SUSTAINABLE AVIATION FUELS

SAF

A GUIDE TO

CURRENT TECHNOLOGY

PROCESS ECONOMICS

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CAVEATS

This paper is for educational purposes.

Not a day seems to pass when one airline or another announces its intention to use sustainable aviation fuel (SAF). Airlines across the world seem to be happy to invest millions of dollars of stockholders funds and financial institutions (managed funds, banks etc.) are being cajoled into investments in demonstration or even investing in commercial production of SAF.

In this paper I want to answer:

- Is SAF viable and sustainable in the long term?
- What is the cost of production of SAF compared to conventional jet-fuel?

By necessity pertinent data is taken from what is immediately available. There is a vast literature in the field which I have not assessed and there may be key pieces of which I am unaware and which would change my general conclusions.

Economic analysis is at the "Concept" level and is subject to an error of +/- 25% to +/-40%.

Best efforts have been made to use appropriate data for the work.

I operate my own superannuation fund which holds shares in various energy companies including oil companies. I am NOT a financial adviser. Before making any investment in SAF or related industries independent advice from a licensed financial advisor should be taken.

SUSTAINABLE AVIATION FUEL (SAF)

1. GENERAL CONSIDERATIONS

Background

The basic technology of modern aircraft (the jet-engine) relies on the use of aviation kerosene (jet-fuel) for operation. This is produced from crude oil by refining operations. In order to lower carbon emissions, there is considerable interest by the major airlines of the world in obtaining sustainable aviation fuel (SAF), that is fuel obtained with no net carbon dioxide (or methane) emissions to the atmosphere. A new aircraft produced today will still be flying in 40y in 2062 so this time horizon must be considered for producing SAF.

An over-riding objective for the airlines for an alternative fuel is that it must be a drop-fuel complying in all respects to the fuel standards of The International Air Transport Authority (IATA). For effective use, such a fuel should be produced from a diverse range of sources in many parts of the world and be available to the local and international aviation industry.

Jet-Fuel

The detail of the IATA specification for mainstream jet-fuel is shown given in Table 1. Jet A is mainly used in the US and Jet A1 in the rest of the world. The fuels are interchangeable. The main differences between these two types is that Jet A1 has a lower freeze point (-47^{o}C, vs. -40^{o}C) and usually has static dissipater additives (SDA) added to help reduce static build up in the fuel during flight. Jet A1 is the preferred fuel for intercontinental flights.

The problem is that a sustainable fuel will have to comply with these standards and in particular Jet A1.

A point of note is the high energy density (especially when expressed in volumetric terms) of jet fuels. This delivers high flight mileage per fill of fuel. The high volumetric energy density of conventional jet-fuel (and other transport fuels such as gasoline and diesel) is a particular feature of petroleum fuels and many of the proposed alternatives struggle to achieve reasonable volumetric energy densities. This is illustrated in Figure 1.

As illustrated in the figure, hydrogen, which is proposed as an alternative to jet-fuel, has a very high mass energy density but very low volumetric density. Other alternatives such as ammonia or alcohols have lower mass and volumetric energy densities compared to conventional jet fuels leading to lower energy per fill and hence lower range. These alternatives will struggle to achieve flying distances required in the modern aviation industry.

