THE NUCLEAR-CLIMATE CONNECTION

… how likely is it really?

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Can nuclear power limit climate change?

1. What needs to be replaced? What metric should we use?
   a. A power metric: replace $X$ TW - all coal plants?
   b. A CO$_2$ emission metric: eliminate $X$ GT/yr of emissions by 20xx?

2. How fast can we build?
   a. What are the key constraints?

3. How expensive would it be?
   a. What are the cost determinants?

4. What about the coupled technical/political issues?
   a. Safety
   b. Security
   c. Waste disposal
   d. Proliferation
   e. Public perception

5. Conclusions – can nuclear power participate in addressing climate change?
Before going any further: What we want is no longer very relevant …

1. There is an ongoing burst of nuclear power plant construction
   a. The “nuclear states”: China, India, S. Korea, Russia
   b. The “nuclear newcomers”: Abu Dhabi, Iran, Turkey, Vietnam, …

2. Their motivations for building are more varied than ours
   a. Energy security, desalination, national pride, preparing for potential “breakout” …

3. The builders and the operators are largely public/private joint ventures
   a. The electricity markets in which building is taking place are largely heavily regulated …

4. What about the political issues?
   a. In most cases, public opposition is minimal – or is suppressed …
To give you an idea of what’s going on …

<table>
<thead>
<tr>
<th>Country</th>
<th># power reactors operational</th>
<th># power reactors under construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>India</td>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td>Japan</td>
<td>43</td>
<td>2</td>
</tr>
<tr>
<td>Russia</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>S. Korea (ROK)</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>Taiwan</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>U.S.</td>
<td>99</td>
<td>4</td>
</tr>
<tr>
<td>World-wide totals:</td>
<td>449</td>
<td>60</td>
</tr>
</tbody>
</table>

Source: IAEA PRIS Database (as of October 2016)
What needs to be replaced (by ~2050)\(^1\)?

1. Total 2012-2014 generating capacity ~6,800 GW
   a. Coal ~ 40.4%, or 2,750 GW generating capacity
   b. Coal capacity factor ~41% (EIA data) > 1,230 GW actually generated on yearly average
   c. Nuclear ~ 5%, or 380 GW generating capacity\(^2\)
   d. World-wide nuclear capacity factor ~81%, U.S. 92.7% (2015)

2. Thus, we need
   a. ~1,330 GW nuclear to replace all existing coal plants
   b. ~330 GW nuclear to replace aging existing nuclear plants

3. All this assumes no growth in demand …

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\(^2\) World Nuclear Association (updated Aug. 2016); note that the nuclear production % is roughly twice as large, e.g., ~10% of total world energy production
How much CO$_2$ do we need to avoid emitting?

1. “Wedges” were introduced by Pacala & Socolow (2004)
   a. 1 wedge ~ 1 GtC/yr by 2054
   b. Socolow & Glaser (2009) revised the wedge definition …
   c. 1 new wedge ~ 4 GtCO$_2$/yr by 2050

2. To cap CO$_2$ emission requires 8 new wedges …

3. Following Socolow & Glaser:
   a. 1 new wedge ~ 1,500 GWe nuclear
How fast can we build?

1. Most of existing reactors were built in the 1960-80 period, when 222 reactors were put in service …
   a. In 1970-80, 139 reactors put into service …
   b. Conservatively: 14 reactors/year, worldwide

2. Modern reactors have larger capacities and capacity factors
   a. Gen III+ reactors (EPR, AP1000, APR-1400) name plate capacity ~ 1,000-1,400 MWe
   b. Average Gen II capacity factors world-wide ~80%
   c. If we assume reactors coming on line by 2020s are APR-1400-like, this translates to 20 GWe/year, with assumed capacity factor comparable to U.S. value (92.7%)
How expensive would it be? Part 1

<table>
<thead>
<tr>
<th>Technology</th>
<th>Size (MW)</th>
<th>Total Overnight Cost in 2015 (2015 $/kW)</th>
<th>Capacity Factor (Annual average, in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>2,234</td>
<td>6,108</td>
<td>92.7</td>
</tr>
<tr>
<td>Wind (land)</td>
<td>100</td>
<td>1,644</td>
<td>32.5</td>
</tr>
<tr>
<td>Wind (off-shore)</td>
<td>400</td>
<td>6,331</td>
<td>~41</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>100</td>
<td>4,168</td>
<td>28.6</td>
</tr>
<tr>
<td>Backup: Advanced CC with CCS</td>
<td>340</td>
<td>2,132</td>
<td>~42</td>
</tr>
</tbody>
</table>

All data from DOE/EIA (2015/2016 data), except for off-shore wind; off-wind data from Denmark (http://energynumbers.info/capacity-factors-at-danish-offshore-wind-farms)
How expensive would it be? Part 2

These numbers hide 2 important factors:

First, the experience of the vendor …

1. KEPCO/Abu Dhabi: 4 APR-1400 (4x1.4 GW), $25B-$30B construction cost (~4.5-5.4 k$/kW)
   a. On time, on budget, first reactor started 2012, on target to operate 2017
   b. KEPCO has build most of ROK’s 25 plants, now building 3 more …

2. AREVA/Finland: 1 EPR (1.6 GW), planned cost EUR 3B
   a. Hugely delayed (start 2005, planned finish 2009, but not yet finished, at least 9 years late), actual cost probably EUR 8.5B
   b. AREVA was created after one of its predecessors – Framatome – finished the last completed reactor in 2000 …

Second, the fact that intermittent energy sources require (very expensive) backup power sources that can ramp up & down on time scales ranging from seconds to the diurnal cycle … and the impact of variable capacity factors …
What have we not talked about – and can make a huge difference?

