Intégration des procédés dans l'industrie papetière
Process Integration in the Pulp & Paper Industry

BIOFUEL PRODUCTION IN AN INTEGRATED FOREST BIOREFINERY – TECHNOLOGY IDENTIFICATION UNDER UNCERTAINTY

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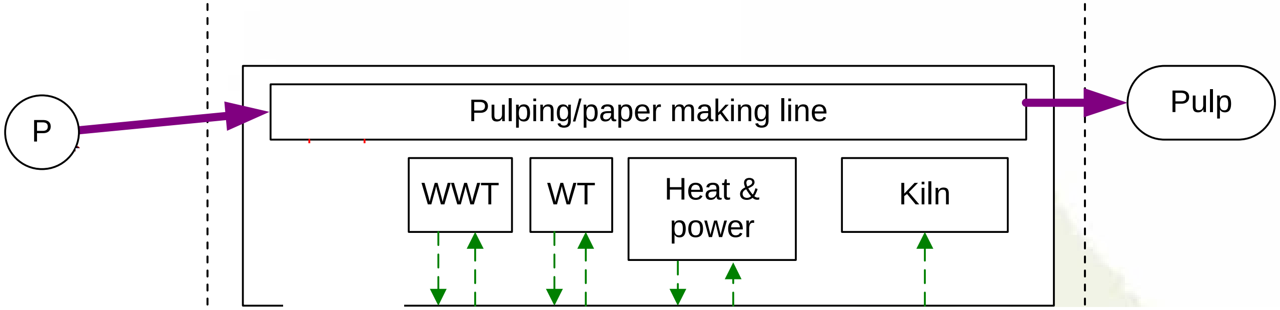
Integrated forest biorefinery for biofuel production

EXAMPLE of feedstock – process – product -combinations



- - → Commodity/waste
○ Raw material
⬭ End product
▭ Process

P = pulpwood

WWT = waste water treatment
WT = water treatment
Kiln = lime kiln

Proposed Integrated Forest Biorefinery (IFBR) scenarios

One extensive work done by Larson et al. (2006)

- Kraft black liquor and woody residues to biofuels (Fischer-Tropsch liguids, Dimethyl ether and mixed alcohols; by-product electricity) using gasification + fuel synthesis & combined cycle power generation
- Main objective was to compare the economics and environmental impacts of above IFBR options with retrofit Tomlinson boiler installation in a hypothetical US Kraft pulp and paper mill
- Conclusion - compared to conventional chemical recovery system retrofit
    - Higher capital investment
    - Higher internal rate of return (IRR), especially if high oil price
- Critical analysis of the study
    - Hypothetical case mill with no P&P production capacity change with biorefinery integration was considered
    - National –level criteria used when feedstocks and products were selected
    - Study considered only thermochemical options that would *fully* replace existing Tomlinson boiler recovery systems
    - Short cuts were used in O&M cost calculation, focus was more on capital investment estimation

Proposed Integrated Forest Biorefinery (IFBR) scenarios

Other proposed IFBR paths

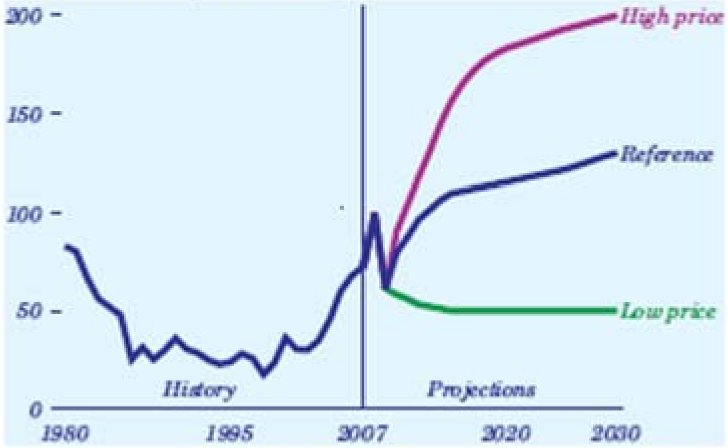
- Value Prior to Pulping (VPP)
  - Amidon et al. (2008), Frederick et al. (2008), van Heiningen et al. (2006) describe different process options for hemicellulose extraction before pulping to produce fuels and chemicals
  - Very high internal rate of return values obtained, however some assumptions (e.g. by-product prices, technological development stage, impacts on paper quality) are either not realistic or still unknown
- Mill repurposing
  - Goyal et al. (2007) and Frederick et al. (2008) discuss of transforming existing pulp mill into a bioethanol plant
  - Critical is to get economic performance to a higher level or adequate products to the market because ethanol only is not profitable based on van Heiningen assessment (2006)
- Other raw materials
  - Hytönen and Aaltonen (2008) studied the use of spruce bark for ethanol and chemical production in a hypothetical Finnish P&P mill
  - Hytönen and Stuart (2009) looked at both agro and forest residues, and pulpwood as feedstock for bioethanol production in a hardwood kraft pulp mill context

Integrated forest biorefinery

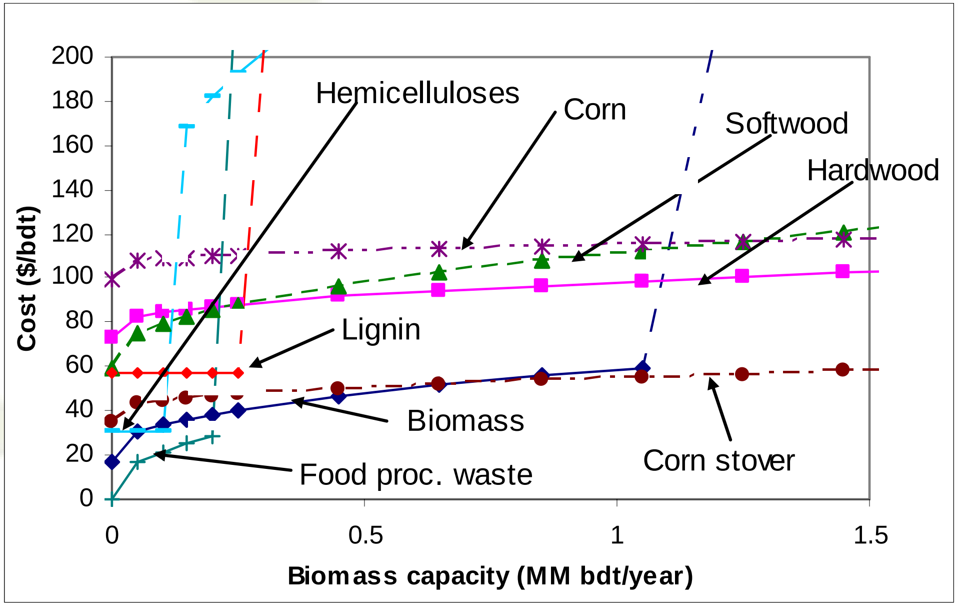
What makes design decision making difficult?

