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The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation

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Abstract: Alcohol-to-jet (ATJ) is a process for the conversion of alcohols to an alternative jet fuel blendstock based on catalytic steps historically utilized by the petroleum refining and petrochemical industry. This pathway provides a means for producing a sustainable alternative jet fuel (SAJF) from a wide variety of resources, offering a near term opportunity for alcohol producers to enter the SAJF market and for the aviation sector to meet growing SAJF demand. In this article, we review the technical background and evaluate selected variations of ATJ processes. Simulation and modeling is employed to assess some ATJ conversion schemes, with a particular focus on comparisons between the use of an ethanol or isobutanol intermediate. While the utilization of isobutanol offers a 34% lower conversion cost for the catalytic upgrading process, the cost of alcohol production is estimated to contribute to over 80% of the total cost at the refinery. The cost of feedstock and alcohol production has a dominant effect on the overall process economics.

1. Introduction

1.1 Alcohols-to-Jet (ATJ) for SAJF Production

A great deal of effort in the last few decades has focused on the development of a sustainable and economically viable process to generate transportation fuels. The aviation industry in particular has recognized that sustainable alternative jet fuels (SAJF) are essential to reduce the environmental impact and

dependence of aviation on foreign sources of oil, improving the sustainability of transportation^[1]. Worldwide, the aviation industry has expressed the need to accelerate the deployment of SAJF, with industry and governmental organizations establishing aspirational goals for increased use of fuels from alternative feedstocks including the International Air Transport Association committing to achieve carbon-neutral growth by 2020 and 50% emissions reductions by 2050^[2]. The aviation industry employs strict regulations for the deployment of new technologies, including those aimed at decarbonizing air travel, in order to maintain consistent and safe operation. Therefore, any new fuels must be fungible with existing aviation turbines and fuel distribution systems; in other words, only “drop-in” biofuels are possible in jet fuel markets. In the United States, all bioderived alternative jet fuel pathways must be approved by ASTM D7566 Standard Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons, following a rigorous qualification process^[3].

Several processes for producing SAJF have been qualified to date and some pathways have been demonstrated with commercial success at limited capacity around the world^[4]. There remains a need, however, to further reduce the cost and increase availability of alternative fuels by developing production through additional sources of available feedstocks^[5]. The most recent addition to the list of qualified alternative jet fuel pathways is the alcohol-to-jet process (ATJ), allowing for production of jet fuel through from alcohol produced through biochemical fermentation routes^[6,7].

The upgrading of an alcohol intermediate to hydrocarbon fuels may be applied to a number of alcohol-producing processes including via conventional fermentation of carbohydrates (including from starch and lignocellulosic sources of carbohydrates) or advanced fermentation using highly modified microbes. In the United States, this concept may be an attractive route for existing ethanol production capacity to overcome the so-called “blendwall”, the market saturation point generated by the limited use for gasoline blends higher than 10 vol.% ethanol, and respond to reduction in demand for other transportation fuels as electric vehicle use rises. While updates to corn and sugarcane ethanol facilities are possibly the most immediate application of the ATJ pathway, its application for lignocellulosic or other non-conventional feedstocks is the same downstream^[8].

To date, several academic techno-economic and lifecycle assessments have been applied to ATJ and other SAJF pathways to estimate cost and impact^[6b,7,9]. It is difficult, however, to use techno-economic assessment to directly compare economic feasibility between pathways that utilize different

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feedstocks and potentially integrate with existing industries and supply chains. In addition, there has been little economic study centered on the technological details of the catalytic upgrading steps providing the foundation for the ATJ pathway (dehydration, oligomerization, hydrogenation, and fractionation) and how their implementation varies depending on the feedstock and alcohol fermentation process used^[10].

In this paper, we will expand upon these data by constructing process economic models for the ATJ pathway using both an ethanol and an isobutanol intermediate. Process simulation and predesign cost estimation will be used to generate cost estimates where data is not currently available outside of private and proprietary research. Assessing the differences between implementations of these routes will assist in understanding the engineering and economic challenges and provide information to elucidate the role of the ATJ pathway in future research and commercial projects.

1.2 Overview of ATJ Fuel and Conversion Process and Commercial Development

A number of companies have been developing the ATJ process toward the goal of commercialization, with some variations between them. Leading the efforts in regulatory approval of ATJ derived fuel are two companies specializing in advanced biochemically engineered fermentation processes: Gevo, Inc and LanzaTech. Gevo, which has partnered with Alaska Airlines for a corn sugar-based ATJ demonstration flight and a cellulosic sugar-based flight as part of the larger Northwest Advanced Renewables Alliance (NARA) consortium^[11]. Gevo touts a proprietary isobutanol fermentation process which utilizes an engineered yeast strain and an advanced integrated separations system called the Gevo Integrated Fermentation Technology (GIFT) process. LanzaTech specializes in the fermentation of gas feedstocks, including steel mill flue gas streams and gasified materials. LanzaTech has recently demonstrated successful production of SAJF from gas-fermented ethanol in partnership with Virgin Atlantic and Pacific Northwest National Laboratory^[12]. Other companies including Butamax and Cobalt Technologies have also contributed to the development of biorenewable butanol production, although they are no longer pursuing ATJ commercialization^[13]. Another approach to ATJ commercialization is the addition of alcohol upgrading to conventional ethanol production; Byogy takes this approach primarily aimed to utilize the large sugarcane ethanol industry in Brazil^[14].

1.2.1 Certification and Qualification of Alternative Jet Fuel from ATJ

To deploy a commercial SAJF production operation in the United States, the technology pathway must undergo approval and meet standards set by ASTM International. A thorough review of the background of this process is provided by Wilson, et.al.^[15]. The conventional standard for jet fuel is defined by

ASTM D1655 Standard Specification for Aviation Turbine Fuels^[16], and details the requirements for petroleum distillates meeting a certain distillation curve and other properties deeming them “fit-for-purpose”. A standard for alternative jet fuels is contained in ASTM D7566 Standard Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons^[3], which provides additional pathways to qualified fuels through an individually added annex for each fuel. The standard is regularly updated and new fuels may be added through an extensive and rigorous review process set forth by ASTM D4054 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives^[15].

Jet fuel blendstock produced through the ATJ pathway is called ATJ-SPK (synthetic paraffinic kerosene) and is approved by ASTM D7566 as part of Annex A5. Currently, only ATJ-SPK produced from an ethanol or isobutanol intermediate is allowed up to a 50% maximum blend. ATJ-SPK derived from other alcohols or mixed alcohols are not currently allowed, but ASTM states that they do intend to expand the standard to include additional alcohols once sufficient test data is available^[16,17,18] (the standard originally only allowed isobutanol, but was revised in 2018 to include ethanol as well). The specification defines ATJ-SPK as alcohols processed through dehydration, oligomerization, hydrogenation, and fractionation. Any fuel not produced through these steps must seek its own qualification to be used as a jet fuel blendstock, including other catalytic alcohol upgrading processes such as the one developed by Vertimass and Oak Ridge National Lab^[19].

Although many requirements are identical between the D1655 and D7566 fuel specifications, several additional stipulations are added for alternative fuels; the differences between them for ATJ-SPK are provided in supplementary document A, Table A1. Numerous concerns regarding specific differences between synthetic chemical blends and fit-for-purpose petroleum distillates has resulted in stricter requirements for alternative fuels.

