

# **A preliminary look at the economics of a new biomass conversion process by Dynamotive**

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## **I. Background**

### **The production of carbon based motor fuels from biomass**

Biomass is the only renewable source of carbon for the manufacture of carbon based fuels. This simple fact implies that if alternative sources of such fuels are to be developed, some form of biomass is the only option.

### **Available technologies**

The only current large scale technologies to produce motor bio-fuels are ethanol and biodiesel derived respectively from corn starch or sugar cane juice, and vegetable oils. Both require specialized crops and utilize only a fraction (typically <40%) of their total biomass.

There have been intensive efforts over the last thirty years or so to extend the range of available biomass sources. The bulk of this effort has focused on utilizing cellulose as a source for production of ethanol. On the other hand several possible alternative cellulose based fuels have been recently commanding attention but all are, like ethanol, intrinsically based on hydrolysis of cellulose to sugars followed by subsequent conversion to various fuels, e.g.

- Butanol fermentation
- Chemical transformation to Valeralactone
- Chemical transformation to Hydrofurans
- Condensation and Hydrogenation of sugars (Virent)

Cellulose is the major component, typically 40-50%, of woody biomass. Of the other components the most important are lignins (~20-30%) and hemicelluloses (~20-30%). It is clear therefore that even if viable technologies are developed, any method that is limited to cellulose can utilize at most 50% of available biomass.

Though lignin comprises only 20-30% of typical lignocellulosic biomass it provides 40-50% of the overall heating value/available energy of the biomass. Dynamotive's focus is therefore on methods that aim to utilize whole lignocellulosic biomass.

Over the years various technologies have been proposed but at present only two appear to be viable propositions:

- **Biomass To Liquids (BTL)**

- Biomass **IN**to Gas**O**il (BINGO)

### BTL Processes

BTL, analogous to GTL, involves gasification of biomass to syngas followed by Fischer-Tropsch synthesis of paraffins/waxes that can be converted to diesel and gasoline fuels. Though the technology has been demonstrated it is however very complex and consequently very capital intensive thus requiring massive economies of scale.

With respect to yields, a joint venture BTL pilot plant between Shell and the Energy Research Centre of The Netherlands (ECN) produced a yield of 120 L diesel fuel/Tonne biomass. Boerringer has predicted that future improvements could allow the yield to increase to 210 L diesel fuel/Tonne biomass.

*"Green' Diesel Production with Fischer-Tropsch Synthesis", Boerringer, H.; Report No. ECN-RX-03-014; Energy Research Centre of The Netherlands: Petten, 2003; <http://www.ecn.nl/files/bio/RX03014.pdf>.*

By-products are electricity and SNG (synthetic natural gas.)

However many studies suggest that BTL plants will have to be very large scale ( $\geq 5000$  tpd) to be economically feasible.

**Bioliq** is another BTL process, a pilot plant for which is now under construction: (<http://www.greencarcongress.com/2008/12/air-liquide-mov.html>)

It is being developed jointly by Lurgi and Forschungszentrum Karlsruhe (FZK) in Germany. Dahmen *et al* of FZK suggest that plant capacities greater than 1 Mt/yr of biosynfuel (~15,000 tpd of biomass would be required if the yield was the maximum 210 L diesel/T biomass!)

*"Cost estimate for biosynfuel production via biosyncrude gasification", E. Henrich, N. Dahmen and E. Dinjus, Biofuels, Bioprod. Bioref. 3:28–41 (2009)*

Since biomass is unfortunately a very diffuse resource, this size of plant would require biomass to be sourced from a very large area so that transportation cost considerations are paramount. The FZK concept is to minimize this cost by first densifying the biomass by pyrolysis and transporting a slurry of biooil and char (so-called "biosyncrude") to the central BTL plant.

Henrich *et al* also provide the following yields:

7 T air-dried straw (15% moisture)  $\Rightarrow$  4.7 T biosyncrude  $\Rightarrow$  1 T biosynfuel

i.e. about 14.3 wt% or 170 L diesel fuel/Tonne air-dried biomass. This is close to the upper bound suggested by ECN/Shell.

