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Softwood to Jet Fuel Techno-Economics for an Integrated Greenfield Biorefinery

NARA Annual Meeting

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Northwest Advanced Renewables Alliance

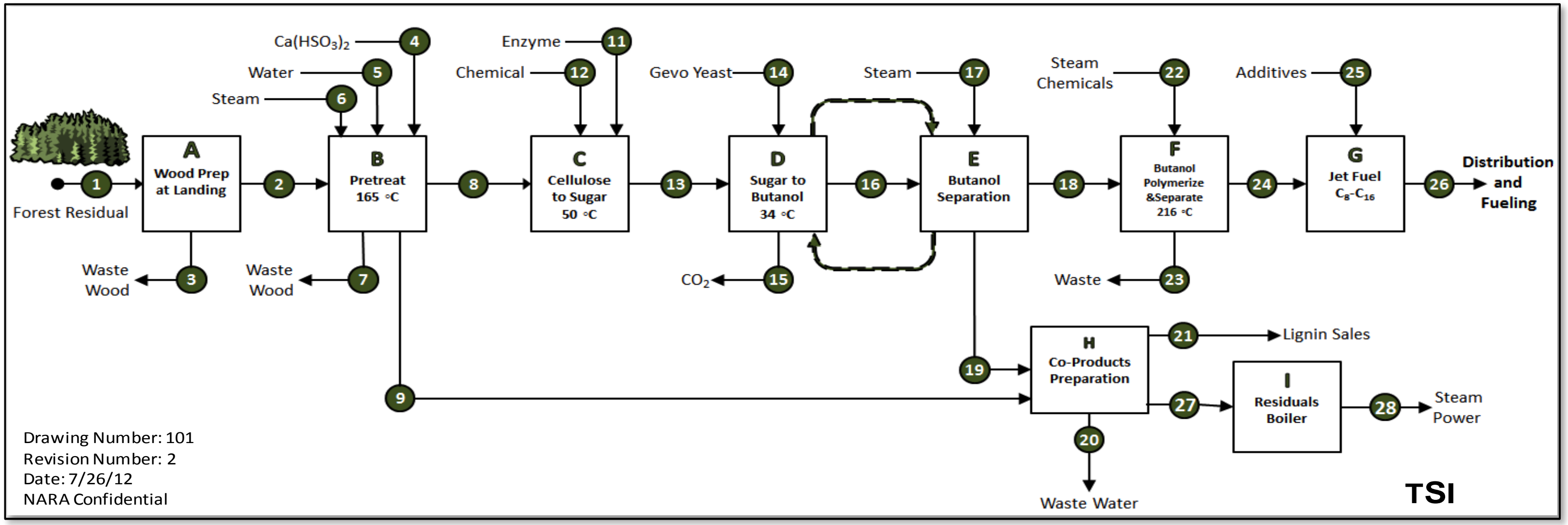
USDA

Background

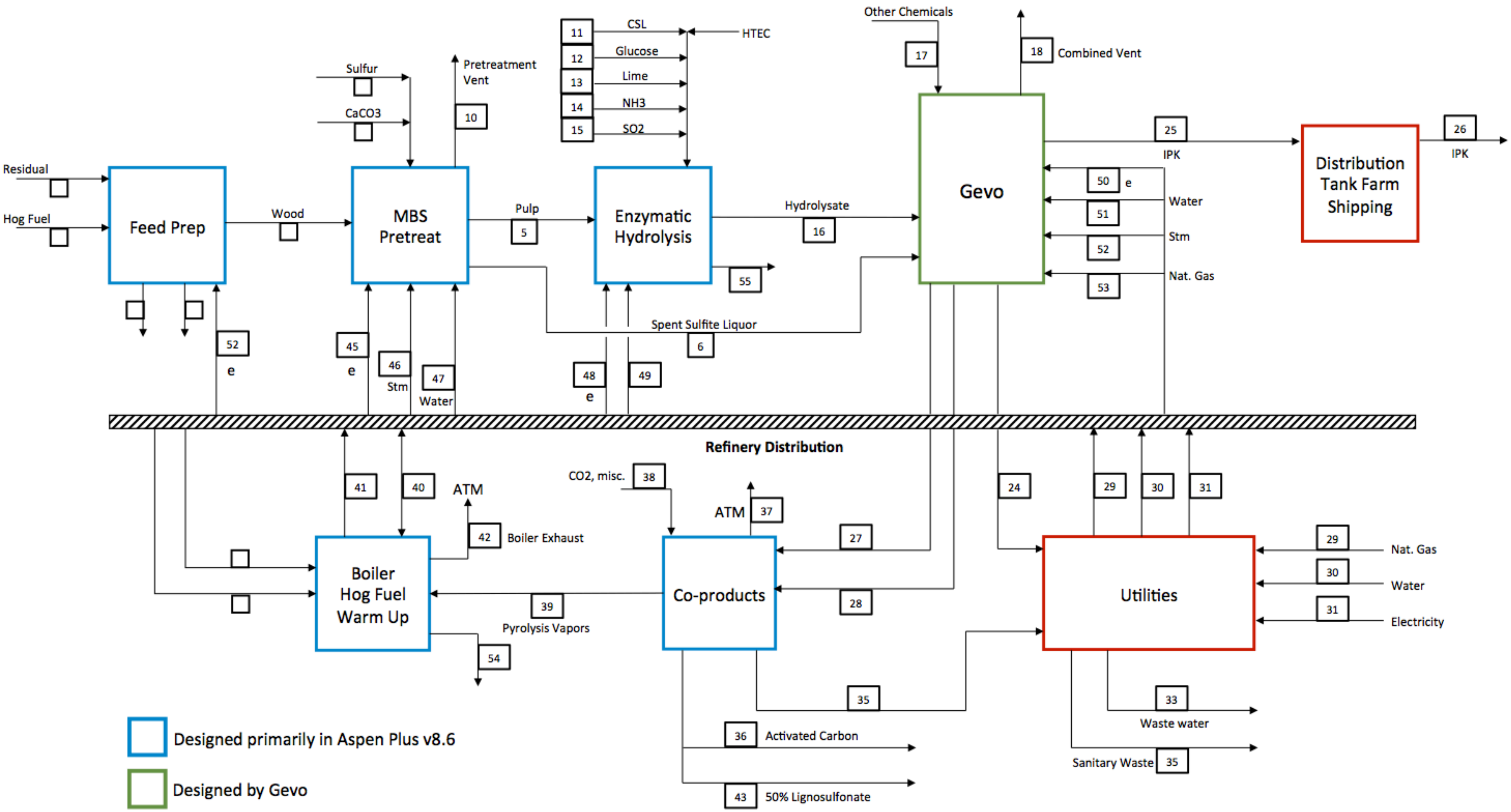
- NARA has assembled and refined expertise in conversion technology for converting PNW softwoods into multiple products. The economics of a greenfield, full scale integrated biorefinery have been estimated, and sensitivity analyses performed.
  - Conversion processes and yields have been developed based upon laboratory tests.
  - Energy and mass balances have been calculated with ASPEN modeling.
  - Capex and Opex have been estimated from best available sources.
  - All of these are incorporated into a TEA model.

NARA Process Simplified Overview

- **Forest Harvest Residuals** are processed in a biorefinery to produce 3 products:
  - Cellulosic sugars are fermented to IBA, this converted to **iso-paraffinic kerosene (IPK,** bio-jet fuel)
  - Hemicelluloses and soluble lignin are sold as **Lignosulfonates**
  - Insoluble lignin and fermentation residuals are converted to **activated carbon.**