- **Costs**
  - Feedstock costs location and capacity dependent
  - → Which raw material should be used?
  - Existing systems' excess capacity utilisation → lower capital investment costs
  - Economy of scale
  - → What is the correct production capacity?
- **Revenues**
  - Price trends unknown
  - → Which fuel should be produced?
- **Technologies**
  - Several technological solutions under development even suitable for same feedstock-product combination
  - → Which process design should be used?

Figure 32. World oil prices in three cases, 1980-2030 (2007 dollars per barrel)



US DOE Annual Energy Outlook 2009



Hytönen et al., P&P Canada, 2009

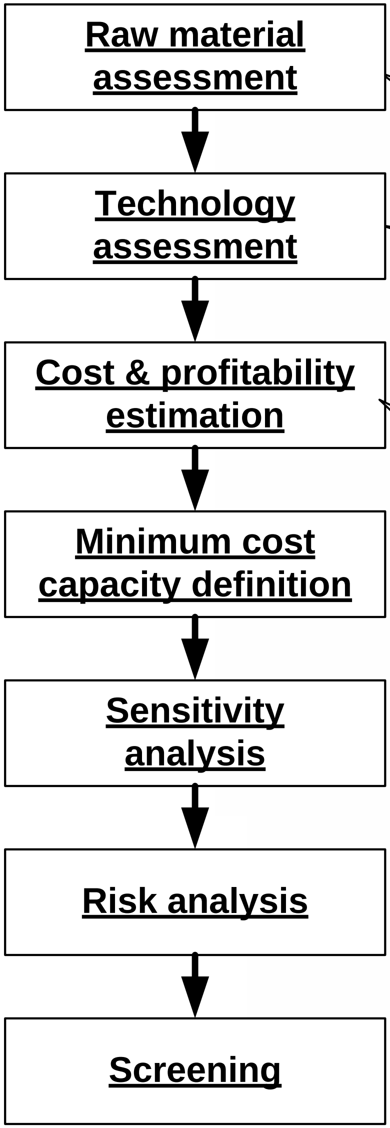
Objectives

- Develop platform for ***early stage screening of retrofit biorefinery scenarios*** using economic return on investment as criteria
- Implement Monte Carlo risk analysis in the screening platform
- Develop heuristics for screening-out non promising biofuel IFBR scenarios at the case mill
- Select a group of most promising IFBR scenarios for the case mill for further design analyses

Outline

- **Assessment methodology**
- **Case study definition**
  - Mill context
  - Integration & Key assumptions
- **Results**
  - After-tax IRR & manufacturing costs as function of plant capacity
  - Minimum cost production capacity
  - Sensitivity analysis
  - Risk analysis (Monte Carlo) and screening out non-promising design scenarios
- **Conclusions & Implications**

Method



Raw material assessment

Technology assessment

Cost & profitability estimation

Minimum cost capacity definition

Sensitivity analysis

Risk analysis

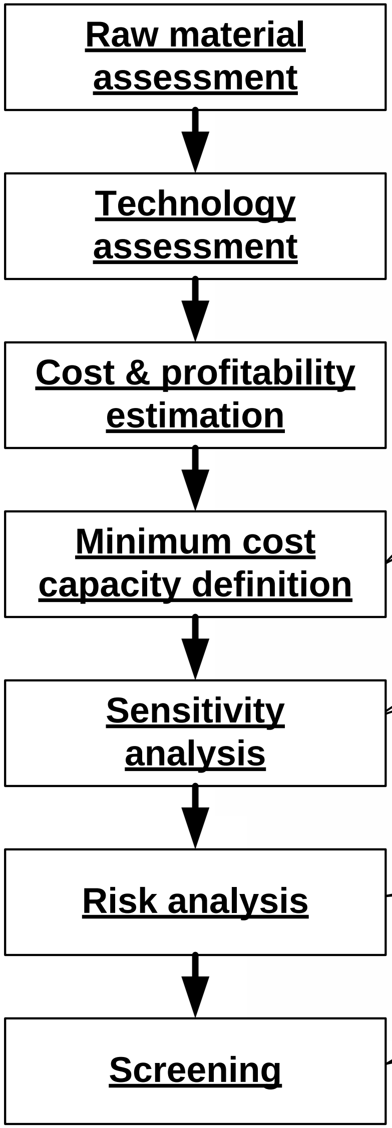
Screening

- Identification of available raw materials
- Supply-curve definition

- Identification and assessment of existing and emerging biofuel production processes
- Synthesis of the processes starting from available raw materials

- Factorial capital cost estimation
- O&M cost calculation
- After-tax Internal Rate of Return (IRR)

Method



Raw material assessment

Technology assessment

Cost & profitability estimation

Minimum cost capacity definition

Sensitivity analysis

Risk analysis

Screening

- Identification of minimum cost capacity based on production costs as function of plant capacity (10% CRF assumed)

- Sensitivity analysis considering economic variables (prices of feedstock, fuels, end products)

- Identification of risk variables
- Definition of probability distributions of the risk variables
- Monte Carlo analysis

- Screening based on after-tax IRR and the variability of after-tax IRR

Case study

Mill context

- North American hardwood kraft pulp and paper mill (1200 bdt pulp/day)
- Interest for biofuel and other bioproduct production from various feedstocks available (agricultural, forest based, food industry wastes, mill streams)
- Processes & products (biofuel production):

	Product	Process
1	Ethanol + higher alcohols	Gasification, MA synthesis, ethanol separation
2	Ethanol	Gasification, syngas fermentation, ethanol purification
3	Ethanol + higher alcohols	Steam reforming, MA synthesis, ethanol separation
4	Ethanol	Steam reforming, syngas fermentation, ethanol purification
5	Mixed alcohols	Gasification, MA synthesis
6	Mixed alcohols	Steam reforming, MA synthesis
7	FTL	Gasification, FT synthesis
8	FTL	Steam reforming, FT synthesis
9	Ethanol	Acid hydrolysis, fermentation, ethanol purification
10	Ethanol	Pre-treatment, enzymatic hydrolysis, fermentation, ethanol purification
11	Ethanol	Acidic pre-hydrolysis, SSF, ethanol purification
12	Ethanol + acetic acid	Near-neutral extraction (GL), acidic hydrolysis, fermentation, ethanol purification

