FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

# Alternative Jet Fuel Supply Chain Analysis

ASCENT 1

## Conversion Pathways to Alternative Fuels

### The Alcohol-to-Jet Pathway

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# Status of ATJ Pathway

- Qualified in ASTM D7566 Standard Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons - Annex A5 in 2016
- Commercialization and research efforts from multiple companies over the last several years
- Prominent recent commercialization efforts by Gevo and LanzaTech
- Fuel and processes demonstrated by several commercial partnerships

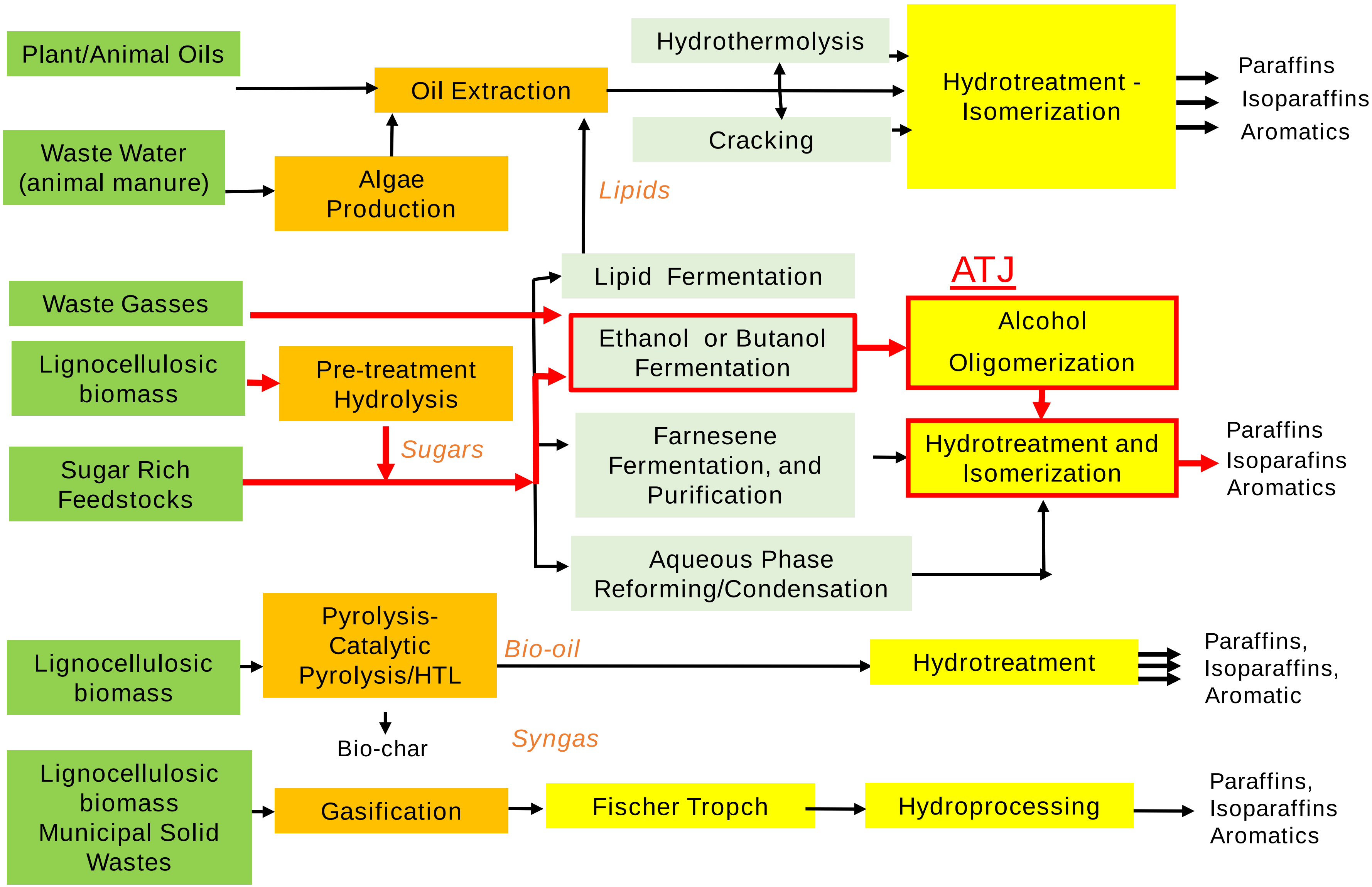
| Alcohol-Producing Process | Companies and Institutions Interested/Invested in Technology | Alcohol Intermediate |
|---|---|---|
| Ethanol Fermentation | LanzaTech/PNNL [Gas], Vertimass* | Ethanol |
| Butanol Fermentation | Gevo | Iso-butanol |
| Catalytic (thermochemical) Conversion of Syngas to Ethanol | PNNL | Ethanol |
| Non-specific | Byogy, White Dog Labs | Varies |

