Status of Evolving Waste to Liquids Technologies for jet fuel, diesel, ethanol, and DME

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RES Kaidi
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Conversion of waste to liquids is still evolving technologically, is more specific to location and end product than coal gasification, but is worth evaluation as an alternative to electric power for future commercial facilities.
$6 billion USD Company
11 China subsidiaries and 4 US subsidiaries
Kaidi builds, owns and operates power facilities
Currently permitted to build 3000+ MW in China

Proven EPC capabilities
Proven expertise in Hydro, Wind and Concentrated Solar Power (CSP) generation
Wuhan R&D Center for new technologies
Owns key technologies
Owns land for Biomass Production
Development of BTL Projects

President Xi Jinping visited Kaidi Biofuel Facilities in 2013
RES Provides Technology and Engineering Services

- **Engineering Packages:**
  - BEDD, Scoping Studies, Feasibility Studies, Process Integration, PDPs
  - Primarily to support Kaidi Wuhan Demonstration development
  - Available to support other Kaidi affiliates and strategic partners

- **Technology Assessments:** TEA’s, TRL assessment, Process and Financial models

- **Technology and Company Reviews:**
  - Due diligence; RES has preformed reviews at various levels on 36+ companies to date, using internally developed tools and processes and publically available information

- **Technology Development:**
  - Internal development of technologies of interest to Kaidi family of companies including WTL with Alter NRG;
  - Technical competence - especially around thermochemical and catalytic processes

- **Project Development Support Services:** For BOO project development

- **Biomass Roadmap Assessment:** Technology and Market Pathways
Waste to Liquids
Commercial vs Evolving

• Commercial
  • Enerkem - MSW Waste to methanol.......evolving to ethanol: Edmonton 2014, Varennes 2018 ((GSTC database)
  • LanzaTech - Waste gases to ethanol: Shaogang- 2018, Accelor Mittal 2019

• Evolving
  • GSTC:
    • “At the same time, demand for smaller, modular gasifiers for biomass and waste gasification is increasing. Generally, gasification of biomass and municipal solid waste does not require the larger gasifiers that are used in industrial applications”
  • UK re-commits funding for waste-to-fuel projects
    • (31 August 2017, Endswaste and Bioenergy) : The government is offering £22m (€23.8m) for the development of advanced waste-based fuels that could help decarbonise aviation and road haulage.
    • The report concludes that applications would most likely concern the production of lignocellulosic ethanol, methane or hydrogen from waste gasification, and fuels manufactured from waste gases, such as carbon monoxide from steel mills.
    • 70 groups showed interest.
    • “GreenSky London arrived on the scene a few years ago — an ambitious project to produce renewable aviation jet fuel from East London’s trash. The project fell down a rabbit hole of delays. Now, a group of four companies including both British Airways and Velocys are back with a partnership to prepare the business case for a commercial scale waste-to-renewable-jet-fuel plant in the UK “

Lots of Press.................but commercial WTL is not simple...
Example WTL Pathways and End Products

- Variations of Fischer-Tropsch syngas to liquids (GTL) via fixed bed cobalt, bubbling bed iron slurry column, or fixed bed microchannel technologies
  - Diesel
  - Jet
  - Waxes and lube oils

- One step DME synthesis:
  - Primary DME market is diluent for LPG
  - Future possible alternative to diesel for transportation

- Bioreactor GTL with Clostridium microbial strains
  - Ethanol
  - Propanol and other chemicals

There are a wide variety of possible processes and liquid end products
Why Liquids?
Driven by low Power Prices

- Low natural gas prices holding down average power prices
- Increasing wind and solar driving down peak power prices
- Difficult to obtain long term power price contracts

Use of clean syngas from waste for storable liquids production may provide better value than power.
USA Wholesale Ethanol* vs Diesel*

- Volatility: Ethanol has been 50% of diesel to 130% of diesel
- Subsidies in form of RINS add additional value, but also uncertainty
- Prices are very location dependent

Liquids values can vary greatly with end product, time and location

Diesel
$1.42/gal

Ethanol
$1.54/gal

*Sept 2017
Australia Wholesale Ethanol vs Diesel*

- Ethanol:
  - AUS$/MT
  - $1250 per MT = $1.00 per liter = $3.80/gal

- Diesel:
  - AUS$/L
  - $1.15 per liter = $4.40/gal

*January 2017
### DME vs LPG and WTI

Arbitrage opportunities exist for specific WTI in specific locations - more so than coal gasification.

- **In China**, DME prices trail just below LPG prices, based on diluent market. DME is made from coal gasification.

- DME can be made from low quality nat gas (CH4/CO2) at much lower cost.