Case study

Integration & Key assumptions

- Integration
    - Excess capacity used fully
        - Boilers, turbines, water treatment, waste water treatment
    - Hemicellulose extraction (10%) has no impact on pulping
    - Lignin separation from black liquor – increased heat demand supplied by fossil fuels
- Key assumptions
    - No subsidies/incentives considered
    - No premium for green fuels considered
    - Fuels saleable with heating value corrected retail price of gasoline/diesel (minus transportation cost of 5¢/gal fuel, Larson et al. (2006))

Results

- Preliminary profitability results for bioethanol production presented in PAPTAC Annual meeting 2009
- Other fuels (FT-liquids and mixed alcohols) have been added since then

Results

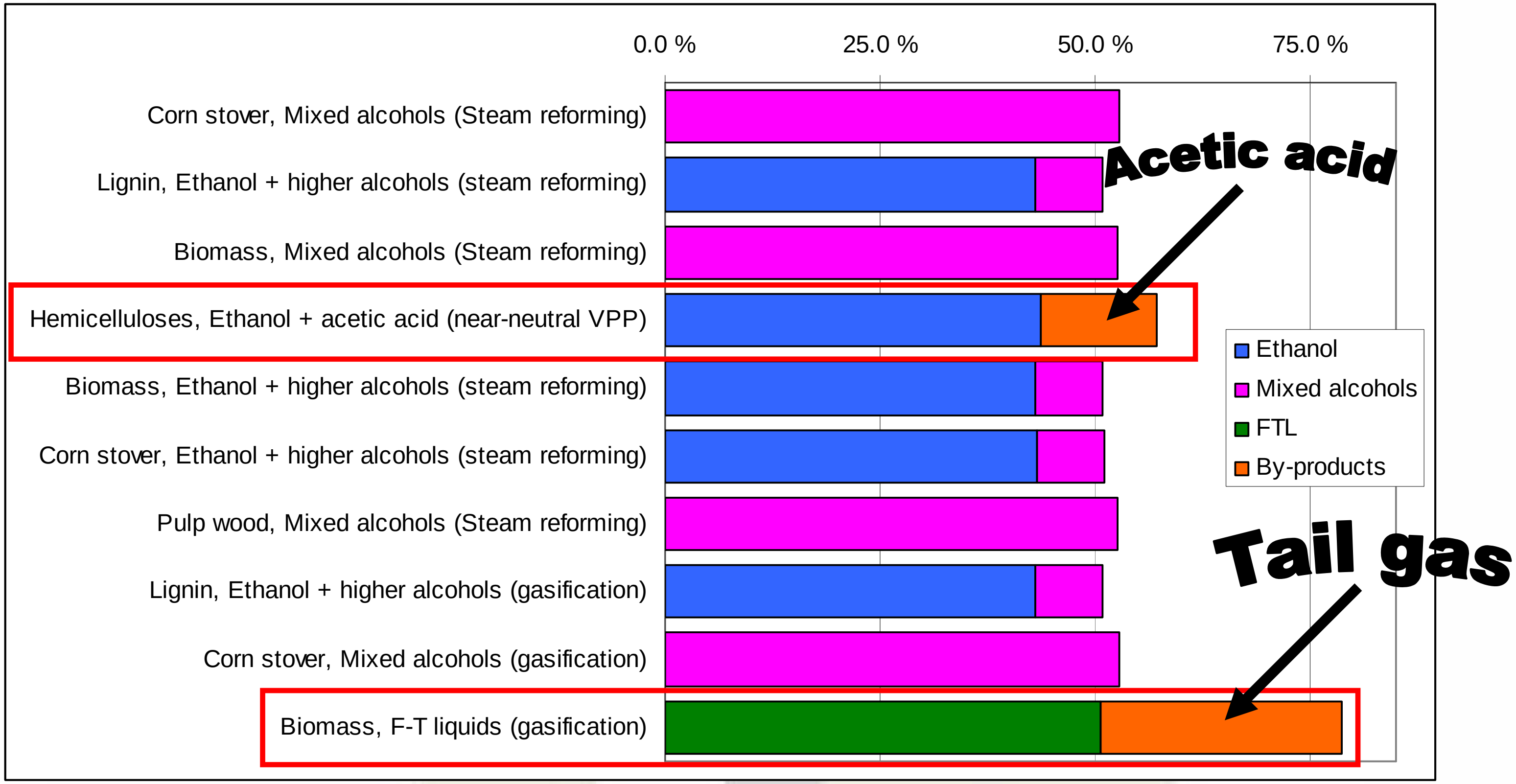
Possible IFBR scenarios

Main Products	Process	Woody biomass (B)	Pulpwood (P)	Hemicelluloses (H)	Lignin (L)	Corn (C)	Corn stover (CS)	Food processing waste (FW)
EtOH MA	Gasification, MA synthesis, EtOH separation	✓*	✓		✓		✓	
EtOH	Gasification, syngas fermentation	✓*	✓		✓		✓	
EtOH MA	Steam reforming, MA synthesis, EtOH separation	✓*	✓		✓		✓	
EtOH	Steam reforming, syngas fermentation	✓*	✓		✓		✓	
MA	Gasification, MA synthesis	✓*	✓		✓		✓	
MA	Steam reforming, MA synthesis	✓*	✓		✓		✓	
FT liquids	Gasification, FT synthesis	✓*	✓		✓		✓	
FT liquids	Steam reforming, FT synthesis	✓*	✓		✓		✓	
EtOH	Acid hydrolysis, fermentation	✓	✓*				✓	
EtOH	Pre-treatment, enzymatic hydrolysis, fermentation	✓	✓*			✓*	✓*	✓
EtOH	Acidic pre-hydrolysis, SSF			✓*				
EtOH Acetic acid	Near-neutral extraction (GL), acidic hydrolysis, fermentation			✓*				

- 42 possible scenarios
- Reference studies available for 14 process designs (✓*)