### **BINGO Upgrading Processes**

Biooil upgrading has been investigated since the 1980's and is still under intensive investigation particularly in Europe, China and North America. The major approaches studied are conventional catalytic cracking (FCC) and hydrotreatment. The preferred approach appears to be hydrotreatment. Perhaps the most advanced program in North America is the DOE sponsored joint development between UOP and Pacific Northwest Laboratory (PNNL). See: [UOP Receives \\$1.5M for Pyrolysis Oil Project from DOE](#).

### **UOP/PNNL process**

The UOP approach is discussed more extensively in

*“Opportunities for Biorenewables In Oil Refineries Final Technical Report”, (2005), DOE Contract Number: DE-FG36-05GO15085.*

A fundamental problem with biooil hydrotreating is that biooil is thermally unstable and consequently very susceptible to cracking to coke with consequent reactor plugging and catalyst deactivation under typical hydrotreatment conditions.

### **Dynamotive BINGO Process**

This process under development by Dynamotive, involves biooil hydro-reforming and overcomes the defects of biooil that retard its acceptance. It involves pyrolysis of biomass to produce a first liquid, biooil, hydro-reforming of biooil to a first improved liquid that can either be directly utilized in blends with hydrocarbon fuels as an industrial fuel or be further upgraded in a second step to transportation grade liquid hydrocarbon fuels. The major by-product from biomass pyrolysis is so-called Biochar/Agrichar which has emerging value for soil productivity enhancement and carbon sequestration.

In comparison with the **Bioliq** process where only the total yield of char + biooil is relevant, Dynamotive's pyrolysis stage is designed to maximize liquid yields which means the pyrolysis process is somewhat more complex since conditions must be established for rapid heating of biomass particles. However since the water will separate during the reforming stage of BINGO, the moisture content of the biooil is not as crucial, thus minimizing potential biomass drying costs.

BINGO is a two stage process.

### Stage 1 (Hydroforming)

The first stage is hydro-reforming of biooil to

- ✓ stabilize it,
- ✓ render it miscible with hydrocarbon liquids,
- ✓ cause phase separation of the water in the biooil,
- ✓ lower its viscosity
- ✓ lower its corrosivity and
- ✓ lower its oxygen content from ~50% in the raw biooil to around 10%.

The reformed biooil product is designated UBA. The data for the following run is typical of the best results achieved so far in bench-scale laboratory tests. The hydro-reforming reaction was carried out in an autoclave.

#### Run #464

<b>Temperature</b>	330 °C
<b>Pressure</b>	~1800 psi
<b>Weight Hourly Space Velocity</b>	~1.5g Biooil/(g-catalyst-hr)
<b>Catalyst</b>	Xxxxxx
<b>Yields (based on raw biooil)</b> (Mass balance closure ~ 98%)	
<b>UBA</b>	45%
<b>Total Gas</b> (~80% CO <sub>2</sub> + 20% CH <sub>4</sub> )	8.1%
<b>Water content of Aqueous phase</b> (81% water)	37.9%
<b>Organics dissolved in Aqueous Phase</b> (~ 38% Methanol + 62% Acetic Acid)	8.9%
<b>H<sub>2</sub> consumption</b>	+ 1.4%

#### UBA properties

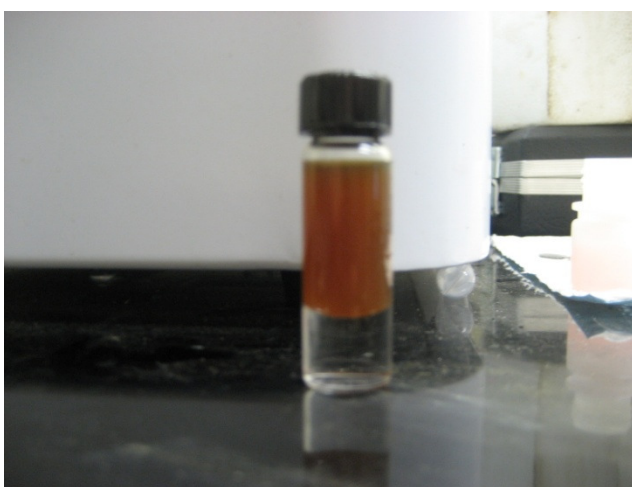
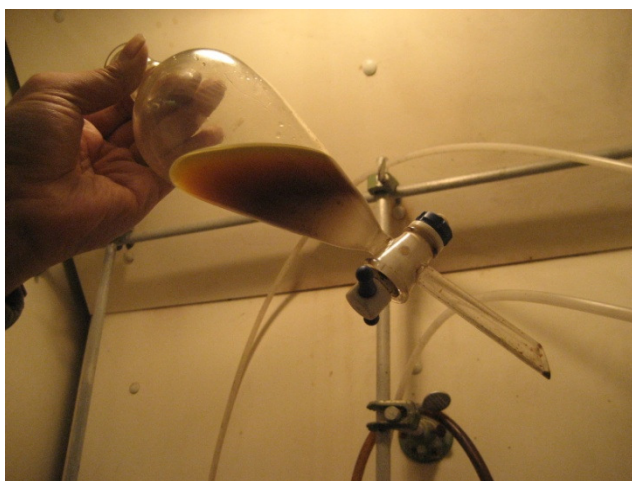
Water content	0.84%
Oxygen content	~10%
HHV	39.5 MJ/kg
Specific Gravity	0.97
TAN, mg KOH/g	37

