Nuclear Power, Advanced Reactors and Sustainable Development

Bojan Petrovic
Nuclear and Radiological Engineering

EAS2803
Georgia Tech
April 1, 2010

Outline

- Some considerations related to sustainable development
- Present status of nuclear power worldwide
- Nuclear power reactors in the US
- Advanced reactors
- Small and medium power reactors
- Nuclear fuel cycle
- Conclusions
Sustainable development – some considerations

Energy is necessary for development, at the same time attention is needed with respect to:

- Environmental impact
- Emission of CO₂ → Climate change
- Particulates emission → health impact
- Resources
- Cost
- Waste
- Land area use
- ....

Energy use

ANNUAL PRIMARY ENERGY CONSUMPTION:
~11 Gtoe (billions ton of oil equivalent) or ~450 QBTU (BTU x 10¹⁵)

(depending on the scenario)
Meeting the growing energy needs

- Energy conservation OR new sources \(\Rightarrow\) need **BOTH**
  (Conserve as much as practical, still need more. In particular, developing nations.)
- Classical/fossil OR renewable/alternative \(\Rightarrow\) need **BOTH**
  Each as much as justified. Reasonable mix. Cannot afford otherwise.
- What is the best option?
  - No free lunch – each option has advantages/disadvantages!
  - Need **responsible** decision process – technical comparison of different options (based on well-defined metrics)

GHG Emissions

- More efficient technologies introduced, yet energy conservation per capita about constant (we want more and more?)
- Thus, total energy demand grows
- Underdeveloped countries cannot avoid increasing consumption

**GHG Emissions**

<table>
<thead>
<tr>
<th>FUEL CHAIN</th>
<th>(1990's)</th>
<th>(2005-2020)</th>
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</thead>
<tbody>
<tr>
<td>Lignite</td>
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<td>265 - 355</td>
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<tr>
<td>Coal</td>
<td></td>
<td>205 - 285</td>
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<tr>
<td>Oil</td>
<td></td>
<td>260 - 365</td>
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<tr>
<td>Natural Gas</td>
<td>85 - 120</td>
<td>250 - 285</td>
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<tr>
<td>Solar PV</td>
<td>5.5 - 7.6</td>
<td>105 - 120</td>
</tr>
<tr>
<td>Biomass</td>
<td>1.1 - 6.3</td>
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</tr>
<tr>
<td>Wind</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

Equivalent grams of carbon per kilowatt hour of electricity

Nuclear reactors generate electricity with very low emissions

Each year, U.S. nuclear power plants prevent 5.1 million tons of sulphur dioxide, 2.4 million tons of nitrogen oxide, and 164 million tons of carbon from entering the earth atmosphere
Contribution of nuclear power to reducing emissions

- Emissions from coal, oil and gas plants emit gases and produce ash
- By substituting nuclear power for fossil fuels, between 1973 and 2000:
  - Nuclear generation of electricity avoided the emission of 66.1 million tons of sulphur dioxide and 33.6 million tons of nitrogen oxides
- Each year, U.S. nuclear power plants prevent 5.1 million tons of sulphur dioxide, 2.4 million tons of nitrogen oxide, and 164 million tons of carbon from entering the earth atmosphere
- “Clean coal” technology may improve situation in the future, but has yet to be demonstrated

(Data provided by Nuclear Energy Institute)

Energy efficiency –
Life-Cycle Energy Ratio (Output/Input) for Energy Technologies

<table>
<thead>
<tr>
<th>ENERGY TECHNOLOGY</th>
<th>LIFETIME ENERGY RATIO AS OF OUTPUT</th>
<th>LIFETIME ENERGY OUTPUT PERCENT</th>
<th>REFERENCE</th>
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</thead>
<tbody>
<tr>
<td>Solar PV (utility)</td>
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<td>20</td>
<td>Uchiyama, 1996</td>
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<tr>
<td>LNG</td>
<td>6</td>
<td>17</td>
<td>Uchiyama, 1996</td>
</tr>
<tr>
<td>Wind</td>
<td>6</td>
<td>17</td>
<td>Uchiyama, 1996</td>
</tr>
<tr>
<td>Solar PV (roof top)</td>
<td>9</td>
<td>11</td>
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<td>Coal</td>
<td>17</td>
<td>6</td>
<td>Uchiyama, 1996</td>
</tr>
<tr>
<td>Nuclear (diffusion enrichment)</td>
<td>21</td>
<td>5</td>
<td>ERDA, 1976; Perry, 1977</td>
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<tr>
<td>Natural Gas-pipe</td>
<td>26</td>
<td>4</td>
<td>Kivisto, 2000</td>
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<tr>
<td>Wind</td>
<td>34</td>
<td>3</td>
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<tr>
<td>Hydro</td>
<td>50</td>
<td>2</td>
<td>Uchiyama, 1996</td>
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<tr>
<td>Nuclear (centrifuge enrichment)</td>
<td>59</td>
<td>2</td>
<td>ERDA, 1976; Perry, 1977</td>
</tr>
</tbody>
</table>