*The Vertimass process is not defined as an ATJ process under the current ASTM D7566 standard


Gevo and Alaska Airlines demonstrate ATJ fuel from forest residuals


LanzaTech partnership with Virgin Atlantic

# AJF Conversion Pathways



# ATJ Pathway Evaluation

Evaluation of ATJ

- ATJ is one of eight pathways originally identified, along with four integration pathways, for study in the project
- Objective to evaluate the pathway based on public information and an unbiased position
- Aim to provide data useful for further analysis of supply chain and integration scenarios

Challenges

- Most ATJ development and testing is based on proprietary technology and private research
- High degree of uncertainty in process and economic model data
- Lack of unity between economic assessments
- Little comparative analysis between differing implementations of ATJ

Main Outcomes

- Design Case Report
- TEA using ASCENT Approach
- Publication

# TEA Methods and ASCENT Standard Approach

Data Sources:

- Available data from commercial efforts
- Literature and academic studies
- Process simulation
- Process design correlations

Types of Data:

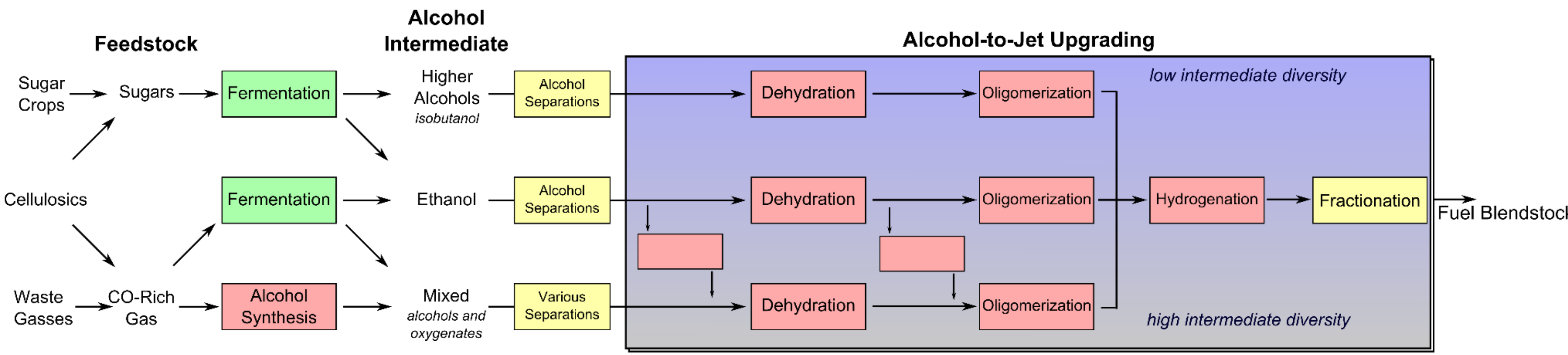
- Mass and energy balance information
- Achievable operations parameters
- Equipment/capital costs
- Utilities and materials costs

Modelling and Approach:

- ASCENT standard approach enables more consistent assessment and internal review
  - Guidance for operational and financial assumptions
  - Consistent assumptions between TEA projects
- A modular approach aims to improve use in further modeling and assessment

# The Alcohol to Jet Pathway

alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK), an SPK produced starting from alcohol and processed through the following steps: dehydration, oligomerization, hydrogenation, and fractionation.
*ASTM D7566*




- Cost and operation of catalytic steps differ between routes
- Higher alcohols inherently offer greater yield during upgrading
- Advanced (gas and higher alcohol) fermentation is typically challenging and relatively expensive
- Ethanol and mixed alcohols provide wider distribution of intermediates/products
- Fuel properties vary between routes
- Co-products vary between routes

# Comparative Analysis of ATJ Routes

Pathways evaluated in publication

Core ATJ:

- Ethanol
- Isobutanol

Feedstock to ATJ:

- Sugars - ethanol
- Sugars - isobutanol

Pathways not evaluated in publication

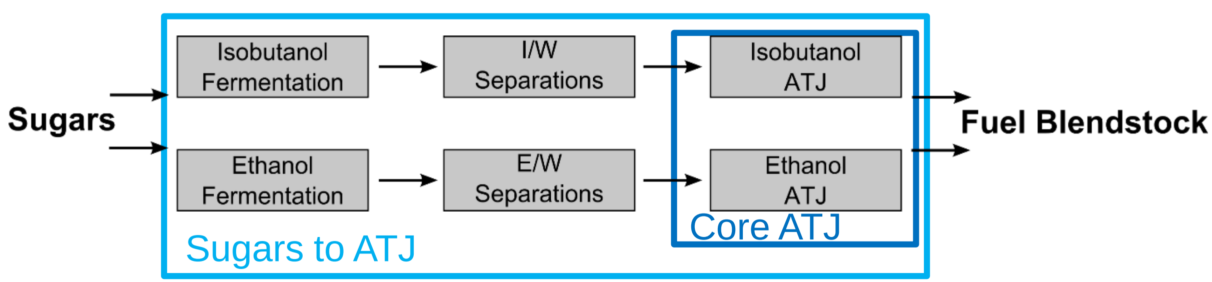
Core ATJ:

- Guerbet condensation
- Mixed oxygenates catalysis

Feedstock to ATJ:

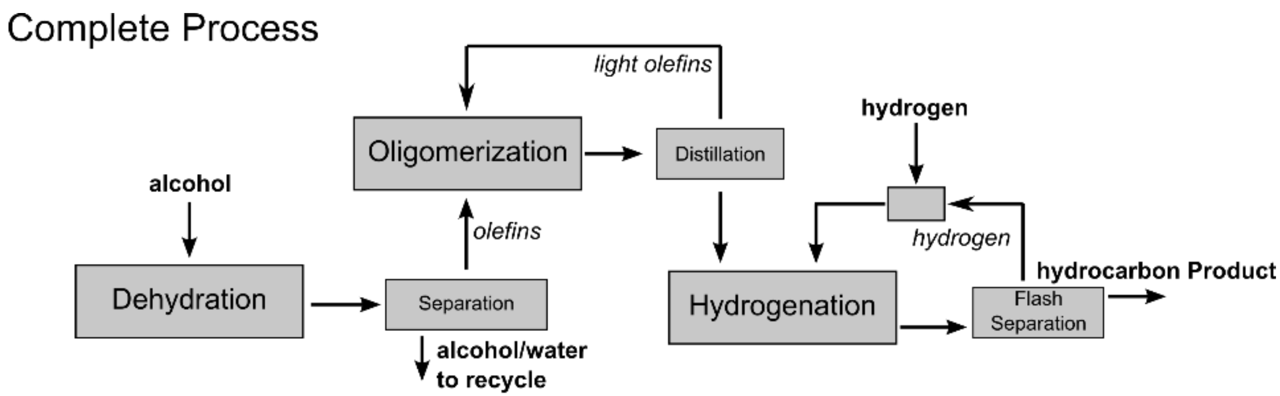
- Gas fermentation
- Thermochemical conversion

- Core ATJ Models: assess conversion costs of alcohol upgrading process (dehydration, oligomerization, hydrogenation, fractionation). Feedstock is alcohol
- Sugar ATJ Models: assess conversion costs including fermentation processing and Core ATJ. Feedstock is a common sugar-based feedstock




"Conversion Costs" are used to assess the relative cost of individual or grouped processing stages within the supply chain

# TEA Scenarios: Core ATJ Scenarios



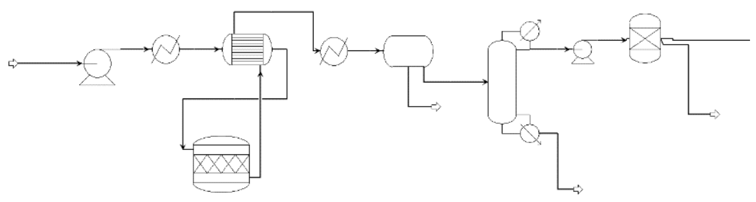

| | Ethanol to Jet | Isobutanol to Jet |
|---|---|---|
| Total Capital Investment, MM$ | 23.8 | 15.4 |
| Mass Yield | 0.60 | 0.75 |
| Hydrogen Feed Requirement, ton/day | 1.29 | 1.62 |
| Fuel Production Rate, MMgal/yr | 11.7 | 14.8 |
| Operating Expenses, MM$/yr | 5.7 | 5.6 |
| Cost per ton of alcohol | $131 | $120 |
| Conversion Cost per gallon of fuel | $0.73 | $0.53 |