#### Points of note:

- As evident from the table above, the water phase is relatively clean so acetic acid (worth on the order of \$1,500/T / \$ 700 /t) can be recovered using conventional technologies. *This has been demonstrated in the laboratory using liquid-liquid extraction.*
- Since the HHV of biooil is ~16 MJ/kg while that of hydrogen is ~121 MJ/kg, it may be seen from the data above that reaction is approximately thermoneutral so that of *the energy content of the biooil has been effectively concentrated in UBA.*
- This implies that the Energy Efficiency of this step is over ~ 80%.

- This also implies that the process requires no complicated heat exchange technology.
- Since UBA still contains ~ 10% oxygen it is not a pure hydrocarbon and needs further treatment to convert it to motor fuel grade products.
- Among the technologies available are FCC (catalytic cracking) and hydrotreatment/hydrocracking.
- UBA blends freely with most hydrocarbon fuels in concentrations up at least 50%.
- *Besides its conversion to motor fuels, UBA, especially if blended with fuel oil, can be used as a drop-in renewable oil replacement fuel for general residential/commercial stationary power and heat generation.*
- No visible coke was produced but catalyst longevity tests must await construction of a pilot plant.
- Deoxygenation of biooil is ~ 80%.
- The corrosivity of UBA as characterized by its TAN (total acid number) is substantially reduced compared to raw biooil (37 versus ~ 150). The water content is also reduced to ~ 1% compared to ~ 20 – 30 % for raw biooil.

A sample of UBA along with some of the aqueous phase is shown in the photographs below



**Stage 2 (Hydrotreating)**

The second stage involves a conventional hydrotreatment over a commercial catalyst. The following results are for a low severity proof-of concept hydrotreatment. UBA was hydrotreated in an autoclave to give a liquid designated UBB, with the following results:

#### Run #466

<b>Temperature</b>	350 °C
<b>Pressure</b>	~1700 psi
<b>Weight Hourly Space Velocity</b>	~2.5 g UBA/(g-catalyst-hr)
<b>Catalyst</b>	Commercial hydrotreating catalyst
<b>Yields (based on UBA)</b> (Mass balance closure ~ 93%)	
<b>UBB</b>	83%
<b>Total Gas</b> (~43% CO <sub>2</sub> + 27% CH <sub>4</sub> + 30% CO, C <sub>2+</sub> )	9.6%
<b>Aqueous Phase</b> (Water content 95%)	8.6%
<b>H<sub>2</sub> consumption</b>	+ 2%

#### UBB properties

Water content	0.05%
Oxygen content	~1 %
HHV	45 MJ/kg
Specific Gravity	0.87
TAN, mg KOH/g	0.9

#### Points of note:

- As evident from the yields of water and CO<sub>2</sub>/CO, oxygen removal is almost complete in UBB.
- The HHV of UBB at ~45 MJ/kg is comparable to that of diesel.
- This is a proof of concept experiment. Commercial hydrotreating catalysts are available that can steer the product towards diesel/gasoline/jet fuel etc. at somewhat higher severity conditions. Hydrogen consumption will be higher under those conditions.
- The clear water phase contains only 5% organics, i.e. low COD/BOD which may be easily handled by water treatment plants.
- The overall yield of UBB from *biooil* is an astonishing 38%.
- Deoxygenation of biooil is ~98%