(source: ANS)

Nuclear power has very favorable output/input ratio
Environmental impact: Footprint (Land use)

- Energy produced by one 1 GWe nuclear power plant is ~8TWh/year
  - Nuclear power plant 1-2 (2) km²
  - Solar PV 20-80 (40) km²
  - Wind 50-800 (200) km²
  - Biomass 4,000-6,000 (5,000) km²

NOTE: Diluted energy density may present some limitations.
For example, the total world production of corn, if all converted to ethanol,
would substitute less than 1/3 of the U.S. current gasoline consumption …..

Nuclear power requires limited land area

Energy production cost

U.S. Electricity Production Costs
1995-2006, In 2008 cents per kilowatt-hour

2008
- Coal - 2.75
- Gas - 0.01
- Nuclear - 1.87
- Petroleum - 17.26

Nuclear power has low electricity production costs

(Source: NEI)
Energy production cost

Nuclear power – higher capital cost per installed peak MW partly offset by higher capacity factors

(Source: NEI)

Energy production cost volatility

- Cost of production in fossil plants significantly depends on fuel
- Nuclear power has limited sensitivity to fuel cost change

(Source: NEI)
True cost – including externalities

Study ExternE, performed in Europe (European Commission), examined external costs

<table>
<thead>
<tr>
<th>Country</th>
<th>Coal &amp; lignite</th>
<th>Peat</th>
<th>Oil</th>
<th>Gas</th>
<th>Nuclear</th>
<th>Biomass</th>
<th>Hydro</th>
<th>PV</th>
<th>Wind</th>
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<td>1-2</td>
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<td>2-3</td>
<td>0.3</td>
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<td></td>
<td></td>
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<tr>
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<td>0.2</td>
<td>3</td>
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<td>1-2</td>
<td>5</td>
<td>0.3</td>
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<tr>
<td>ES</td>
<td>2-4</td>
<td>2-5</td>
<td>1</td>
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<td>GR</td>
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<td>0.25</td>
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<tr>
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<td>0.3</td>
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<tr>
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<tr>
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<td>0.5</td>
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<td>1-2</td>
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<td></td>
<td>0.15</td>
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</tbody>
</table>

* sub-total of quantifiable externalities (such as global warming, public health, occupational health, material damage)
** biomass co-fired with lignites

Nuclear power and renewable sources have significantly lower external costs than fossil plants

Potential role of nuclear power in sustainable development

- Low emission
- Low land area use
- Favorable output/input energy factor
- Competitive cost
- Low external cost, thus low true total cost
- U/Th resources sizeable (on the order of hundred(s) years for once through fuel cycle, thousands years with reuse of irradiated fuel)
- Waste is a concern, but technologically manageable
- Several prominent “founding fathers” of the environmental movement, based on evaluating feasible alternatives, came to the position that nuclear power may offer a valid option to mitigate climate change
  - Patrick Moore - Greenpeace founder
  - Stewart Brand - Whole Earth Catalog founder
  - James Lovelock - Gaia theorist
  - Recent UN IPCC report (May 2007) acknowledges the potential role of nuclear power

Nuclear power has a role to play in sustainable development. Otherwise, it is difficult to imagine satisfying energy needs without significantly increasing the load on environment.
Nuclear Power Plants

Nuclear power plants – past/present/future

- Early Prototype Reactors:
  - Shippingport
  - Dresden, Fermi I
  - Magnox

- Commercial Power Reactors:
  - LWR-PWR, BWR
  - CANDU
  - AGR

- Advanced LWRs:
  - ABWR
  - System 80+
  - AP600

- Evolutionary Designs Offering Improved Economics for Near-Term Deployment
  - AP1000

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Timeline:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
A typical nuclear power plant (NPP) based on a loop-type PWR (Pressurized Water Reactor)