Conversion costs represent costs from the isolated ATJ unit (MSP calculated with no feedstock costs)

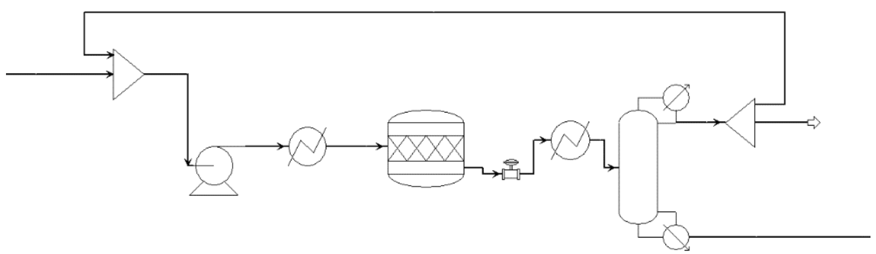
Scale based on 200 tons/day alcohol

# TEA Scenarios: Core ATJ Scenarios

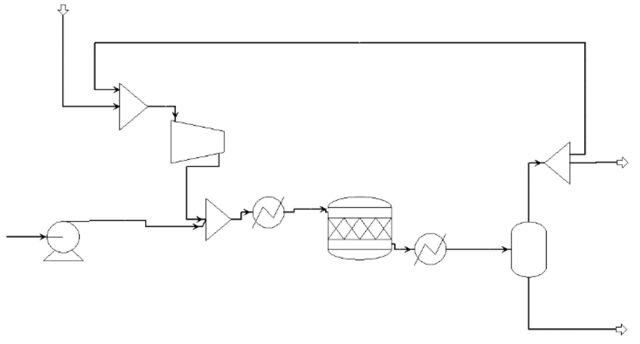
Dehydration



Oligomerization



Hydrogenation



Operating Expenses (MM$/yr)

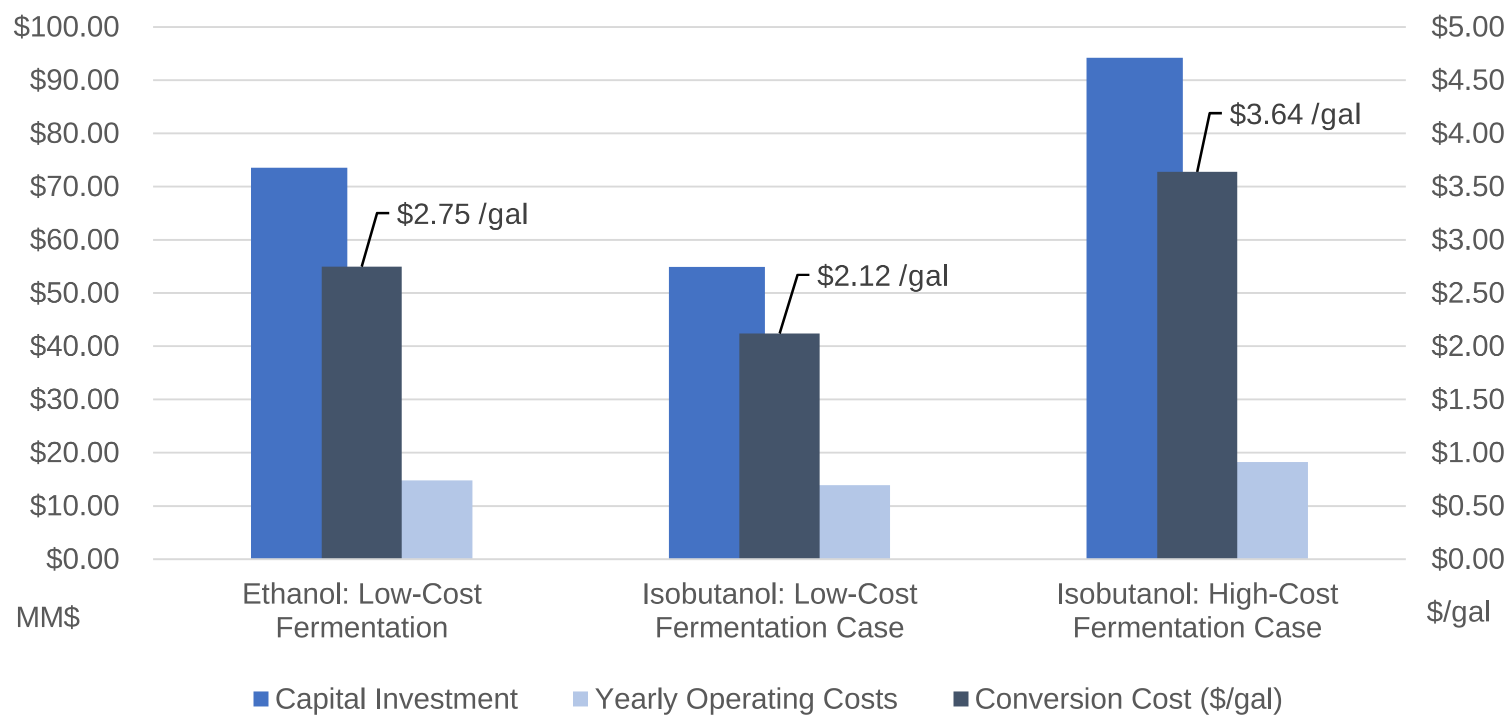
| | Ethanol to Jet | Isobutanol to Jet |
|---|---|---|
| Utilities | 1.9 | 2.2 |
| Catalyst | 0.5 | 0.6 |
| Hydrogen | 0.5 | 0.6 |
| Fixed OpEx | 2.9 | 2.2 |
| Total OpEx | 5.7 | 5.6 |

