Market and economic assessment of nuclear power – focus on Canada and USA

Edward Kee
The NECG slides that follow are not a complete record of this presentation and discussion. The views expressed in these slides and the discussion of these slides may not be comprehensive and may not reflect the views of NECG’s clients or the views of my colleagues.
Introduction

- Edward Kee
  - CEO and Principal Consultant – NECG
  - Affiliated Expert – NERA Economic Consulting

- Market and economic assessment of nuclear power

- Focus on Canada and USA
Conclusion/Summary

- U.S. existing nuclear power threatened
  - Private ownership and electricity markets
  - Low natural gas prices + subsidized renewables

- No new nuclear in U.S. and Canada
  - Vogtle and Summer approved a decade ago

- Loss of nuclear power will
  - Reduce nuclear industrial capability
  - Lower nonproliferation influence
  - Increase reliance on natural gas generation
How nuclear power works:

*power from fission*
How nuclear power works: nuclear fuel cycle

- Enrichment
- Conversion
- Fuel fabrication
- Reprocessing
- Power generation
- Spent fuel storage
- Waste disposal
- Milling
- Mining

PHWR
How nuclear power works: pros and cons

**Pros**
- High power density
- Long life (60+ years)
- No emissions
- Reliable, dispatchable
- Stable production cost

**Cons**
- High capital cost, long construction period
- Public fear and opposition
- Decommissioning and SNF funded by owner
- Specialized operators and managers
- Nuclear safety regulator oversight
Global nuclear power: operating reactors

- USA
- France
- Japan
- China
- Russia
- Korea
- India
- Canada
- UK
- Ukraine

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Global nuclear power: reactors under construction

- China
- Russia
- India
- USA
- Korea
- Japan
- Ukraine
- France
- UK
- Canada

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Canadian nuclear fleet: operational units

- **Bruce**
  - A: 4 reactors; 750 MWe
  - B: 4 reactors; 817 MWe

- **Darlington** – 4 reactors; 878 MWe

- **Pickering** – 6 reactors; 515 MWe
  - Units 2 & 3 in permanent shutdown

- **Point Lepreau** - 1 reactor; 660 MWe
Arkansas Nuclear 1&2
Beaver Valley 1&2
Braidwood 1&2
Browns Ferry 1&2&3
Brunswick 1&2
Byron 1&2
Callaway
Calvert Cliffs 1&2
Catawba 1&2
Clinton
Columbia
Comanche Peak 1&2
Cooper
D.C. Cook 1&2
Davis-Besse
Diablo Canyon 1&2
Dresden 2&3
Duane Arnold
Farley 1&2
Fermi 2
FitzPatrick
Ginna
Grand Gulf 1
Harris 1
Hatch 1&2
Hope Creek 1
Indian Point 2&3
La Salle 1&2
Limerick 1&2
McGuire 1&2
Millstone 2&3
Monticello
Nine Mile Point 1&2
North Anna 1&2
Oconee 1&2&3
Oyster Creek
Palisades
Palo Verde 1&2&3
Peach Bottom 2&3
Perry 1
Pilgrim 1
Point Beach 1&2
Prairie Island 1&2
Quad Cities 1&2
River Bend 1
Robinson 2
Saint Lucie 1&2
Salem 1&2
Seabrook 1
Sequoyah
1&2
South Texas
Summer 1
Surry 1&2
Susquehanna 1&2
Three Mile Island
1
Turkey Point 3&4
Vogtle 1&2
Waterford 3
Watts Bar 1&2
Wolf Creek 1

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# U.S. nuclear fleet: companies & status