Worldwide use of nuclear power

- Major source of electricity in several countries

### Nuclear Power Units by Nation

<table>
<thead>
<tr>
<th>Nation</th>
<th># Units (in operation)</th>
<th>Net MWe (Total)</th>
<th>Nation</th>
<th># Units (in operation)</th>
<th>Net MWe (Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>2</td>
<td>935</td>
<td>Australia</td>
<td>1</td>
<td>976</td>
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<tr>
<td>Armenia</td>
<td>7</td>
<td>5,801</td>
<td>Belgium</td>
<td>7</td>
<td>5,801</td>
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<tr>
<td>Brazil</td>
<td>2</td>
<td>1,901</td>
<td>Bulgaria</td>
<td>2</td>
<td>1,906</td>
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<tr>
<td>Canada</td>
<td>22</td>
<td>15,164</td>
<td>China</td>
<td>11</td>
<td>8,694</td>
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<td>Czech Republic</td>
<td>6</td>
<td>3,574</td>
<td>Czech Republic</td>
<td>6</td>
<td>3,574</td>
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<tr>
<td>Finland</td>
<td>4</td>
<td>4,696</td>
<td>Germany</td>
<td>17</td>
<td>14,420</td>
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<tr>
<td>France</td>
<td>58</td>
<td>63,130</td>
<td>Germany</td>
<td>17</td>
<td>14,420</td>
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<tr>
<td>Germany</td>
<td>17</td>
<td>14,420</td>
<td>Hungary</td>
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<td>1,820</td>
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<tr>
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<td>17</td>
<td>3,732</td>
<td>India</td>
<td>17</td>
<td>9,232</td>
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<td>0</td>
<td>1</td>
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<tr>
<td>Japan</td>
<td>15</td>
<td>47,134</td>
<td>Japan</td>
<td>54</td>
<td>50,130</td>
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<tr>
<td>Mexico</td>
<td>2</td>
<td>1,369</td>
<td>Mexico</td>
<td>2</td>
<td>1,369</td>
</tr>
</tbody>
</table>

**Total:** 439 units, 375,043.4 GWe

### Nuclear Power Units by Reactor Type, Worldwide

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th># Units (in operation)</th>
<th>Net MWe (Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized light-water reactors (PWR)</td>
<td>265</td>
<td>244,701.1</td>
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<tr>
<td>Boiling light-water reactors (BWR)</td>
<td>92</td>
<td>84,720.3</td>
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<tr>
<td>Gas-cooled reactors, all types</td>
<td>18</td>
<td>9,794</td>
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<tr>
<td>Heavy-water reactors, all types</td>
<td>48</td>
<td>25,147</td>
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<tr>
<td>Graphite-moderated light-water reactors (LGR)</td>
<td>15</td>
<td>10,219</td>
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<tr>
<td>Liquid-metal-cooled fast-breeder reactors (LMFR)</td>
<td>1</td>
<td>550</td>
</tr>
</tbody>
</table>

**Total:** 439 units, 375,043.4 GWe

(source: ANS)
Nuclear power plants in the U.S.

- 104 operating reactors in 31 states
- 69 PWRs, 35 BWRs
- 102,800 MWe

(source: NEI)

Pressurized Water Reactor (PWR)

Boiling Water Reactor (BWR)

Nuclear power plants in the U.S.

- Mature technology
- Excellent operating record (~90% overall capacity factor)
- Improvement in operation (capacity factor) fully compensated “retirement” of older plants

(source: NEI)


Capacity Factor (%)

10 20 30 40 50 60 70 80 90 100


Total Generation

Nuclear Generation

32% Growth

47% Growth

21% Growth

112 plants

104 plants

(source: NEI/ANS/INL)
Status of existing nuclear power plants in the U.S.

- Economical
- Utilities interested to extend operation through license renewal

New nuclear power plants in the U.S.?

- No new orders for a long period of time
- However, recently 20+ new NPPs considered at 10+ sites
- Utilities preparing “Construction/Operating License” applications, EPC, ...
- Nuclear renaissance?
New nuclear power plants in the U.S.?  