Results

Processing efficiencies of 10 example scenarios

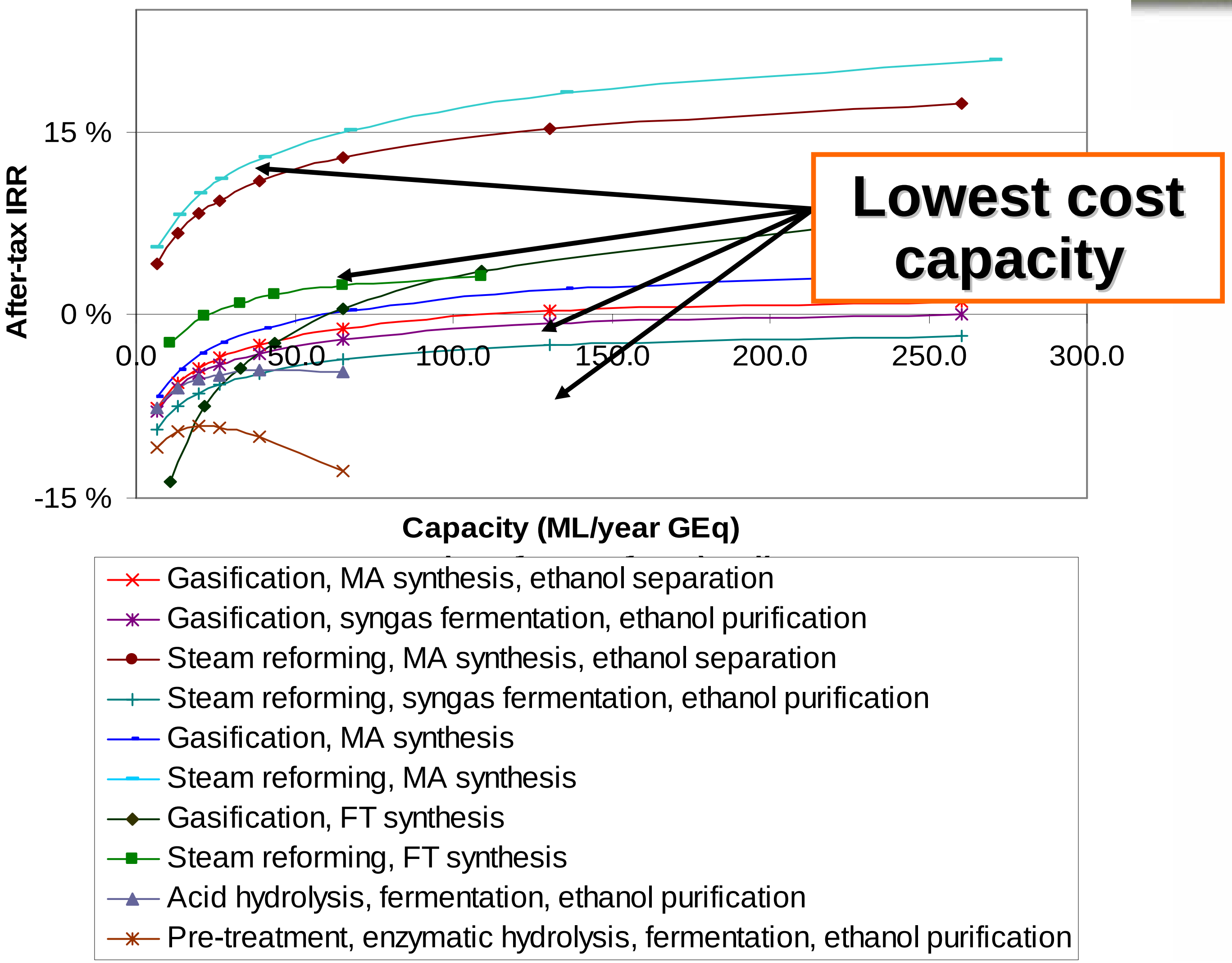


- ***Processing efficiency = Energy content of products as percent of feedstock energy content (higher heating value used throughout the study)***
- Differences are result of
  - process design (e.g. FTL scenario is once through FT synthesis whereas MA scenarios recycle tail gas having higher fuel yield) and
  - feedstock (e.g. hemicelluloses are mainly C5 sugars that are assumed to be possible to be fermented to ethanol with high yield whereas other feedstock consist of sugars and lignin leading to lower yield)

Results

Profitability & Prod. costs as function of capacity

Feedstock – woody biomass



Lowest cost capacity

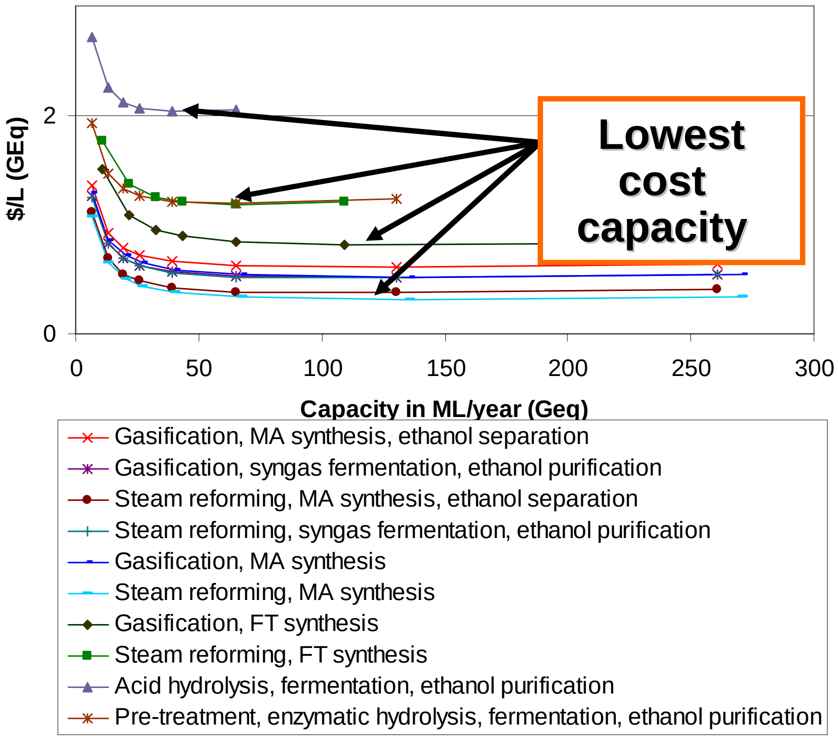
- Base case analysis using fixed input values and future trends
- Plant capacities cover raw material availability ranges

Results

Low cost production capacity

- Bio- and thermochemical scenarios have different economies of scale due to yield and investment cost factor differences
- Different raw materials have different low cost capacity for the same process design
- In general the low cost capacity range is lower than reported for stand-alone plants in literature (Wright et al. (2007))
  - Biochemical ethanol - 570 ML/year GEq vs. 150 ML/year GEq in this study
  - FTL – 1500 ML/year GEq vs. 50-100 ML/year GEq in this study

