Perspectives on Greenhouse Gas Emissions and Energy Payback Ratios for Fusion Power

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Objective

- Calculate the Energy Payback Ratio (EPR) for Coal, Natural Gas, Fission, Wind, and DT Fusion Electrical Power Plants
  Perform “Birth to Death Analysis”

- Calculate the Greenhouse Gas Emissions Associated With Coal, Natural Gas, Fission, Wind, and DT Fusion Electrical Power Plants
  Include all fossil input to fuel and structural materials procurement, operations, and decommissioning

- Assess How the U.S. Electrical Generating System Can “Do Its Share” to Meet the 1997 Kyoto Limits
  Consider the 1990 minus 7% case
The Energy Investment in a Power Plant is Comprised of Many Components

- Energy to Decommission Reactor GJ / GWe
- Energy to Construct Reactor GJ / GWe
- Material Inventory kg material i / GWe
- Power Plant Equipment Operation GJ / GWe
- Capital Energy Investment
- Fuel Gathering GJ / GWe
  - Natural Gas
  - Coal
  - Uranium
  - Deuterium & Lithium
- Energy To Operate Reactor
- Total GJ / GW_e - yr
Calculation of Energy Payback Ratio (EPR)

\[
\text{EPR} = \frac{E_{n,L}}{(E_{\text{mat},L} + E_{\text{con},L} + E_{\text{op},L} + E_{\text{dec},L})}
\]

where
- \(E_{n,L}\) = the electrical energy produced over a given plant lifetime, \(L\).
- \(E_{\text{mat},L}\) = total energy invested in materials used over plant lifetime, \(L\).
- \(E_{\text{con},L}\) = total energy invested in construction for a plant with lifetime, \(L\).
- \(E_{\text{op},L}\) = total energy invested in operating the plant over the lifetime \(L\).
- \(E_{\text{dec},L}\) = total energy invested in decommissioning a plant after it has operated for a lifetime, \(L\).
## Summary of the Normalized Energy Investments Made in Electrical Generating Plants - (TJ\textsubscript{th}/Gw\textsubscript{e}y)

<table>
<thead>
<tr>
<th>Process</th>
<th>Natural Gas</th>
<th>Coal</th>
<th>Fission</th>
<th>Wind</th>
<th>DT Fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Related</td>
<td>7,327</td>
<td>2,318</td>
<td>1,299</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Plant Materials &amp; Construction</td>
<td>90</td>
<td>147</td>
<td>195</td>
<td>875</td>
<td>927</td>
</tr>
<tr>
<td>Operation</td>
<td>323</td>
<td>440</td>
<td>239</td>
<td>489</td>
<td>318</td>
</tr>
<tr>
<td>Decommissioning</td>
<td>3</td>
<td>20</td>
<td>191</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7,743</strong></td>
<td><strong>2,925</strong></td>
<td><strong>1,923</strong></td>
<td><strong>114</strong></td>
<td><strong>1,326</strong></td>
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The Energy Payback Ratio Varies by a Factor of Nearly 6 Between Natural Gas and Fusion Power.
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<tr>
<td>Fuel Related</td>
<td>77</td>
<td>17</td>
<td>10</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>Plant Materials &amp; Construction</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Operation</td>
<td>385</td>
<td>956</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Decommissioning</td>
<td>0.02</td>
<td>0.2</td>
<td>1.0</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>464</td>
<td>974</td>
<td>15</td>
<td>14</td>
<td>11</td>
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Relative to the CO$_2$ Emissions of Coal, Those from Nuclear and Wind Technologies are Low, But Not Zero

Tonnes CO$_2$/GW$_e$

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<td>11</td>
</tr>
</tbody>
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U.S. Electricity Generation Contribution

% Coal Generated Electricity

% Natural Gas & Oil Generated Electricity

1999: 19%
U.S. Electricity Generation Contribution

- % Nuclear & Renewable Generated Electricity
- % Coal Generated Electricity
- % Natural Gas & Oil Generated Electricity

Year 1999: 30% Nuclear & Renewable, 51% Coal, 19% Natural Gas & Oil
Using this mixture of technologies, 1999 U.S. Electricity Production of 3.7 million GW, resulted in GHG emissions of about 2.2 billion metric tonnes.

If the following "mixtures" could have been used to produce the same amount of electricity, they would have emitted the same amount of CO₂ equivalent.

Mixtures to the RIGHT of the line, would result in fewer emissions, while mixtures to the LEFT of the line would result in higher emissions.
If we wanted to **increase electricity consumption** to projected 2010 levels (4.2 million GWₜₜₜ), and still **decrease emissions** to the Kyoto target, the constant emission line would shift further to the right.