A sample of UBB is shown in the photographs below:



For comparison with the Bioliq BTL process, note that the Dynamotive's pyrolysis process typically would give biooil yields of about 70-75% from woody biomass and 60-65% from bone dry wheat straw. The yields will in fact be somewhat greater for straw containing 15% moisture. **Thus the overall yield of hydrocarbon liquids from wheat straw is estimated to be  $0.45 \times 0.65 \times 100 = 29\%$  UBA or 24% UBB.** As far as we can determine this would be the highest yield of hydrocarbon liquids from whole biomass ever reported. It far exceeds the 14% biomass to diesel reported for the Bioliq BTL process; even when account is taken of the likelihood that yields of motor fuels -as opposed to unspecified hydrocarbons - in the final step will be somewhat lower on account of the higher severity hydrotreatment that would be required.

### Production Costs





In order to keep the production cost of UBA from biomass separate we will attempt to assess the additional cost of operating the hydroformer for production of UBA. Thus all biooil production cost will be subsumed into the biooil cost.

Thus UBA production costs include:

- Fixed costs for hydroformer + Liquid –Liquid Extractor
  - o Capital service charges
  - o Labour
  - o Depreciation
  - o Maintenance
  - o Taxes and insurance
  - o Plant overheads
- Variable costs of hydroformer
  - o Hydrogen cost
  - o Biooil cost
  - o Utilities
- Credit offsets for by-products

**Example: Base case: 200 tpd biomass pyrolysis plant.**

At 65% yield it will produce 130 tpd biooil + ~20 tpd biochar. This will be converted to  $0.45 \times 130 = 58.5$  tpd UBA

$\equiv 58.5 \text{ (m}^3 \text{ UBA)/d} \equiv 355 \text{ (bbl UBA)/d} + 5.5 \text{ tpd Acetic Acid.}$

The total volume of aqueous phase is ~ 52 T or ~13,000 gal.

**Hydrogen costs:**

Hydrogen can be sourced from petroleum refineries for less than \$3/kg for small scale deliveries out of pipeline range. The hydrogen consumption for UBA is 14 kg/(T biooil) and \$3/kg for H<sub>2</sub>.

Conversion to UBB would require an additional 9kg H<sub>2</sub>/(T Biooil) of Hydrogen. Thus it seems that this final stage would best be carried out in an oil refinery where hydrogen is cheapest and where it could be co-processed with petroleum.

**Biooil cost**

In their DOE report referenced above, UOP assume the fuel value of biooil is \$4.7/MMBTU. This is equivalent to \$4.9/GJ = \$79/T. Assume this is the nominal production cost (including feedstock cost) of biooil. In our model we are allocating \$ 8 per GJ (which we believe represents total cost net of char credit and incorporates fiber costs at \$ 30 per tonne, operational costs, Capex amortization based on \$ 29.3 million 200 tpd bio oil plant and median interest expense).

### Acetic acid credits

Acetic acid is assumed to be worth ~\$800/T. Since daily production is 7.2 T. If we assume a recovery rate of 90% This would be equivalent to ~ \$5,180 per day which would sufficient to offset part of the hydrogen cost. In the event of having the last stage process (UBB) in a refinery where the cost of hydrogen would be significantly lower the full cost of hydrogen would be offset.

### CO<sub>2</sub> and biochar credits

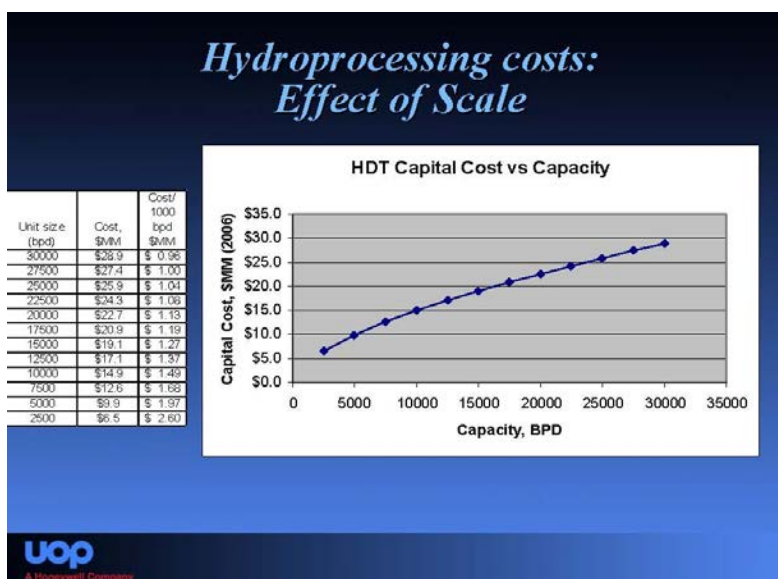
UOP assumes a CO<sub>2</sub> credit of \$30/T in their projections. In the following char will be priced on its fuel value, the same as coal. CO<sub>2</sub> credits for fuel use or for carbon sequestration/soil enhancement would add to this value.