<table>
<thead>
<tr>
<th>Company/operator</th>
<th>Operating reactors</th>
<th>Under construction</th>
<th>M (merchant)</th>
<th>R (regulated)</th>
<th>P (public power)</th>
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<tr>
<td></td>
<td>#</td>
<td>MWe</td>
<td>#</td>
<td>MWe</td>
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<td>Entergy</td>
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<td>FPL Group</td>
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<td>Southern Co</td>
<td>6</td>
<td>5,817</td>
<td>2</td>
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<td>Dominion</td>
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<td>2,520</td>
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<td>Luminant</td>
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<td>2,400</td>
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<td>Pacific Gas &amp; Electric</td>
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<td>2,300</td>
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<td>Indiana Michigan Power Co (AEP)</td>
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<td>2,069</td>
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<td>Union Electric Co. (Ameren Missouri)</td>
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<td>1,193</td>
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<td>DTE Electric Co.</td>
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<td>1,124</td>
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<td>R</td>
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<td>South Carolina Electric &amp; Gas</td>
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<td>971</td>
<td>2</td>
<td>2,234</td>
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<td>Nebraska Public Power District</td>
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<td>766</td>
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<td>P</td>
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</table>
U.S. nuclear fleet: total operating capacity

Source: NECG nuclear database; EIA AEO; NECG analysis
Electricity industry issues: 
*industry structure*

![Diagram of electricity industry structure](image)

- **Investors**
  - Power Plants
  - System Dispatch
  - TRANSMISSION
  - DISTRIBUTION
  - RETAIL SERVICES

- **Government**
  - Electricity Ministry
  - Citizens and taxpayers

- **Consumers**
  - MWh
  - $
Electricity industry issues: Canadian industry structure

- **Canadian nuclear power plants**
  - Mostly owned by government utilities
  - Similar to public power utilities in the US
  - Little or no electricity market risk to revenue
  - Government decision-making is important

- **Bruce Power leases the assets at the Bruce nuclear power plant and sells electricity through long-term agreements with Ontario IESO**
Electricity industry issues:
U.S. electricity markets / regions

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Electricity industry issues: nuclear in electricity markets

- No revenue for key nuclear benefits
  - Capacity (except capacity market)
  - Clean (i.e., no CO2) operation
  - Long-term asset operation
  - Stable fuel costs
  - Generation fuel diversity

- Nuclear operating costs fixed; nuclear SRMC = zero
- No benefit from load following
- Overnight shut down difficult
- Bid as price taker – revenue linked to market prices
Electricity industry issues: negative market prices

- Negative prices allowed in electricity markets
  - Nuclear at max output between refueling outages, negative prices = payments to market operator
  - Happens when more inflexible generator offers than demand for electricity in a trading period
  - Inflexible (price taker or must run) bids will not be dispatched off by market operator

- Nuclear operating flexibility possible, but only makes economic sense if it stops negative prices
Electricity industry issues:
**U.S. state regulation of nuclear**

- **States that have not restructured**
  - Regulatory risk for nuclear plants
  - State disallowances in 1970s and 1980s, due to imprudence, excess capacity, cost overruns
  - Utility reluctance to invest in nuclear (or any large generating plant)

- **State role in regulatory approvals**
  - Integrated Resource Planning processes
  - Utility self-build option treated like a bid
  - Approval to build comes with high degree of certainty
## Nuclear economics: U.S. nuclear operating cost

<table>
<thead>
<tr>
<th>Category</th>
<th># of plants</th>
<th>Fuel cost ($/MWh)</th>
<th>O&amp;M cost ($/MWh)</th>
<th>Ongoing CapEx ($/MWh)</th>
<th>Total ($/MWh)</th>
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</thead>
<tbody>
<tr>
<td>U.S. average</td>
<td>58*</td>
<td>6.91</td>
<td>20.62</td>
<td>7.97</td>
<td>35.50</td>
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<tr>
<td><strong>Site configuration</strong></td>
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<tr>
<td>Single unit</td>
<td>23</td>
<td>7.10</td>
<td>27.15</td>
<td>10.26</td>
<td>44.52</td>
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<tr>
<td>Multiple unit</td>
<td>35</td>
<td>6.85</td>
<td>18.74</td>
<td>7.31</td>
<td>32.90</td>
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<tr>
<td><strong>Operator</strong></td>
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<tr>
<td>Single plant</td>
<td>12</td>
<td>7.49</td>
<td>22.05</td>
<td>9.30</td>
<td>38.84</td>
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<tr>
<td>Fleet operator</td>
<td>46</td>
<td>6.74</td>
<td>20.21</td>
<td>7.58</td>
<td>34.53</td>
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</tbody>
</table>