ASPEN Process Flow Overview



Designed primarily in Aspen Plus v8.6

Designed by Gevo

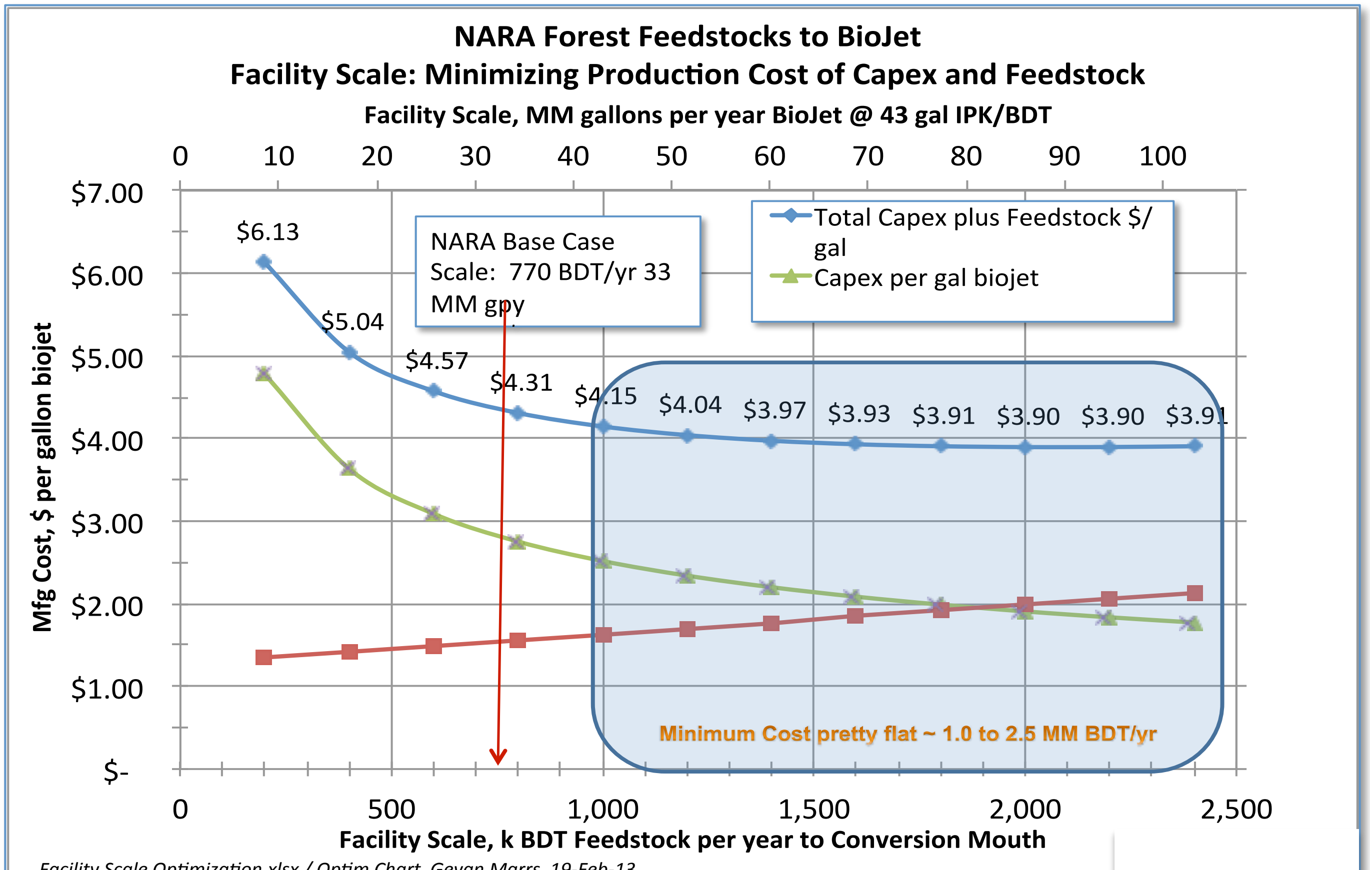
Designed by TEA team based on literature

The Feedstock

- Forest Harvest Residuals are an abundant, underutilized, renewable source available at large scale.
  - tree tops, branches, broken logs and chunks

Conversion Plant Scale