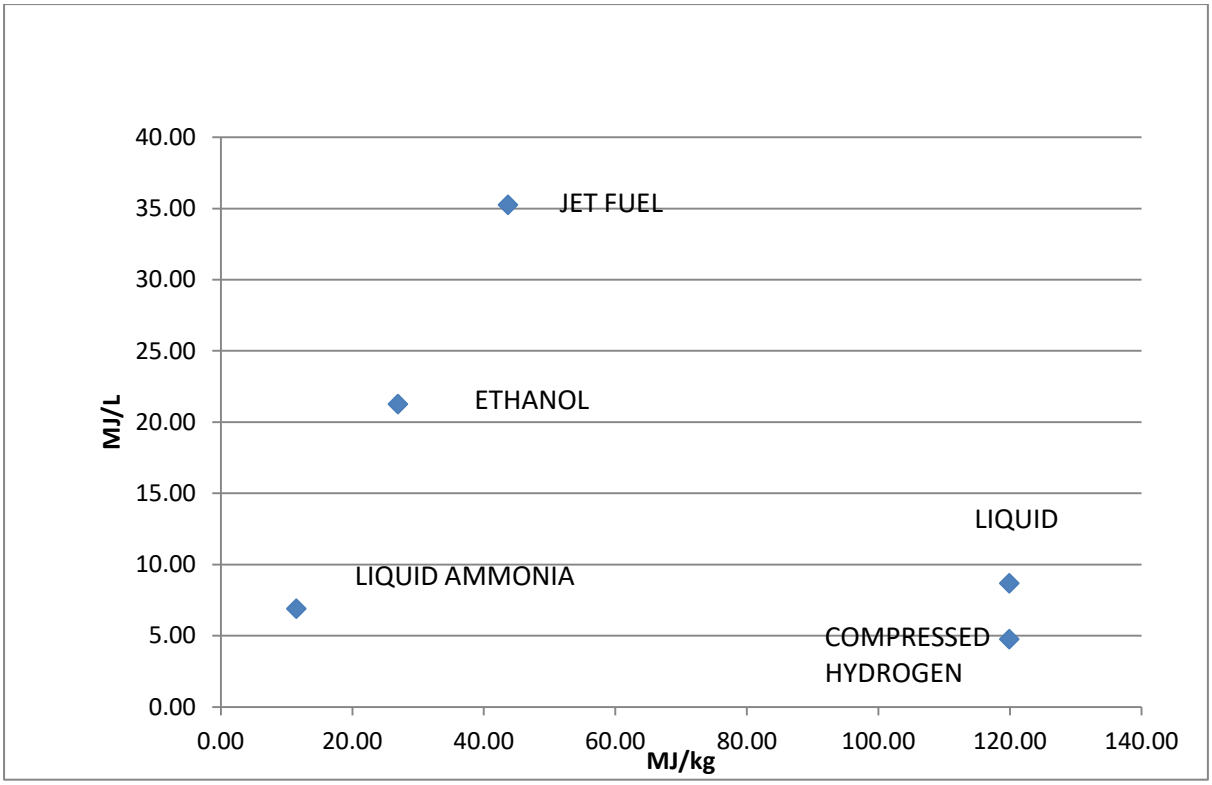


Figure 1: Volumetric and Mass Energy Densities of SAF alternatives.

Considering the volatility of jet-fuel (Table 1) places the preferred components to be hydrocarbons in the range of C_{10} to C_{15} paraffins. Furthermore, in order to meet the freezing point specification (-47^{o}C) these paraffins should be highly branched to achieve such low freeze points.

So the challenge is to sustainably produce a highly branched paraffin mixture in the C_{10} to C_{15} range from sources that produce no carbon emissions.

Alternative Approaches

At this time, three approaches to produce SAF are under development:

1. The use of a bio-crop as a feedstock to produce a vegetable oil that can be processed into SAF.
2. The use of the Fischer-Tropsch process to produce SAF from a synthesis gas (carbon monoxide and hydrogen) which is made from biomass (such as agricultural waste) or possibly from carbon dioxide and hydrogen. The carbon dioxide could be a waste industrial stream or extracted from the atmosphere. The hydrogen could be made by electrolysis (green hydrogen) or from coal or gas incorporating carbon capture and storage (blue hydrogen).
3. The use of ethanol, produced from sugar/corn syrup or lignocelluloses by fermentation or via methanol. This is then used to produce ethylene or lower olefins which are oligomerised, hydroenated and isomerised into SAF.

COSTS

Before considering the separate approaches it is worth noting some of the basic economics for the production if an SAF route is to viable.

We are concerned with the production of hydrocarbons so it is the cost of carbon feedstock that is a fundamental economic parameter. For biofuel sources and ethanol routes, this is the cost of agricultural production which is determined by a wide variety of factors - crop type, yield, location.

To the basic feedstock cost is to be added the processing cost, which for some routes can be high. Allowance should be made for by-products which would also be produced with zero carbon emissions and the by-product credits could reduce the processing costs.

One of the major points to note especially for agricultural feedstock is the opportunity cost of producing another product. For example food crops instead of biofuel costs or the sale of sugar rather than the production of ethanol. But as well as food crops there is increasing demand for the use of sustainable fuels for the much larger transport fuel market (gasoline and diesel) which now includes marine diesel fuel.

Finally we should consider the scale required. Prior to Covid-19 the world demand for jet fuel was about 7.9 million barrels/day this approximates to 300 million tonnes of carbon per year. If this is to be made from biomass with an approximate carbon content of 60% this will require 510 million tonnes of biomass and this will be far greater if we consider the demand for the transport fuel sector at large. Compare this with the world wheat and rice production of about 750 million tonnes per year each. Clearly there could be a major issue with trying to produce all of SAF from biomass and feeding the world's population.