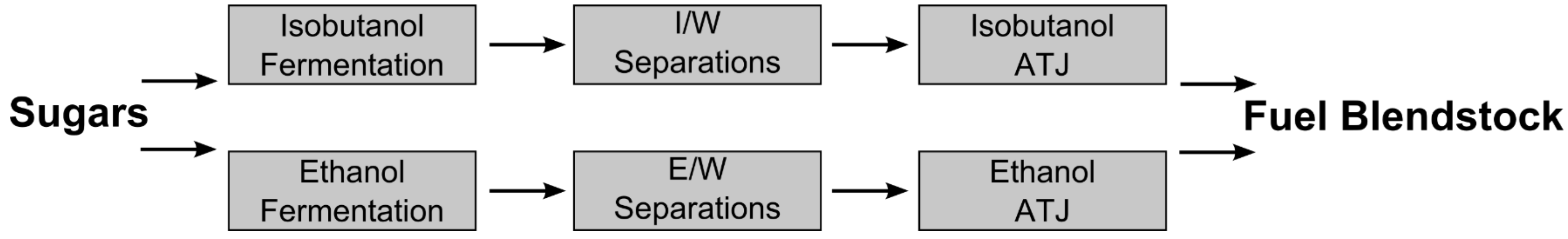
Equipment Costs by Unit (MM$)

| | Ethanol to Jet | Isobutanol to Jet |
|---|---|---|
| Dehydration | 1.52 | 0.39 |
| Oligomerization | 1.40 | 0.43 |
| Hydrogenation | 1.41 | 1.44 |
| Fractionation | 0.09 | 0.09 |

