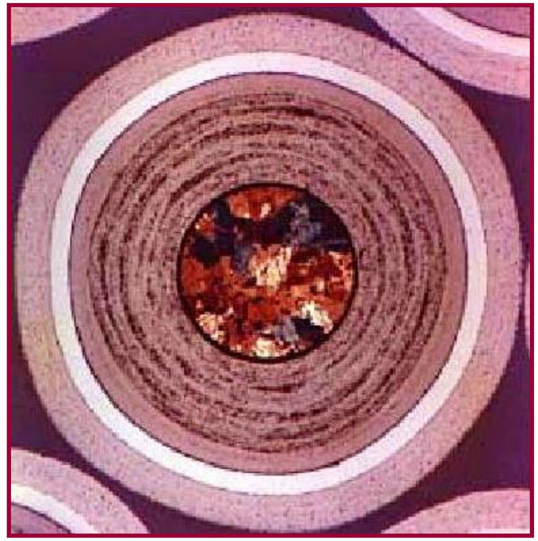
Challenge 3: Enhance Safety

LWRs with traditional safety systems may incur fuel damage and significant radionuclide (Cs, I) releases during unmitigated severe accident conditions

New safety goals after Fukushima:

- Demonstrate passive safety with ‘infinite’ coping time
- Eliminate need for evacuation of locals after severe accidents

Opportunities for innovation in NPP safety



Accident tolerant fuels

Offshore siting

Non-volatile, inert coolants

Risk-informed regulations

WHAT MIT CAN DO

Susan Hockfield
(MIT President Emeritus)

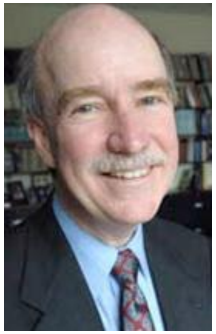
MITei
MIT Energy Initiative

Ernie Moniz
(US Energy Secretary)

- Launched in 2006 by Susan Hockfield and Ernie Moniz
- Development and deployment of low-carbon energy technologies and increasing the efficiency of conventional energy technologies
- Sponsored by industry, government and the NGO sectors
- >$600 million in member contributions
- 1/3 of MIT's faculty works with MITEI on energy and climate topics

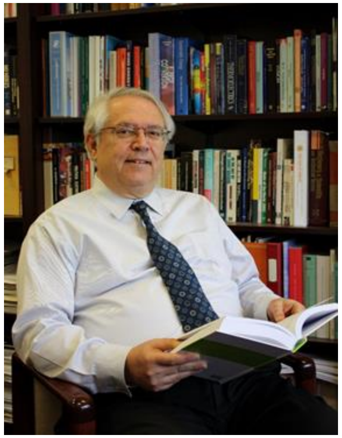
Rafael Reif (MIT President)

"The world needs an aggressive but pragmatic transition plan to achieve a **zero-carbon global energy system**. […] I urge everyone to join us in rising to this historic challenge."



Bob Armstrong (MITEI Director)

Center for Advanced Nuclear Energy Systems (CANES)



Founder: Mujid Kazimi

One of eight MITEI Low-Carbon Energy Centers (LCEC)

Director: Jacopo Buongiorno

12 full time NSE faculty, 4 research staff
+ 20 faculty and staff from other MIT units
(e.g. NRL, MechE, DMSE)

Co-Director: John Parsons

CANES Research Volume ~$10M/year

EDF
Alfred P. Sloan Foundation 1934
مؤسسة الكويت للتقدم العلمي
Kuwait Foundation for the Advancement of Sciences
Established 1976
KFAS
DE LA RECHERCHE À L'INDUSTRIE
cea
Sandia National Laboratories
SINAP
AREVA
HITACHI
KEPCO
Skoltech
Skolkovo Institute of Science and Technology
EPRI ELECTRIC POWER RESEARCH INSTITUTE
NASA
King Abdulaziz City for Science and Technology
Exelon
산업통상자원부
MINISTRY OF TRADE, INDUSTRY & ENERGY
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GE
KAPL
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bp
AFOSR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
DCNS
TerraPower
ABB
BETTIS LABORATORY
CASL
Consortium for Advanced Simulation of LWRs
SUTD-MIT INTERNATIONAL DESIGN CENTRE

MISSION

We develop transformative methods, materials and technologies to make fission energy systems more:

- **Affordable**
- **Easy to deploy**
- **Safe**
- **Sustainable**

CANES' Agenda for Nuclear Innovation

Performance Requirements	Deployment: Near Term (<15 years)	Deployment: Mid Term (15-35 years)	Applications and Stakeholders
Superior Economics • Reduce overnight capital cost by ≥30% • Maintain profitability in renewable-intensive markets	Baseload ALWRs (with cheap storage and/or syn fuel production)	Liquid-salt reactors Offshore floating reactors Liquid-metal fast reactors High-temp gas reactors	• Baseload electricity generation (power generators) • Electrification of transportation sector (automotive industry, power generators) • Synthetic fuel and H_2 production (energy companies) • Energy-hungry businesses (manufacturing, smelters, data centers)
Superior Safety • Demonstrate passive safety with 'infinite' coping time • Eliminate need for evacuation of locals after severe accidents • Adopt risk-informed regulations			
Superior Sustainability • Dispose of spent fuel safely, securely and permanently • Maintain strict control of fissile material throughout the fuel cycle	Deep boreholes disposal of spent fuel Regional enrich. centers; domestic fuel banks	Deep boreholes disposal of spent fuel Regional enrich. centers; domestic fuel banks Regional fuel take-back centers	• High-level waste management (drilling, mining companies) • Prevent proliferation of nuclear weapons (IAEA, governments)
21st Century Technologies Applied to Nuclear Plants	Nanotechnology 3D printing Modular construction Hi-Fi modeling & simulation Robotics and prognostics	Nanotechnology 3D printing Modular construction Hi-Fi modeling & simulation Robotics and prognostics	• Fuel and reactor component fabrication (nuclear vendors, shipbuilding companies) • Reactor operations, maintenance and emergency response (nuclear utilities)

REACTOR CONCEPTS TO REDUCE THE CAPITAL COST AND ENHANCE THE SAFETY OF NPPs

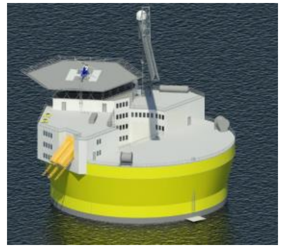
Offshore floating nuclear power plant (OFNP)

