Economical feasibility of the biomass-fusion hybrid concept

Kenzo Ibano, Ryuta Kasada and Satoshi Konishi
Graduate school of Energy Science, Kyoto University
Biomass-fusion hybrid concept

- **Biomass**
- **Gasification chamber**
- **FT process**
- **H2+CO**
- **Turbine Generator**
- **Fuel Cell**
- **Electricity**
- **Oil**

- **Boiler**
- **Turbine Generator**
- **Electricity**
- ** GNOME-0**
- ** GNOME-1 & 2**
- ** GNOME-3**

- Fusion neutron Heat
  - "apparent" energy multiplication

- $\eta = 50\%$
The biomass-fusion hybrid concept can be a cheaper option. Energy conversion efficiency makes a difference. Apparent energy multiplication of 2 (hydrogen) or 1 (oil) is expected. 100 MW class reactor can be achieved with $R_p \approx 5\,\text{m}$ and $\beta \approx 3$.
The biomass-fusion hybrid concept produce different products.

Energy prices are competitive.

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Equivalent Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>1 gallon = 130 MJ</td>
</tr>
<tr>
<td>Bio ethanol</td>
<td>1 gallon = 85.8 MJ</td>
</tr>
<tr>
<td>Electricity</td>
<td>1 kWh = 3.6 MJ</td>
</tr>
</tbody>
</table>

All units were converted into mills/kWh.

US Energy Information Administration (2011)
The biomass-fusion hybrid concept requests some original features

- High-temperature system (blanket, pipe, HEX)
- Biomass gasification system \( \sim 1000 \, ^\circ C \)
- Oil conversion plant
- Fuel cell fee
- Fuel fee (12 mills/kWh)
- No Turbine

How does they affect COE/COP?
Basics of Cost Analysis
Cost analysis

\[ COE = \left\{ \frac{C_{ac} + C_{om} + C_{scr} + C_{fuel}}{8760 \times P_e \times f_{av}} + C_{dec} \right\} \times F \] (1.5) (1.0)

\[ C_{ac} \]: accounting capital  \hspace{1cm} C_{dec} \]: Waste & shut down
\[ C_{om} \]: maintaining  \hspace{1cm} P_e \]: Electricity output [MW]
\[ C_{scr} \]: periodic replace \hspace{1cm} f_{av} \]: utilization rate
\[ C_{fuel} \]: fuel fee(D)

utilization rate = \frac{electricity output}{rated output \times time} \times 100 \%)

availability rate = \frac{operation time}{time} \times 100 \%(%)
Accounting Capital cost

\[ C_{ac} = C_{build-direct} \times f_{indirect} \times f_{interest} \times f_{pay back} \]

(1.2) \quad (1.1303) \quad (0.05828)

\( C_{ac} \): accounting capital

\( C_{build-direct} \): direct construction

\( f_{indirect} \): in-direct fee ratio

\( f_{interest} \): interest during construction

\( f_{pay back} \): capital recovery factor

**Direct building cost**

\[ C_{\text{build-direct}} = C_{\text{comp}} + C_{\text{CD}} + C_{\text{BOP}} \]

- \( C_{\text{build-direct}} \): direct construction
- \( C_{\text{CD}} \): Additional heating
- \( C_{\text{comp}} \): component cost
- \( C_{\text{BOP}} \): Balance of plant

\[ C_{\text{comp}} = \sum \{ c^d_{\text{material}} + c^d_{\text{manufacture}} + c^d_{\text{assembly}} \} [\$/\text{kg}] \times W [\text{kg}] \]

\[ C_{\text{CD}} = c^{\text{CD}} [\$/\text{MW}] \times P [\text{MW}] \]

\[ C_{\text{BOP}} = C_{\text{building}} + C_{\text{other}} \]

- \( C_{\text{building}} \) \( \propto V^{0.67} \)
- \( C_{\text{other}} \) \( \propto P_{th}^{0.6} \)
Periodic replacement

Periodic replace:

\[ C_{\text{scr}} = C_{\text{comp}}^{\text{BLK}} \times f_{\text{scr}}^{\text{BLK}} + C_{\text{comp}}^{\text{DIV}} \times f_{\text{scr}}^{\text{DIV}} \]

Peak flux \( \sim 1 \text{ MW/m}^2 \) flux \( \Rightarrow \sim 14 \text{ years} \)
Cost estimations
GNOME parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER</th>
<th>GNOME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>$R_p$</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>$A$</td>
<td>3.1</td>
</tr>
<tr>
<td>Current</td>
<td>$I_p$</td>
<td>15 MA</td>
</tr>
<tr>
<td>Max field</td>
<td>$B_{\text{max}}$</td>
<td>11.8 T</td>
</tr>
<tr>
<td>Average temperature</td>
<td>$\langle T_e \rangle$</td>
<td>8.9 keV</td>
</tr>
<tr>
<td>Density</td>
<td>$f_{\text{GW}}$</td>
<td>-</td>
</tr>
<tr>
<td>Bootstrap</td>
<td>$f_{\text{BS}}$</td>
<td>-</td>
</tr>
<tr>
<td>Fusion power</td>
<td>$P_{\text{fus}}$</td>
<td>500 MW</td>
</tr>
<tr>
<td>Heating</td>
<td>$P_{\text{CD}}$</td>
<td>73 MW</td>
</tr>
<tr>
<td>Neutron wall load</td>
<td>$P_n$</td>
<td>0.57 MW/m²</td>
</tr>
</tbody>
</table>

Low power, low-Q. Small $R_p$. 12 TF coils. (Nb$_3$Sn)
Systems codes

Input: Phy & Eng constrains

Consistency solving for physics

Determination of radial build

Parameter set

Secondary quantities

Electricity output
Amount of materials
Cost examination

CRIEPI code: FUSAC
Cost evaluations were taken for various options.