- Feedstock cost to a central point increase as facility scale increases, but economy of scale of the plant decreases cost per unit consumed.
  - This tradeoff leads to a facility scale target of about 770,000 BDT/year feedstock through conversion, or 2,200 tons per day.



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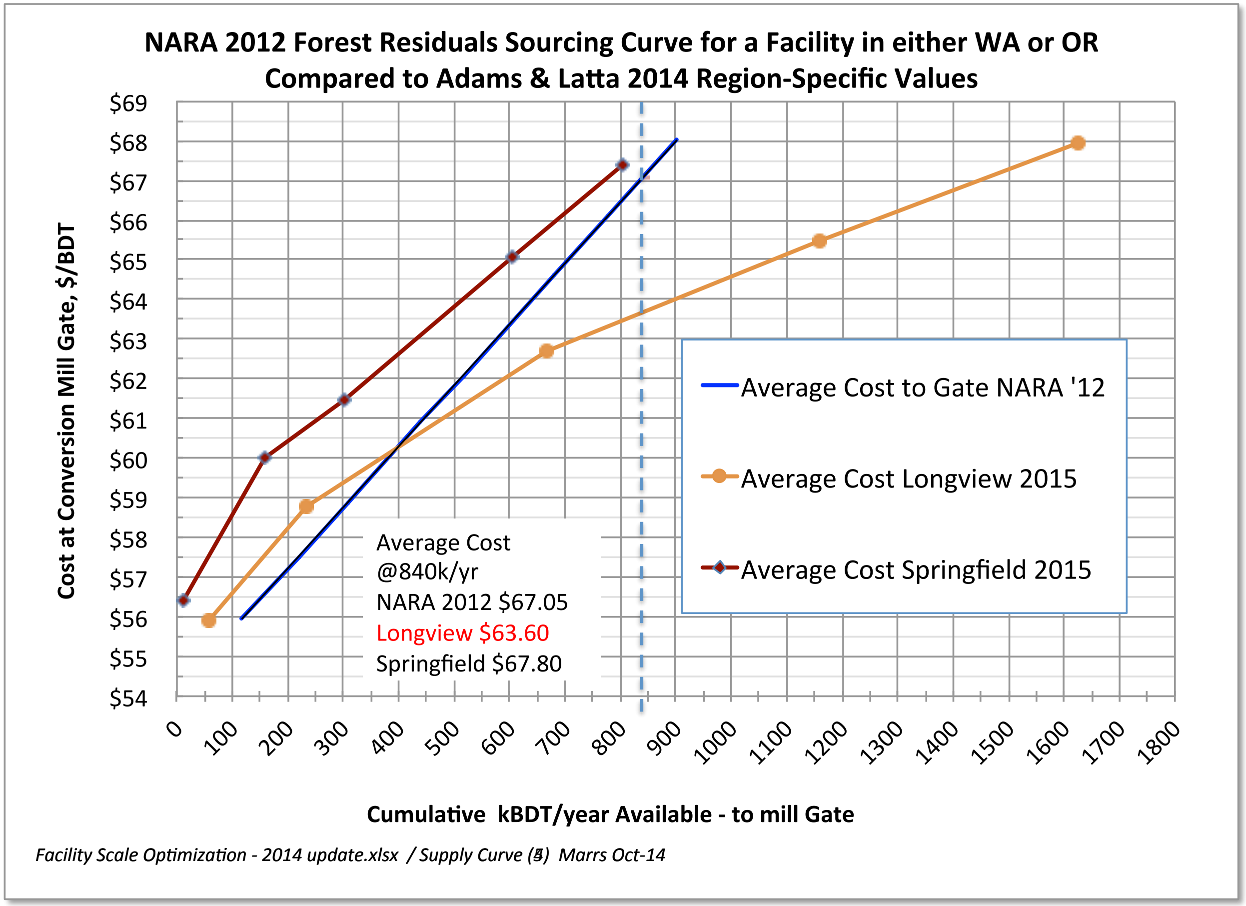
Feedstock Delivered Cost