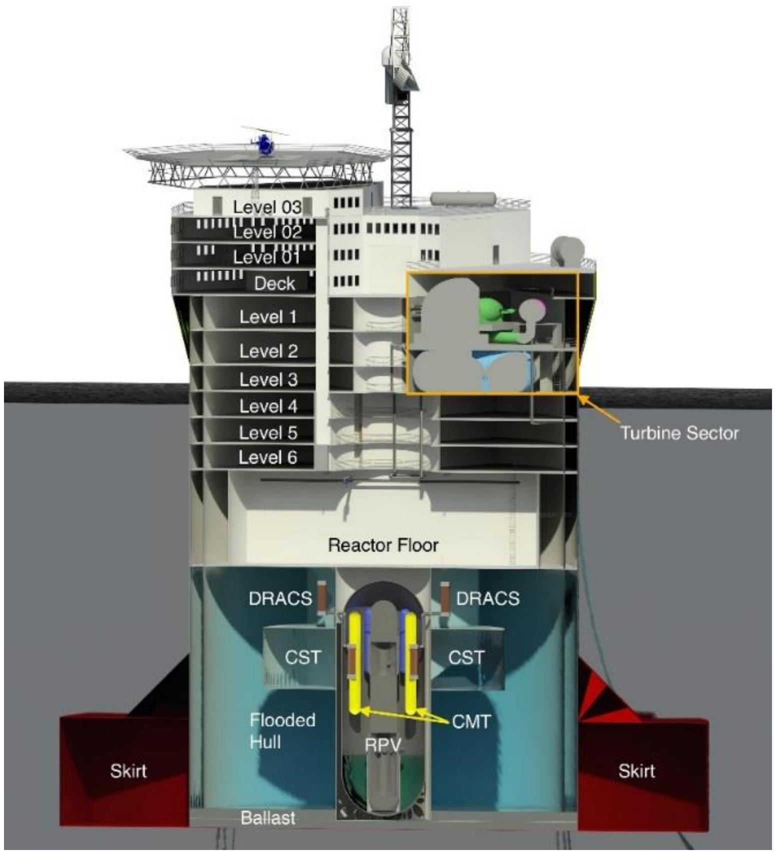

Floating rig

\+


Nuclear reactor

=

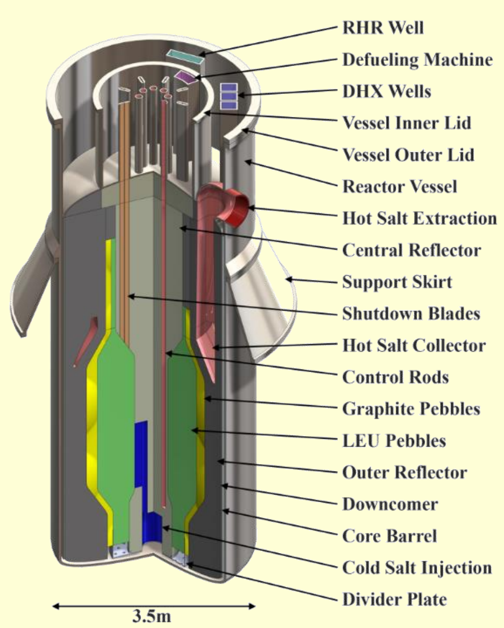

OFNP



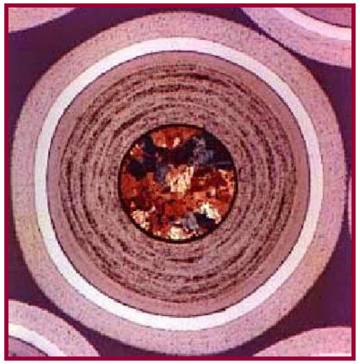
- Entirely built and decommissioned in a shipyard: faster and cost-effective plant construction (<36 months)
- Reduced capital cost (>90% cut in reinforced concrete)
- Transported to the site, moored 5-12 miles offshore, in relatively deep water (~100 m): insensitive to earthquakes and tsunamis
- Submarine AC cable connects to grid
- Reactor could be large LWR (1100 MWe), SMR (300 MWe) or other design
- Nuclear island underwater: ocean heat sink ensures indefinite passive decay heat removal (no Fukushima scenario)

Profs. J. Buongiorno, M. Golay, N. Todreas

Fluoride-Salt-Cooled High-Temperature Reactor (FHR)



Builds upon existing technology



Fuel: TRISO particle fuel, no failure up to ~1650°C, strongly negative Doppler feedback

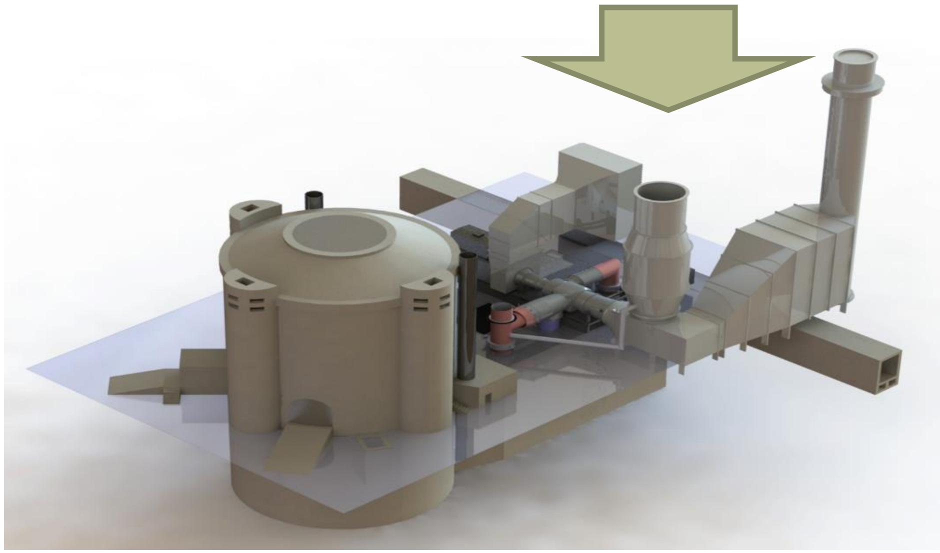
Coolant: FLiBe liquid salt, low-pressure, chemically inert, large margin to boiling (1430°C), high heat capacity, enables power density up to 10x gas-cooled reactors

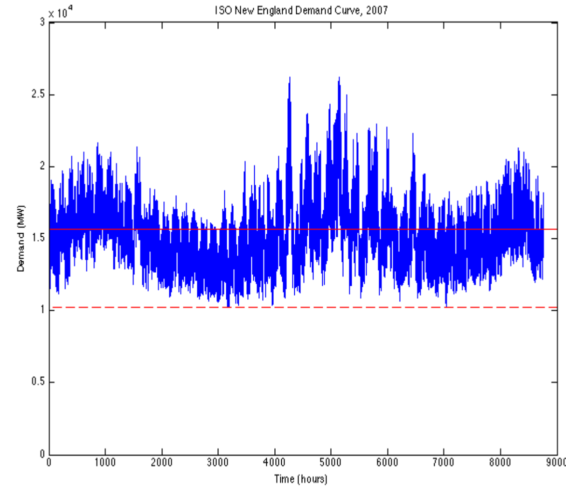
Power Cycle: Modified natural-gas air Brayton power cycle with General Electric 7FB turbo-compressor