* Costs exclude shutdown plants and Fort Calhoun, Fitzpatrick and Pilgrim (that did not submit data to EUCG in 2015)

## Nuclear economics: U.S. nuclear capital cost & LCOE

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Size</th>
<th>Overnight capital cost ($/kW)</th>
<th>Overnight capital cost ($)</th>
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</thead>
<tbody>
<tr>
<td>Advanced CCGT</td>
<td>2 x 500</td>
<td>$956</td>
<td>$1.0 billion</td>
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<tr>
<td>Advanced nuclear</td>
<td>1 x 1,000</td>
<td>$6,108</td>
<td>$6.1 billion</td>
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</table>

Source: EIA AEO – Table 1b [https://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf](https://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf)

<table>
<thead>
<tr>
<th>Plant type</th>
<th>CF</th>
<th>Levelized capital cost ($/MWh)</th>
<th>Fixed O&amp;M ($/MWh)</th>
<th>Variable O&amp;M with fuel ($/MWh)</th>
<th>Transmission ($/MWh)</th>
<th>Total system LCOE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced CCGT</td>
<td>87%</td>
<td>15.4</td>
<td>1.3</td>
<td>38.1</td>
<td>1.1</td>
<td>55.8</td>
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<tr>
<td>Advanced nuclear</td>
<td>90%</td>
<td>75.0</td>
<td>12.4</td>
<td>11.3</td>
<td>1.0</td>
<td>99.7</td>
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Nuclear life extension: *CANDU Refurbishment*

- **Refurbishment**
  - Operate 30 yrs., refurbish, operate for 30 yrs.
  - Expensive and difficult
  - Learning from completed refurb projects

- **Status:**
  - Done – Wolsong-1, Point Lepreau, Bruce 1&2
  - In progress – Embalse
  - Planned – Bruce 3 - 8, Darlington
  - Pickering – extend operation without refurbishment
  - Gentilly – retired without refurbishment
Nuclear life extension: 
**U.S. approach**

- U.S. NRC operating licenses had 40 year term
- License renewal (i.e., to 60 years)
  - In 1998, first units (Calvert Cliffs) approved
  - 84 (of 99) units approved
  - Some applications under review
- Subsequent license renewal (i.e., to 80 years)
  - Studies and analyses
Nuclear operating flexibility: Concepts

- Zero marginal cost $\Rightarrow$ base load operation

- Several approaches
  - Regulation (i.e., frequency control)
  - Load following (daily)
  - Cycle on/off (weekly, seasonal)

- Technically feasible
  - France & Germany
  - New reactor designs capable
  - Reactor power variation vs steam dump
Nuclear operating flexibility: Bruce Power (steam dump)

Ontario - 4 to 10 Sep 2013

Wind output
Nuclear output reduction

Source: Scott Luft; Cold Air blog (http://coldair.luftonline.net/); based on archived data from 201336 Weekly Report (i.e., for 4 to 10 September 2013); NECG analysis
Nuclear operating flexibility:
U.S. experience

- Columbia (Energy Northwest) cycles to facilitate Pacific Northwest hydro system

- 2016 – Exelon Illinois units
  - Done when electricity market negative prices likely
  - Output reduced 10-15% based on steam plant ops
  - NRC discussion and approval
  - FERC and market operator discussion and approval
  - Market power issues?
Nuclear market failure: U.S. early retirement

- Units retired early
  - Kewaunee, Vermont Yankee, Fort Calhoun, Crystal River, San Onofre, Zion, etc.