1.2.2 Production of Alcohols as Jet Fuel Intermediates

The general ATJ concept is not specific as to the type of alcohol fed to catalytic upgrading to hydrocarbons. Several alcohols currently derived from renewable feedstocks have been under consideration for use in ATJ conversion including ethanol, n-butanol, and iso-butanol. While yeast fermentation of sugar from edible plants is often claimed as the oldest biochemical conversion process developed by mankind, the fermentation of saccharides from non-food plant biomass or other non-conventional carbon sources requires more sophisticated techniques often involving modified microbes and additional process units. Thermochemical routes to convert biomass to alcohols may alternately be used, often through gasification and catalytic steps, although pathways using mixed oxygenates other than alcohols are typically explored as well^[14e,20].

The production of alcohols higher than ethanol through biochemical routes has been thoroughly investigated, and

previous methods have been generally considered too costly for biofuels production compared to ethanol when evaluated as an alcohol fuel^[21]. Many newly developed fermentation technologies may improve the availability of many cost-competitive alcohols or alcohol mixtures in the near future and may achieve more favorable economics when used to provide alcohol for ATJ conversion.

Due to the chemistry of the dehydration and oligomerization processes, higher alcohols have a higher theoretical yield through ATJ upgrading although the maximum theoretical carbon yield is identical. Oligomerization chemistry differs with higher alcohols requiring a lower degree of oligomerization, possibly resulting in lower oligomerization costs. In contrast, alcohols with lower carbon numbers may carry the advantage of achieving a more even distribution of carbon numbers in the final product, enabling the resulting product to have a smoother distillation curve and more closely resemble conventional petroleum-based jet fuel which is a complex mixture containing hundreds of hydrocarbons^[15,22].

Table 1 summarizes several variations of alcohol intermediates under investigation for ATJ conversion by companies and research institutions. The range of products resulting from each process has considerable ramifications for the expected properties of the jet fuel ultimately produced. Fuels that offer a narrower range of products may encounter challenges in achieving the required properties of jet fuel, possibly leading to limited allowable blend ratios as the ASTM standards are updated. However, conversion processes with a narrower range of products, i.e. purer chemical compounds, do offer potential for these companies to market them as higher-value co-products.

Table 1. Comparison of various advanced alcohol-producing technologies explored and currently in development for use in ATJ upgrading and their resulting hydrocarbon products

Alcohol-Producing Process	Companies and Institutions Interested/Invested in Technology	Alcohol Intermediate	Comments and Reference
Conventional Sugar Fermentation	LanzaTech/PNNL, Vertimass*	Ethanol	[19,23]
Gas Fermentation	LanzaTech/PNNL	Ethanol	Non-sugar feedstock (waste gasses or syngas) ^[14e,20b,23,24]
Sugar to Butanol Fermentation	Gevo	iso-butanol	[25]
Catalytic (thermochemical) Conversion of Syngas to Ethanol	PNNL	Ethanol	Non-sugar feedstock ^[14e,21c]
Non-specific	Byogy, White Dog Labs		[13,26]

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

Among these concepts is Gevo's GIFT process which involves continuous product separation alongside a metabolically engineered yeast to produce isobutanol, which is not naturally produced in useful amounts^[27]. However, the engineering of stable fermentation units can encounter additional challenges when using genetically modified biocatalysts^[28]. Another advanced fermentation technology is the gas fermentation process developed by LanzaTech, which generates products such as ethanol through the fermentation of waste gasses from other industrial processes (e.g. steel mill flue gas)^[11a]. Although these waste gasses are typically not biogenic, their fermentation displaces carbon emissions that would otherwise not be utilized for a chemical product and they are an extremely cost-effective feedstock. However, gas fermentation technologies have been known to involve additional challenges including gas-liquid mass transfer limitations^[20b,24].

The separation of alcohols from fermentation broth provides a source of capital and operating expenses, and will differ in implementation depending on the alcohol intermediate. Although separation of pure alcohol from water is primarily carried out through distillation, other processes are typically required to overcome a water/alcohol azeotrope. In the case of ethanol, mixtures up to 95.6% by weight are achievable purely through distillation; the use of a pressure-swing molecular sieve column is the current industrial standard for generating fuel grade ethanol^[14h]. In the case of butanol (both n-butanol and iso-butanol), the azeotrope is self-entrained, forming a heterogeneous azeotrope with two liquid phases. Pure alcohol streams can be obtained using a decanter feeding each phase to a separate stripping column.^[14i]

For use in ATJ conversion, however, distillation to the azeotrope concentration without further processing is likely sufficient because the dehydration catalyst is tolerant to the presence of small levels of water.

1.2.3 Upgrading Alcohols to Hydrocarbon Fuels: The "Core Alcohol-to-Jet" Technology

The core of the ATJ Process is a concept developed to bridge the gap between alcohols that can be easily produced from renewable resources and the high-quality hydrocarbon fuels necessary for jet turbines. This process is based on three catalytic reactions depicted in Figure 1: alcohol dehydration, olefin oligomerization, and hydrogenation, followed by fractionation of the synthetic paraffin product. Similar technologies built around olefin oligomerization have been historically used to generate a variety of liquid fuels including gasoline and diesel and are fully capable of generating hydrocarbons in the jet range as well^[25,30]. In practice, a mixture of synthetic paraffins are created in the kerosene range and fractionated off to produce a viable jet blendstock and the remaining cuts are used for products in the naphtha and/or diesel range.

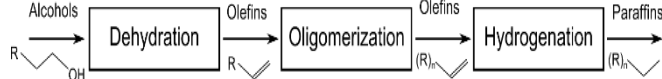


Figure 1. The Core Catalytic Steps in the ATJ Process

The catalytic dehydration of alcohol has predominantly been utilized as a pathway to produce ethylene from renewable ethanol as an alternative source to petrochemically derived ethylene and dates back to the 1960s. Ethanol dehydration has been explored extensively with a variety of catalysts including zeolites, silicoaluminumphosphates, and heteropolyacid catalysts^[31,32]. Specialized ethanol-to-ethylene heterogeneous catalysts such as Syndol have become commercially available with high selectivity and conversion^[32,33]. Dehydration of higher alcohols is less explored, although isobutanol dehydration has been reported achievable using a variety of heterogeneous catalysts including zeolites, alumina, and acid catalysts also with relatively high conversion^[14b,25,32,34]. Dehydration reactions for isobutanol can produce a mixture of butene isomers and even initiate oligomerization reactions but a high selectivity toward isobutene in the dehydration step is reportedly preferred for isobutanol conversion^[34].

The removal of the hydroxy group from alcohols during dehydration generates water and results in a reduction of mass. On a total mass basis, higher alcohols obtain a higher yield from dehydration compared to short-chain alcohols although the carbon yield is identical in theory. The production of water inside the reactor requires dehydration catalysts to be water-tolerant but the oligomerization reaction system may not be tolerant to water and it must be completely removed from the dehydrated product. Depending on the temperatures, pressures, and performance of the design, a combination of distillation, liquid-liquid separation, and molecular sieves might be used to remove water. If there is low conversion in the dehydration reactor, unreacted alcohols may be recycled by feeding this stream to the prior alcohol/water separation unit (if the alcohol is produced through fermentation).