<table>
<thead>
<tr>
<th>License Applicant</th>
<th>Reactor(s)</th>
<th>Location</th>
<th>Model</th>
<th>Startup Target</th>
<th>Licensing Status</th>
<th>Commercial Status</th>
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<tbody>
<tr>
<td>Accurate Energy</td>
<td>Callaway-2</td>
<td>Fountain, FL</td>
<td>U.S. EPR</td>
<td>Indefinite</td>
<td>Suspended, at applicant’s request</td>
<td>Vendor negotiations</td>
</tr>
<tr>
<td>Dominion</td>
<td>North Anna-3</td>
<td>Mineral, VA</td>
<td>(BWR)</td>
<td>2017</td>
<td>Direct EIS, Site EIS, Cell target 2011</td>
<td>Vendor bids under review</td>
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<tr>
<td>Detroit Edison</td>
<td>Fermi-3</td>
<td>Monroe, Mich.</td>
<td>ESBWR</td>
<td>2016 or later</td>
<td>COL target 2012</td>
<td>Vendor negotiations</td>
</tr>
<tr>
<td>Duke Energy</td>
<td>Lee-1, -2</td>
<td>Safford, S.C.</td>
<td>AP1000</td>
<td>2023 (FV1)</td>
<td>COL target 2013</td>
<td>Vendor negotiations</td>
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<tr>
<td>Entergy</td>
<td>River Bend-3</td>
<td>St. Francisville, La.</td>
<td>(FBR)</td>
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<td>Suspended, at applicant’s request</td>
<td>Vendor bids under review</td>
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<td>FPL Energy</td>
<td>Turkey Point-6, -7</td>
<td>Florida City, FL</td>
<td>AP1000</td>
<td>2020, 2022</td>
<td>Awarding review schedule</td>
<td>Vendor negotiations</td>
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<tr>
<td>Luminaid</td>
<td>Centracocha Rock-3, -4</td>
<td>Cinco Ranch, Texas</td>
<td>US-APWR</td>
<td>2016 or later</td>
<td>COL target 2012</td>
<td>Term sheet with vendor</td>
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<tr>
<td>MRG/STARRY</td>
<td>South Texas-3, -4</td>
<td>Palacios, Texas</td>
<td>ABWR</td>
<td>2016, 2017</td>
<td>COL target 2012</td>
<td>EPC contract signed</td>
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<tr>
<td>MidState/Finergy</td>
<td>Canal Gap-1</td>
<td>Pearl, Miss.</td>
<td>(FBR)</td>
<td>Indefinite</td>
<td>Suspended, at applicant’s request</td>
<td>Vendor bids under review; current status unknown</td>
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<td>Scottbrown, Ala.</td>
<td>AP1000</td>
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<td>Awarding site technical data</td>
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<td>Bellefonte</td>
<td>Danville, Pa.</td>
<td>EPR</td>
<td>2016</td>
<td>COL target 2012</td>
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<td>Progress Energy</td>
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<td>New Hill, N.C.</td>
<td>AP1000</td>
<td>2016 or later</td>
<td>COL target 2012</td>
<td>Vendor negotiations</td>
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<td>SCANA/Santee Cooper</td>
<td>Summer-2, -3</td>
<td>Parris, S.C.</td>
<td>AP1000</td>
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<td>COL target 2012</td>
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<td>Southern Nuclear</td>
<td>Wolf-3, -4</td>
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<td>VEC/El Paso Nuclear</td>
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<td>Lantana, FL</td>
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<td>COL target 2012</td>
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<td>Nine Mile Point-3</td>
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<td>Suspended, at applicant’s request</td>
<td>Vendor negotiations</td>
</tr>
</tbody>
</table>

(source: ANS)

Generation III+ Reactor Designs

(Examples: ABWR ➔ ESBWR
AP1000 – Advanced Passive PWR)
Generation III: ABWR (Advanced Boiling Water Reactor)

- Advanced Boiling Water Reactor - ABWR
- Developed by General Electric, Hitachi and Toshiba
- 1,300-1,400 MWe capacity
- 4 units constructed in Japan
- 4 units under construction in Taiwan and Japan

(source: GE / Hitachi)

Gen III+: ESBWR (Economic Simplified BWR)

(source: GE / Hitachi)
Gen III+: The AP-1000

AP1000 reactor system

- Simpler system configuration
- Greater margins in materials selected and size of components
- No reliance on availability of AC electrical power for safety function
- More time for operators to take action if transient event occurs
- Improved economics

(source: Westinghouse)
Passive safety systems eliminate components

(source: Westinghouse)

AP1000 passive core cooling system

- AP1000 has no reliance on AC power
  - Passive Decay Heat Removal
  - Passive Safety Injection
  - Passive Containment Cooling
- Long term safe shutdown state > 72 hours without operator action

(source: Westinghouse)
Modular design for simplified construction

- Constructed with 300 large modules
- Factory manufacture and assembly of modules
- Pre-testing and inspection prior to shipment
- 36 month construction schedule independently supported

(source: Westinghouse)

Advanced SMRs (Small/Medium Power Reactors)

Examples: Integral Advanced PWRs
- IRIS
- mPower
SMR / Grid-Appropriate Power Reactors

SMR = small/medium reactor = up to 300/700 MWe

- Why small/medium reactors (SMRs)?
- Rule of thumb: Largest size power plant shouldn’t be larger than ~10% of the grid capacity
- For a large 1,600 MWe unit $\rightarrow$ grid larger than 15 GWe needed. Many countries don’t have

- About 1/3 of currently operating reactors are SMRs
- About 1/3 of currently being built reactors are SMRs
- SMRs are performing safely and economically
- Large plants are not a feasible solution in all situations (countries/markets with limited grid or financial)

SMRs

Small/medium reactors
Strong international interest, coordinated through IAEA
Range of technological options

- LWR (light-water cooled reactor)
  - IRIS
  - mPower
  - nuScale
  - …..