- Forest Harvest residuals are assumed to be harvested with the following costs:
  - Stumpage, Loading, Grinding, Hauling to millsite



2014 estimates for a target location (Longview, WA)

840,000 BDT through the gate at average of$63.60 / BDT

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Process Overview - IPK

- Feedstock is pretreated to allow enzymatic hydrolysis of cellulosic sugars to simpler sugars.
- Sugars are fermented to iso-butanol (IBA).
- IBA is polymerized and dehydrated to Isoparaffinic Kerosene (IPK).
- IPK can then be blended 50:50 with petro-jet to make aviation fuel.
- Facility would produce 36 MM gal IPK / year
- Assumed selling price of $3.09 / gal IPK
- Carbon Credit premium for renewable bio-fuel (via RINs) is another $2.12 / gal IPK.
- Annual revenue from IPK is $188 MM.

Process Overview - Lignosulfonates

- Mild bisulfite pretreatment of feedstock dissolves some lignin and many hemicelluloses.
- This solution of lignin and sugars is fermented to remove sugars, then (with some process chemicals), has an established market as a sugar-free lignosulfonate.
- NARA facility would produce 196 k dry tons of sugar-free lignosulfonates (LS).
- Assumed selling price is $200 / dry ton
- Annual revenue from LS is $39 MM/year.