The oligomerization of alkenes and short chain olefins to form higher is a well-established reaction in the petrochemical industry with a variety of forms dating back to the 1930s and using a variety of homogeneous or heterogeneous catalysts in single or multiple reactor configurations^[30b-c,32]. In the context of the alcohol-to-jet pathway, alkenes produced by alcohol dehydration must be oligomerized to the desired distribution of hydrocarbon chain lengths; typically ranging from 8 to 16 carbons for the kerosene range. Careful design of the oligomerization process is necessary to achieve an appreciable yield in the desired range and able to meet fuel specifications.

The design for the oligomerization unit will vary between different alkenes fed to the process, and different catalyst systems may be preferable depending on the alcohol intermediate used. Several commercial ethylene oligomerization processes have been developed including the Cheveron-Phillips Zeigler one-step process, the Zeigler two-step process, and the Shell Higher Olefins Process. Ethylene oligomerization for ATJ conversion typically achieves a carbon length distribution

centered around C10 and C12 and ranging from C4 to C20+^[6c,30,32,35].

Iso and n-butene oligomerization has been extensively explored, but is less developed commercially than its ethylene counterpart^[25,32,36]. The formation of C12 trimers and C16 tetramers is preferred for the jet range with or without the use of recycle or a secondary reactor to drive further drive the growth of C8. A molar selectivity of 20% C8, 70% C12, and 10% C16 has been described for isobutene oligomerization using an Amberlyst-35 catalyst^[25,32].

Depending on the catalyst, further isomerization and cracking may occur during oligomerization to generate some additional products including intermediate-numbered (i.e. C9 or C11) carbon chains, cyclic olefins, and even aromatics^[37]. These side reactions may be beneficial for an ATJ conversion scheme as it improves the diversity of the product's composition to achieve a smoother distillation curve or to meet other product requirements.

The use of a branched alcohol (i.e. isobutanol) will result in a higher degree of carbon branching in the oligomerized product and final product. Branching has a complex and varied effect on the resulting fuel properties reportedly including cold flow properties, freeze point, and cetane number^[22]. While some of these properties are not part of the ASTM specification, they are important in the generation of other fuel ranges such as gasoline and diesel. While high degrees of branching may favorably affect cold flow properties it is also associated with a lower cetane number, an effect that is not well understood at this time.

The hydrogenation unit is yet another process used frequently in the petrochemical industry, which saturates the remaining double bonds of the olefins after completion of oligomerization. Sufficiently saturated product is critical to ensure a low reactivity of the fuel. Like the other two reaction stages, hydrogenation can occur over a solid catalyst. Hydrogen gas is fed to the reaction in excess to ensure near complete conversion of olefins to paraffins. A recycle system for the remaining hydrogen in the product stream can be achieved with a gas/liquid separation and a compressor to return the recycle gas to the pressure of the feed.

A supply of hydrogen is required for hydrogenation and will contribute an additional source of production cost. Depending on the nature of the plant as a whole, a facility may purchase hydrogen or produce it on-site through a number of possibilities, including using a biomass feedstock^[38]. A cellulosic ATJ biorefinery might benefit from one of these methods considering the availability of lignin residuals left from saccharification and fermentation, but depending on the available price of other hydrogen from sources such as natural gas. In the case of existing corn ethanol facilities retrofitted for ATJ, on-site bio-hydrogen production is less attractive as residual solids are already used for the production of distiller's grain.

2. Results and Discussion

Process economic models were built to conduct Techno-Economic Analysis (TEA) for the production of ATJ-SPK through the upgrading of ethanol and isobutanol separately. Process simulation in Aspen Plus was used to assist in estimating process requirements and costs where not available in literature, primarily for the Core ATJ units. Further details on the construction of these simulations and economic models are provided in Section 4: Computational Methods.

The techno-economic analysis based on these models was conducted at two levels: first, the core ATJ process to upgrade alcohol to jet fuel was evaluated on a common basis of the amount of alcohols processed. Second, a more complete ATJ process upgrading sugars (including both fermentation and the Core ATJ models) was evaluated on a common basis of an amount of sugar processed. The first level includes more detailed capital cost estimates based on Aspen simulations described here, while the second level expands these evaluations to include a fermentation process based on other TEAs; these two levels are intended to allow for better evaluation of process configurations given different feedstock and industry integration options.

It is important to note the limitations posed by the methods used in these models. Although principles of predesign cost estimation and techno-economic analysis, these analyses are no substitute for cost estimates generated using a complete process design and market analysis. Uncertainty levels are high enough that scientific comparisons between these models and current practices cannot be made; however, they do provide insight into comparative differences between process variations.

2.1 Comparisons of Core ATJ Cases

Each Core ATJ design case was compared at a reference capacity of 200 tons per day of alcohol fed to the process. Table 2 summarizes key details of the mass balances and yield from these models; this data, normalized for hydrocarbon production (10 million gallons of fuel at consistent density) is given in Table 3^[7,14b,25]. While model outputs are reported to a significant digit at the \$0.01 level, note that uncertainty levels in the results remain significant.

	Ethanol to Jet	Isobutanol to Jet
Overall Mass Yield	0.60	0.75
Fuel Production Rate, k-ton/yr	39.15	49.25
Oligomerization Recycle Ratio	1.27	0.02
Fuel Product Distribution Selected	10%/70%/20%	30%/70%/0%

(Gasoline/Jet/Diesel)

Table 3. Mass Balance Details from Core ATJ Models, normalized for 36.3 thousand tons (10 million gallons of ATJ-SPK) of fuel product per year

	Ethanol to Jet	Isobutanol to Jet
Feed Rate of Alcohol (ton/day)	185	147
Hydrogen Requirement (ton/day)	1.1	1.1

The differing nature of ethylene and isobutylene oligomerization result in some key differences in the design and output of the modeled reactor system. Isobutylene oligomerization results in a product that is predominantly C12 and C16 olefins, and the recycle loop consists of mostly C8 products; there is little further growth past the jet fuel range. Ethylene oligomerization, however, produces a wider range of carbon lengths in both the product and recycle stream. As a result, the modeled ethanol-to-jet case involved a broader distribution around the jet range and the oligomerization system involves a larger recycle ratio. Fuel product distribution was chosen based on the product ranges of model compounds at steady state operation. The effective recycle ratio (flow rate of the recycle stream/flow rate of fresh feed) for both systems is shown in Table 2. Further details on the operation of each reactor system is described in the computation methods section, Table 10.

This approach captures, to a degree, the differences in design between ethylene and isobutylene oligomerization within the models under a common design methodology; practical implementations of the process may instead require alternate reactor configurations depending heavily on the catalyst(s) of choice. A distribution of fuel products was selected based on the range of carbon chains in the product stream attained by the Aspen model. A maximum of 70% jet fuel was selected in both cases with the remainder of product from the jet range diverted to the gas or diesel fraction because some portion of the jet range *product will need to be fractioned off to attain the required distillation curve and properties to meet specifications as a jet fuel blendstock.*

Economic results from the Core ATJ Process are given in Table 4. Note that the conversion cost listed in the bottom row represents the added cost for an alcohol-producing facility to convert production to jet fuel in terms of dollars per gallon of fuel blendstock. In other words, conversion cost is calculated as the minimum fuel selling price under the assumption that the costs of alcohol production are factored elsewhere (feedstock costs are assumed to be zero for comparative purposes in this analysis). It is well recognized that the alcohol feedstock cost may have a large impact on the overall process economics. The purpose of this approach is to isolated the feedstock cost, and provide a comparison of the core ATJ based on two different molecules: ethanol and isobutanol.