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### Electricity Production (10⁶ GWeh)
- 3.7
- 4.2

### CO₂ Emission (10⁹ tonnes)
- 2.2
- 1.7

**Below Target Emission Level**
An Increasing Reliance on Nuclear and Renewable Sources is Required, to Satisfy Proposed Kyoto Emission Targets at Anticipated U.S. Electricity Growth Rates (1.3%).
Future Electrical Growth assumed 1.3%

**Target assumes that the U.S. electric industry meets its proportion of the Kyoto commitment by reducing emissions to 7% below its 1990 baseline.

*Future Electrical Growth assumed 1.3%

**Target assumes that the U.S. electric industry meets its proportion of the Kyoto commitment by reducing emissions to 7% below its 1990 baseline.
The Absolute Amount of Electricity Required From Nuclear/Renewable Sources is More Than 4 Times the 2000 Level if the U.S. is to Meet the 1997 Kyoto GHG target**.

*Future Electrical Growth assumed 1.3%
**Target assumes that the U.S. electric industry meets its proportion of the Kyoto commitment by reducing emissions to 7% below its 1990 baseline.
What If the Level of Electricity from Fission and Hydro Sources Remain Constant in the 2000-2050 Time Period?

Assume: New fission and hydro replace retired fission and hydro in the 2000-2050 period.

- **The electricity generated from other low GHG emitting sources (wind, solar, fusion, etc.) must increase dramatically after 2010.**
Implies potential for any nuclear or renewable technology other than fission or hydroelectricity.

Future Electrical Growth assumed 1.3%

Target assumes that the U.S. electric industry meets its proportion of the Kyoto commitment by reducing emissions to 7% below its 1990 baseline.
Conclusions

- The “birth to death” analysis of energy payback ratios (EPR’s) for electrical generating plants reveals that DT fusion plants have one of the highest EPR values at 24.
  
  This compares to 4-23 for conventional (natural gas, coal, fission, and wind) power stations.

- The greenhouse gas emission rate per GW_{e}h for DT fusion plants is low at 11 tonnes CO_{2}/Gw_{e}h.
  
  This compares favorably to 14-15 for wind and fission respectively and 464 to 974 for natural gas and coal respectively.
Conclusions (cont.)

- Adherence to the 1997 Kyoto agreement’s emission rate (1990 minus 7%) and 1.3%/y electricity demand growth rate will require quadrupling the nuclear/renewable capacity in the United States over the next 50 years (not considering replacements).

Factoring in replacements, quadrupling requires approximately 600 new 1,000 MWₑ low-greenhouse gas emitting electricity-generating power plants in the U.S. over the next 50 years.
There are Two Methods to Measure Energy Input to Power Plants

Process Chain Analysis (PCA)

<table>
<thead>
<tr>
<th>Material</th>
<th>GJ/tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>207</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.4</td>
</tr>
<tr>
<td>Copper</td>
<td>131</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>53</td>
</tr>
<tr>
<td>Vanadium</td>
<td>3711</td>
</tr>
<tr>
<td>Rocket Fuel (LH₂)</td>
<td>460</td>
</tr>
<tr>
<td>Rocket Fuel (LOₓ)</td>
<td>10</td>
</tr>
<tr>
<td>Titanium (for lunar mining equipment)</td>
<td>444</td>
</tr>
</tbody>
</table>

Input/Output (I/O)

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Energy Intensity (GJ/1977$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Construc.</td>
<td>32</td>
</tr>
<tr>
<td>Elect. Utility</td>
<td>23</td>
</tr>
<tr>
<td>Auto Repair</td>
<td>23</td>
</tr>
<tr>
<td>Railroad</td>
<td>49</td>
</tr>
<tr>
<td>Paving</td>
<td>192</td>
</tr>
</tbody>
</table>

unit mass \( \frac{\text{GJ}}{\text{GW}_e \text{ or } \text{GW}_e \text{y}} \)

"service" \( \frac{\text{unit "service"}}{\text{GW}_e \text{ or } \text{GW}_e \text{y}} \)
20 Years of Increased Reliance on Coal and Nuclear Power Sources Stalled in the 1990's

- 1970
- 1980
- 1990
- 1999
If Fission and Hydro Sources are Kept Constant, Other Sources of Low GHG Emitting Power Plants Are Needed No Later Than 2010 if the U.S. is to Meet the 1997 Kyoto GHG Target.

Implies potential for any nuclear or renewable technology other than fission or hydroelectricity.
Future Electrical Growth assumed 1.3%
Target assumes that the U.S. electric industry meets its proportion of the Kyoto commitment by reducing emissions to 7% below its 1990 baseline.
There Would Have to be a Major Shift Toward Nuclear/Renewable and Natural Gas Technologies, In Order to Immediately Comply With the 1997 Kyoto Emission Target for the U.S.

Any point along this line would satisfy the 1997 Kyoto emission target for the U.S. at 1999 electricity generation rates.