- **In Canada**, DME may be used for diluent for bitumen and tied to WTI instead of LPG, (which is 1/3 of China price in Canada)

WTI at $52/barrel/ 42 gal per barrel/ 5.4 lbs/gal of DME x 2200 lbs/MT = $533/MT

RMB 3897 = $590/MT
Variations in Syngas from MSW

- High BTU: 6,000 Btu/lb
- Medium BTU: 5,000 Btu/lb
- Low BTU: 4,000 Btu/lb

<table>
<thead>
<tr>
<th>Units</th>
<th>High BTU</th>
<th>Feed Gas</th>
<th>Low BTU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6,000 Btu/lb MSW</td>
<td>5,000 Btu/lb MSW</td>
<td>4,000 Btu/lb MSW</td>
</tr>
<tr>
<td>Volume Flowrate</td>
<td>Nm³/hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>67,800</td>
<td>62,700</td>
<td>58,200</td>
</tr>
<tr>
<td>Energy Flowrate</td>
<td>GJ/hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>405</td>
<td>315</td>
<td>220</td>
</tr>
<tr>
<td>Composition:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO vol%</td>
<td>29%</td>
<td>25%</td>
<td>20%</td>
</tr>
<tr>
<td>H₂ vol%</td>
<td>14%</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td>CO₂ vol%</td>
<td>10%</td>
<td>13%</td>
<td>15%</td>
</tr>
<tr>
<td>N₂ vol%</td>
<td>6%</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>CH₄ vol%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>H₂O vol%</td>
<td>36%</td>
<td>41%</td>
<td>48%</td>
</tr>
</tbody>
</table>

Syngas quality, including CO/H₂ ratios, % CH₄ and energy flow rates vary with type of waste.
Variations in Conversion Rates

• Assumes 1000 MT/day MSW
  • ~6000 btu/lb (14.0 MJ/kg)

• Upgraded FT Liquids yields by weight
  • ~70-75% Diesel or Jet
  • And ~25-30% Naphtha

<table>
<thead>
<tr>
<th>End Product</th>
<th>Desired H2/CO ratio</th>
<th>Net Power requirements MW</th>
<th>Estimated production rates in gals per ton MSW</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DME</td>
<td>1:1</td>
<td>12</td>
<td>73</td>
<td>4</td>
</tr>
<tr>
<td>FT Liquids</td>
<td>1.8:1</td>
<td>4</td>
<td>31</td>
<td>7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>&lt; 1:1</td>
<td>13</td>
<td>59</td>
<td>7</td>
</tr>
</tbody>
</table>

Actual conversion rates vary with H2/CO ratios, process, net energy requirements and TRL
End Product Values per ton MSW
Example: Australia Wholesale Prices-January 2017

• Actual expected conversion rate, not theoretical max.
  • Syngas to Power at $60/MW
  • Syngas to Diesel at $1.15/l
  • Syngas to Ethanol at $1.00/l
  • Syngas to DME at $650 per ton

<table>
<thead>
<tr>
<th>Product Conversion</th>
<th>Conv rate</th>
<th>price/unit</th>
<th>value per ton MSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel FT liquids/ton</td>
<td>31</td>
<td>$4.40</td>
<td>$136</td>
</tr>
<tr>
<td>Ethanol gal/ton</td>
<td>59</td>
<td>$3.80</td>
<td>$224</td>
</tr>
<tr>
<td>Power MW/ton</td>
<td>1.2</td>
<td>$60.00</td>
<td>$72</td>
</tr>
<tr>
<td>DME gal/ton</td>
<td>73</td>
<td>$1.88</td>
<td>$137</td>
</tr>
</tbody>
</table>

Calculate relative value of various end products per ton of waste
Production Costs
Syngas Cleanup Issues

- Power
  - BTU/SCF
  - Ingress of air; N2 dilution
  - Syngas stability

- Jet or Diesel
  - Sulfur < 50 ppb
  - Tars
  - CO2

- DME
  - Varies from MSW or from low quality nat gas

- Ethanol
  - Reliability, on stream factor
  - HCN
  - Acetylene
  - Oxygen

Syngas cleanup issues and costs are significantly different depending on target end products.
WTL for jet and diesel has been discussed a lot, but is still technologically challenging.
### CAPITAL, REVENUE AND OPERATING COSTS