Table 4. Comparison of Core ATJ Design Case Models

	Ethanol to Jet	Isobutanol to Jet
Total Capital Investment, MM\$	\$24.6	\$15.4
OpEx, MM\$/yr	\$6.6	\$5.6
Jet Fuel Production Rate, MMgal/yr	7.55	9.50
Gasoline Production Rate, MMgal/yr	1.29	4.87
Diesel Production Rate, MMgal/yr	2.26	0
Cost per ton of alcohol	\$146	\$120
Conversion Cost ATJ-SPK (\$/gal)	\$0.86	\$0.52

Scale: 200 ton/day alcohol feed

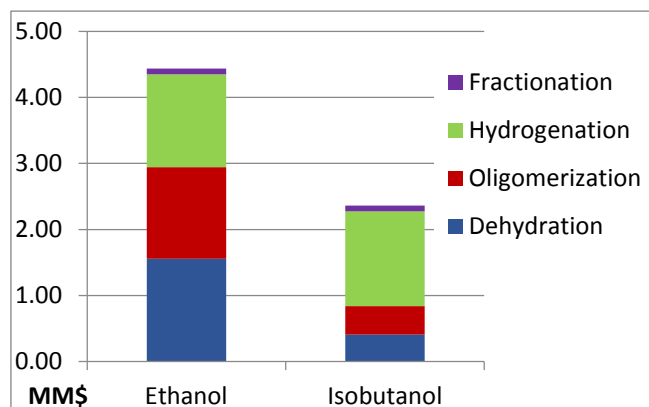
The cost of production is presented here in two ways: in terms of the cost to convert a ton of feed alcohol into fuel, and as the cost of production for a gallon of ATJ-SPK product. Further breakdown of capital and operating costs used in this model are described in Tables 5 and 6.

Table 5. Capital Costs in MM\$

	Ratio Factor	Ethanol to Jet	Isobutanol to Jet
Purchased Equipment Cost (PEC)		4.4	2.6
Total Direct Costs	3.55 × PEC	16.9	10.5
Fixed capital investment (FCI)	4.99 × PEC	23.3	14.3
Working Capital	0.20 × Yearly OpEx	1.3	1.1
Total Capital Investment		24.6	15.4

A break-down of how each reaction stage contributes to the base purchased equipment costs shown in the top row of Table 5 is shown in Figure 2. Each stage includes the costs of reactors as well as separation and other equipment maintaining recycle operation; this includes the added cost of additional alcohol/water separation (included under dehydration). In these models, lower capital costs of separation, dehydration, and oligomerization of isobutanol and isobutylene result due to some more favorable thermodynamic properties over ethanol and ethylene; notably due to the added need for additional gas

compression of ethylene where isobutylene can be handled in the liquid state under pressure.

**Figure 2.** Base purchased equipment cost breakdown for standalone ATJ cases at a scale of 200 ton/day feed.

A comparison of operating expenses for both cases is given in Table 6. The most notable difference between the upgrading of ethanol and higher alcohols is the increased need for recycle in the oligomerization reaction step. This results in increased capital costs and energy requirements that accompany higher flow rates through the reactor and distillation units. Fixed operating expenses include labor, maintenance, and insurance; with the exception of labor, this value is estimated as a percentage of fixed capital investment (FCI), leading higher fixed OpEx for the ethanol to jet case.

Table 6. Operating Expenses in MM\$ / year

	Ethanol to Jet	Isobutanol to Jet
Utilities	2.7	2.2
Catalyst	0.5	0.6
Hydrogen	0.5	0.6
Fixed OpEx	2.9	2.2
Total OpEx	6.6	5.6

2.2 Comparisons of ATJ from Sugar Cases

The analysis of the core ATJ process show that higher alcohols are favorable for the conversion to drop-in aviation fuels. However, the catalytic upgrading represents only a segment of the production process. An integrated SAJF conversion process starting from renewable feedstock is a complex process and the economics can be influenced by multiple factors and many unit operations. Due to a high level of technology uncertainty, a

precise and detailed determination of the complete economics of ATJ is difficult to obtain.

While higher alcohols are favorable to the core conversion process, the technology readiness toward generating different alcohols differs. In general, the production of higher alcohols through fermentation can require more sophisticated equipment and additional costs associated with genetically modified biocatalysts as well as a lower yield of alcohol from sugars. Ethanol fermentation from sugar is much more mature technology compared to isobutanol fermentation using sugar as a feedstock.

Models were constructed to evaluate scenarios for the conversion of a sugar feedstock that is converted via either ethanol or isobutanol fermentation, followed by the ATJ design scenarios described above. Since the details of advanced fermentation technologies currently under commercial development are not publicly available, assumptions regarding these systems were made for comparative purposes. Humbird, et.al. provides a baseline of costs and yield for conventional ethanol fermentation. For isobutanol production, a lower theoretical mass yield of sugars to alcohols is possible and actual yield may be even lower. In addition, higher capital cost due to additional equipment requirements such as larger fermenters and continuous product separation, although there is little data available regarding the costs associated with proprietary isobutanol fermentation processes.

Table 7 provides a summary of key assumptions for three fermentation cases. Conventional ethanol fermentation costs are estimated from data provided by Humbird, et.al. Two isobutanol fermentation cases are assessed; the first reflects a fermentation process with the same capital and operating expenses as ethanol fermentation while the second assumes double capital and variable operating expenses (excluding waste water treatment). The low and high-cost isobutanol production alternatives are selected to represent a rough bound for the total cost of an integrated isobutanol fermentation system based on publication from Gevo Inc.^[27].

For comparative purposes, the fermentation yields in both ethanol and isobutanol models are based on 90% of the theoretical maximum (max. 51.2% for ethanol and 41.2% for isobutanol).

Table 7. Fermentation Unit Parameters

	Ethanol Fermentation	Isobutanol Fermentation (low cost)	Isobutanol Fermentation (high cost)
Mass Yield	0.46	0.37	0.37
Purchased Equipment Cost (MM\$)	7.7	7.7	15.4
Variable Operating Costs (MM\$)	1.2	1.2	2.4

Basis: 435 ton/day sugars

An economic analysis of each case was then carried out using the separation and Core ATJ data presented previously to estimate total conversion cost of sugars to jet fuel, shown in Table 8. The basis for these models is 435 ton/day of sugars, corresponding to the previously used scale of 200 ton/day in the ethanol case. As before, the feedstock price (for sugar) in both cases is assumed to be zero for comparative purposes. The mass yield for both alcohols are similar because the higher yield of isobutanol to jet works to cancel out the lower fermentation yield. Note that in both isobutanol conversion cases, the reduced volume of alcohols and added efficiency of ATJ through higher alcohols results in reduced capital costs for the Core ATJ unit.

Either ethanol or butanol can also be obtained from sources other than sugar fermentation. For example, steel mill off-gasses have been shown as a very attractive source for ethanol production through gas fermentation, which can significantly influence the final fuel cost. However, the analysis conducted in this paper only focuses on sugar derived alcohol.