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Turbine</th>
<th>High temp. system</th>
<th>Biomass fuel</th>
<th>Fuel Cell</th>
<th>Oil plant</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNOME-0</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td>GNOME-1</td>
<td>○</td>
<td>○</td>
<td>High</td>
<td>○</td>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td>GNOME-2</td>
<td>○</td>
<td>○</td>
<td>Cheap</td>
<td>○</td>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td>GNOME-3</td>
<td>○</td>
<td>○</td>
<td>High</td>
<td></td>
<td>○</td>
<td>Oil</td>
</tr>
</tbody>
</table>

FC, FT plant, HEX costs were applied to $C_{\text{other}}$.

\[
C_{\text{BOP}} = C_{\text{building}} + C_{\text{other}} \propto V^{0.67} \propto P_{th}^{0.6}
\]
## Basic values used for the analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell</td>
<td>$40K \times (P_{fc}(W)/700)^{0.6}$</td>
</tr>
<tr>
<td>FT plant</td>
<td>$C.I. / C.I.<em>{1975} \times 158K \times P</em>{yearly}(ML)^{0.715}$</td>
</tr>
<tr>
<td>HEX</td>
<td>$M&amp;S/M&amp;S_{1975} \times 4764 \times (P_{fus}(MW)/0.1)^{0.849}$</td>
</tr>
<tr>
<td>HEX-SiC</td>
<td>$C_{SiC} \times \text{Cost}_{HEX}$</td>
</tr>
<tr>
<td>Turbine Generator</td>
<td>$240.3 \times (P_{e}(MW)/1200)^{0.83}$</td>
</tr>
</tbody>
</table>

*Based on a commercial SOFC for household use.*

*Based on a commercial ethylene plant.*

0.1 MW/m² limit at HEX (dx=1.0 cm, dT=25K, $\lambda=40$ W/m/K.) (scaling for < 500 m²)

$C_{SiC} = 4$ (twice cost, two HEX)

*C.I. : CEPCI C.I._{1975}=182.4, C.I._{2009}=539.6
M&S_{1975}=444.3, M&S_{2007}=1362.7

H. Saito “Cost handbook for the chemical plants.”
ARIES website
A patent for a Graphite HEX with a SiC surface layer does exist. The patent says the HEX can handle up to 1273K.

JP 特空平 7-225095
Basic values used for the analysis

SiC HEX $C_{\text{SiC}} = 4$

- Fuel cell
- Ethylene (FT)
- Turbine & Generator

- Turbine + Generator
- Fuel cell
- Ethylene plant
- HEX SiC--base $C_{\text{SiC}} = 4$
# Blanket component price

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume (m³)</th>
<th>Weight (kg)</th>
<th>Price (k$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>4.5 x10⁻³</td>
<td>87</td>
<td>10.4</td>
</tr>
<tr>
<td>F82H</td>
<td>3.5 x10⁻²</td>
<td>270</td>
<td>11.7</td>
</tr>
<tr>
<td>SiC₉/SiC</td>
<td>5.4 x10⁻²</td>
<td>170</td>
<td>99</td>
</tr>
<tr>
<td>He (8MPa)</td>
<td>2.5 x10⁻²</td>
<td>0.35</td>
<td>7.0 x10⁻²</td>
</tr>
<tr>
<td>PbLi</td>
<td>1.13</td>
<td>10000</td>
<td>88</td>
</tr>
<tr>
<td>Module</td>
<td>1.2</td>
<td>10500</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>370</strong></td>
<td><strong>3200 tonn</strong></td>
<td><strong>62 M$</strong></td>
</tr>
</tbody>
</table>

Total cost = 50 %

Material cost base from ARIES website is used.
Result
COE of GNOME with FC

COE = 150.598 mills/kWh with $P_{\text{fus}} = 364$ MW
GNOME reactor weight & cost

Cost of reactor components (M$)

- **divertor, 5.3**
- **blanket, 137**
- **shield, 90**
- **structure, 54**
- **coil, 153**

**Total ~ 439 M$**

**ARIES-ST**

- **shield, 107**
- **structure, 65**
- **coil, 97**

**Total ~ 317 M$**

*from ARIES website*
Building cost

![Graph showing the relationship between building cost and fusion power for different energy sources: Turbine, Fuel cell, Oil, and Current drive power. The graph indicates that building cost increases with fusion power for all sources, with Fuel cell having the highest cost at higher fusion powers.](image-url)
COE/COP analysis

FT plant case, $P_{CD}$ is supplied by 100 mills/kWh
Summary

- Cost estimation effort has been taken for the biomass-fusion hybrid concept.
- The concept shows economical feasibility than turbine particularly for a low fusion power devices.
- COP < 100 mills can be achieved with 500-1000 MW fusion power.