Table 1. IATA Standards for Jet Fuel

JET FUEL SPECS			JET A	JET A1	ASTM Test Method
COMPOSITION					
Appearance			Clear & Bright	Clear & Bright	
Acidity		mgKOH/g	0.10	0.02	D3242
Aromatics	Max	vol%	25	25.0	D1319
Total Aromatics	Max	vol%		26.5	
Sulphur	Max	wt%	0.30	0.30	D1266,D1552,D2622,D4294
Sulphur mercaptan	Max	wt%	0.0030	0.0030	D3227
VOLATILITY					
IBP		C		REPORT	D86
10% recovery	Max	C	205	205.0	
50% recovery			REPORT	REPORT	
90% recovery			REPORT	REPORT	
Final Boiling Point	Max	C	300	300.0	
Residue	Max	vol%	1.5	1.5	
Distillation loss	Max	vol%	1.5	1.5	
Flash Point	Min	C	38	38.0	D56, D3828
Density@15C		kg/cm	775 - 840	775.0 - 840.0	D1298, D4052
FLUIDITY					
Freezing Point	Max	C	-40	-47	D2386, D5972
Viscosity@-20C	Max	cSt	8.0	8.000	D445
COMBUSTION					
Lower Heating Value	Min	MJ/kg	42.8	42.80	D3338, D4529, D4809
Smoke Point	Min	mm	25	25.0	D1322
Smoke Point AND	Min	mm	18	19.0	D1322
naphthalenes	Max	vol%	3.0	3.00	D1840
CORROSION					
Copper strip	Max	2h@100C	1	1	D130
THERMAL STABILITY					
JFTOT DELP@260C		mmHg	25	25	D3241
Tube Deposit	Max		<3	<3	
CONTAMINANTS					
Gum	Max	mg/100mL	7	7	D381
Water reaction interface	Max		1b	1b	D1094
MSEP Rating					D3948
Fuel without SDA	Min			85	
Fuel with SDA				70	
OTHER					
Conductivity					D2624
at point of use	Max		450		
at time of transfer				50 - 450	
BOCLE	Max	mm		0.85	D5001

2. SAF from Agricultural Sources

The conversion of agricultural crops to biofuels is now well established. There are two main themes one via ethanol (which will be discussed in more detail later) and one via vegetable oils to produce biodiesel. Biodiesel is produced as a blend of fatty acid methyl esters (FAME) from vegetable oils and fats by a trans-esterification process of the oil's fatty acid gylcol esters. For SAF there are two problems:

1. The FAME components are not generally suitable for SAF due to their high melting point (see Table 1 for jet fuel specifications)[1].

This can be addressed by hydrogenating the oil glycol esters to remove all of the oxygen present and so produce a linear hydrocarbon chain and propane (double bonds within the chain are also reduced in the process). This process is well known and proceeds by either total hydrogenation of the esters or by hydrogenation and elimination of carbon dioxide. This latter route produces a hydrocarbon chain one carbon number less. The two routes are approximately evenly divided and so the product has a even distribution of carbon numbers in the product than is often the case with the feedstock (Figure 2.1).