Table 8. Sugars to Fuel Conversion Cases

	Ethanol Fermentation	Isobutanol Fermentation (low cost)	Isobutanol Fermentation (high cost)
Mass Yield	0.274	0.277	0.277
Alcohols Processed (ton/day)	200	161	161
Total Capital Investment, MM\$	\$77.4	\$55.0	\$94.2
OpEx, MM\$/yr	\$15.8	\$13.9	\$18.4
Jet Fuel Production Rate, MMgal/yr	7.56	7.65	7.65
Gasoline Production Rate, MMgal/yr	1.29	3.92	3.92
Diesel Production Rate, MMgal/yr	2.26	0	0
Conversion Cost, \$/gallon jet fuel	\$2.84	\$2.23	\$3.37

Basis: 435 ton/day sugars

Although isobutanol fermentation may theoretically reach up to 80% of the maximum yield of ethanol fermentation, actual yields achieved in practice may differ depending on the specific fermentation process. Typical modern corn ethanol process can attain a fermentation yield of 98% theoretical maximum^[39]. Isobutanol yield from proprietary processes are not available in

detail, but Gevo announced they achieved 1.80 to 1.85 gallons of isobutanol per bushel of corn in 2015 (about 34.4% from sugars, or 83.5% of theoretical maximum for isobutanol)^[40]. Using these fermentation yield figures (98% and 83.5% theoretical), the above conversion costs become \$2.52 for ethanol and \$2.21/\$3.37 for the isobutanol cases.

2.3 Sensitivity Analysis and Effect of Alcohol Price

A straightforward way to evaluate the comparative costs of alcohol-to-jet conversion from ethanol and isobutanol is to approach the cost using a total alcohol production price. The uncertainty of costs using an alternate or advanced fermentation process is then contained within this price. This approach estimates a general trend in the relationship between ATJ upgrading costs from different alcohol intermediates, although it should be noted that any realistic scenario involves additional variables. A plot of these data is given in Figure 3. The vertical dotted line at \$534/ton (\$1.76/gal) denotes the 2013 to 2017 average cost of ethanol production^[41]. At this price for ethanol, the cost of alcohol feedstock makes up 79.2% of the MSP in the ethanol-to-jet base case scenario.

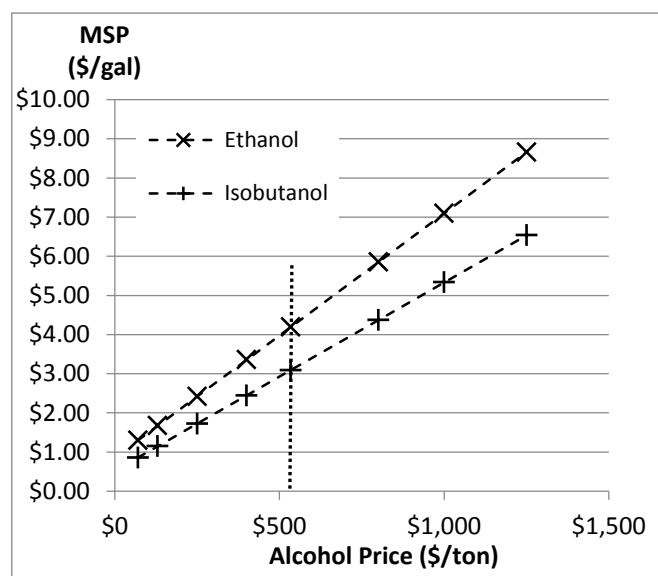


Figure 3. Relationship between minimum selling price (MSP) and alcohol price using an ethanol or isobutanol intermediate. Although isobutanol conversion offers economic benefits for alcohol-to-fuel upgrading, they may be offset by a higher cost for the intermediate alcohol.

Conversion of isobutanol is predicted to be cheaper than conversion of ethanol given the same price of alcohol. It needs to be emphasized that uncertainty between these models and real-world scenarios considerably complicates this analysis; a robust and direct comparison between both cases should be evaluated on a case-by-case basis, however. Compared to the

average cost of ethanol, an isobutanol price of 1.41 times larger (\$755/ton) results in equal selling prices through both pathways in our models. In an integrated biorefinery, the price of alcohol will typically represent a function of both the price of feedstock at the gate and conversion cost of feedstock to alcohols, both adding considerably to the cost. The use of extremely low-cost feedstocks, such as steel mill flue gas as in some implementations by LanzaTech, can greatly reduce the final product selling price.

To assess the impact of variations in assumptions and process performance within the process model, sensitivity analysis results for both Core ATJ models is shown in Figure 4. This analysis demonstrates the effect of an increase or decrease in a cost category for each model. Each input is varied to reflect a range of 50% to 150% of the base case scenario.

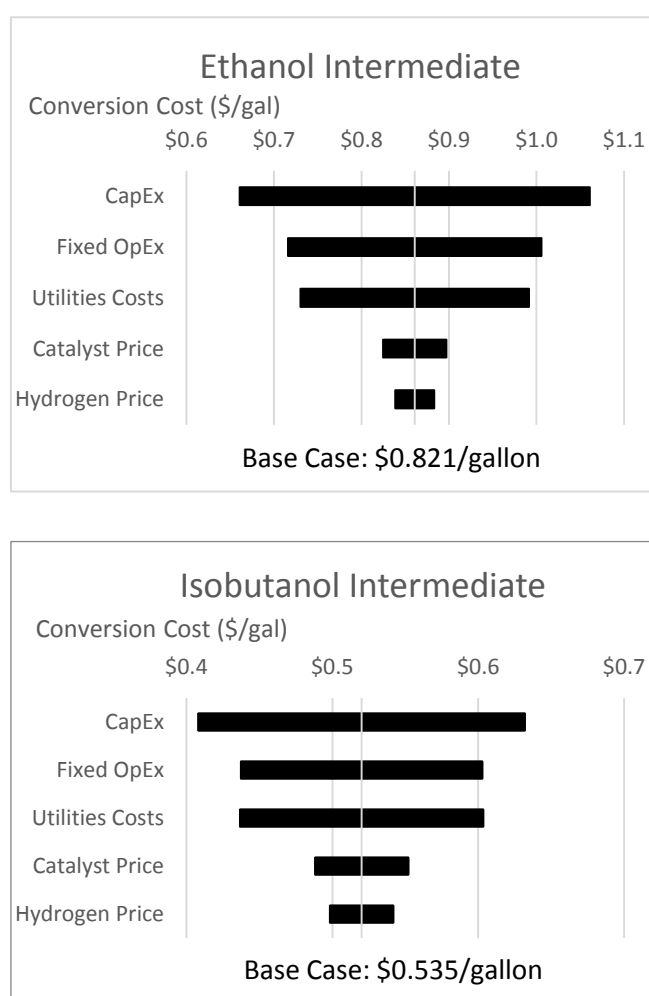


Figure 4. Sensitivity analysis of model parameters on jet fuel conversion cost for ethanol-to-jet and isobutanol-to-jet scenarios from an alcohol feedstock. The bars reflect a reduction or increase in each input by 50% from the base case.

Other modeling of alcohol-to-jet conversion strategies in literature show the highest sensitivity to feedstock cost as well

as the overall conversion of raw feedstock to fuels (including fermentation and sugar preparation)^[8a,14b]. In our assessment, we find that ATJ production through both ethanol and isobutanol fermentation routes achieve similar total yield (see Section 2.2). Our models do agree that the total cost of alcohols has a dominant effect on process economics. Thus, a conversion pathway which utilizes both fermentation to higher alcohols and a low-cost production of fermentable feedstock would be an ideal scenario, although no such technology is publicly under development at this time.