Drs. C. Forsberg, L. Hu

FHR with Nuclear Air-Brayton Combined Cycle (NACC)

Stored Heat and/or Natural Gas

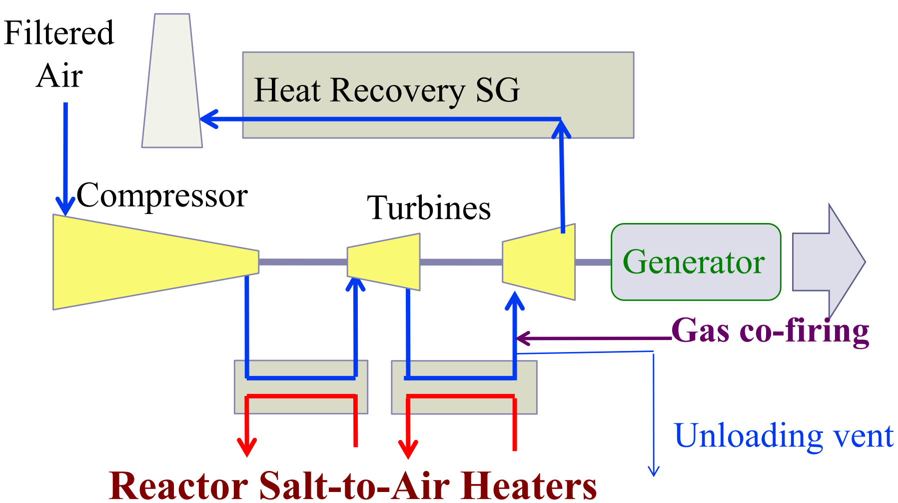




Base-Load Reactor

Gas Turbine

Variable Electricity



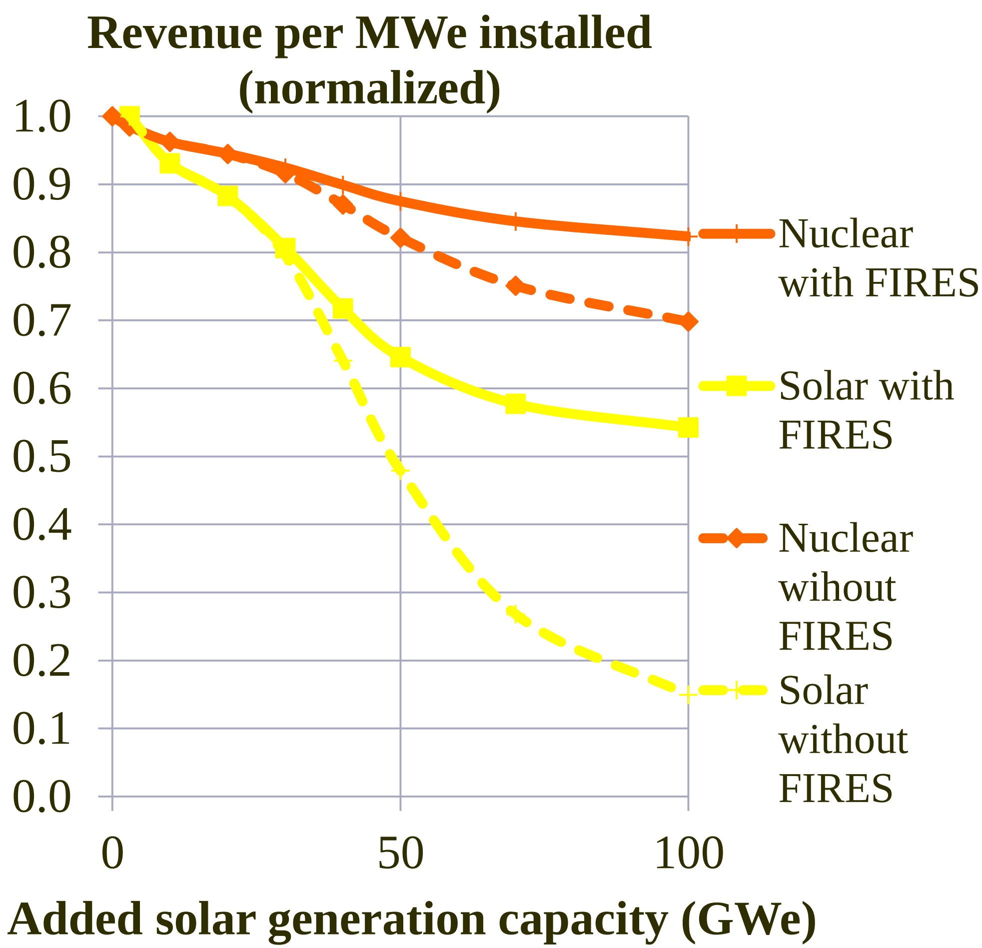
- Peak electricity with natural gas or hydrogen
- Highest efficiency conversion of NG to electricity
- Very fast response because peak power off base load
- 50 to 100% greater revenues than base-load plant