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>$MM</td>
<td>325</td>
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<tr>
<td>Capital Cost per unit capacity</td>
<td>$/BPD</td>
<td>445,200</td>
</tr>
<tr>
<td>Average Liquid Fuel Sales Price (for 10% IRR Equity Cash Flow)</td>
<td>$/gal</td>
<td>4.40</td>
</tr>
<tr>
<td>Liquid Fuel Revenue (1st year)</td>
<td>$MM/yr</td>
<td>41.9</td>
</tr>
<tr>
<td>Tipping Fee Revenue (@ $60 per wet ton, 1st year)</td>
<td>$MM/yr</td>
<td>18.6</td>
</tr>
<tr>
<td>Power Net Import Cost (@ $60 per MW, 1st year)</td>
<td>$MM/yr</td>
<td>2.1</td>
</tr>
<tr>
<td>Variable Operating Cost (1st year)</td>
<td>$MM/yr</td>
<td>10.7</td>
</tr>
<tr>
<td>Fixed Operating Cost (1st year)</td>
<td>$MM/yr</td>
<td>15.9</td>
</tr>
<tr>
<td>Debt Finance Cost (1st year, 60/40 Leverage, 7% for 10 years)</td>
<td>$MM/yr</td>
<td>11.3</td>
</tr>
<tr>
<td>Plant Headcount</td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

### DESIGN BASIS

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of AlterNRG G-65 gasifiers</td>
<td>1</td>
</tr>
<tr>
<td>Number of FT Units</td>
<td>1</td>
</tr>
<tr>
<td>Availability (After 1st Year)</td>
<td>90</td>
</tr>
</tbody>
</table>

### INPUTS

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW (As received, 20 wt% moisture)</td>
<td>TPD</td>
</tr>
<tr>
<td>Total MSW (dry biomass equivalent on HHV basis)</td>
<td>TPD</td>
</tr>
<tr>
<td>Coke</td>
<td>TPD</td>
</tr>
<tr>
<td>Electrical Power (Import)</td>
<td>MW</td>
</tr>
</tbody>
</table>

### OUTPUTS (PRODUCTS & BYPRODUCTS)

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel or Jet Fuel</td>
<td>BPD</td>
</tr>
<tr>
<td>Naphtha</td>
<td>BPD</td>
</tr>
<tr>
<td>Total Fuel Production</td>
<td>BPD</td>
</tr>
<tr>
<td>Total Fuel Production</td>
<td>MTPA</td>
</tr>
<tr>
<td>Sulfur</td>
<td>TPD</td>
</tr>
<tr>
<td>Slag</td>
<td>TPD</td>
</tr>
</tbody>
</table>

WTL breakeven prices are high compared to current market pricing, requiring high tipping fees.
Block Flow Diagrams for DME
Plasma gasification plus one step DME synthesis vs Low quality nat gas and dry reforming to one step DME

- DME vs Ethanol
  - Both C2H6O, but very different characteristics
  - Produce from MSW syngas, or from low quality nat gas (CH4/CO2) with dry reforming and one step conversion
  - DME as future substitute for diesel, diluent for LPG, solvent for bitumen extraction

Syngas can come from MSW gasification or from dry reforming of low quality nat gas
China DME Price RMB 3908 = $593 per metric ton

Production cost as low as $275 per metric ton if from low quality natural gas

Production costs and processes can vary greatly with location


**: RES Kaidi Commercial model for 1,000 MTPA Nat Gas to DME plant, using XPRIZE technologies: Dry Reforming + 1-step DME

Most promising process pathway according to independent COSIA report; CO2 Conversion Technologies for Oil Sands Activities; Sept 2015
WTL, combining gasification (thermochemical) and bioreactors (biochemical), looks promising.
Evolving MSW Syngas to Ethanol
Demonstrated by both LanzaTech and Alter NRG

**3 CO + 3 H₂ → EtOH + CO₂**
- **CO:H₂ ratio**: 1:1

**4 H₂ + 2 CO → EtOH + H₂O**
- **CO:H₂ ratio**: 1:2

**Syngas (e.g. MSW)**
Demonstrated at site

Ethanol from MSW syngas is still evolving, but has been proven at demonstration scale

Source: LanzaTech
Ethanol from MSW syngas can be as attractive as from waste gases, depending on tipping fees.
Future Technology Platform for WTL

Bioreactor is “hardware”
- Same reactor vessel (microbe, reactor)
- Same set of operating conditions (T, P)
- Same syngas feedstock

Microbes are On-demand “software” using the same hardware
- Minor: improved efficiency, tolerance
- Major: new product molecule

For WTL, the flexibility to produce various end products from waste can counter price volatility
• Wholesale power prices are relatively low due to low coal and natural gas prices. Increasing renewable energy from wind and solar affects power prices and contracts making gasification to power difficult

• Liquids including ethanol, jet fuel, diesel and DME do not vary in concert with power prices and may provide better value per ton of MSW

• Understanding arbitrage opportunities is important and is more specific to location, process, end product than coal gasification is (was).

• Progress continues in understanding of syngas quality, syngas cleanup and conversion efficiencies for development of waste to liquids technologies

• Microbial conversion technologies using bioreactors for conversion to fuels and chemicals are implemented in an increasing number of commercial facilities. Flexible production facilities combining gasification and bioreactors is an exciting evolving integrated WTL process

• Conversion of MSW to liquids is worth evaluation as an alternative to electric power for commercial facilities
THANK YOU