2.4 Alternate Alcohol-Upgrading Conversion Pathways

Besides the direct conversion of alcohols to the core ATJ process, other intermediate stages have been proposed to increase the molecular weight and variability of alcohols. Although not reportedly used in any upcoming commercial applications of ATJ, the Guerbet reaction has seen research attention in and outside of the context of ATJ^[14e,42]. This reaction includes several steps that result in a mix of higher chain-length and branched alcohols along with a fraction of other side products, primarily aldehydes. Direct conversion of ethanol to isobutene has also been considered, a step that would eliminate the need for dehydration downstream but generates additional CO₂ possibly resulting in a net reduction of carbon efficiency^[20a,43].

These alternate concepts aim to improve ethanol-to-jet approaches by increasing the variability (in terms of length and branching qualities) of the alcohol to better fit desired fuel profiles downstream. This approach also introduces opportunities for co-products (ketones, esters, higher alcohols). The use of additional intermediate stages, however, involves the addition of capital expenses associated with another catalytic reactor and separation system for recycle. A pathway scope showing some of these alternative conversion processes is shown in Figure 5.

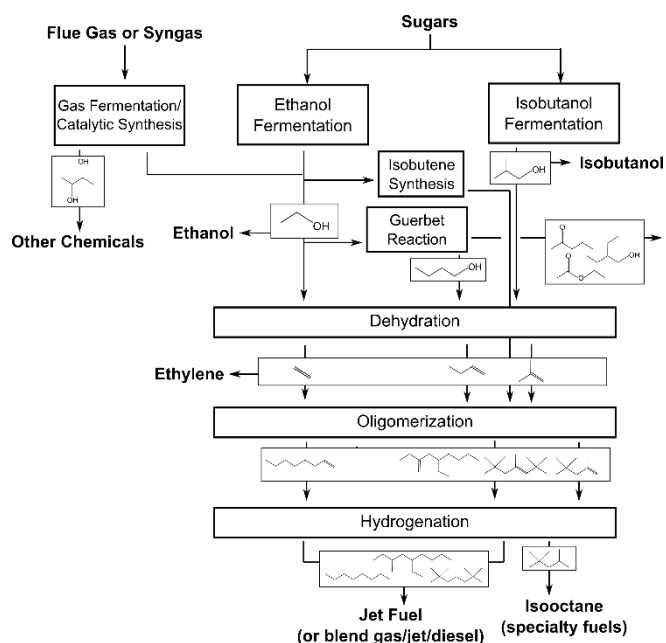


Figure 5. Scope of the ATJ Pathway highlighting potential co-product opportunities using different intermediates.

3. Conclusions and Recommendations

Considering the consistent and rising demand for aviation fuels worldwide, the alcohol-to-jet pathway offers a solution for alcohol producers to enter the market for drop-in fossil fuel alternatives. New alcohol production capacity using new and high-tech fermentation technologies to convert industry residuals such as flue gasses or lignocellulosic residues may also see the adoption of ATJ conversion as well in the near future. Several companies are achieving varying levels of success in developing the implementation of the ATJ process as a route to improve the commercial viability of advanced fermentation technologies. Recent qualification of ATJ fuel into ASTM standards and its demonstration in commercial aircraft also indicates momentum toward further developments and improvements to the process in the near future.

The ATJ pathway enables the use of alcohols from a variety of sources to be used as a platform molecule for jet fuel production and no particular alcohol production strategy is required to generate a qualifying ATJ-SPK fuel as long as it produces either ethanol or isobutanol. Both the conventional ethanol industry, such as corn or sugarcane-based fermentation, as well as businesses investing in new and advanced alcohol production technologies can benefit from the ability to enter drop-in fuel markets using the ATJ pathway. With further advances in conversion technologies, even lignocellulosic biorefinery concepts may utilize ATJ through fermentation of cellulose hydrolysate or gasified biomass.

Although a variety of alcohol process streams, including ethanol, higher alcohols, and mixed alcohols, can theoretically be used as an intermediate for ATJ conversion, the process differs considerably in terms of engineering and implementation of the process depending on the alcohol used. ASTM Standards recognize their differences and requires a separate qualification process for a given alcohol; ethanol and isobutanol are the only alcohols currently qualified. Any new AJF pathway based on n-butanol, mixed alcohols/oxygenates, or other intermediates will not only require separate qualification but will involve differently engineered catalyst and separation systems.

The primary difference in implementation between ethanol-to-jet and isobutanol-to-jet lie in the configuration and catalyst selections involved in dehydration and oligomerization to produce higher olefins. Once olefins are produced in the appropriate range, the remaining hydrogenation and fractionation steps are similar regardless of process. In both cases, the main functional challenge in designing an ATJ reaction scheme is to drive the formation of oligomers to maximize yield in the appropriate range needed to meet fuel specifications. Although fractionation allows for further refinement of the product to meet specifications, it is important to increase value by ensuring as much of the product is recovered as jet fuel or another marketable co-product.

ATJ from short-chain alcohols like ethanol generally provides superior flexibility to generate a wide range of fuel products, due to the more varied nature of the oligomerized ethylene streams. Isobutanol oligomerization, however, carries certain advantages in terms of processing costs and has a

greater mass yield in terms of alcohol conversion. Although there are trade-offs between the conversion costs from ethanol and isobutanol, the deciding factor between which process achieves better economics is the cost of producing the alcohol intermediate. Since the cost of producing alcohols through fermentation is a function of both the fermentation unit and the cost of sugar (or alternative feedstock) price, the selling price of ATJ fuel is highly dependent on the technology used for alcohol production. An alcohol-production process with a high carbon yield from a low-cost feedstock is ideal.

It should be noted that public policy-based incentives for biofuels production such as those offered by the Renewable Fuel Standard or the Low Carbon Fuel Standard in the United States can significantly affect the decision-making of biofuels businesses. The ability to generate renewable identification numbers (RINs) or other carbon credits may ultimately determine the economics of any SAJF pathway. The ability to upgrade alcohols as a platform molecule, produced from a variety of sugar, waste, cellulosic, and other sources, may allow SAJF producers the flexibility to appropriately capitalize on both low cost and incentivized feedstocks that are available.

The models explored in this study represent portions of a complete biorefinery that would realistically implement ATJ conversion. The success of ATJ biorefinery projects would rely on numerous other factors including feedstock availability and cost, supply chain and infrastructure, and co-product generation. The sales of co-products, including additional fuel cuts besides jet, has a significant effect on minimum selling price particularly when the co-product is priced considerably higher or lower than the jet fraction; higher-value co-products would be a major benefit to an ATJ process. Feedstock cost shows the greatest sensitivity toward improving process economics. However, the production of isobutanol or other higher alcohols over or in addition to ethanol provides significant improvement, provided that the combined cost of alcohol production is not significantly impacted. Further research and development into alcohol-production processes that utilize low-cost feedstocks and generate higher alcohols is recommended.

Several areas have been identified as key bottlenecks that can determine the viability of ATJ production in the near term. We make the following recommendations and conclusions based on results from our models:

- At an average alcohol price in our models, the production of alcohol feedstock for ATJ upgrading is estimated to contribute approximately 80% of the production cost for jet blendstock at the refinery. Improvements to alcohol production to generate low-cost alcohols is key to improving viability of ATJ.
- Use of higher alcohols can provide favorable thermodynamics for lower cost separation and catalytic upgrading stages, with our models showing a 34% cost reduction in conversion cost for isobutanol over ethanol. A greater production cost for higher alcohols could easily negate this benefit however, depending on the state and costs of advanced fermentation technology used to produce the alcohol.