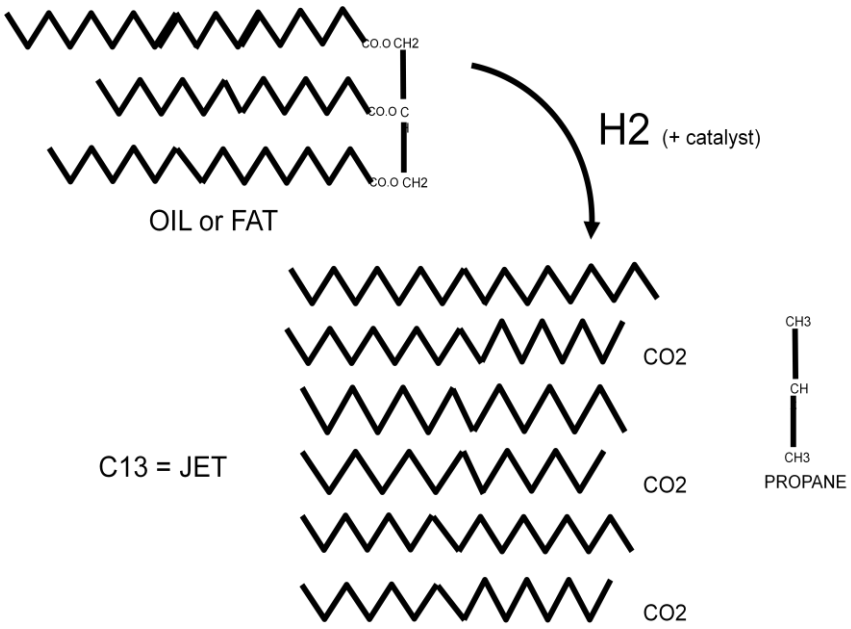


Figure 2.1 Hydrogenation and decarboxylation processes

The catalysts for this can be simple refinery hydro-processing catalysts. These can be adapted to isomerise the paraffin chain to lower the melting point of the product. If necessary a second isomerisation stage is used to perform this duty to achieve the require jet fuel cold flow properties.

[1] There have been many trials using FAME as a minor jet fuel component. Some specifications for jet-fuel limit FAME to <50ppm: DEF STAN 91 - 91

2. The generally low yield of the required C_{10} to C_{15} hydrocarbon chain.

The most common chain length is in the C_{16} to C_{18} range which makes many agricultural oils eminently suitable for diesel fuel. Chain varies with oil or fat source and within each specific type of oil or fat the relative chain lengths vary with growing location and season. Many vegetable oils and animal fats can be used for producing biodiesel, the properties of some of the prominent proposed feedstocks are given in Table 2.1.

As can be seen from the table most of the favoured feedstock contain very little amounts of C_{10} to C_{15} components desired for jet-fuel. The exception is coconut oil which has a high C_{12} and C_{14} content.

Since the quantity of coconut oil is limited, the alternative approach to obtaining high yields of SAF is to use selective cracking of high molecular weight chains into the hydrocarbon range required. As seen in the table rapeseed has a high level of C_{22} content. This can be hydrogenated and selectively cracked to an average chain length of C_{11} which when isomerised is suitable for SAF.

There is now a major interest in growing crops with high of C_{22} content like rapeseed. *Brassica Carinata* is one and is becoming a favoured crop, which after genetic engineering, can potentially deliver yield of over 50% of the C_{22} fatty acid component.

Economics and Sustainability

In block-flow form the process to make SAF is shown in Figure 2.2.