ENERGY STORAGE AND ENERGY SINKS THAT COUPLE WELL WITH NUCLEAR PLANTS AND RENEWABLES

Firebrick Resistance-heated Energy Storage (FIRES) for daily fluctuations

- Firebrick electrically heated when electricity prices are low
- Hot firebrick provides hot air to partly substitute for natural gas in industrial furnaces
- Couples well with NACC
- Expected capital cost less than $5/kWh
- Changes electricity price curves
- Stops price collapse when high renewable generation is online
- Aids nuclear and renewables

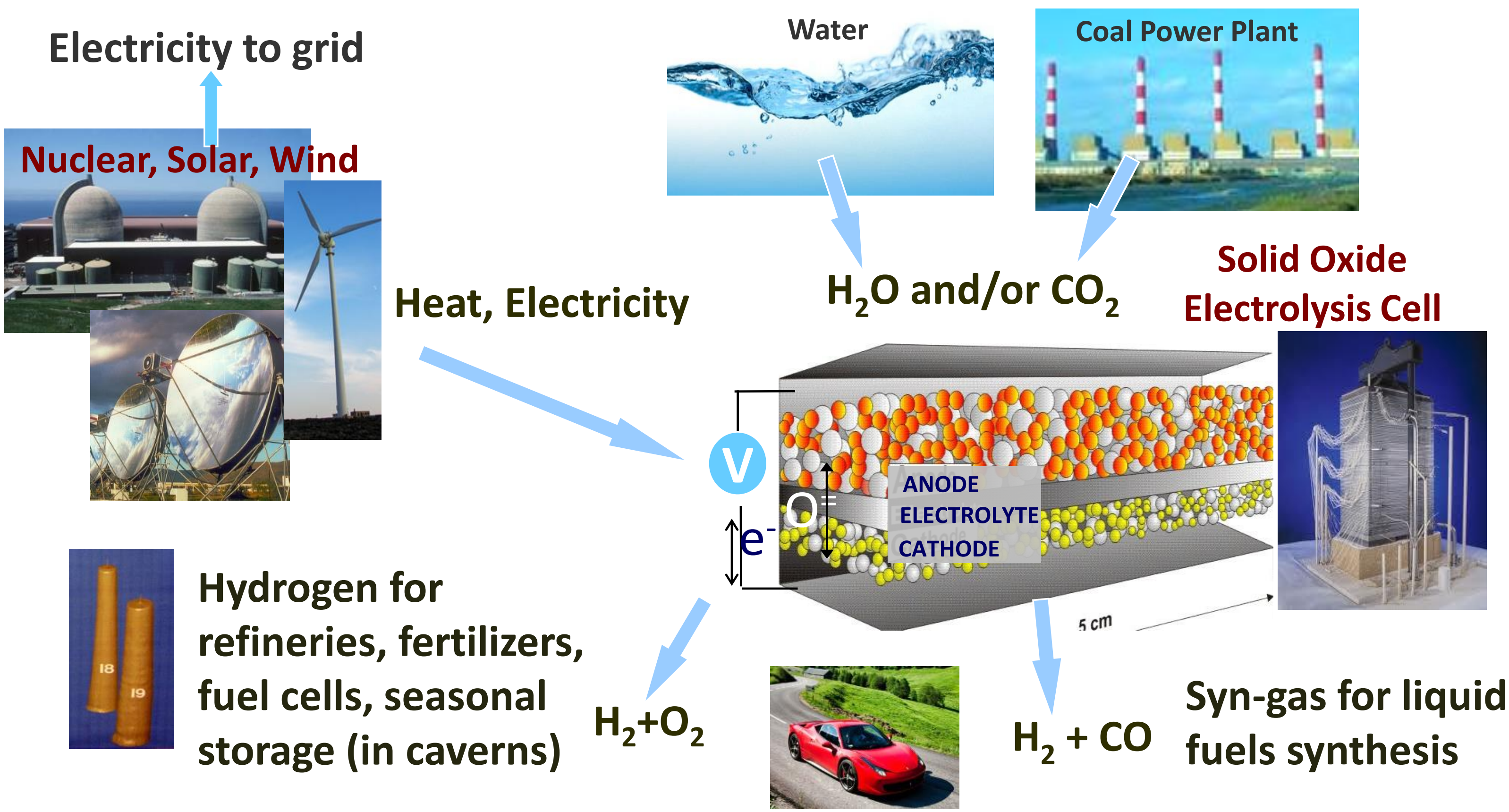
Tokyo Electric example



Dr. C. Forsberg

Synthetic Fuels and H_2 from High-Temperature Electrolyzers

- Can absorb electricity from renewables and/or nuclear plants at times of high generation and low demand
- Avoids daily electricity price collapse
- SOEC technology is at developmental stage (support by DOE/NASA)



Profs. B. Yildiz, A. Ghoniem

Navy's process to make jet fuel from seawater

Electricity + Water + CO_2 → Fuel

