Nuclear Power - Greenhouse Gas Emissions & Risks
A Comparative Life Cycle Analysis

Vasilis Fthenakis
Brookhaven National Laboratory
www.pv.bnl.gov
Columbia University
www.clca.columbia.edu

Presentation at the California Energy Commission Nuclear Issues Workshop,
Panel 4 “Environmental, Safety, and Economic Implications of Nuclear Power”
Sacramento, CA, June 28, 2007
The Nuclear Fuel Cycle

M, Q: material and energy inputs
E: effluents (air, water, solid)
Review of GHG Emissions from Nuclear Fuel Cycle

GHG emissions (g CO2-eq./kWh)

- United States, DeLucchi 1991
- Australia (hypothetical), ACA 2001
- Sweden, Vattenfall 2004
- Switzerland (case 1), Dones 2003
- Switzerland (case 2), Dones 2003
- Japan, Hondo 2005
- World, Storm and Smith 2005

- Except enrichment
- Waste Management
- Operation
- Decommissioning
- Construction
- Enrichment
- Conversion/Fabrication
- Minning/milling
Breakdown of GHG Emissions from Nuclear Fuel Cycle

Vattenfall 2002, Sweden
D (France): 20%
C: 80%

Hondo 2005, Japan
D (US): 67%
D (France): 22%
C: 11%

Dones et al, 2005, Switzerland PWR
D (France): 60%
C: 40%

Dones et al, 2005, Switzerland BWR
D (US): 13%
D (France): 55%
C: 32%

D: Diffusion enrichment  C: Gas centrifuge enrichment

Waste Disp.
Operation
Const./Decomm.
Enrichment
Conv./Fab.
Minning/milling
# BNL Reference Case - Conditions for US Nuclear Fuel Cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor lifetime (yrs)</td>
<td>40</td>
</tr>
<tr>
<td>Burn-up ($\text{MWd}_{\text{th}}/\text{kgU}$)</td>
<td>42</td>
</tr>
<tr>
<td>Enrichment mix (%) EIA -1998-2002</td>
<td>- Diffusion (US)-34%</td>
</tr>
<tr>
<td></td>
<td>(France)-11%</td>
</tr>
<tr>
<td></td>
<td>- Centrifuge (mix)-19%</td>
</tr>
<tr>
<td></td>
<td>- dilution highly enriched uranium (Russia)-36%</td>
</tr>
<tr>
<td>Upstream Electricity Mix for enrichment</td>
<td>20% coal</td>
</tr>
<tr>
<td></td>
<td>80% Tennessee Valley Authority grid</td>
</tr>
<tr>
<td>Ore grade (% U$_{3O8}$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Capacity factor (%)</td>
<td>85</td>
</tr>
<tr>
<td>Thermal efficiency (%)</td>
<td>35</td>
</tr>
<tr>
<td>Product/tail assay (% U$^{235}_3$)</td>
<td>3.8/ 0.25</td>
</tr>
<tr>
<td>Parameters</td>
<td>Min.</td>
</tr>
<tr>
<td>---------------------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Energy for diffusion enrichment</td>
<td>2400 kWh/SWU&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Electricity source for enrichment</td>
<td>100% from US avg.</td>
</tr>
<tr>
<td>Ore concentration (% U)</td>
<td>12.7 (Canada)</td>
</tr>
<tr>
<td>LCA method: Construction stage</td>
<td>Process-based</td>
</tr>
</tbody>
</table>

<sup>a</sup> Separative Work Unit  
<sup>b</sup> Tennessee Valley Authority
### Process Based vs. Economic Input/Output LCA

#### Example: Construction –1 GW NPP-

<table>
<thead>
<tr>
<th></th>
<th>Construction Cost ($2000)</th>
<th>CO₂ emission (g/ kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL ref case</td>
<td>Process-Based</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Steel, concrete, copper)</td>
<td></td>
</tr>
<tr>
<td>BNL worst case</td>
<td>EI/O</td>
<td>4.5 billion</td>
</tr>
<tr>
<td>Storm 2005, baseline</td>
<td>EI/O</td>
<td>7.5 billion</td>
</tr>
<tr>
<td>ISA 2006 baseline</td>
<td>EI/O</td>
<td>1.3 billion</td>
</tr>
</tbody>
</table>

EI/O LCA may overestimate GHG emissions
Process-based LCA may slightly underestimate GHG emissions
*Degree of overestimate of underestimate depends on the detail of material and energy inventories*
Life Cycle GHG Emissions
-A process-based LCA comparison-

GHG (g CO2-eq./kWh)