- Reactor and catalyst design for the oligomerization unit should be directed to efficiently generate product-range fuels with recycle in mind, to minimize equipment costs through smaller recycle requirements.
- Within the catalytic upgrading process, capital expenses contribute a significant impact on economics. Reduction in equipment and facilities costs, potentially through integration with existing industrial facilities and infrastructure, offers the largest area for reduction in risk for the installation of an ATJ conversion unit.

Current efforts in the development of this technology are carried out by private entities with proprietary processes. Although our models attempt to capture and predict the performance of these systems, we cannot conclude that either the ethanol or isobutanol to jet cases will offer superior economics now or in the future. As separate processes, they offer different advantages depending on many factors, and should be considered on a case-by-case basis. Biochemical production of alcohols from cheap, but relatively difficult to ferment, feedstocks might achieve a lower production cost using an ethanol intermediate. Alternately, where conventional sugar feedstocks are available, production of higher alcohols may be a preferred strategy to reduce cost.

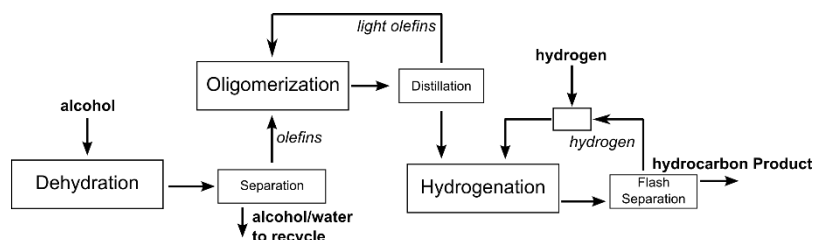
4. Computational Methods

4.1 Process Design Cases and Cost Estimation

Estimates for the capital and operating expenses for various stages of the process were collected from literature when available, augmented by our own process simulations generated using Aspen Plus. Cost estimate data was collected from Humbird, et. al.^[44] for details of ethanol production and separation (also used to estimate isobutanol production costs) as well as Tan, et. al.^[146] for data regarding catalytic reactor costs. Details for the Core ATJ process and isobutanol separation were gathered using Aspen Plus simulations described below. Details of the references for capital and operating cost estimates are available in the spreadsheets contained in the supplementary documents of this report. To estimate total capital costs, a factored approach based from Peters and Timmerhaus^[45] was used to correlate additional costs such as installation, outside battery-limits, and indirect costs from the costs of major process equipment and the assumption that the process is an "add-on" to an existing facility.

Variable operating expenses for utilities and materials were based on process models with cost data from EIA, Humbird et. al., Chu et. al., and Turton et. al.,^[44,46]. The cost of steam delivery was estimated based on the natural gas costs for equivalent energy rates. Fixed operating expenses were adapted from Peters, et. al.,^[45] for maintenance, Jones et. al.,^[47] for taxes and insurance, and Marrs et. al.,^[48] for cost of labor.

Cost analysis comparisons were conducted using a discounted cash flow model, with financial and operation assumptions summarized in Table 9. These assumptions are



based on recommendations and economic analyses by Bann, et. al., and Petter, et. al.,^[14c,49]. Further details of these calculations can be found in the supplementary spreadsheets for this paper.

Table 9. Summary of Financial and Operation Assumptions for Cash Flow Models

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%
Discount Rate, Real/Nominal	10% / 12.2%
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

4.2 Process Modelling and Simulation

Aspen Plus simulations were used to help estimate process information (mass/energy balance, module costs, and utility requirements) for the catalytic conversion steps and for isobutanol/water separation. Key differences are present between the upgrading process for ethanol and isobutanol, which were modeled separately. Although the costs for the dehydration of ethanol to ethylene has already been extensively studied in literature^[31,33,50], the process was modeled in our simulations to maintain consistent analyses between isobutanol and ethanol cases. Figure 6 includes a block diagram of the process flow units for both Core ATJ units. Detailed diagrams

showing the unit operations in each model are provided in the supplementary documents, Figures A1 and A2.

Figure 6. Block Diagram of the ATJ Process Model

Process simulations were carried out using the Unifac thermodynamic package and components from the Aspen databanks as pure compounds for water, ethanol, isobutanol, ethylene, and isobutylene. Mixtures of olefins and SPK are simulated using model compounds; higher olefin and paraffin mixtures are grouped by carbon numbers in the lengths dominantly produced.

For each reactor system (dehydration, oligomerization, and hydrogenation), equipment for the reactors, heat exchangers, pumps/compressors, and separation units needed for maintaining recycle are simulated. Costs used for alcohol/water separation includes costs due to added capacity to a co-located unit for fermentation broth separation. The conditions of each reactor (temperature/pressure) were assumed based on literature values and the actual conversion of each is simplified with fixed single pass conversion parameters and product distributions also assumed based on literature. The operating conditions of each reactor may vary between different implementations, depending on specific catalyst performance and process streams. A summary of some of these assumed key parameters is shown in Table 10 and more detailed descriptions follow.

Dehydration reactors are assumed to achieve a 90% single-pass conversion of alcohol. The product from dehydration is separated, removing water and unreacted alcohols to be sent back to water/alcohol separation for recycle^[31b,33,34]. Ethylene separation involves higher pressures than isobutene separation as well as a requirement for very low temperature refrigerant. A molecular sieve is included to further eliminate water from the distillate stream; nearly complete removal of water is necessary to avoid contamination in the oligomerization reactor system.

The design of oligomerization reactor systems will differ depending on the selected catalyst. It is not the goal of this model to assess the performance of any individual catalyst or design, but to predict and compare the overall costs following common design principles and assumptions. A heterogeneous catalyst reactor system is modeled with a recycle configuration to drive the reaction to the target carbon range. A distillation column separates the reactor product. Light olefins (primarily C8 and smaller) are recovered in the distillate with a target of 10%

C8 olefins directed to the bottoms product. Distillate is recycled through the oligomerization reactor where olefins further grow reacting with fresh feed. The presence of a higher amount of light olefins results in a larger recycle ratio and the need for a larger reactor. Catalyst costs and lifetime are based on Tan, et. al.^[9]. A 2% purge is included from the recycle steam.

A 3:1 molar feed of hydrogen is maintained to the hydrogenation reactor. Due to the excess hydrogen feed, a 100% conversion is assumed and the recycle system is included to reuse hydrogen. The gas recycle system results in hydrogen usage close to the theoretical requirement. This includes equipment for gas/liquid separation at 50° C and 200 psig, as well as a compressor for recycled gas. A 2% purge stream is included to remove impurities and may be used as boiler fuel to recover its energy.

A finishing section was added to make final adjustments in product distribution and properties, completing the process of generating the fuel blendstock. This was modeled as the addition of two distillation columns, both similar in design to the column used in the oligomerization loop. The real implementation of the process may involve more complex fractionation of multiple products or removal of a significant portion of product during finishing, but for the purposes of this model it was assumed to have no effect on the ultimate yield or distribution of the product. Practically, the fuel blendstock production will include a range of fuels in addition to jet, potentially including naphtha, gasoline, and diesel although the

Table 10. Reactor Conditions Used in Core ATJ Models

	Dehydration ^[31c,34]		Oligomerization ^[14e,20a,25,30b,35a]		Hydrogenation ^[14e,20a,25]
	Ethanol	Isobutanol	Ethanol	Isobutanol	Ethanol and Isobutanol
Temperature [°C]	340	325	250	100	100
Pressure [psig]	55	60	300	250	250
Single Pass Conversion/Distribution	90%	90%	40% C10 20% C8, C12 10% C6, C16	20% C8 70% C12 10% C16	100%
Recycle Configuration	recycle integrated with separation of feed alcohols		recycle designed to drive conversion to higher olefins (C12+)		3:1 molar feed of H ₂ ; recycle of H ₂ is included

distribution of products varies depending on implementation^[14e,f]. In these models, production of jet range is favored although some portion of the jet range product is assumed to be fractionated off in order to attain a distillation curve necessary to meet jet fuel specifications. The remaining hydrocarbon product is treated as either a gasoline or diesel co-product. To relate the sale of these fractions to the selling price of jet fuel, both fuel co-products are correlated linearly to the calculated minimum selling price of jet fuel according to EIA data from 1983 through 2016^[51].