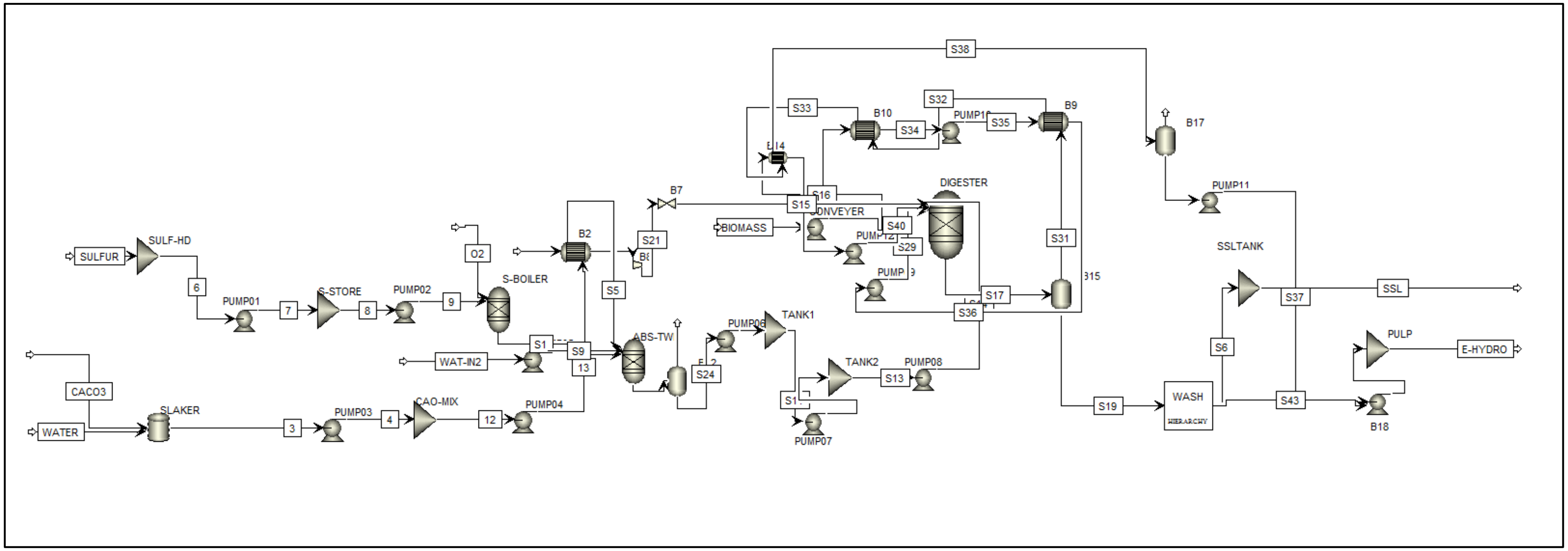
Process Overview – Activated Carbon

- Solids from feedstock remain after fermentation of sugars (FRS), consisting of mostly lignin and spent yeast.
- FRS can be pyrolized and activated to produce Activated Carbon (AC).
- AC has a potential market as a material to remove mercury from power plant flue gas.
- NARA facility would produce 66k dry tons / year
- Assumed selling price of $1,500 per dry ton
- Annual revenue would be $99 MM.

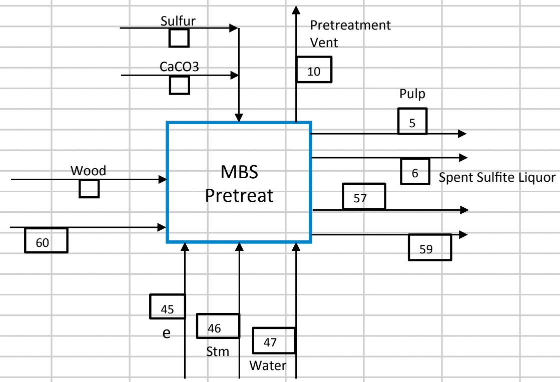
Process for Techno-Economic Analysis

- Production processes defined by years of laboratory to pilot scale work by NARA participants.
- Reactions and product yields incorporated into ASPEN mass and energy balance model to quantify flows at scale.
- Capital cost estimates for full facility pulled from available sources and scaled per ASPEN results.
- Operating costs were derived from ASPEN flow quantities and literature costs (chemicals, power, labor, etc.)
- All these pulled together in DCF-ROI analysis based upon NREL corn-stover to ethanol TEA model.

- Mild Bi-Sulfite Pretreatment of forest residuals
  - Process flow and equipment layout



ASPEN model mass and energy



	Stream: Short tons/hour												
Component	4	5	8	9	10	6	45	46	47	56	57	59	60
	Forest Residuals	Pretreated Pulp	Sulfur	Calcium Carbonate	Pretreatment Combined Vent	Spent Sulfite Liquor	Electricity	Steam In	Process Water	Cooling Water In	Cooling Water Out	Steam Out	Caustic In
Water	61.11	142.55	-	-	1.253	247.797	-	-	321.51	3030	3030	-	-
Glucan	37.34	35.41	-	-	-	-	-	-	-	-	-	-	-
Xylan	4.90	2.55	-	-	-	-	-	-	-	-	-	-	-
Arabinan	1.12	0.70	-	-	-	-	-	-	-	-	-	-	-
Galactan	2.67	1.41	-	-	-	-	-	-	-	-	-	-	-
Mannan	10.50	5.65	-	-	-	-	-	-	-	-	-	-	-
Ash	0.43	0.43	-	-	-	-	-	-	-	-	-	-	-
Insoluble Lignin	25.89	18.48	-	-	-	-	-	-	-	-	-	-	-
Soluble Lignin	0.41	1.65	-	-	-	10.902	-	-	-	-	-	-	-
Bark	3.18	3.18	-	-	-	-	-	-	-	-	-	-	-
Extractives	5.22	0.65	-	-	-	4.56	-	-	-	-	-	-	-
Glucose	-	0.26	-	-	-	1.79	-	-	-	-	-	-	-
Xylose	-	0.32	-	-	-	2.26	-	-	-	-	-	-	-
Arabinose	-	0.06	-	-	-	0.39	-	-	-	-	-	-	-
Galactose	-	0.17	-	-	-	1.21	-	-	-	-	-	-	-
Mannose	-	0.66	-	-	-	4.64	-	-	-	-	-	-	-
$CaCO_3$	-	-	-	3.25	-	-	-	-	-	-	-	-	-
Sulfur	-	-	3.30	-	-	-	-	-	-	-	-	-	-
Bisulfite	-	0.19	-	-	-	1.37	-	-	-	-	-	-	-
SO2	-	-	-	-	0.031	-	-	-	-	-	-	-	-
Steam (klb)	-	-	-	-	-	-	-	158.6	-	-	-	42.6	-
Elec. (MWhr)	-	-	-	-	-	-	1.50	-	-	-	-	-	-
Acetic Acid	-	0.27	-	-	-	-	-	-	-	-	-	-	-
Furfural	-	0.15	-	-	-	-	-	-	-	-	-	-	-
CO2	-	0.02	-	-	0.782	-	-	-	-	-	-	-	-
NaOH	-	-	-	-	0.125	-	-	-	-	-	-	-	0.125
Subtotal BDT	91.7	72.2	3.3	3.3	-	27.1	-	-	-	-	-	-	-
BDT/yr	769913.8	606564.0	27720.0	27300.0	-	227824.8	-	-	-	-	-	-	-
Total	152.8	214.8	3.3	3.3	-	274.9	-	-	-	-	-	-	-
Total tons/yr	1283238	1803984	27720	27300	-	2309320	-	-	-	-	-	-	-