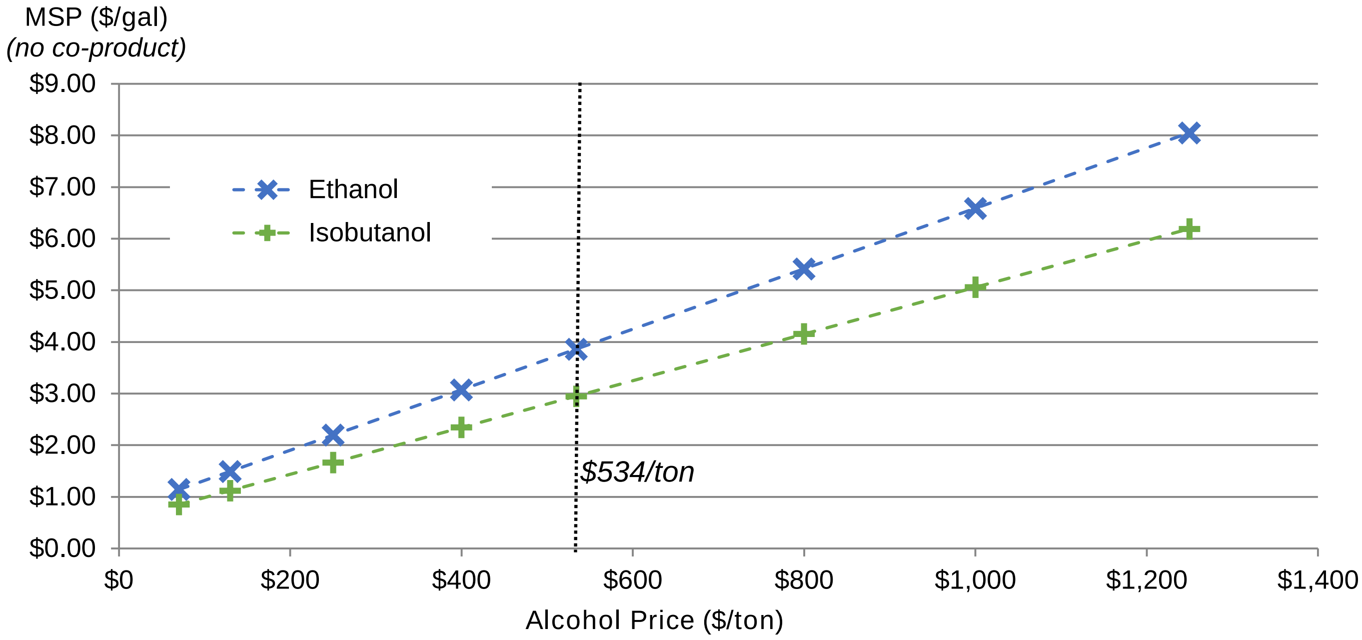
# TEA Scenarios: Fermentation Cases

| | Ethanol-to-Jet | Isobutanol-to-Jet |
|---|---|---|
| Fermentation Mass Yield | 0.46 | 0.37 |
| Overall Mass Yield | 0.274 | 0.277 |



# ATJ Intermediate Comparisons




- Avg. ethanol price of $534/ton: $3.86/gal MSP
- Equivalent MSP at $735/ton isobutanol
- 86%/90% cost attributed to alcohol production