- Electrolytic Cation Exchange Module (E-CEM) simultaneously extracts CO_2 (92% efficiency) and produces H_2 from seawater (no chemicals needed)
- Two-step catalytic process turns CO_2 and H_2 into jet fuel

- Fuel's energy content is equal to 60-80% of electricity input
- 23,000 gal of seawater per gal of fuel
- Current cost estimate is $6/gal
- Demonstrated at lab scale
- CO_2 is 140 times more concentrated in seawater, than air (100 mg/L vs 0.77 mg/L)
- Carbon-neutral jet fuel, if nuclear electricity is used + would contribute to de-acidification of oceans

ADVANCED CROSS-CUTTING CAPABILITIES AND TECHNOLOGIES

Robots for Nuclear Plants

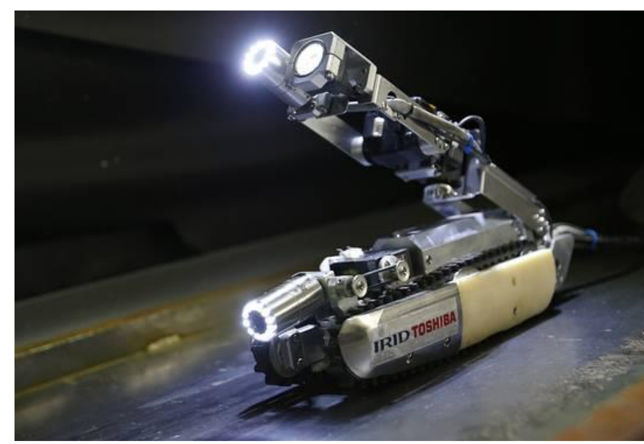
Brokk 100

Pipe Inspection robot
(Savannah River)

Bolt inspection robot
(Westinghouse Electric Company)

Robots currently used in NPPs:

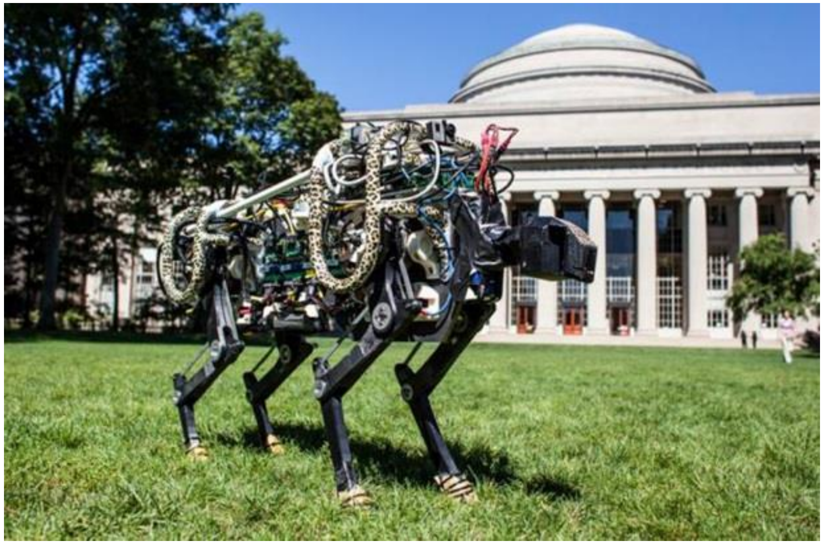
- Specialized machines for specific tasks
- Inspection purposes
- Limited mobility
- Quasi-static position control