• Safety & security of operations – actual and perceived …
• Waste management …
• (Non-)proliferation …
• Public perception …
Safety — and the lessons learned from the past

Fukushima-Daiichi, 3 Mile Island, Chernobyl, ...

» Serious incidents are rare, but highly impactful ...
» All of the serious incidents were ultimately traced to a combination of construction design flaws, regulatory failure, and operator failure(s) ...

My view ...

» New construction must be based on Gen III+ or beyond designs: passive safety features exist and are key!
» A truly independent regulator, with serious enforcement powers, is essential – operating a nuclear plant is not the same as operating a gas-fired or coal-burning plant ...
  • Independence is not assured outside the U.S. – consider that an independent regulator was put in place in Japan only AFTER Fukushima-Daiichi …
  • Public acceptance will depend on trust – easy to lose, hard to rebuild …
Security – Part 1: The loci of grid vulnerability …
Security – Part 2:

Attacks on nuclear power plants can have 2 very different objective:

• Disabling the reactor plant itself …
  ◆ Not a very effective tactic: Challenging penetration, and far more vulnerable alternate targets with same destructive result
  ◆ Example: The Doel 4 reactor incident in Belgium (Aug. 2014)

• Gaining access to radioactive materials …
  ◆ Penetration to core and its fuel is very challenging – preferable target is the spent fuel storage …
  ◆ Removal of spent fuel is suicidal … more likely is a ‘dirty bomb’ incident

• The ‘insider’ threat …
Waste management …

Nuclear waste is dangerous, so that careful attention must be paid to store it for very long periods of time – millennia …

But: The U.S. – after some 60+ years of nuclear power, still does not have a formal, agreed-upon, and funded nuclear waste strategy

The same is true virtually everywhere else – with the exception of Sweden and Finland …

» The obstacle is not missing technology, but politics, and lack of political will …

» In the U.S., the Presidential Blue Ribbon Commission (BRC) recommendations remain to be implemented …
What about proliferation?

• The U.S. is not usually regarded as a proliferation threat, but economic pressures do drive technology developments that, when disseminated, can lead to serious proliferation concerns
  • Example: the development of laser separation

Elsewhere …

• The Nuclear Non-proliferation Treaty has been reasonably successful: 1 violation (N. Korea), 1 conflict (Iran) since it went into force
  • India, Israel, Pakistan never signed …

• Concern revolves around use of nuclear power as a ‘stalking horse’ for weapons and “breakout” (cf., Iran)
What about public perception?

• Nuclear energy began with high favorables …
  • “Our Friend the Atom”: Disneyland TV series episode in 1957 …
  • Eisenhower’s “Atoms for Peace” initiative …

• Inattention, lack of transparency, ignorance …
  • Technical weaknesses: Graphite as moderator??? Effects of low dosages?
  • Misunderstanding of regulatory regime: Independence required!!
  • India’s breakout, based on diversion of fissile material from a CANDU research reactor, part of “Atoms for Peace” …
  • Inevitable coupling of nuclear weapons and nuclear energy …
  • The 3 major accidents: Chernobyl, 3 Mile Island, Fukushima Daiichi

• Transparency works …
  • Finland & Sweden’s efforts for long-term nuclear waste storage …
  • Canada’s re-boot of their nuclear waste program …
So – let’s take the optimistic route, and assume that safety, security, waste disposal, and proliferation issues can be resolved – and that public acceptance issues are addressed, and do not become a world-wide obstacle …
What does all this imply? Part 1

1. Assuming a build rate of 20 GW/year:
   a. We can replace all existing coal plants and all existing nuclear power plants by ~2100 …
   b. If coal to be eliminated by a 2050 target, the maximum build rate would need to be at least doubled, to 40 GW/year

2. Again assuming a 20 GW/year build rate (and a nuclear capacity factor of 0.927):
   a. We can reach 1 new wedge in 80 years …
   b. If the target date is 2050, we would again have to slightly more than double the build rate …
What does all this imply? Part 2

Could nuclear do it all?

Clearly NO by 2050, or even 2100 – we need at least 8 wedges:

2050 target: required build rate ~380 reactors/yr
2100 target: required build rate ~150 reactors/yr

Similar calculations – with similar conclusions – apply to all other carbon-free energy production technologies …

Conclusions: In order to reach a carbon-free energy sector, we will need a mix of energy technologies – no one technology will save us – and we will need the political will to actually do this …
... which brings us to the discussion