- Non-LWR
  - 4S
  - PBMR
  - SVBR
  - …
EXAMPLE: IRIS Project

- IRIS project started as a U.S. DOE – Nuclear Energy Research Initiative (NERI) program in 1999.
- IRIS designed such to fulfill Gen IV objectives (safety, economics, proliferation resistance, waste management) using proven technology, with deployment by 2020 (earlier than other Gen IV systems)
- Energy markets in developing countries need near/mid-term smaller-power reactors

IRIS Fundamental Approach

- Simplicity
- Economy
- Safety

- IRIS uses proven light water technology
- Implements engineering innovations and new solutions, but no radical changes nor new technology development
- Simplicity ensures safety and economy and reliability
**IRIS**

- Advanced integral light water reactor
- Innovative, simple design
- Safety-by-design™ eliminates a number of accidents
- Capability of being licensed without emergency response requirements
- International team
- Anticipated competitive economics
- Cogeneration (desalination, district heating, synthetic fuel)
- NRC pre-application underway
- Design Certification testing program underway
- Interest expressed by several countries
- Anticipated commercially available: 2015 to 2017
- Very compact design on seismic isolators

---

**Integral Primary System Reactor**

- Simplifies design by eliminating loop piping and external components.
- Enhances safety by eliminating major classes of accidents.
- Compact containment and small NPP footprint enhances economics and security.

---

100-335 MWe/module
IRIS Design Features
Integral Vessel

- 100-335 MWe PWR
- Long Life core, up to 4 years
- 8 helical-coil steam generators
- 8 axial flow fully immersed primary coolant pumps
- Internal control rod drive mechanisms
- Integral pressurizer with large volume-to-power ratio
- Uses Safety-by-Design™ Approach

IRIS Enhanced (Three-Tier) Safety Philosophy

1. **Safety-by-Design™**
   Aims at eliminating by design possibility for accidents to occur. Eliminates systems/components that were needed to deal with those accidents.

2. **Passive Safety Systems**
   Protect against still remaining accidents and mitigate their consequences. Fewer and simpler than in passive LWRs.

3. **Active Systems**
   No active safety-grade systems are required. But, active non-safety-grade systems contribute to reducing CDF (core damage frequency).

IMPROVED SAFETY WITH SIMPLIFIED DESIGN
IRIS Plant Site Layout – Flexibility of Modular Deployment

- Basic configurations:
  - Single unit (335 MWe)
  - Twin unit (670 MWe)
  - Offered individually or in multiples
- Attractive economics. Cost of electricity competitive with other nuclear and non-nuclear sources
- Compact footprint (~1,000 ft by 1,500 ft for a 1,000 MWe site)
- For larger utilities, requiring at least 1,000 MWe, three single modules or two twin units.
- For smaller grids or developing countries, single units at different sites may be more practical.

Multiple twin-units
(2 twin-units, 1,340 MWe)

Economics of Modular Deployment

<table>
<thead>
<tr>
<th>Year from start</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRIS 1 335 MWe</td>
<td>Construction</td>
<td>Operation →</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>IRIS 2 335 MWe</td>
<td>Construction</td>
<td>Operation →</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>IRIS 3 335 MWe</td>
<td>Construction</td>
<td>Operation →</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

- Modular power plants enable staggered build
- Previous unit produces power and supports construction of the next unit
- Significantly reduced cash outflow as compared with a single large unit – may be a decisive consideration for smaller markets and countries with limited resources
- Limited financial exposure (limited capital at risk)
EXAMPLE: B&W mPower Reactor

- Babcock & Wilcox
- Modular
- Integral PWR
- 125 MWe
- 4.5 year cycle

Generation IV
“Generation IV”

- Initiated by DOE about 10 years ago
- Key requirements evolved over time, focusing on the following characteristics
  - Economics
  - Safety, security
  - Improved use of uranium/thorium resources
  - Improved waste management
  - Ability to transmute (“burn”) nuclear waste
  - Generally available after ~2030

GIF

- Generation-IV International Forum (GIF)
  - Thirteen members have signed the GIF Charter: Argentina, Brazil, Canada, People’s Republic of China, Euratom, France, Japan, Republic of Korea, the Russian Federation, Republic of South Africa, Switzerland, the United Kingdom and the United States.
  - Identified 6 types of reactor systems within Gen-IV of interest to GIF members:
    - VHTR – Very-High-Temperature Reactor
    - GFR – Gas-Cooled Fast Reactor
    - MSR – Molten-Salt Reactor
    - LFR – Lead-cooled Fast Reactor
    - SFR – Sodium-Cooled Fast Reactor
    - SCWR – Supercritical-Water-Cooled Reactor
  - US interest primary in VHTR and SFR, and Fuel Cycle
  - VHTR → NGNP (Next Generation Nuclear Plant)
Overview of Gen-IV Systems