- Planned early retirements
  - Palisades (2018)
  - Pilgrim (2019)
  - Oyster Creek (2019)
  - Indian Point 2 & 3 (2020, 2021) - maybe 2024, 2025
  - Diablo Canyon 1 & 2 (2024, 2025)

- Other units at risk in Ohio and elsewhere
Nuclear market failure: concept

- When the market (defined broadly) does not support activities with net public benefits

- Net public benefits: when total (public + private) benefits greater than total costs

- Activities or investments with private losses will not go forward, despite net public benefits

NECG Commentary #14 - [http://nuclear-economics.com/14-market-failure/](http://nuclear-economics.com/14-market-failure/)
Nuclear market failure: what is going on?

- Low electricity market prices

- U.S. practice and policy led to:
  - No compensation for public benefits of nuclear power
  - Separation of generating assets from rest of system
  - Decisions based on market value of commodity power

- When electricity and capacity prices are low:
  - Merchant nuclear plants lose money
  - Regulated & public power nuclear units increase rates
  - New nuclear projects look unprofitable
Nuclear market failure: no value for public benefits

Positive economic benefits

Environmental benefits

Electrical system benefits

Profits in electricity market
Nuclear market failure: ways to stop or fix it

- Role for government due to public benefits:
  - Costs on negative externalities (e.g., carbon pricing)
    - Difficult, too little, uncertain, linked to politics
    - Indirect benefits for nuclear in markets
    - Revenue neutrality in electricity markets (e.g., Finland)
  - Compensation to support positive externalities
    - Tax credits (similar to those for renewables)
    - New York and Illinois ZEC payments
    - UK incentives for new nuclear (e.g., Hinkley Point C)
  - Government ownership (Ontario, China, Russia, UAE, etc.)

Nuclear market failure: Pilgrim case study

690 MWe BWR

Original operating license expired in Jun 2012; renewed in 2012; new expiry Jun 2032

Plant is operating; plans to retire on 31 May 2019

ISO-NE market

- Estimated operating costs - $44.52/MWh
  $350,000/MWe/year, or $237 million/year

- Sale of electricity & capacity in ISO-NE market
  – Actual LMP at generator LMP node
  – Actual generator output
  – Actual SEMASS Zonal capacity prices
Nuclear market failure: Pilgrim financial performance
Nuclear market failure: 
**ISO-NE electricity & gas prices**

Nuclear market failure: *ISO-NE wholesale electricity prices*

- Lower demand, driven by milder weather, and lower natural gas prices led to six lowest monthly LMP in last two years:
  - Mar 2016: $17.20
  - Jun 2015: $19.61
  - Jun 2016: $21.24
  - May 2016: $21.29
  - Dec 2015: $21.35
  - Oct 2016: $22.72
Nuclear market failure: 
*Palisades early retirement*

- Profitable PPA (for Entergy)
- Electricity market price < generation cost
- Termination benefits for seller and buyer
# U.S. nuclear fleet: planned units