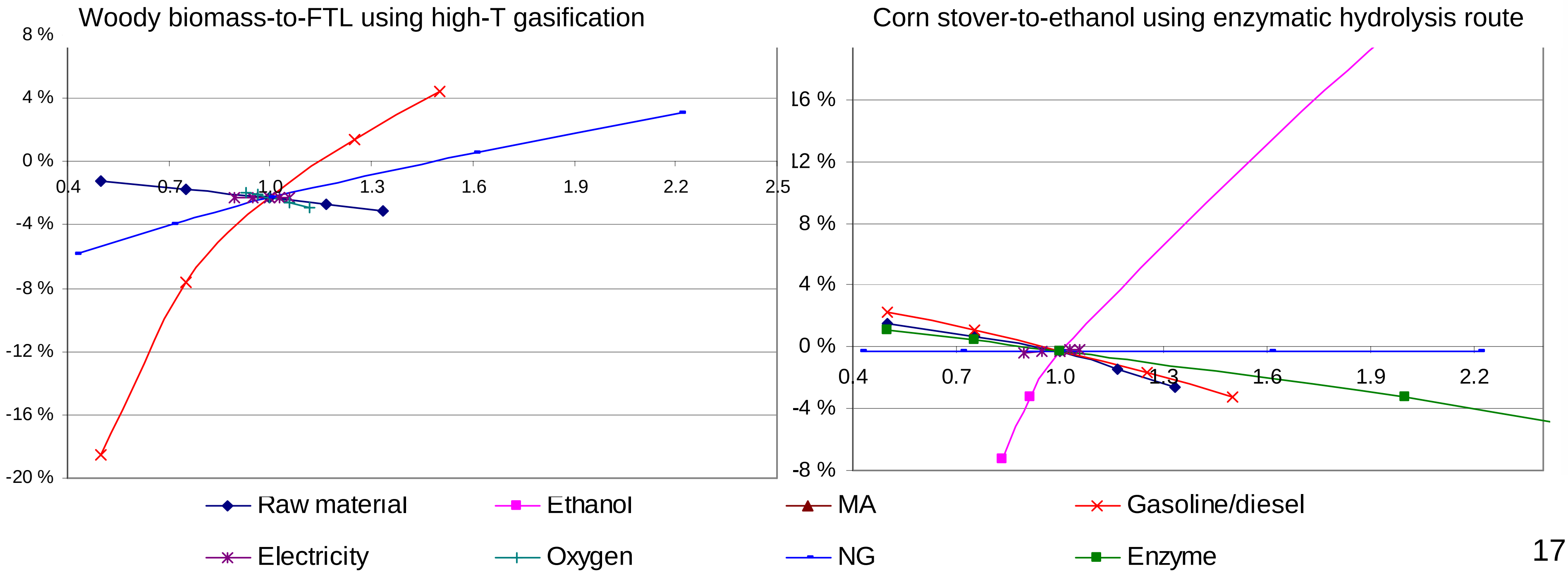
→ **Economy of scale is different for integrated forest biorefinery compared to stand-alone case**



Results

Sensitivity analysis

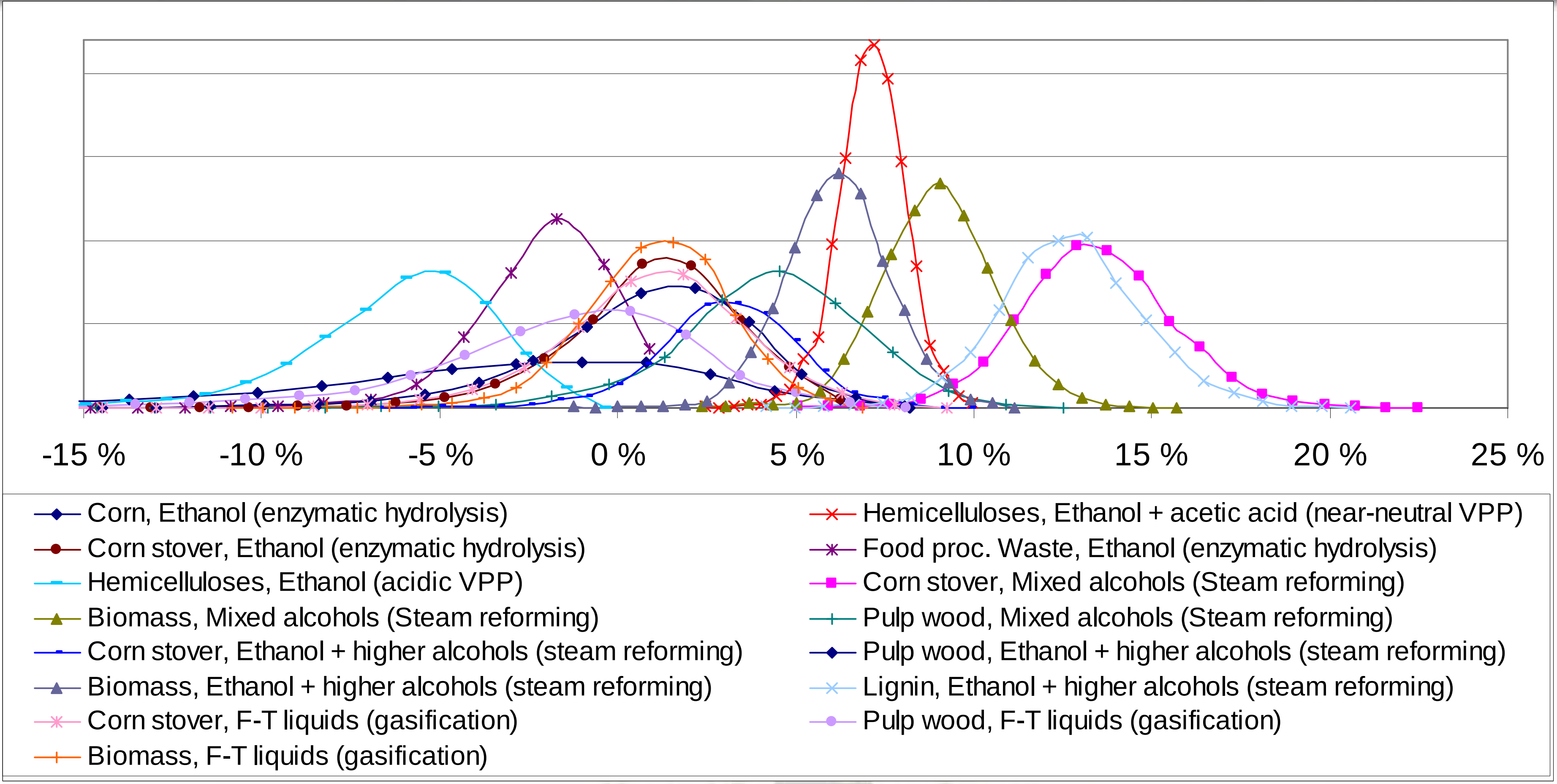
- Varying cost/price over a reasonable range to assess the sensitivity of the IRR
- Example sensitivity analysis figures above
- Main conclusion
    - End product prices are most important variables
    - Fossil fuel prices have big impact on all scenarios through transportation costs
    - Enzyme cost in biochemical scenarios important since its range is large (0.1 – 3 $/gal EtOH used)
    - Electricity price and oxygen cost important variables but variables are relatively certain