Table 6.1 Overview of Generation IV nuclear energy systems

<table>
<thead>
<tr>
<th>System</th>
<th>Neutron spectrum</th>
<th>Coolant</th>
<th>Temp.</th>
<th>Fuel</th>
<th>Fuel cycle</th>
<th>Size (MWe)</th>
<th>Main uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFR (gas-cooled fast reactor)</td>
<td>fast</td>
<td>helium</td>
<td>850°C</td>
<td>235U &amp; MOX</td>
<td>closed, in-situ</td>
<td>258</td>
<td>electricity &amp; hydrogen</td>
</tr>
<tr>
<td>LFR (liquid-cooled fast reactor)</td>
<td>fast</td>
<td>Pb or Pb-Bi</td>
<td>550-800°C</td>
<td>235U &amp; MOX</td>
<td>closed, regional</td>
<td>50-150, 300-400</td>
<td>electricity &amp; hydrogen</td>
</tr>
<tr>
<td>MSR (molten salt reactor)</td>
<td>opothermal</td>
<td>fluoride salts</td>
<td>700-850°C</td>
<td>UF₆ in salt</td>
<td>closed, in-situ</td>
<td>1 000</td>
<td>electricity &amp; hydrogen</td>
</tr>
<tr>
<td>SFBR (sodium-cooled fast reactor)</td>
<td>fast</td>
<td>sodium</td>
<td>550°C</td>
<td>235U &amp; MOX</td>
<td>closed</td>
<td>300-1 800</td>
<td>electricity</td>
</tr>
<tr>
<td>SCWR (supercritical water-cooled reactor)</td>
<td>thermal/ fast</td>
<td>water</td>
<td>510-550°C</td>
<td>UO₂</td>
<td>Open/ closed</td>
<td>1 500</td>
<td>electricity</td>
</tr>
<tr>
<td>VHTR (very high temperature gas reactor)</td>
<td>thermal</td>
<td>helium</td>
<td>1 000°C</td>
<td>UO₂</td>
<td>open</td>
<td>250</td>
<td>hydrogen &amp; electricity</td>
</tr>
</tbody>
</table>

VHTR – Very High Temperature Reactor

- Gas-cooled (He)
- Very high exit temperature: 1000°C or 850°C
- Two “flavors”: - prismatic fuel - pebble-like fuel
- High temperature process heat
- Hydrogen production
- High thermodynamic efficiency
- Thermal spectrum
- Deep burn option
- Technological basis (HTGR - PB, FSV, AVR, HTTR, HTR-10, ...)

The Very High Temperature Reactor (VHTR) system uses a thermal spectrum and a once-through cycle. The VHTR system was primarily aimed at nearer-term deployment of a system for high-temperature process heat applications with a focus on thermochemical hydrogen production at superior efficiency. The VHTR system has coolant outlet temperatures above 1000°C, which enables high-temperature combustion without carbon emissions. The reference VHTR reactor concept has a 400-MWe helium-cooled core based on a prismatic or pebble fuel. The VHTR system can be scaled to meet high-temperature process heat demands, including the equivalent of over 300,000 gallons of gasoline per day.
**GFR – Gas-Cooled Fast Reactor**

- Gas-cooled
- 300-600 MWe
- Fast spectrum
- Closed fuel cycle; management of actinides and/or conversion of fertile uranium → improved sustainability
- Potentially hydrogen production

(source: DOE / GIF)

---

**LFR – Lead-Cooled Fast Reactor**

- Lead-cooled or LBE-cooled
- Range of power levels (50-1200 MWe)
- Fast spectrum
- High temperature and efficiency
- Enhanced safety (large thermal inertia, high boiling point)
- Management of actinides and/or conversion of fertile uranium → improved sustainability
- Potentially hydrogen production

(source: DOE / GIF)
MSR – Molten Salt Reactor

- Molten salt – coolant, fuel may also be dissolved
- 1000 MWe reference
- Thermal/epithermal spectrum
- High temperature (700-800°C) and efficiency
- Enhanced safety (small fissile content, low pressure)
- Closed fuel cycle – on-line reprocessing
- Effective for disposition/burn of Pu and MA
- Suitable for Th cycle

SFR – Sodium-Cooled Fast Reactor

- Sodium-cooled
- Range of power levels 150-1500 MWe
- Fast spectrum
- Closed fuel cycle; aqueous or pyrometallurgy processing; management of actinides
- Mid-high temperature (550°C exit)
SCWR – Supercritical-Water-Cooled Reactor