- Materials
- Operation
- Transportation
- Fuel Production

Coal (Kim and Dale 2005)
Natural Gas (Kim and Dale 2005)
Petroleum (Kim and Dale 2005)
Nuclear (Baseline - Fthenakis and Kim, 2005)
PV, CdTe (Fthenakis and Kim 2006)
PV, mc-Si, (Fthenakis and Alsema, 2006)
Framework for Evaluation of Life-Cycle Risks in Electricity Production

Risks

- Direct Economic
  - Normal operation
  - Accidental Routine/Severe
  - Difficult to evaluate risks

- External

Benefits

- Energy
- Welfare
- Economic development
- National Security

Fthenakis¹, Kim¹, Colli² A., and Kirchsteiger² C.,
¹ Brookhaven National Laboratory, Upton, NY, U.S.
² European Commission, DG Joint Research Centre, Institute for Energy, Petten, The Netherlands
Accidental Risks in Electricity Production

GaBE project, Paul Scherrer Institute (PSI), ENSAD 1969-2000
Maximum Consequences per Accident

<table>
<thead>
<tr>
<th>Source</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>434</td>
</tr>
<tr>
<td>Oil</td>
<td>3000</td>
</tr>
<tr>
<td>NG</td>
<td>100</td>
</tr>
<tr>
<td>LPG</td>
<td>600</td>
</tr>
<tr>
<td>Nuclear (Chernobyl)</td>
<td>9000-33000</td>
</tr>
<tr>
<td>Nuclear (except Chernobyl)</td>
<td>125</td>
</tr>
<tr>
<td>PV, PSI</td>
<td>100</td>
</tr>
<tr>
<td>PV, BNL</td>
<td>2</td>
</tr>
</tbody>
</table>
Climate Change and Fossil Fuel Depletion Risks
-Is there a tenable solution?

- Nuclear Energy
  - Spent fuel management
  - Proliferation risks

- Coal with C sequestration
  - Reliability/Cost
  - Residual pollution

- Wind
  - Resource limits
  - Intermittency

- Solar
  - Cost
  - Intermittency
The President’s *Advanced Energy Initiative*

Initiated significant new investments and policies in:

- **Clean Coal technology**
- **Nuclear Power**
  - Global Nuclear Energy Partnership (GNEP) to address spent nuclear fuel, eliminate proliferation risks, and expand the promise of clean, reliable, and affordable nuclear energy
- **Renewable Solar and Wind energy**
  - Reduce the cost of solar PV technologies so that they become cost-effective by 2015 and expand access to wind energy.
The President’s Advanced Energy Initiative

“To safeguard our future economic health as well as national security, we must move aggressively to diversify our energy sources.”

-DOE Secretary Samuel Bodman
Golden, CO, July 7, 2006

“I’d put my money on the sun and solar energy. What a source of power! I hope we don’t have to wait till oil and coal run out before we tackle that.”

-Thomas Edison
The Solar America Initiative (SAI)

SAI Goal: Achieve Grid Parity Nationwide by 2015

Projected Cost Reductions for Solar PV

- Solar PV Cost Range
- Residential & Commercial Rates
- Utility Generation

YEAR

2005  2010  2015

cents/kWh (2005$)

35¢  30¢  25¢  20¢  15¢  10¢  5¢  0¢

Without SAI

With SAI
200,000 square miles of desert land in the SW is suitable for constructing solar power plants.

This area receives 3,600 quadrillion Btu of solar irradiation per year.

If just 3% of this energy is converted to electricity, we satisfy the total US annual energy consumption.

Throughout the rest of the country, sunlight can be used for distributed (rooftop) PV systems.

*From Zweibel, Mason, Fthenakis. “An Imminent Solar Solution to Climate Change and Energy Security for the US”, in press*
- PV and compressed air energy storage (CAES) for 24-hour electricity
- Concentrating Solar Power with heat storage, also dispatchable
- Plug-in hybrids powered by solar electric (80%) and biofuels (20%)
- Wind as complement and nighttime backup to solar
- Low-cost solar, an essential, enabling technology
- US SW solar enough to provide US energy self-sufficiency

Conclusions

• A Life Cycle Framework is necessary for a complete description of the sustainability of energy technologies.

• It enables a holistic approach encompassing resource availability and costs, potential risks and benefits to the US economy and the environment for current and future generations.

www.pv.bnl.gov
www.clca.columbia.edu
Contributors

- Hyung Chul Kim, Brookhaven National Laboratory
- James Mason, Hydrogen Research Institute
- Ken Zweibel, PrimeStar Solar

www.pv.bnl.gov
www.clca.columbia.edu