Woody biomass-to-FTL using high-T gasification

Corn stover-to-ethanol using enzymatic hydrolysis route

Results

Monte Carlo analysis – Probability distribution of after-tax IRR

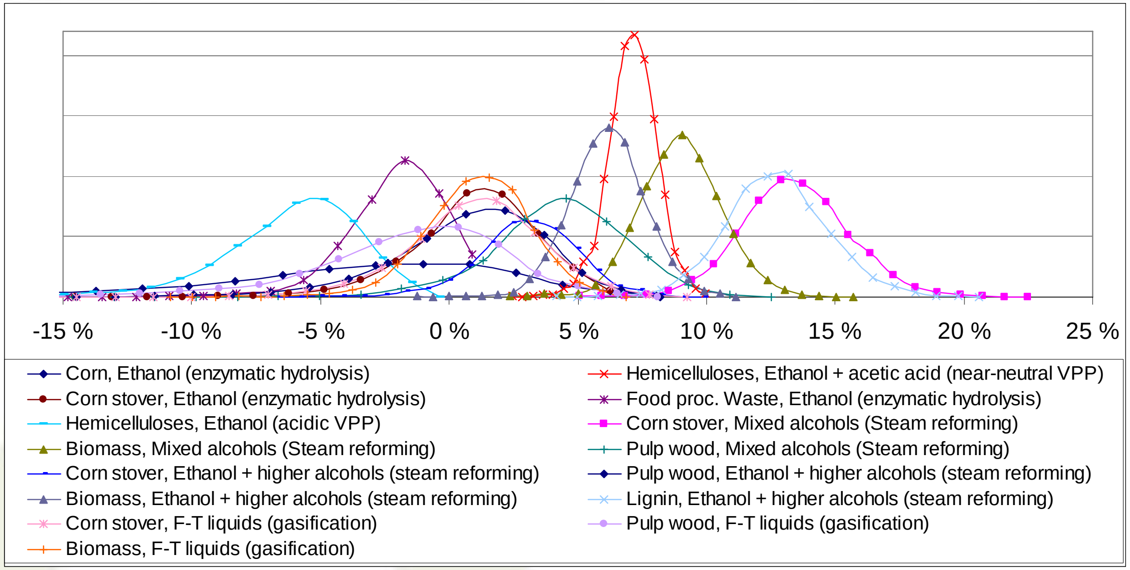


- Possibility to visually compare the uncertainty of achieving the expected IRR values
- Most promising scenarios are relatively uncertain but not most uncertain
- Least risky scenario is the near-neutral VPP (red high peak)

Results

Monte Carlo analysis – interpretation of results

- Expected IRR value is the average value from the distribution
- Riskiness of the result measured mathematically with standard deviation



- Standard deviation can be converted to e.g. 95% confidence interval ($\pm 2\sigma$)

→Downside profitability, or worst case scenario profitability, from the lower limit of the interval ($IRR_{downside} = IRR_{expected} - 2\sigma$)

Results

Screening out non promising scenarios

- 10 most promising scenarios based on expected after-tax IRR
- Remarks:
  - Plant capacity ranges from very small (~5MMGPY) to large (100MMGPY)
  - Investment costs differ between design scenarios
  - Ranking based on downside IRR very similar to ranking done based on expected IRR

Feedstock, product (process)	Capacity (ML/year)	TPI (M$)	IRR	Downside IRR
Corn stover, Mixed alcohols (Steam reforming)	379	308	13.0 %	8.7 %
Lignin, Ethanol + higher alcohols (steam reforming)	189	159	12.3 %	8.2 %
Biomass, Mixed alcohols (Steam reforming)	95	99	8.7 %	5.5 %
Hemicelluloses, Ethanol + acetic acid (near-neutral VPP)	19	61	6.9 %	5.0 %
Biomass, Ethanol + higher alcohols (steam reforming)	95	117	5.9 %	2.9 %
Corn stover, Ethanol + higher alcohols (steam reforming)	379	364	3.4 %	-0.6 %
Pulp wood, Mixed alcohols (Steam reforming)	189	161	3.4 %	-11.1 %
Lignin, Ethanol + higher alcohols (gasification)	189	294	1.5 %	-5.1 %
Corn stover, Mixed alcohols (gasification)	379	569	0.7 %	-6.0 %
Biomass, F-T liquids (gasification)	95	251	0.6 %	-3.5 %

Results

Screening heuristics for the case mill

- Thermochemical biofuel production scenarios are more profitable but have higher capital investment costs
- Lowest cost feedstocks (woody biomass and corn stover) are most promising raw materials
- Steam reforming as syngas production process is more promising process step than high-T gasification
- Mixed alcohols and ethanol seem to be more promising biofuels compared to FTL at the case mill
- High value, non-fuel by-products can lower risks (enhance the downside profitability) substantially

Conclusions

- Economies of scale in IFBR differ substantially from stand-alone case
- Different screening metrics would result in different group of most promising scenarios; possible metrics resulting from this case study analysis
  - After-tax IRR, Total project investment cost, uncertainty of IRR, processing efficiency
- It is critical to use same basis and comparable metrics to be able to screen-out scenarios with confidence
- At the case mill (based on expected after-tax IRR) most promising scenarios are:
  - Using steam reforming process step
  - Producing mixed alcohols (and/or) ethanol from the mixed alcohols
  - From low cost feedstocks (corn stover and biomass)
  - E.g. – Corn stover-to-mixed alcohols with steam reforming process (380 ML/year = 100MMGPY)
- Because integration of biorefinery options was considered in a simplified way, all integration impacts could not be included → more detailed integration impact analysis (e.g. impact on pulp and paper production costs) is needed to further rank the most promising scenarios.

