What are the key challenges for nuclear and how to address them
- Findings from a new MIT study -

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Director, Center for Advanced Nuclear Energy Systems
First challenge: don’t lose ground
Existing NPPs are approaching the end of their original license

Decommission vs. License extension

- Lose jobs and tax revenues
- Emissions increase
  US examples: Vermont Yankee, SONG, Pilgrim, Diablo, etc.

- Investment needed
- Will plant be profitable?
License extension for current NPPs is usually a cost-efficient investment with respect to emission-equivalent alternatives (the example of Spain)

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</tr>
</thead>
<tbody>
<tr>
<td>[1] Incremental Capacity (MW)</td>
<td>7,117</td>
<td></td>
<td></td>
<td>109,800</td>
<td>30,160</td>
<td>49,134</td>
<td>32,411</td>
</tr>
<tr>
<td>[2] Incremental Generation (GWh)</td>
<td>46,015</td>
<td></td>
<td></td>
<td>46,011</td>
<td>46,014</td>
<td>46,838</td>
<td>46,014</td>
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<tr>
<td>[3] Incremental Capacity Factor</td>
<td>74%</td>
<td></td>
<td></td>
<td>5%</td>
<td>17%</td>
<td>11%</td>
<td>16%</td>
</tr>
<tr>
<td>[4] Incremental Unit Cost (€/MWh)</td>
<td>34.96</td>
<td></td>
<td></td>
<td>157.02</td>
<td>61.24</td>
<td>76.27</td>
<td>60.95</td>
</tr>
<tr>
<td>[5] Incremental System Cost, gross annual (€ millions)</td>
<td>1,609</td>
<td></td>
<td></td>
<td>7,225</td>
<td>2,818</td>
<td>3,572</td>
<td>2,804</td>
</tr>
<tr>
<td>[6] Incremental System Cost, gross PV 10 years (€ millions)</td>
<td>11,298</td>
<td></td>
<td></td>
<td>50,743</td>
<td>19,793</td>
<td>25,091</td>
<td>19,697</td>
</tr>
<tr>
<td>[7] Difference to Nuclear (€ millions)</td>
<td></td>
<td></td>
<td></td>
<td>39,446</td>
<td>8,495</td>
<td>13,794</td>
<td>8,399</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>349%</td>
<td>75%</td>
<td>122%</td>
<td>74%</td>
</tr>
</tbody>
</table>

License extension for all 7 reactors

All reactors are shutdown and replaced by renewables + batteries to keep same emissions

Preserving the existing NPP fleet in the US will require compensating it for its zero-carbon value.

- A $12-17/MWh credit is enough to keep US nuclear power plants open.
- Zero Emission Credits are doing the job in NY, IL and NJ.
- Approach endorsed also by some nuclear-skeptical orgs (e.g., Union of Concerned Scientists).
For new NPPs it is all about cost
Why are new NPPs in the West so expensive and difficult to build?

- >90% detailed design completed before starting construction
- Proven NSSS supply chain and skilled labor workforce
- Fabricators/constructors included in the design team
- A single primary contract manager
- Flexible regulator can accommodate changes in design and construction in a timely fashion

ASIA

- Started construction with <50% design completed
- Atrophied supply chain, inexperienced workforce
- Litigious construction teams
- Regulatory process averse to design changes during construction
Aggravating factors

Construction labor productivity has decreased in the West
Construction and engineering wages are much higher in the US than China and Korea

Estimated effect of construction labor on OCC (wrt US):
-$900/kWe (China)
-$400/kWe (Korea)

Source: Bob Varrin, Dominion Engineering Inc.
Where is the cost of a new NPP?

- Civil works, site preparation, installation and indirect costs (engineering oversight and owner’s costs) dominate overnight cost
- Schedule and discount rate determine financing cost

Sources:
- APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
- EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication, 2017
What innovations could make a difference?

- Standardization on multi-unit sites
- Seismic Isolation
- Modular Construction Techniques and Factory/Shipyard Fabrication
- Advanced Concrete Solutions

<table>
<thead>
<tr>
<th>Work Structure</th>
<th>Rebar arrangement</th>
<th>Form work (assembling)</th>
<th>Placing concrete</th>
<th>Form work (removal)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RC</strong></td>
<td></td>
<td><strong>Wooden form</strong></td>
<td><strong>Concrete</strong></td>
<td><strong>Concrete</strong></td>
</tr>
<tr>
<td><strong>28days</strong></td>
<td>13days</td>
<td>7days</td>
<td>4days</td>
<td>4days</td>
</tr>
<tr>
<td><strong>SC</strong></td>
<td></td>
<td><strong>Steel plate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>14days</strong></td>
<td>—</td>
<td>10days</td>
<td>4days</td>
<td>—</td>
</tr>
</tbody>
</table>

Applicable to all new reactor technologies
With these innovations it should be possible to:

- Shift labor from site to factories ⇒ reduce installation cost
- Standardize design ⇒ reduce licensing and engineering costs + maximize learning
- Shorten construction schedule ⇒ reduce interest during construction