Mild Bi-sulfite Pretreatment of forest residuals

Capital Costs

- Based upon defined equipment needs and size per ASPEN modeling, estimates pulled from best available sources.

Process Area		Purchased Cost, MM$	Installed Cost, MM$
Feedstock handling			$ 47.7
Pretreatment			$ 206.2
Enzymatic Hydrolysis			$ 76.8
Fermentation, Separation, Alcohol-to-Jet			$ 188.9
Lignin Co-products			$ 123.9
IPK Product Storage and Distribution			$ 10.0
Multi-fuel Boiler			$ 43.2
Utilities			$ 134.7
Totals			**$ 831.4**
Warehouse	% of ISBL	4.0%	$ 20.8
Site development (Inlcuded in ASPEN Utilities block)	% of ISBL	0.0%	$ -
Additional piping (included in other blocks)	% of ISBL	0.0%	$ -
Total Direct Costs (TDC)		4.0%	**$ 852.2**
Prorateable expenses	10% of TDC	10%	$ 85.2
Field expenses	10% of TDC	10%	$ 85.2
Home office & construction fee	20% of TDC	20%	$ 170.4
Project contingency	10% of TDC	10%	$ 85.2
Other costs (start-up, permits, etc.)	10% of TDC	10%	$ 85.2
Total Indirect Costs	**% of TDC**	**60%**	**$ 511.3**
Fixed Capital Investment (FCI)			**$ 1,363.5**

Indirect costs included per NREL assumptions.

Total Capital Investment = $1,363 MM

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Operating Costs

- Based upon quantities from ASPEN model, best available prices, opex by department estimated.

Manufacturing Costs (million $ per year)	
Feedstock + Handling	$70.5
Pretreatment Opex	$10.1
Enzymatic Hydrolysis	$27.9
Fermentation, Separation & Alcohol-to-Jet	$36.4
IPK Product Storage and Distribution	$0.1
Power Boiler	$4.4
Lignin Co-products	$35.8
Utilities	$17.4
Fixed Costs (Labor, Prop Tax, Insurance, Maint.)	$78.3
Total Manufacturing Costs	**$280.89**

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Revenue streams

- Quantities and assumed selling price
- Co-products contribute almost the same amount to revenue as does renewable bio-jet.

Case 13.2 Integrated Facility producing IPK, Lignosulfonates, and Activated Carbon				
Annual Revenue				
Product	Annual Product	Units (millions)	Revenue $/Unit	Total Annual Revenue, $MM
Iso-Paraffinic Kerosene - IPK	36.2	gallons	$ 3.09	$ 111.71
Cellulosic RINs	61.4	C-RINS	$ 1.25	$ 76.80
Lignosulfonates	196,224	Dry tons	$ 200	$ 39.24
Activated Carbon	66,192	Dry tons	$ 1,500	$ 99.29
Total Annual Revenue (million $ per year)				**$ 327.04**

Discounted Cash Flow - IRR

- 30-year project life, 100% equity funding, 10% cost of capital, 8-year depreciation.
- Bottom line results – Greenfield IBR: 0.1% IRR