- Supercritical-water cooled to increase efficiency compared to other water-cooled systems
- Potential stability issues
- 1700 MWe

Supercritical-Water-Cooled Reactor System (SCWR)
The Supercritical-Water-Cooled Reactor (SCWR) system features an open cycle with a thermal neutron spectrum reactor as the primary option. The system uses a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water to achieve a thermal efficiency approaching 44%. The reference plant has a 1700 MWth power level and a reactor outlet temperature of 550°C. The SCWR system is highly ranked in economics because of the high thermal efficiency and plant simplification. The SCWR is noted good in safety, and proliferation resistance and physical protection. The SCWR is primarily aimed at electricity production, whereas its high thermal efficiency and plant simplification may provide a breakthrough in system economics.

VHTR / NGNP – 2 Flavours
- Prismatic fuel
- Pebble bed
NGNP – VHTR
Prismatic Fuel Design

- Fuel based on small multi-layer kernels, TRISO particles
- Embedded into prismatic fuel compacts

![Diagram of Fuel Design](source: GA)

NGNP – VHTR
Pebble Bed Modular Reactor (PBMR)

- Primary barrier (ceramic coated fuel particles) retains radioactive nuclides
- Helium is a single phase coolant and chemically & radiologically inert
- Very low power density and large thermal capacity ensures slow temperature transient behavior (no operator action for ~96 hours)
- Core heat removed by conduction through structures and radiation out of the reactor to passive cavity cooling system
- Passive heat transfer and high fuel melt temperature basically rule out a core melt possibility
**Pebble Bed Modular Reactor (PBMR)**

- Small High Temperature (900°C)
- Helium Cooled Reactor (165 MWe)
- Fuel in Spherical Fuel Elements
- On-line Refueling
- Direct Cycle Gas Turbine Generator
- Inherent Passive Safety Design
  - Fuel integrity maintained under most severe postulated accidents, with no early operator action required

**VHTR/PBMR Applications**

**TWO BROAD APPLICATIONS:**
- Electricity generation, including water desalination
- Process heat applications, needing process temperatures up to 900°C, with options for process steam/cogeneration

**PROCESS HEAT APPLICATIONS**
- Steam Generation
  - Oil Sands Recovery
  - Enhanced Oil Recovery
  - Cogeneration, including Desalination, Ethanol
- Steam Methane Reforming
  - Hydrogen
  - Ammonia
  - Methanol
- Water-Splitting
  - Bulk Hydrogen
  - Coal-to-Liquids
  - Coal-to-Gaseous Fuels
Fuel Cycle and Waste Management

Nuclear Fuel Cycle

- Front end
  - Mining (today mainly ISL)
  - Milling
  - Enrichment
  - Fuel fabrication
- In-core residence time
  - Energy production
  - Irradiation
  - Isotopic change
- Back end
  - Waste management
  - Reprocessing
  - Ultimate disposal of (residual) waste

(source: OECD)
Nuclear Fuel Cycle – Resources

- RAR- “Reasonably Assured Resources”
- Currently known - ~100+ years in once-through thermal systems
- 50-300 times more with conversion of fertile uranium and thorium
- Additionally, non-traditional resources (from phosphates to coal ash to seawater)

Table 4.12 Lifetime of uranium resources (years)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Identified resources ~4.7 MtU</th>
<th>Total conventional resources ~ 14.8 MtU</th>
<th>Total conventional resources plus phosphates ~ 35.4 MtU</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWRs once through</td>
<td>85</td>
<td>270</td>
<td>675</td>
</tr>
<tr>
<td>Progressive introduction of FBRs*</td>
<td>4 250</td>
<td>13 500</td>
<td>33 750</td>
</tr>
</tbody>
</table>

* It is assumed that the progressive introduction of fast breeder reactors (FBRs) multiplies by 50 the amount of electricity generated by 1 tonne of uranium.

(source: OECD)