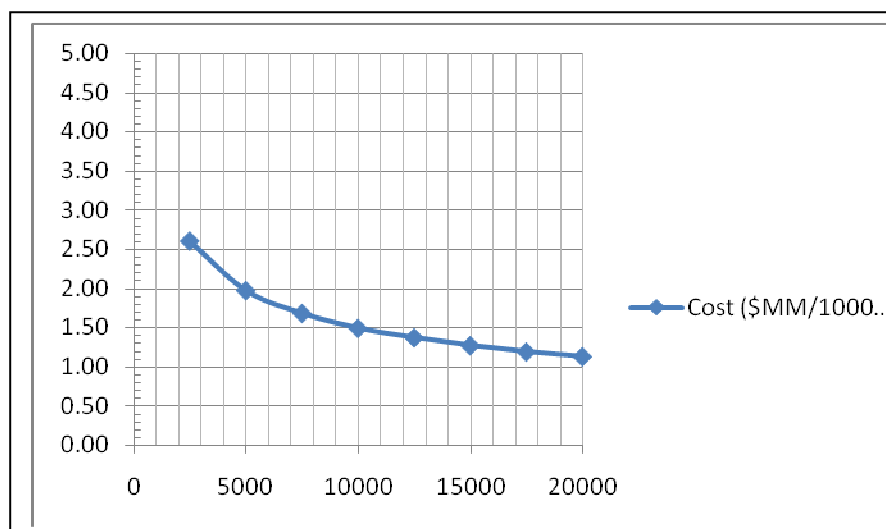
Use as a raw material for activated carbon production may represent an even higher value application. In our model char is valued at approximately \$ 150 per tonne (see bio oil production model and assumptions).

### Capital cost

The reforming reactor size is the volumetric rate of biooil which is about ~108 m<sup>3</sup>/d or ~ 680 bbl/day, assuming biooil SG = 1.2. UOP capital cost data for hydrotreaters is shown below. Extrapolation of this data to ~ zero size suggests our small reactor has a unit capital cost in the range of ~ \$MM 3.0-4.0/1000 tpd so that the total for 130 tpd biooil is ~\$MM 0.5 for a single hydroformer.

We conservatively take \$7 M. Thus assuming the pyrolysis plant costs \$MM29.3 the total capital cost for pyrolysis plant + hydroformer + extractor is ~\$MM36.3.





**Capital cost per unit of fuel output:** Ethanol has a HHV of ~ 30MJ/kg. The HHV of UBA is ~40 MJ/kg so that 1kg UBA is equivalent to 1.3 kg ethanol. The output of 58.5 tpd UBA is equivalent to 76 tpd = 26,300 gal/d Ethanol, or 8.7 Mgal ethanol equivalent/yr.

Thus for a total capital cost of \$MM36.3, the capx per gal ethanol is  $\$36.3/8.4 = \$4.32/(\text{gal ethanol/yr})$ . This can be compared with the \$8.75/ (gal ethanol/yr) of the BP-Verenium lignocellulosic ethanol project recently announced. See (<http://phx.corporate-ir.net/phoenix.zhtml?c=81345&p=RssLanding&cat=news&id=1257761>)

Note 1: The Dynamotive BINGO process uses a variant of standard hydrotreating technology. No new reactor designs need to be developed. There is variation only in the mode of operation, catalyst, and process parameters.

Note 2: On account of the higher space velocity of Dynamotive BINGO, reactor sizes for a specified production rate and hence capital costs will be reduced compared to the UOP data.