DCFROR Worksheet - all $ MM														
Year	Annual Averages	-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed Capital Investment		$109	$818	$436										
Land		$8												
Working Capital				$68										
Loan Payment					$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Loan Interest Payment		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Loan Outstanding Principal		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
IPK Sales	$111.71				$111.71	$111.71	$111.71	$111.71	$111.71	$111.71	$111.71	$111.71	$111.71	$111.71
Cellulosic RINs	$76.80				$76.80	$76.80	$76.80	$76.80	$76.80	$76.80	$76.80	$76.80	$76.80	$76.80
Octane	$0.00				$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
12:00:00 AM	$0.00				$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Lignosulfonates	$39.24				$39.24	$39.24	$39.24	$39.24	$39.24	$39.24	$39.24	$39.24	$39.24	$39.24
Activated Carbon	$99.29				$99.29	$99.29	$99.29	$99.29	$99.29	$99.29	$99.29	$99.29	$99.29	$99.29
Total Annual Sales	**$327.04**			**Total Annual Sales**	**$327.04**	**$327.04**	**$327.04**	**$327.04**	**$327.04**	**$327.04**	**$327.04**	**$327.04**	**$327.04**	**$327.04**
Annual Manufacturing Cost														
Feedstock					$70.45	$70.45	$70.45	$70.45	$70.45	$70.45	$70.45	$70.45	$70.45	$70.45
Baghouse Bags					$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09
Other Variable Costs					$132.08	$132.08	$132.08	$132.08	$132.08	$132.08	$132.08	$132.08	$132.08	$132.08
Fixed Operating Costs					$78.27	$78.27	$78.27	$78.27	$78.27	$78.27	$78.27	$78.27	$78.27	$78.27
Total Product Cost	$280.89				**$280.89**	**$280.89**	**$280.89**	**$280.89**	**$280.89**	**$280.89**	**$280.89**	**$280.89**	**$280.89**	**$280.89**
Annual Depreciation														
General Plant Writedown					14%	24.49%	17.49%	12.49%	8.93%	8.92%	8.93%	4.46%		
Depreciation Charge	*$44.0*			Depreciation Charge	$188.67	$323.34	$230.92	$164.90	$117.90	$117.77	$117.90	$58.89	$0	$0
Remaining Value					$1,132	$808	$577	$412	$295	$177	$59	$0		
Steam Plant Writedown					3.75%	7.22%	6.68%	6.18%	5.71%	5.29%	4.89%	4.52%	4.46%	4.46%
Depreciation Charge	*$1.44*				$1.62	$3.12	$2.88	$2.67	$2.47	$2.28	$2.11	$1.95	$1.93	$1.93
Remaining Value					$42	$38	$36	$33	$30	$28	$26	$24	$22	$20
Total Depreciation					$190.29	$326.46	$233.80	$167.57	$120.37	$120.05	$120.01	$60.84	$1.93	$1.93
Net Revenue	$0.71			Net Revenue	($144.13)	($280.30)	($187.65)	($121.42)	($74.21)	($73.90)	($73.86)	($14.68)	$44.23	$44.23
Losses Forward				Losses Forward		($144.13)	($424.44)	($612.08)	($733.50)	($807.72)	($881.61)	($955.47)	($970.16)	($925.93)
Taxable Income	($534.84)			Taxable Income	($144.13)	($424.44)	($612.08)	($733.50)	($807.72)	($881.61)	($955.47)	($970.16)	($925.93)	($881.70)
Income Tax	*$0.00*	0.00%		Income Tax	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Annual Cash Income	$46.15	$ 117.08	$818	$504	$46	$46	$46	$46	$46	$46	$46	$46	$46	$46
Discount Factor	*10.000%*	*1.2100*	*1.1000*	*1.0000*	*0.9091*	*0.8264*	*0.7513*	*0.6830*	*0.6209*	*0.5645*	*0.5132*	*0.4665*	*0.4241*	*0.3855*
Annual Present Value	$435				$42	$38	$35	$32	$29	$26	$24	$22	$20	$18
Total Capital Investment + Interest		$142	$900	$504										
Net Present Worth				**-$1,106.5742**										
Internal Rate of Return	**0.09%**	$ (117.08)	$ (818.08)	$ (504.48)	$ 46.15	$ 46.15	$ 46.15	$ 46.15	$ 46.15	$ 46.15	$ 46.15	$ 46.15	$ 46.15	$ 46.15

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Basic reasons for low return

- High capital costs, low annual revenue compared to annual operating costs.
  - That is, the process is complex, the yields of products are (relatively) low, and the market value of many are basically commodity pricing.