In other industries (e.g. chemical plants, nuclear submarines) the capital cost reduction from such approaches has been in the 10-50% range
The reward

The business opportunity for nuclear expands dramatically, even at modest decarbonization targets, if its cost decreases.
Societal concerns about NPP safety and HLW
Nuclear actually has the lowest public health impact of all energy sources

~13,000 premature deaths annually in the U.S. from coal production and combustion
4-7 millions worldwide

Source: https://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/#3593fadf709b

(includes Chernobyl, Fukushima)
Fukushima has changed perceptions about nuclear energy once again

New safety goals are in order:

• Extend coping time during station blackout (post-Fukushima retrofits are doing the job + ATF will help further)

• Demonstrate passive safety with ‘infinite’ coping time

• Eliminate need for evacuation of locals after severe accidents
One person’s total lifetime volume of HLW if they used nothing but nuclear energy for their whole life

The volumes are small!
Current practice in the US

- Spent fuel in storage pools for 5-10 years
- Then transferred to sealed dry casks: 80 casks needed for all spent fuel produced by a 1000-MW reactor in 60 years (again small volumes)
- Dry casks are completely safe to handle and last for decades with minimal maintenance
Ultimate disposal is in geological repositories

Robust technical options are available (excavated tunnels or deep boreholes); challenges are always political, with examples of success (Finland, Sweden) and failure (U.S.)
Value proposition for advanced reactors
A richer set of potential missions:
- cheap grid-connected electricity (with flexible ops)
- process heat and high temperature applications
- microreactors for off-grid electricity and heat
- desalination

Small Modular Reactors

High Temperature Gas-Cooled Reactors

+ other Gen4
A small (but not insignificant) potential market for nuclear heat

~240 million metric tons of CO₂-equivalent per year (>7% of the total annual U.S. GHG emissions)

Methodology:
- EPA database for US sites emitting 25,000 ton-CO₂/year or more
- Site must need at least 150 MWₜₜ of heat
- Nuclear heat delivered at max 650°C (with HTGR technology)
- At least 2 reactors per site for assured reliability
- Heat from waste stream not accessible
- Costs not evaluated

Hydrogen and/or synfuels could be the game changer for nuclear heat
Demonstrated inherent safety attributes:
- No coolant boiling
- High thermal capacity
- Strong negative temperature/power coefficients
- Strong fission product retention in fuel, coolant and moderator
- Low chemical reactivity

Engineered passive safety systems:
- Heat removal
- Shutdown

= 

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

Design certification of NuScale in the US is showing NRC’s willingness to value new safety attributes
The jury is still (very much) out on the economic potential of advanced reactors

<table>
<thead>
<tr>
<th>Cost ($/kWe)</th>
<th>HTGR</th>
<th>SFR</th>
<th>FHR (Large)</th>
<th>FHR (Small)</th>
<th>MSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Size</td>
<td>4 x 600 MWth</td>
<td>4 x 840 MWth</td>
<td>3400 MWth</td>
<td>12 x 242 MWth</td>
<td>2275 MWth</td>
</tr>
<tr>
<td>Design Stage</td>
<td>Conceptual approaching Preliminary</td>
<td>Conceptual approaching Preliminary</td>
<td>Early conceptual</td>
<td>Early conceptual</td>
<td>Early conceptual</td>
</tr>
<tr>
<td>Direct Cost</td>
<td>2400</td>
<td>2500</td>
<td>2100</td>
<td>2300</td>
<td>2500</td>
</tr>
<tr>
<td>Indirect Cost</td>
<td>1400</td>
<td>1600</td>
<td>1400</td>
<td>1300</td>
<td>1700</td>
</tr>
<tr>
<td>Contingency</td>
<td>800</td>
<td>800</td>
<td>1100</td>
<td>1100</td>
<td>1200</td>
</tr>
<tr>
<td>Total Overnight Cost</td>
<td>4600</td>
<td>4900</td>
<td>4600</td>
<td>4700</td>
<td>5400</td>
</tr>
<tr>
<td>Interest During Construction</td>
<td>600</td>
<td>700</td>
<td>600</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>Total Capital Invested</td>
<td>5200</td>
<td>5600</td>
<td>5200</td>
<td>5400</td>
<td>6100</td>
</tr>
</tbody>
</table>

1. E. Ingersoll, "International Nuclear Project Costs, Proprietary and Confidential
Don’t believe any cost estimates from vendors until design is mature (rule of thumb: ~2 million man-hours).
What stifles innovation in the nuclear industry?

- Current large, stick-built, baseload product is the perfect storm of negative attributes
- Need paradigm shift to smaller, serial-built systems with broader mission and recognized low-carbon value
High upfront costs and long time to see return on investment for new reactor technologies

Early government support is needed.

Four “levers”:

- Share R&D costs
- Share licensing costs
- Milestone payments
- Production credits
Take-away messages from the MIT study

- The opportunity is carbon
- The problem is cost
- There are ways to reduce it
- Government’s help is needed to make it happen
The Future of Nuclear Energy in a Carbon-Constrained World

AN INTERDISCIPLINARY MIT STUDY

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

This study is supported by generous grants and donations from

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James Del Favero
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