Acknowledgements

- Funding:
  - Natural Sciences and Engineering Research Council of Canada (NSERC) Environmental Design Engineering Chair at *École Polytechnique de Montréal*
  - VTT Technical Reseasch Centre of Finland
  - Biorefine Technology Programme of Finnish Funding Agency for Technology and Innovation (TEKES)
- Case study mill personnel

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Thank you!

Questions?

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Results – Additional slide

- List of all scenarios: production capacity (ML/year), main fuel yield (L/bdt), processing efficiency, capital investment cost ($/L GEq), variable cost ($/L GEq), by-product credits ($/L GEq) and IRR

Products (process)		Feedstock [a]	Capacity (ML/year)	Yield (L/bdt)	Processing efficiency	Capital investment ($/L GEq)	Variable costs ($/L GEq)	By-product Credits ($/L GEq)	After-tax IRR
1	Ethanol + higher alcohols (gasification)	B	95	338	51 %	3.3	0.3	0.2	-5.4 %
2	Ethanol (gasification + fermentation)	B	95	338	43 %	4	0.1	0.2	-9.0 %
3	Ethanol + higher alcohols (steam reforming)	B	95	338	51 %	1.8	0.2	0.1	5.9 %
4	Ethanol (steam reforming + fermentation)	B	95	338	43 %	4.7	0.1	0.2	-10.4 %
5	Mixed alcohols (gasification)	B	95	397	53 %	2.8	0.3	0.1	-2.7 %
6	Mixed alcohols (Steam reforming)	B	95	397	53 %	1.5	0.2	0.0	8.7 %
7	F-T liquids (gasification)	B	95	237	79 %	2.3	0.3	0.2	0.6 %
8	F-T liquids (steam reforming)	B	57	133	68 %	2.8	0.4	0.4	-1.4 %
9	Ethanol (acid hydrolysis)	B	95	130	25 %	5.7	1.5	1.7	-
10	Ethanol (enzymatic hydrolysis)	B	57	179	23 %	4.3	0.8	0.5	-
11	Ethanol + higher alcohols (gasification)	P	189	345	51 %	2.7	0.5	0.2	-11.4 %
12	Ethanol (gasification + fermentation)	P	189	345	43 %	3.3	0.4	0.2	-15.4 %
13	Ethanol + higher alcohols (steam reforming)	P	189	345	51 %	1.5	0.4	0.1	0.0 %
14	Ethanol (steam reforming + fermentation)	P	189	345	43 %	3.9	0.3	0.2	-16.4 %
15	Mixed alcohols (gasification)	P	189	405	53 %	2.2	0.4	0.1	-7.7 %
16	Mixed alcohols (Steam reforming)	P	189	405	53 %	1.2	0.4	0.0	3.4 %
17	F-T liquids (gasification)	P	189	242	78 %	1.6	0.5	0.2	-2.4 %
18	F-T liquids (steam reforming)	P	95	136	68 %	2.4	0.8	0.4	-9.1 %
19	Ethanol (acid hydrolysis)	P	189	160	31 %	4.1	1.7	1.4	-
20	Ethanol (enzymatic hydrolysis)	P	189	254	32 %	2.4	0.9	0.4	-21.5 %
21	Ethanol (acidic VPP)	H	38	409	77 %	4	0.4	0.2	-6.8 %
22	Ethanol + acetic acid (near-neutral VPP)	H	19	232	57 %	4.7	0.7	1.2	6.9 %

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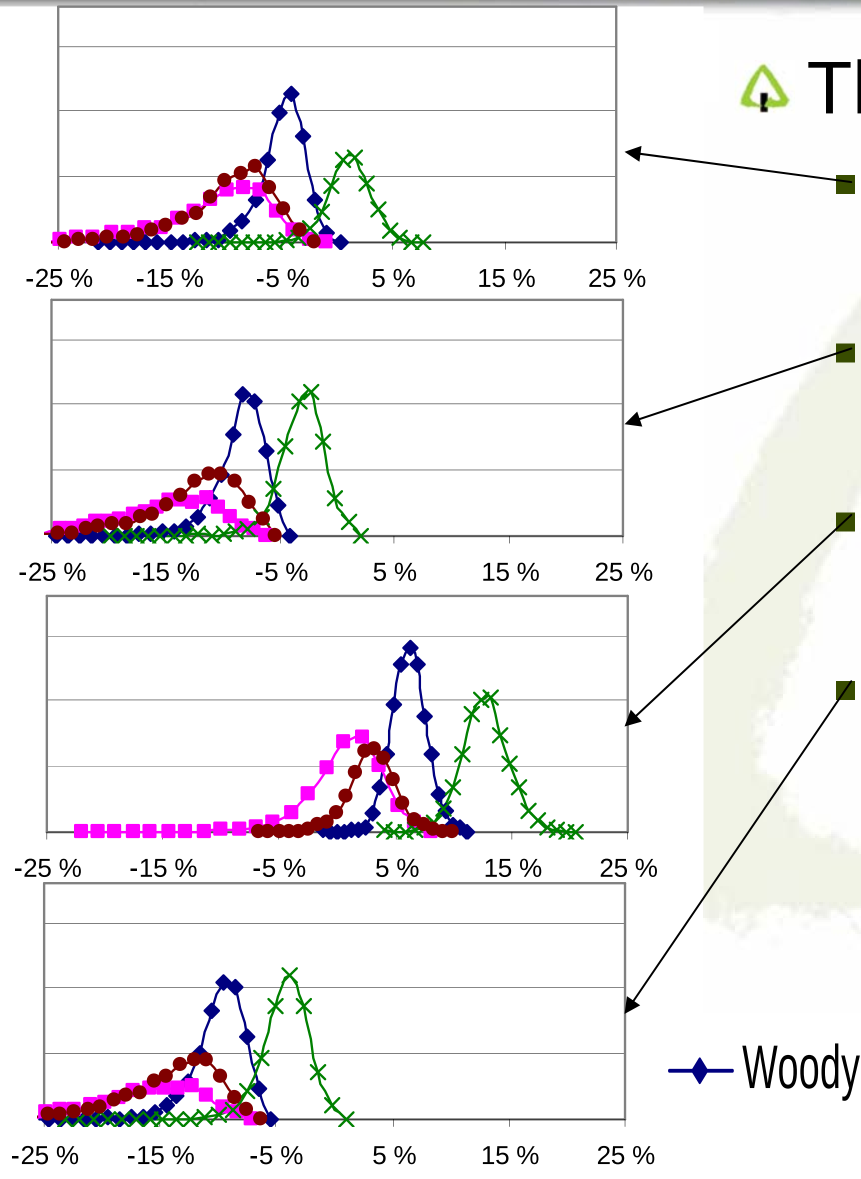
Results – Additional slide

