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

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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.
• Landis Young Member Engineering Achievement Award, American Nuclear Society, 2011.
• Best Paper Award at the 1st Micro/Nanoscale Heat Transfer Int. Conf., Tainan, Taiwan, January 6-9, 2008
• 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
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 Mm³/day, produced with RO (3.5 kWh/m³) and 90% capacity factor
WHY WE LIKE NUCLEAR
Nuclear plants require much less fuel than fossil plants and emit no CO₂

Fuel energy content

**COAL (C):** \[ C + O_2 \rightarrow CO_2 + 4 \text{ eV} \]

**NATURAL GAS (CH}_4):** \[ CH_4 + O_2 \rightarrow CO_2 + 2H_2O + 8 \text{ eV} \]

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

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

**COAL (40% efficiency):**
\[ 10^9/(0.4\times 4\times 1.6\times 10^{-19}) \approx 3.9 \times 10^{27} \text{ C/sec} (=6750 \text{ ton/day}) \]

**NATURAL GAS (50% efficiency):**
\[ 10^9/(0.5\times 8\times 1.6\times 10^{-19}) \approx 1.6 \times 10^{27} \text{ CH}_4/\text{sec} (=64 \text{ m}^3/\text{sec}) \]

**NUCLEAR (33% efficiency):**
\[ 10^9/(0.33\times 200\times 1.6\times 10^{-13}) \approx 1.0 \times 10^{20} \text{ }^{235}\text{U}/\text{sec} (=3 \text{ kg/day*}) \]

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

<table>
<thead>
<tr>
<th>Resource type and size [Million tonnes U]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redbook Identified (Reasonably Assured + Inferred)</td>
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<tr>
<td>7.6</td>
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</tbody>
</table>

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 km² 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.

Low-carbon electricity supply: Nuclear has scaled much faster

(average annual increase in zero-carbon kilowatt hours per capita during peak decade for nuclear (blue) and renewable (green) electricity generation)

*For nuclear, the 10-year period of most rapid scale-up; for solar and wind, the most recent 10-year period.*
There are >440 nuclear power plants worldwide mostly built in a period of only 25 years

Courtesy of MIT graduate student Mark Reed
67 new reactors are in various stages of construction

- Olkiluoto – Finland
- Flamanville – France
- Rostov – Russia
- Shimane – Japan
- Lungmen – Taiwan
- Taishan – China
- Kudankulam – India
- Shin kori – S. Korea
Nuclear constitutes a large near-term business opportunity

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

$740 Billion Global Nuclear Energy Market Over Next 10 Years

Sources: International Atomic Energy Agency; World Nuclear Association; U.S. Department of Commerce
Nuclear is already the largest emission-free electricity source in the US and the EU by far.

Sources of Emission-Free Electricity 2014

- Nuclear 62.9%
- Solar, Wind & Geothermal 17.1%
- Hydro 19.9%

US data

~595,000,000 ton of CO₂ emissions (equivalent to 135 million cars) avoided in the US in 2014.
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)
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.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capacity Factor (%)</th>
<th>Range of Levelized Costs (2013 $/MWh)</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Dispatchable</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Combined Cycle</td>
<td>87</td>
<td>68.6</td>
<td>72.6</td>
</tr>
<tr>
<td>New Nuclear</td>
<td>90</td>
<td>91.8</td>
<td><strong>95.2</strong>*</td>
</tr>
<tr>
<td>Advanced Coal (IGCC with CCS)</td>
<td>85</td>
<td>132.9</td>
<td>144.4</td>
</tr>
<tr>
<td><strong>Intermittent</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>35</td>
<td>65.6</td>
<td>73.6</td>
</tr>
<tr>
<td>Utility-Scale Solar PV</td>
<td>25</td>
<td>97.8</td>
<td>125.3</td>
</tr>
</tbody>
</table>

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

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

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<table>
<thead>
<tr>
<th>Project Cost $/kW (2016 Dollars)</th>
<th>Hinkley Point C</th>
<th>NuGen Moorside</th>
<th>US AP1000s</th>
<th>Japan</th>
<th>UAE Barakah</th>
<th>China AP1000s</th>
<th>Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0</td>
<td>$8,300 - $9,600</td>
<td>$4,400 - $8,700</td>
<td>$6,000 - $7,800</td>
<td>$4,200 - $6,100</td>
<td>~$3,900</td>
<td>~$3,100</td>
<td>$2,200 - $2,600</td>
</tr>
<tr>
<td>Units included</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>

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

Prefab reinforced concrete

Advanced robotics to reduce # of operators and guards

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

- Hydrogen generation
- Load following
- Hydrogen generation

Couple to inexpensive energy storage

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

Socially unacceptable

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
- Non-volatile, inert coolants
- Offshore siting
- Risk-informed regulations
WHAT MIT CAN DO
• 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

“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.”