NARA Revenue V13	Amount	Units	Price per uni	Total Revenue, $fMM/yr	Tons/yr	Yield on Wood	Unit Value on Weight Basis, $/BDT
Iso-Paraffinic Kerosene - IPK	36.2	gallons	$ 3.09	$ 111.71	112,980	13%	$ 989
Cellulosic RINs	61.4	C-RINS	$ 1.25	$ 76.80	NA		$ 680
Total for celllosic IPK							*$ 1,669*
Lignosulfonates	196,224	Dry tons	$ 200	$ 39.24	196,224	23%	$ 200
Activated Carbon	66,192	Dry tons	$ 1,500	$ 99.29	66,192	8%	$ 1,500
Total Annual Revenue (million $ per year)				**$ 327.04**		**44%**	

Increasing return: Reduce Capital

- Due to depreciation and tax impacts, effect of Capex not intuitively obvious.
- Assume that Capex is reduced (cut in half) for usable departments by re-purposing a pulp mill.

	Capital Costs, million $		
Unit Operation	**Greenfield**	**Repupose**	Savings
Feedstock handling	$48	*$24*	
Pretreatment	$206	*$103*	
Enzymatic Hydrolysis	$77	$77	
Fermentation, Separation & Alcoh	$189	$189	
Lignin Co-products	$124	$124	
IPK Product Storage and Distribut	$10	$10	
Multi-fuel Boiler	$43	*$22*	
Utilities	$135	*$67*	
Total Installed Equipment Cost	**$831**	**$615**	$216
Added Direct + Indirect Costs	$608	$453	
(% of TCI)	42%	42%	
Total Capital Investment (TCI)	**$1,439.6**	**$1,068.4**	$371
IRR	0.1%	1.4%	

Cutting Capex by half for Feedstock handling, Pretreatment, Boiler and Utilities only increases IRR to 1.4%

Essentially the issue is that Revenue is not large enough compared to Operating costs.

Need to make more, highly valued products in a simpler process…

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What would it take to increase IRR?

- Can increase Revenue, decrease Opex, reduce Capex, or some combination of these three factors.

Aribtrary results needed to get high IRR from NARA IBR			
Cut Opex by 1/2 or 3/4			
Capex	Opex	Revenue	IRR
$ 1,441	$ 281	$ 327	0.1%
$ 1,441	$ 140	$ 327	9.4%
$ 1,441	$ 70	$ 327	12.8%
Increase Revenue by 50% or 100%			
$ 1,441	$ 281	$ 327	0.1%
$ 1,441	$ 281	$ 491	10.6%
$ 1,441	$ 281	$ 654	17.8%
Drop Capex by 25% or 50%			
$ 1,441	$ 281	$ 327	0.1%
$ 1,081	$ 281	$ 327	1.4%
$ 721	$ 281	$ 327	3.6%

- With the base case Revenue only slightly higher than Opex, reducing Capex does not have a big influence.

What does it take to get to 25% IRR?

- One change at a time:
  - Opex cannot be reduced enough to get to 25%
  - Revenue would have to go up by 2.6 times ($850 MM/ yr)
  - Capex would have to decline by 93% ($104 MM)

Aribtrary results needed to get high IRR from NARA IBR			
Cut Opex by 1/2 or 3/4			
Capex	Opex	Revenue	IRR
$ 1,441	$ 281	$ 327	0.1%
$ 1,441	$ 140	$ 327	9.4%
$ 1,441	$ 70	$ 327	12.8%
$ 1,441	$0	$ 327	15.9%
Increase Revenue by 50% or 100%			
$ 1,441	$ 281	$ 327	0.1%
$ 1,441	$ 281	$ 491	10.6%
$ 1,441	$ 281	$ 654	17.8%
$ 1,441	$ 281	$ 850	25.0%
Drop Capex by 25% or 50%			
$ 1,441	$ 281	$ 327	0.1%
$ 1,081	$ 281	$ 327	1.4%
$ 721	$ 281	$ 327	3.6%
$ 104	$ 281	$ 327	25.0%

None of these, by themselves, seems very plausible.

Examine combinations.

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Combinations to get high IRR

- With semi-realistic simultaneous conceivable improvements, a high IRR *could* be achieved.

Combinations Getting to high IRR			
Cut Capex and Opex by 25% each, Increase Revenue by 50%			
Capex	Opex	Revenue	IRR
$ 721	$ 211	$ 491	17.7%
Cut Capex and Opex by 25% each, Increase Revenue by 100%			
$ 721	$ 211	$ 654	25.7%

Conclusions

- Vast reductions in Capex and Opex alone are not sufficient to get high IRR.
- Need **substantial Revenue increase** *in addition to* plausible reductions in Capex and Opex.
  - IPK yield and market price, even with renewable fuels premium, has little room for measurable improvement.
  - Doubtful that quantities or market prices for LS and AC can change appreciably,
- Therefore, one needs to produce more, of higher-valued, slate of products, in a simpler (less costly) process.