Capital cost of a Liquid-Liquid extraction unit for acetic acid is unknown but likely to be low. Assume < \$MM 1.

**Production Cost Summary (see spreadsheet attached).**

**Assume: 200 tpd biomass Pyrolysis plant/hydroformer producing 58.5 tpd UBA. Worst case assumptions are made for capital costs and hydrogen costs.**

‡ Taken the same as the value used for the Sandia/GM study referenced below (Check Desmond)

‡ Assuming straight line depreciation of capital over 15 years.

‡‡**Ethanol Equivalency** Since 1 kg UBA  $\equiv$  1.33 kg EtOH on an energy equivalent basis, and the

density of ethanol is 0.79, 1 kg  $\equiv$  0.45 gal EtOH. The yield of UBA in ethanol equivalents is

therefore 132 gal (Ethanol Equivalent)/(ton UBA).

To put this in perspective, in the recently concluded (Nov/08) joint study between Sandia National Laboratories and General Motors' R&D Center, the "90-Billion Gallon Biofuel Deployment Study", it was assumed that sufficient R&D would lead to an ethanol yield from lignocellulosic biomass of 95 gal/ton (<http://hitectransportation.org/news/>).

† Char yield of 20% assumed. \$75/T is a current price for coal.

**Exclusions:**

No Carbon Credits have been considered in the cost model.

No Capex reduction potential – grants / tax credits.

No Production credits.

No Employment credits.

No accelerated depreciation.

### **Comparison with UOP/PNNL process**

The UOP study envisages hydrotreating/hydrocracking "pyrolytic lignin" to gasoline. They estimate the capital cost of a hydrotreating/hydrocracking unit producing 1010 bpd of gasoline from 2250 bpd Pyrolytic lignin and 21.4 tpd hydrogen is \$MM30. They conclude that their process is economically attractive at a biooil price of \$18/bbl at a crude oil price of \$50/bbl.

Since Pyrolytic lignin comprises only 20-30% of biooil, 2250 bbl/d lignin is equivalent to 9000 bbl/d biooil (or 1500 tpd biooil). Their hydrogen usage of 5.7% (for gasoline production) is significantly higher than our 1.4% to UBA and 2.3% to UBB.

**It is suggested by Boerrigter that Bioliq technology could produce “biofuel” for around €0.50 a liter (\$2.49 a gallon) at a Bioliq plant with an annual production capacity of around 1 million tonnes. We conclude that a small-scale BINGO process is highly competitive with large scale BTL processes.**

### **Conclusions**

- Apart from any technical challenges, both cellulosic ethanol and pyrolytic lignin hydrotreating have the fundamental disadvantage that they utilize only a part of whole lignocellulosic biomass. Our process effectively utilizes all biomass components with the added bonus that a by-product is Biochar/Agrichar.
- Biochar can be either burned to generate heat/power, steam gasified to generate hydrogen, converted to activated carbon, or used as a combination soil enhancer and carbon sequestration agent. Acetic acid and methanol are other recoverable by-products. We have used for cost modeling purposes lowest value factor – heating value equivalent against coal. Carbon sequestration potential 3.5 tonnes CO<sub>2</sub> per tonne applied to soil has not been factored.
- The reasons for the low yields (i.e. low carbon efficiency) of gasification/FT schemes like Bioliq relate to the high exothermicity of the FT reaction arising from the release of carbon as CO<sub>2</sub> which necessarily lowers the carbon utilization efficiency, together with the carbon losses on gasification. Our process utilizes carbon much more efficiently but at the cost of requiring hydrogen.
- Our breakthrough has been essentially to find a way to utilize the whole of the biooil. The competing UOP biooil based process utilizes only a part of the biooil and requires more hydrogen per unit of biooil.
- The new process has the potential to be a significant step forward towards the goal of efficient conversion of biomass to liquid hydrocarbon fuels. It also appears to have the potential to be economically feasible on the small scales appropriate to the diffuse character of biomass resources. No new reactor technology is required, though the process must be verified at the pilot plant level.
- Time to market: Dynamotive’s platform pyrolysis technology is available today providing a time advantage vs other processes. Virent / Range Fuels (Ehtanol) 2012, Dupont (ethanol)2012, Lurgi / FZK (Pyrolysis 40 tpd) 2012.