Rafael Reif (MIT President)

Bob Armstrong (MITEI Director)
Center for Advanced Nuclear Energy Systems (CANES)

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

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

Founder: Mujid Kazimi

Director: Jacopo Buongiorno

Co-Director: John Parsons
CANES Research Volume ~$10M/year
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

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<tr>
<th>Performance Requirements</th>
<th>Deployment</th>
<th>Applications and Stakeholders</th>
</tr>
</thead>
</table>
| **Superior Economics**                   | **Near Term (<15 years)**: Baseload ALWRs (with cheap storage and/or syn fuel production) | • Baseload electricity generation (power generators)  
• Electrification of transportation sector (automotive industry, power generators)  
• Synthetic fuel and H₂ production (energy companies)  
• Energy-hungry businesses (manufacturing, smelters, data centers) |
|                                          | **Mid Term (15-35 years)**: Liquid-salt reactors, Offshore floating reactors, Liquid-metal fast reactors, High-temp gas reactors |                                                                                               |
| **Superior Safety**                      |                                                                           | • Baseload electricity generation (power generators)  
• Electrification of transportation sector (automotive industry, power generators)  
• Synthetic fuel and H₂ production (energy companies)  
• Energy-hungry businesses (manufacturing, smelters, data centers) |
|                                          |                                                                           |                                                                                               |
| **Superior Sustainability**              | **Deep boreholes disposal of spent fuel**                                 | • High-level waste management (drilling, mining companies)  
• Prevent proliferation of nuclear weapons (IAEA, governments) |
|                                          | **Regional enrich. centers; domestic fuel banks**                         |                                                                                               |
|                                          | **Regional fuel take-back centers**                                       |                                                                                               |
| **21st Century Technologies Applied to Nuclear Plants** | **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)

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

Builds upon existing technology

**Fuel:** TRISO particle fuel, no failure up to $\sim 1650^\circ$C, strongly negative Doppler feedback

**Coolant:** FLiBe liquid salt, low-pressure, chemically inert, large margin to boiling ($1430^\circ$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
FHR with Nuclear Air-Brayton Combined Cycle (NACC)

Stored Heat and/or Natural Gas

Base-Load Reactor

Gas Turbine

- 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

Dr. C. Forsberg
Synthetic Fuels and H₂ 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)

\[
\text{H}_2 + \text{CO} \rightarrow \text{H}_2\text{O and/or CO}_2
\]

Electricity to grid

Nuclear, Solar, Wind

Heat, Electricity

H₂O and/or CO₂

Solid Oxide Electrolysis Cell

Coal Power Plant

Syn-gas for liquid fuels synthesis

Refineries, fertilizers, fuel cells, seasonal storage (in caverns)

H₂ + O₂

Hydrogen for

Water

Electricity to grid

H₂ + CO

Syn-gas for liquid fuels synthesis

Profs. B. Yildiz, A. Ghoniem
Navy’s process to make jet fuel from seawater

- **Electrolytic Cation Exchange Module (E-CEM)** simultaneously extracts CO₂ (92% efficiency) and produces H₂ from seawater (no chemicals needed)
- Two-step catalytic process turns CO₂ and H₂ into jet fuel

\[ \text{Electricity} + \text{Water} + \text{CO}_2 \rightarrow \text{Fuel} \]

- 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
- CO₂ 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 currently used in NPPs:
- Specialized machines for specific tasks
- Inspection purposes
- Limited mobility
- Quasi-static position control
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
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

Center for Advanced Nuclear Energy Systems (CANES)
A MIT-IE Low-Carbon Energy Center

NSE
Nuclear Science and Engineering

MIT Energy Initiative