Detailed cost estimates of an ethanol separation unit is available in the NREL corn stover ethanol facility report^[44], which

was adapted for use in this model. The separation of butanol and isobutanol, however, is carried out using a separate separation scheme. Cost and utility requirements for this process was estimated using an Aspen Plus model diagrammed in Figure 7.

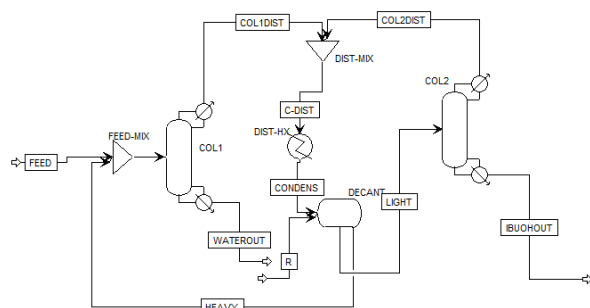


Figure 7. Aspen Plus Model of Isobutanol Separation Unit

The isobutanol separator system is based on the *n*-butanol separation unit model by Luyben, et. al.^[52]. The heterogeneous azeotropic distillation configuration is capable of achieving 99.9% purity of both isobutanol and water using two distillation columns, with both distillate streams fed to a condenser and decanter between them. This model includes a feed of fermentation broth (3% isobutanol) to column 1, as well as a recycle stream (31% isobutanol) of the combined water/isobutanol waste recovered from the core ATJ unit. Since the recycle stream is high enough alcohol concentration to separate into two liquid phases, it is fed directly to the decanter.

At the conditions used in our model, the added capacity from the recycle stream accounts for 26% of the total capacity of the entire separation unit. Due to economy of scale, using the separation unit for both fermentation broth and dehydration recycle is more economical than separate units. In the analysis of standalone alcohol upgrading, it is assumed that a separation unit for fermentation broth is already accounted for and thus only the additional cost of a 26% increase in capacity of the required equipment is considered as capital expenses contributing to the conversion cost. In the ethanol-to-jet case, the dehydration unit to produce ethylene does not require this recycle and this added cost is not included.

Several utilities are utilized throughout the process model, including cooling water, refrigeration, natural gas, wastewater treatment, and steam. The usage of each utility was estimated through simulation and a cost per unit of usage was assigned for each utility. This follows the assumption that the ATJ unit is co-located within a larger facility (ie. a brownfield facility) capable of supplying these utilities. The steam utility used is high-pressure steam at 250°C. Process units operating above this temperature are heated by natural gas using process furnaces incurring greater equipment costs. Using a low or medium-pressure steam utility would therefore result in increased capital expenses and steam usage diverted to natural gas.

Tables 11 and 12 provide additional cost estimation details for both Core ATJ models, broken down to the three major process units. Installation costs are estimated as part of the ratio factors outlined by Peters, et al., which are also used to estimate outside battery limits costs. Expanded versions of these tables, with process flow rates and costs/utility usage for individual unit operations (Tables A2, A3, and A4) are available in the supplementary documents.

Table 11. Unit-Level Details for Core Ethanol-to-Jet Model

	Dehydration	Oligomerization	Hydrogenation and Fractionation
Primary Flow Streams (lb/min)	Feed Rate: 308 Product: 169 To Recycle: 139	Feed Rate: 169 Product: 165	Feed Rate: 165 Product: 167
Equipment Costs (MM\$)	\$1.6	\$1.4	\$1.5
Installation Costs* (MM\$)	\$2.5	\$2.2	\$2.4
Inside Battery Limits Capital Cost (MM\$)	\$4.1	\$3.6	\$3.9
Utilities Usage	Electricity: 1337 kW Steam: 1669 kW Refrigeration (-50°C): 2196 kW Gas: 2137 kW Waste Water: 20 kGal/day	Electricity: 208 kW Steam: 154 kW Cooling Water: 3937 kW Gas: 1695 kW	Electricity: 20 kW Steam: 300 kW Cooling Water: 1774 kW

*(Includes equipment installation, piping, electrical, and instrumentation)

Table 12. Unit-Level Details for Core Isobutanol-to-Jet Model

	Dehydration	Oligomerization	Hydrogenation and Fractionation
Primary Flow Streams (lb/min)	Feed Rate: 308 Product: 207 To Recycle: 101	Feed Rate: 207 Product: 205	Feed Rate: 205 Product: 207
Equipment Costs (MM\$)	\$0.4	\$0.4	\$1.5
Installation Costs* (MM\$)	\$0.6	\$0.7	\$2.5
Inside Battery Limits Capital Cost (MM\$)	\$1.0	\$1.1	\$4.0
Utilities Usage	Electricity: 6 kW Steam: 2497 kW Cooling Water: 3368 kW Gas: 869 kW Waste Water: 12 kGal/day	Electricity: 7 kW Steam: 240 kW Cooling Water: 1301 kW Gas: 1442	Electricity: 78 kW Steam: 300 kW Cooling Water: 1951 kW

*(Includes equipment installation, piping, electrical, and instrumentation)

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Highlights:

- The alcohol-to-jet pathway (ATJ) was recently been qualified under ASTM specifications ASTM D7566 Annex 5 for the production of drop-in aviation fuel.
- A variety of alcohols (e.g. ethanol, butanol) produced from different processes (e.g. thermochemical or biochemical) may be catalytically upgraded to SPK suitable for use as drop-in aviation fuel blendstock.
- Process economic models for ATJ were developed to estimate conversion costs in several conversion technologies using ethanol or isobutanol feedstock. Trade-offs between ethanol and higher alcohols are explored.
- Recommendations are made for the development of advanced fermentation technologies and the use of low cost feedstocks to reduce the cost of ethanol or higher alcohols for ATJ production.

Keywords: keyword 1 • keyword 2 • keyword 3 • keyword 4 • keyword 5

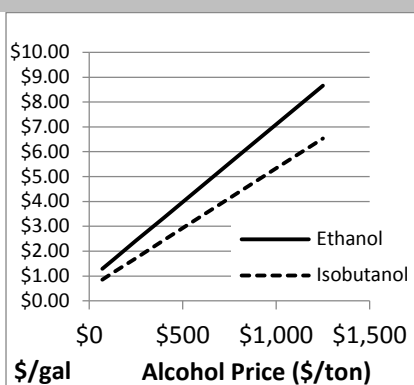
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FULL PAPER

The ATJ Process provides a promising pathway for the production of alternative drop-in hydrocarbon fuels using sustainably produced alcohols. In this paper, we discuss the key engineering barriers and use techno-economic assessment to evaluate potential commercial implementations of this imminent alternative fuels process.



Scott Geleynse, Kristin Brandt, Manuel Garcia-Perez, Michael Wolcott, Xiao Zhang

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