<table>
<thead>
<tr>
<th>Project</th>
<th>Type</th>
<th>State</th>
<th>Owner</th>
<th>NRC status</th>
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<tbody>
<tr>
<td>Fermi-3</td>
<td>Regulated</td>
<td>Michigan/MISO</td>
<td>DTE</td>
<td>COL issued</td>
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<tr>
<td>Levy County 1 &amp; 2</td>
<td>Regulated</td>
<td>Florida</td>
<td>Duke</td>
<td>COL issued</td>
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<tr>
<td>South Texas Project 3 &amp; 4</td>
<td>Merchant</td>
<td>ERCOT</td>
<td>NRG + CPS</td>
<td>COL issued</td>
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<td>W. S. Lee 1&amp;2</td>
<td>Regulated</td>
<td>South Carolina</td>
<td>Duke</td>
<td>COL issued</td>
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<td>North Anna-3</td>
<td>Regulated</td>
<td>Virginia/PJM</td>
<td>Dominion</td>
<td>COL under review</td>
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<td>Turkey Point 6 &amp; 7</td>
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<td>Florida</td>
<td>FPL</td>
<td>COL under review</td>
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<td>Comanche Peak 3 &amp; 4</td>
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<td>ERCOT</td>
<td>Luminant</td>
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<td>Harris 2 &amp; 3</td>
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<td>North Carolina</td>
<td>Duke</td>
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<td>Bell Bend</td>
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<td>PJM</td>
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<td>Bellefonte 3 &amp; 4</td>
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<td>Alabama</td>
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<td>NYISO</td>
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<td>Texas</td>
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<td>Clinton</td>
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# U.S. nuclear fleet: reactor designs

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<th>Reactor Design</th>
<th>Vendor/applicant</th>
<th>NRC status</th>
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<td>ABWR</td>
<td>GE</td>
<td>DC approved</td>
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<tr>
<td>ABWR (DCR Amendment)</td>
<td>STPNOC/Toshiba</td>
<td>DC approved</td>
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<tr>
<td>AP600</td>
<td>Westinghouse</td>
<td>DC approved</td>
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<tr>
<td>AP1000</td>
<td>Westinghouse</td>
<td>DC approved</td>
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<td>ESBWR</td>
<td>GE-Hitachi</td>
<td>DC approved</td>
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<td>System 80+</td>
<td>Westinghouse</td>
<td>DC approved</td>
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<td>ABWR (DCR renewal)</td>
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<td>APR1400</td>
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<td><strong>NuScale Power Module</strong></td>
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<td>ABWR (DCR renewal)</td>
<td>Toshiba</td>
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</tr>
</tbody>
</table>
Nuclear power innovation: reactor generations and status

Generation I
- Early Prototypes
  - Shippingport
  - Dresden
  - Magnox

Generation II
- Commercial Power
  - PWRs
  - BWRs
  - CANDU

Generation III
- Advanced LWRs
  - CANDU 6
  - System 80+
  - AP600

Generation III+
- Evolutionary Designs
  - ABWR
  - ACR1000
  - AP1000
  - APWR
  - EPR
  - ESBWR

Generation IV
- Revolutionary Designs
  - Safe
  - Sustainable
  - Economical
  - Proliferation Resistant and Physically Secure


Gen I | Gen II | Gen III | Gen III+ | Gen IV
Nuclear power innovation: new reactor designs

- Technology “lock-in” for light water reactors
  - 60+ years of building and operating
  - 16,000+ reactor-years of experience
  - High costs = response to learning and accidents

- “New” reactor concepts
  - Small Modular Reactor (SMR) + Gen IV designs
  - Real vs paper reactors – Rickover 1953 letter
  - Little or no construction/operating experience
  - Same electricity economics as large reactors

- Current drivers are governments, VC, patents
Nuclear power innovation: *SMR concept*

- **Small light water reactors**
  - Expected to be easier to license
  - Higher safety due to integral PWR reactor design, passive safety concepts and sub-grade construction
  - Reactor module removed for refueling/maintenance
  - Modularity and factory build
  - Multiple units on same site
  - Smaller source term (i.e., type and amount of radioactive material released due to an accident)

- **Lower requirement for access to cooling water**
Nuclear power innovation: Gen IV reactor concepts

Alternative reactor coolant approaches

- Higher level of intrinsic safety
- Avoid water-cooled reactor accidents
- Avoid many of the safety features required for water-cooled reactors
- May allow simpler, cheaper, safer nuclear power plants

Higher-temperature heat energy

- More efficient electricity generation
- Potential for smaller generator (e.g., helium Brayton cycle or supercritical CO2 cycle)
- May facilitate air cooling
- May allow use in industrial processes
Long-term nuclear power strategy