# Barriers Toward ATJ Commercialization and Development

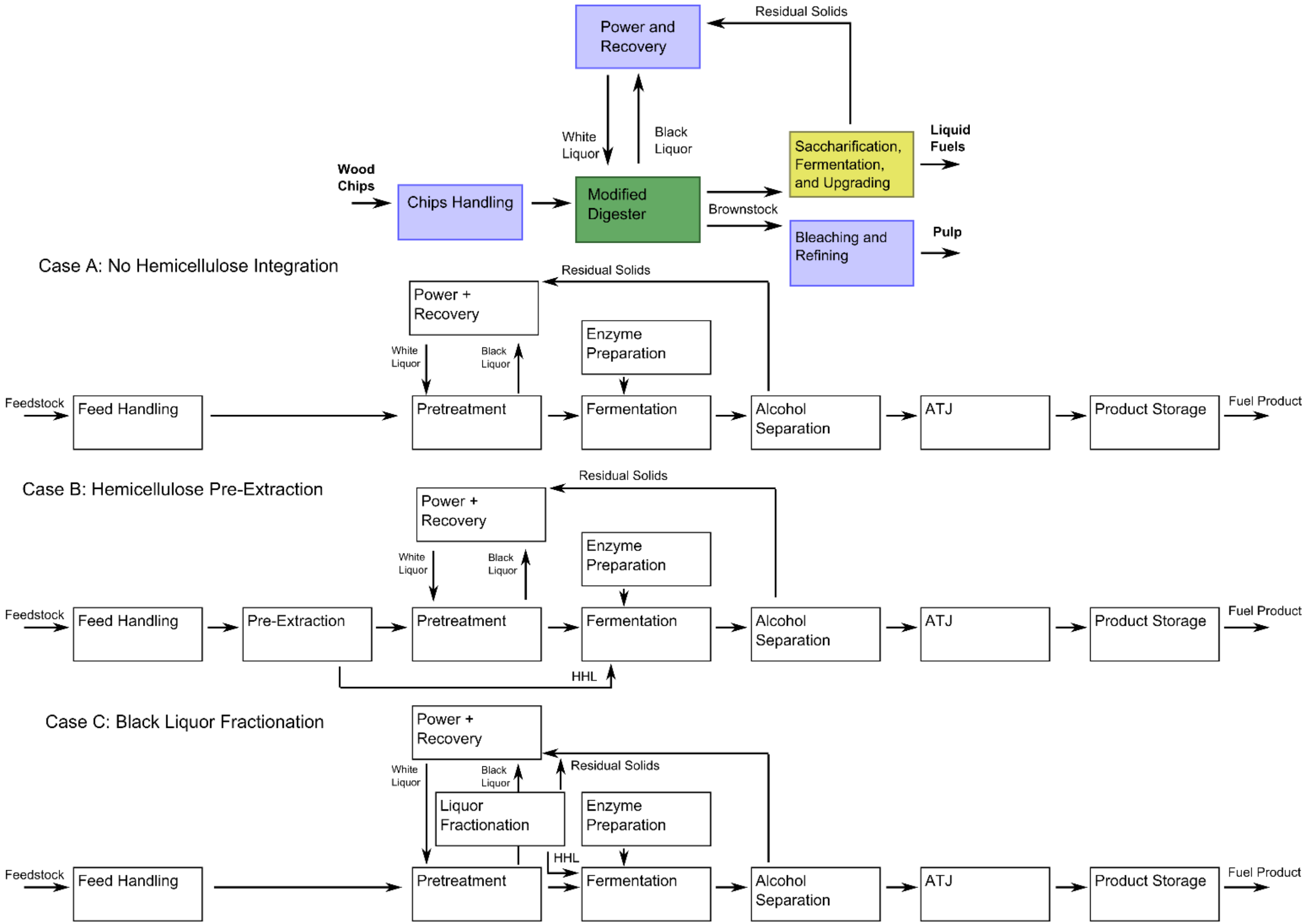
- Cost and performance of alcohol production is the primary barrier toward low-cost ATJ-SPK
- Relatively narrow product distribution of SPK leads to challenges in fuel properties without additional catalytic steps
- Lack of detailed information on key process steps (e.g. advanced fermentation, catalytic upgrading) for modeling and research

# Recommendations for ATJ Development

- Produce low cost alcohols through the utilization of cheap/waste feedstocks
- Reduce cost of higher alcohols production
- Improve oligomerization reactor design and catalysts to minimize capital and operating costs
- Encourage catalytic conversion to wide product/intermediate distribution but without impacting total conversion costs
- Utilize integration opportunities with infrastructure and other industries