Inspection robot
(TOSHIBA)

Prof. S. Kim

Robots - The MIT Edge

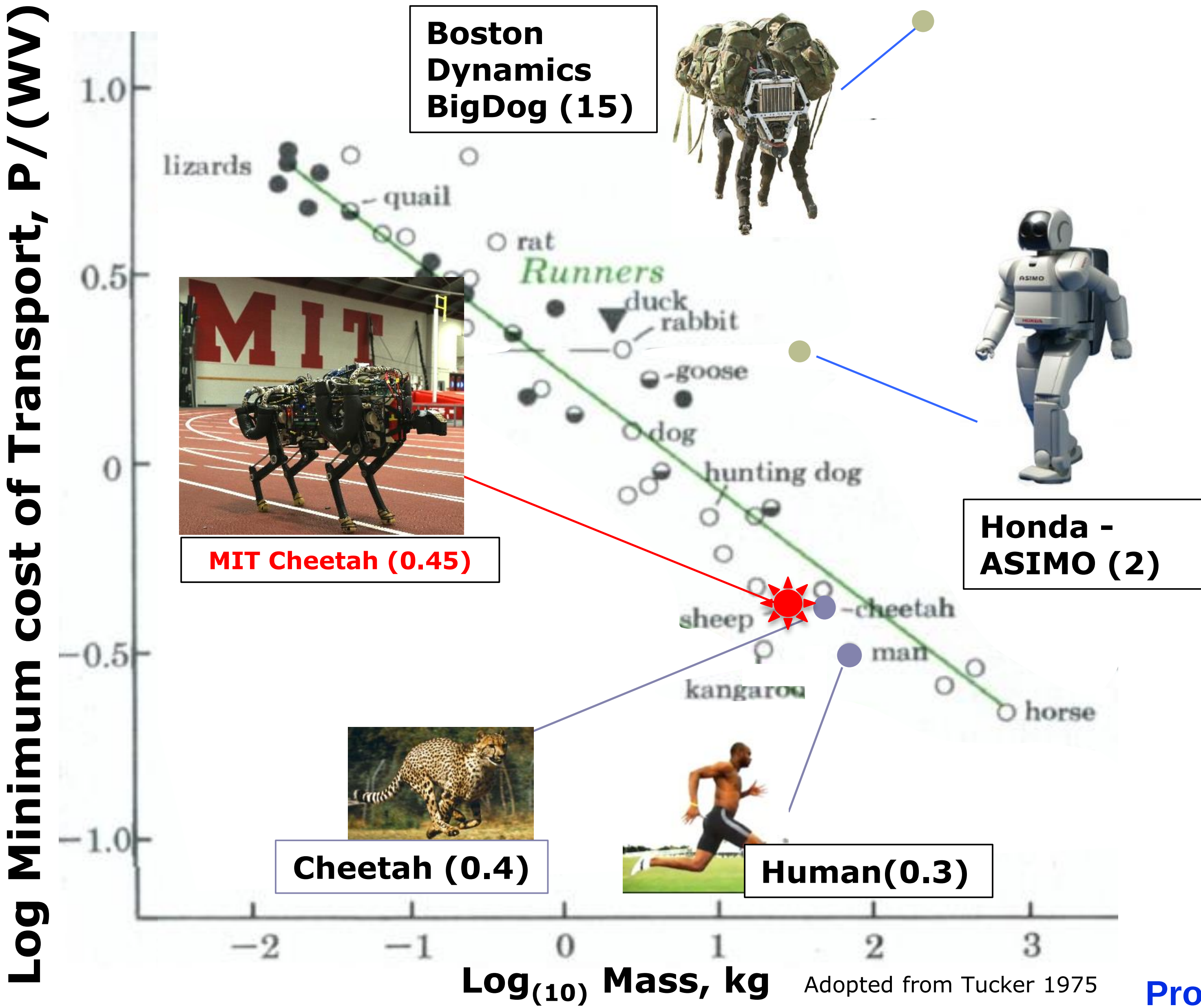


Physical interaction is key to expanding the applications of robots in NPPs:

- Advanced legged systems can access 'hard to reach' spaces
- Beyond position controlled machine, dynamic manipulation through novel tele-operation interface with force feedback
- Routine inspection via autonomous navigation
- Replacement of security guards
- In the long-term (e.g. decommissioning) robots can be as efficient as human

Prof. S. Kim

Robots - The MIT Edge (2)