Nuclear fleet build in home country

Nuclear is low cost energy option

National nuclear vendor & supply chain

Nuclear learning & scale benefits

Export market sales + ownership

National nuclear industrial strategy

Nuclear industrial capacity development
Summary and conclusions:

- U.S. nuclear market failure caused by
  - Low electricity market prices
  - No compensation for nuclear public benefits
  - Merchant, regulated & public power at risk
  - Only government can fix this problem

- U.S. and Canada losing ground to national nuclear companies
Edward Kee

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Attachment/references

- NRC - http://www.nrc.gov/info-finder/reactors/


- ANS Special Committee on nuclear in the states
Reading: NECG publications

- http://nuclear-economics.com/resources/publications/

- Papers/Articles/Presentations
  - Market failure and nuclear power (BAS)
  - Carbon pricing not enough to help nuclear power (WNN)
  - Can nuclear succeed in liberalized power markets? (WNN)
  - U.S. nuclear industry in decline (NEI magazine)
  - Role of government in nuclear (KP paper)
  - Rescuing U.S. merchant nuclear power (Electricity Journal)
  - Impact of carbon pricing on nuclear power (IFNEC/NEA)
  - World experience - nuclear and electricity markets (JAIF)
  - IAEA workshop courses 2015
Reading: NECG Commentaries

- Selected Commentaries
  - #16 – Peak Nuclear Power
  - #15 – Existential Threat [to nuclear power]
  - #14 – Market Failure & Nuclear Power
  - #13 – Davis-Besse
  - #12 – Nuclear [operating] flexibility
  - #10 – Merchant nuclear – role for government
  - #5 – Revenue certainty
  - #4 – Lessons from Vermont Yankee early retirement
  - #3 – Nuclear base load
  - #2 – Short-Run Marginal Cost
  - #1 – Long-term assets in Short-term world

http://nuclear-economics.com/commentary/
Ownership equivalents
- Cooperative arrangements
- Regulatory participation agreements
- Pass-through PPA

Nuclear project finance
- PPA Guarantees needed
- Lender / investor requirements

Hedge Agreement (CfD)

Nuclear PPAs different
- Long development period
- Greater risk in development
- Longer term/tenor
- Low-probability, high-impact nuclear events
- Externalities (Decom, SNF, TPL insurance)
- Nuclear regulation
- Nuclear fixed/variable costs imply special pricing terms
How nuclear power works:

**high power density**

Fuel consumption (not to scale)

About 3 million metric tons of coal per year

About 20 metric tons of nuclear fuel per year

1,000 MWe coal-fired power plant

1,000 MWe nuclear power plant

Waste products (not to scale)

About 7 million metric tons of waste per year, including CO2 that is released into the air and as much as 200,000 metric tons of solid waste (ash)

About 20 metric tons of used nuclear fuel per year (much less if reprocessing used)

### Technology Comparison Table

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capacity Factor, %</th>
<th>Square Miles Needed for 1,000 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>32-47</td>
<td>260-360</td>
</tr>
<tr>
<td>Solar</td>
<td>17-28</td>
<td>45-75</td>
</tr>
<tr>
<td>Nuclear</td>
<td>90</td>
<td>1.3</td>
</tr>
</tbody>
</table>

The table summarizes the approximate land required by wind and solar technologies to match the electricity produced annually by a 1,000-MW nuclear power plant.

28 Feb 2017

Nuclear Power market and economic assessment - focus on Canada and USA
How nuclear power works: high safety

Deaths per trillion kWh

Nuclear has the lowest death print, even with the worst-case Chernobyl numbers and Fukushima projections, uranium mining deaths, and use of Linear No-Threshold (LNT) hypothesis.

Source: Forbes 10 Jun 2012 (http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/#46700df49d22); NECG analysis
Bruce Refurbishment Agreement

- Signed at end of 2015
- NERA team did fairness opinion -