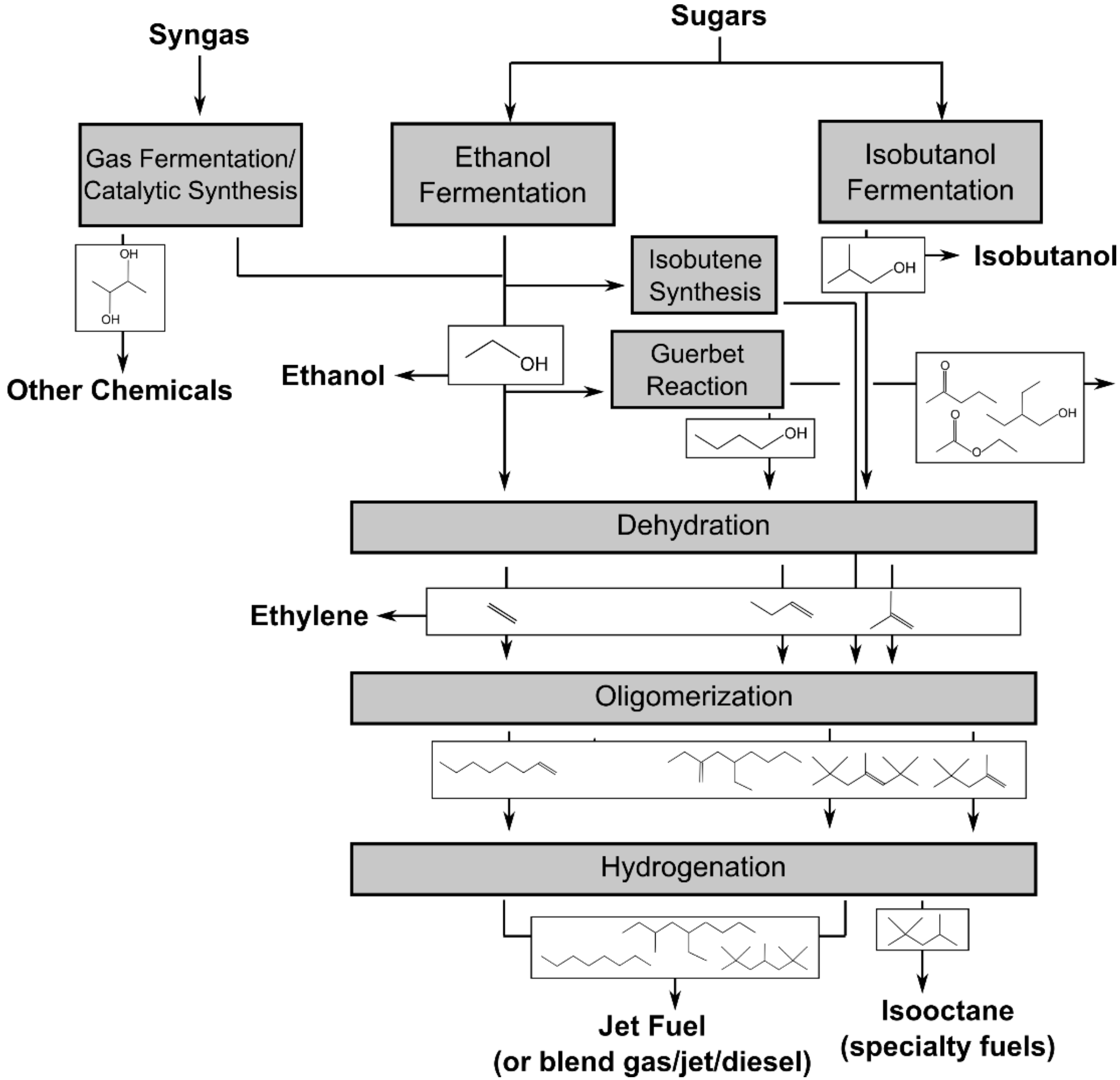
# Example of Model Application to Integrated Facility Modeling

## Pulp Mill Integration with ATJ Conversion



# Questions

The ATJ "Road Map"



# TEA Methods and Assumptions

| Parameter | Assumed Value |
|---|---|
| Cost Year | 2015 |
| Process Uptime | 90% |
| Plant financing | 30% equity |
| Plant Life | 20 years + 3 years for construction |
| Income tax rate | 16.9% |
| Inflation | 2% |
| Working Capital | 20% yearly OPEX |
| Depreciation schedule | 7 years, MACRS schedule |
| Construction spending schedule (% of FCI) | 8% first year, 60% second year, 32% third year |
| Maintenance | 6% TPEC |

| Financial Assumptions | |
|---|---|
| **Equity** | 30% |
| Loan Interest | 8% |
| Loan Term, years | 10 |
| **Working Capital (% yearly OPEX)** | 20% |
| **Salvage Value** | |
| General Plant | 0 |
| **Depreciation Period (Years)** | |
| General Plant | 7 |
| Steam/Electricity System | 20 |
| Depreciation 7 YR | 200% |
| **Construction Period (Years)** | 3 |
| % Spent in Year 1 | 8% |
| % Spent in Year 2 | 60% |
| % Spent in Year 3 | 32% |
| Start-up Time (Years) | 0.75 |
| Feedstock use (% of Normal) | 50% |
| Variable Costs (% of Normal) | 75% |
| Fixed Cost (% of Normal) | 100% |
| Production Rate, start up (%) | 50% |
| **Real Discount Rate** | 10% |
| **Nominal Discount Rate** | 12.20% |
| Income Tax Rate | 16.9% |

| Input | Value |
|---|---|
| Feedstock Loss (%) | 0% |
| hours per day | 24 |
| Feedstock Cost ($/ST) | $668 |
| electricity cost ($/kwh) | $0.069 |
| natural gas cost ($/k cf) | $4.6 |
| natural gas cost ($/MMbtu) | $4.5 |
| Refrigeration Cost, -50C ($/MMBTU) | $13.8 |
| Water Cost ($/kg) | $0.00001 |
| Inflation Rate | 2.0% |
| Hydrogen Cost ($/ST) | $1,089 |
| WWT Cost ($/kgal) | $2.06 |