Adopted from Tucker 1975

Prof. S. Kim

3D Printing of NPP Components

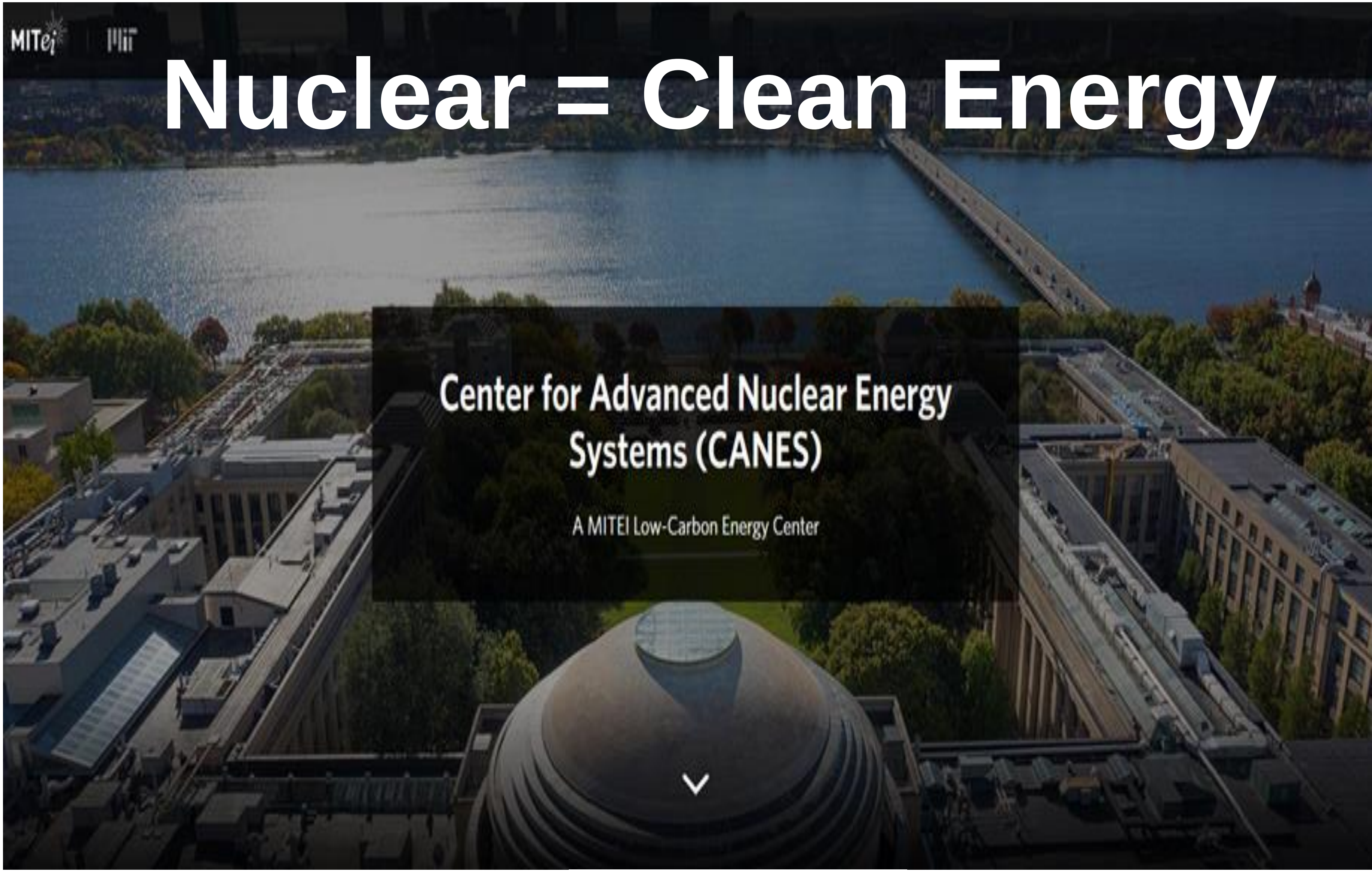
Fabricate nuclear components with complex geometries without welding. Nuclear QA available from weapons program

CFD-designed, 3D-printed components
Use of CFD to drive the design of fuel assemblies, core internals, entire components for performance optimization, not fabrication

3D printing of composite materials
Tailored properties for corrosion resistance and/or radiation damage resistance, e.g., get a sound bond between a HCP and BCC Zry material with large composition differences by grading the chemistry

Profs. N. Fang, E. Baglietto, R. Ballinger, A. Slocum, D. Whyte

Nuclear = Clean Energy



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science : systems : society