Nuclear Fuel Cycle – Resources

Known Recoverable Resources* of Uranium 2007

<table>
<thead>
<tr>
<th>Country</th>
<th>tonnes U</th>
<th>percentage of world</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1,243,000</td>
<td>23%</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>817,000</td>
<td>15%</td>
</tr>
<tr>
<td>Russia</td>
<td>540,000</td>
<td>10%</td>
</tr>
<tr>
<td>South Africa</td>
<td>420,000</td>
<td>8%</td>
</tr>
<tr>
<td>Canada</td>
<td>432,000</td>
<td>9%</td>
</tr>
<tr>
<td>USA</td>
<td>344,000</td>
<td>8%</td>
</tr>
<tr>
<td>Brazil</td>
<td>278,000</td>
<td>6%</td>
</tr>
<tr>
<td>Namibia</td>
<td>270,000</td>
<td>5%</td>
</tr>
<tr>
<td>Niger</td>
<td>274,000</td>
<td>5%</td>
</tr>
<tr>
<td>Ukraine</td>
<td>200,000</td>
<td>4%</td>
</tr>
<tr>
<td>Jordan</td>
<td>112,000</td>
<td>2%</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>111,000</td>
<td>2%</td>
</tr>
<tr>
<td>India</td>
<td>73,000</td>
<td>1%</td>
</tr>
<tr>
<td>China</td>
<td>69,000</td>
<td>1%</td>
</tr>
<tr>
<td>Mongolia</td>
<td>62,000</td>
<td>1%</td>
</tr>
<tr>
<td>other</td>
<td>210,000</td>
<td>4%</td>
</tr>
<tr>
<td>World total</td>
<td>5,489,500</td>
<td></td>
</tr>
</tbody>
</table>

Reasonably Assured Resources plus Inferred Resources, to US$ 130/kg U, 1/1/07, from OECD NEA & IAEA, Uranium 2007: Resources, Production and Demand (“Red Book”)

(source: NEI)

Around 2007, known resources over 2 years increase by ~15% due to exploration (price started to rise, came back down)
Spent fuel management issues

- Decay heat $\rightarrow$ typically limiting for repository design
- Radiotoxicity $\rightarrow$ environmental/health concerns
- Reprocessing?

Spent Nuclear Fuel

- 2% Transuranics (Pu, Np, Am, Cm) $\rightarrow$ Long term dose, heat generation
- 5% Fission Products $\rightarrow$ Heat generation, long-term dose
- 93% Uranium $\rightarrow$ Waste volume
Decay Heat

- Decay heat is the initial limiting factor for geological repository
- Mid-term:
  - Fission products: Cs, Sr
  - Actinides: Pu
- Long-term:
  - Am

(source: DOE/ANL)

Fuel Cycle Closure

RED – Once through
GREEN – Closed cycle

- Spent nuclear fuel – reprocessed, separated, reused
- **Fast spectrum waste burner reactor**
- Only residual waste (much smaller amount) requires geological repository
- Reduced heat load and radiotoxicity
- Better use of resources

(source: DOE/ANL)
Closed Fuel Cycle with Recycle

NOTE: Yucca Mountain is not considered any more for repository, used here as a reference amount

- In once-through scenario, a Yucca Mountain-like repository would be filled up by 2030
- With advanced recycle, it would be sufficient to the end of century and beyond

Waste Transmutation in Subcritical Systems

- Instead of a critical reactor, the burner/transmuter is based on a subcritical systems (driven by external neutron source)
- More complex technological issues, and typically more expensive to construct/operate, but also provides additional flexibility for spent fuel management
- Economics should be considered on the whole system level (power generation + waste management)

- Accelerator-driven systems
- Hybrid fusion-fission
Spent Nuclear Fuel and High Level Waste Management

- Any energy production generates waste
- Nuclear plant waste lasts long time but is a relatively small quantity (concentrated energy, concentrated waste → may be viewed as advantageous)
- Waste is confined (while burning fossil fuel spreads wastes into the atmosphere)

- All high-level waste since the beginning of commercial nuclear power in the U.S. would by volume occupy less space than a football field piled 15 feet high

- If over your entire lifetime all electricity was generated by a modern PWR, your share of the wastes would fit comfortably into a 2-gallon wastepaper basket.

Conclusions
Recap of some nuclear power key characteristics / issues

Safety, Cost, Resources, Environmental

- Safety – good track record, further improved in new designs
- Cost of electricity – competitive
- Larger capital cost, but smaller long-term fuel cost
- Small/medium modular reactors reduce investment requirements
- Fuel resources – in current operating modus sufficient for 100+ years with conversion of fertile uranium / thorium sufficient for thousands of years
- Small footprint, low GHG emission, small externalities

- Spent fuel and high level waste management – essential for long-term sustainability. Perceived as main concern. Significant policy issues. Technologically manageable. (It does require significant funding and time to fully develop into a economically viable large-scale process, however, it will be largely based on extending, improving, optimizing and scaling up existing technologies.)

- Nuclear power - need to be compared to other means of energy generation using consistent metrics

Summary and Conclusions

- Current technology nuclear power plants generate electricity in a safe and economical manner

- Advanced reactors and advanced nuclear fuel cycle (with recycling) are needed to satisfy long-term goals (improved resources/waste management)

- Nuclear power has a role in satisfying sustainable development requirements
Thank you

Questions?