- List of all scenarios: production capacity (ML/year), main fuel yield (L/bdt), processing efficiency, capital investment cost ($/L GEq), variable cost ($/L GEq), by-product credits ($/L GEq) and IRR

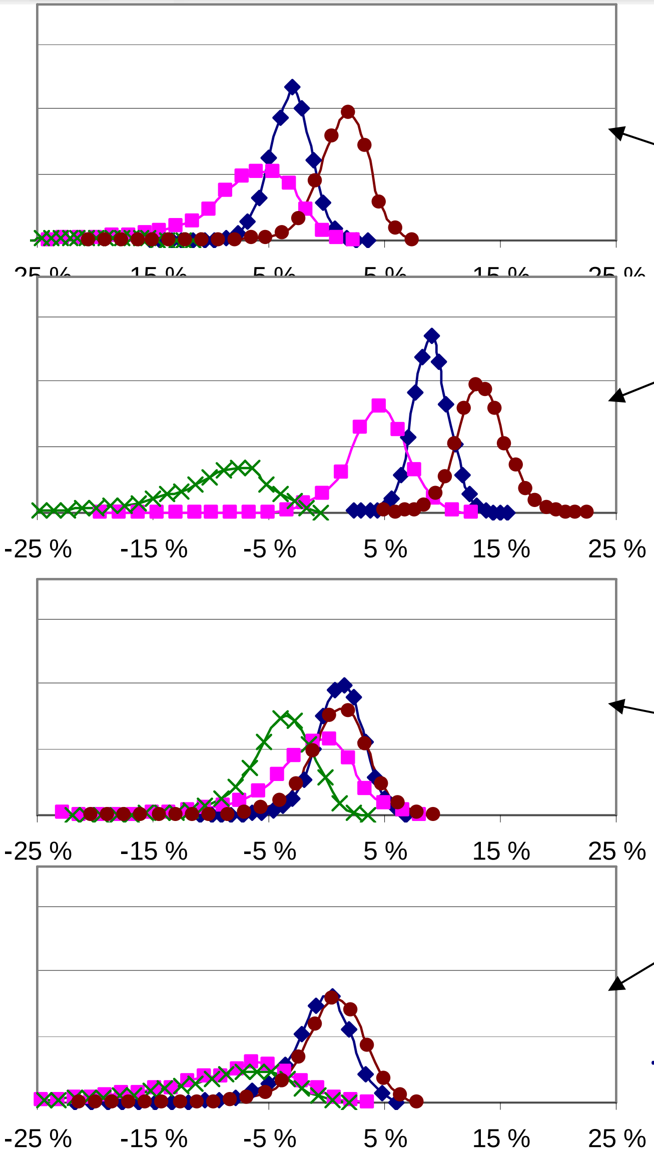
	Products (process)	Feedstock [a]	Capacity (ML/year)	Yield (L/bdt)	Processing efficiency	Capital investment ($/L GEq)	Variable costs ($/L GEq)	By-product Credits ($/L GEq)	After-tax IRR
23	Ethanol + higher alcohols (gasification)	L	189	477	51 %	2.3	0.3	0.2	1.5 %
24	Ethanol (gasification + fermentation)	L	189	477	43 %	3.2	0.1	0.1	-3.7 %
25	Ethanol + higher alcohols (steam reforming)	L	189	477	51 %	1.2	0.2	0.1	12.3 %
26	Ethanol (steam reforming + fermentation)	L	189	477	43 %	3.6	0.1	0.1	-4.8 %
27	Mixed alcohols (gasification)	L	189	561	53 %	1.9	0.4	0.1	-20.6 %
28	Mixed alcohols (Steam reforming)	L	189	561	53 %	1	0.3	0.0	-10.3 %
29	F-T liquids (gasification)	L	57	335	70 %	2.7	0.3	0.2	-4.8 %
30	F-T liquids (steam reforming)	L	57	188	68 %	2.4	0.7	0.4	-9.7 %
31	Ethanol (enzymatic hydrolysis)	C	379	424	91 %	0.7	0.6	0.1	-4.7 %
32	Ethanol + higher alcohols (gasification)	CS	379	269	51 %	2.5	0.5	0.3	-10.4 %
33	Ethanol (gasification + fermentation)	CS	379	269	43 %	2.9	0.4	0.2	-13.0 %
34	Ethanol + higher alcohols (steam reforming)	CS	379	269	51 %	1.4	0.3	0.2	3.4 %
35	Ethanol (steam reforming + fermentation)	CS	379	269	43 %	3.4	0.3	0.2	-14.4 %
36	Mixed alcohols (gasification)	CS	379	315	53 %	2.1	0.4	0.2	0.7 %
37	Mixed alcohols (Steam reforming)	CS	379	315	53 %	1.1	0.3	0.1	13.0 %
38	F-T liquids (gasification)	CS	189	189	86 %	1.8	0.4	0.3	0.2 %
39	F-T liquids (steam reforming)	CS	95	128	83 %	2.4	0.5	0.4	-0.2 %
40	Ethanol (acid hydrolysis)	CS	379	179	44 %	3.1	1.2	1.0	-22.5 %
41	Ethanol (enzymatic hydrolysis)	CS	379	341	55 %	1.2	0.5	0.2	0.3 %
42	Ethanol (enzymatic hydrolysis)	FW	19	235	51 %	2.4	0.8	0.1	-2.7 %

Results – Additional slide



- Thermochemical EtOH
  - Gasification, MA synthesis, ethanol separation
  - Gasification, syngas fermentation, ethanol purification
  - Steam reforming, MA synthesis, ethanol separation
  - Steam reforming, syngas fermentation, ethanol purification

Results – Additional slide



- MA
  - Gasification, MA synthesis
  - Steam reforming, MA synthesis
- FTL
  - Gasification, FT synthesis
  - Steam reforming, FT synthesis

Results – Additional slide

- Most promising biochemical scenario is near-neutral VPP followed by corn stover to ethanol through enzymatic hydrolysis route (assumed enzyme cost 0.1$/gal EtOH)