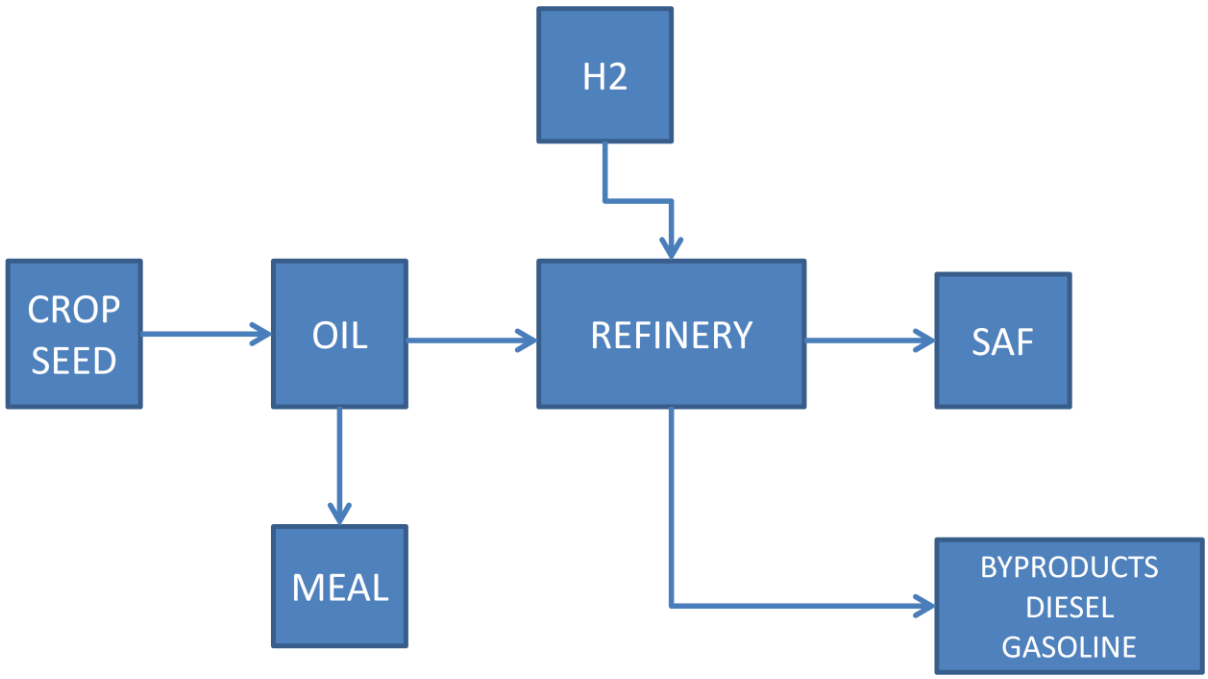


Figure 2.2: Production of SAF from Crop Seeds

TABLE 2.1: Fatty Acid Composition of some oils and fats considered for biofuels.

	Iodine No.	C8:0	C10:0	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	C20:0	C22:1
Neem	69					30		55	15			
Karanja						18		71	11			
Malhua	55 - 70					45.2		37	14.3			
Jetropha	<120					20		46	35			
Cotton	90 - 140				0.8	22.9	3.1	18.5	54.2	0.5		
Sunflower	110 - 143				0.1	6	5.9	16	71.4	0.6		
Soybean	117 - 143				0.1	10.3	4.7	22.5	54.1	8.3		
Sesame	104 - 120					10	5	41	43			
Safflower	126 - 152				0.1	6.6	3.3	14.4	75.5	0.1		
Coconut	6 to 12	8.3	6	46.7	18.3	9.2	2.9	6.9	1.7			
Oilive	75 - 94					11	3.6	75.3	9.5	0.6		
Palm	35 - 61	0.1	0.1	0.9	1.3	43.5	4.9	39	9.5	0.3		
Palm Olein	86 - 107			0.3	1.15	40.55	4.25	41.1	11.9	0.35	0.4	
Peanut	80 - 106					10.4	8.9	47.1	32.9	0.5		0.2
Corn	103 - 140					9.9	3.1	29.1	56.8	1.1		
Rapeseed	94 - 120					2.7	2.8	21.9	13.1	8.6		50.9
Canola					0.1	3.9	3.1	60.2	21.1	11.1		0.5
Tallow (beef)	25 - 48		0.1	0.1	3.3	25.2	19.2	48.9	2.7	0.5		
Tallow (lamb)	41				4.6	24.6	30.5	36	4.3	1.1		
Lard	53 - 77		0.1	0.1	1.4	25.5	15.8	47.1	8.9	1.1		
Linseed	168 - 204					4.92	2.41	19.7	18.03	54.94		
B. Carinata	109					3.15	0.93	9.30	16.59	20.09	0	49.94

Nomenclature: C18:1 means 18 carbon atom 1 double bond etc.

These unit processes are considered in turn.

Crops

A principal consideration for the choice of crop is the yield of seed and oil per year. The data for some crops of interest is shown in Table 2.2.

Table 2.2: Yearly oil yields for some biofuel crops

Crop	kg oil/ha/yr
sunflowers	800
soybean	375
sesame	585
safflower	655
rapeseed	1000
peanut	890
olives	1019
oil palm	5000
maize (corn)	147
jatropha	1590
cotton	273
coconut	2260

Note of the field crops, the high yield of rapeseed (Canola and *B. Carinata* are similar) and the very high yield for the plantation crop oil palm. These high oil yields makes them attractive propositions for biodiesel (FAME) and green diesel (by hydrogenation). Soybean, which has relatively low yield is also widely used for biodiesel production in the US. Jatropha is becoming increasingly developed as a biofuel source in India.

As for SAF, as noted earlier coconut has limited availability but *B. Carinata* (which is similar to rapeseed) is becoming increasingly of interest as a SAF feedstock.

The main problem for the use of agricultural crops is the availability of productive land. There are several problems:

1. Is the crop to be produced going to displace food crops resulting in human food shortages. This is a major concern to legislators and many (EU) demand proof that biofuel crops have no impact in this regard.
2. Is the crop going to be produced on virgin land. A main concern is the clearing of rainforests which has occurred across South East Asia to develop vast oil palm plantations.
3. Does the crop require unsustainable levels of water irrigation. There is increasing concern about the use of water for all purposes. There would be a concern if water was required for irrigation of biofuel crops especially in semi-arid and arid areas.
4. Is the SAF crop going to displace biodiesel (FAME) crops for sustainable motor diesel production. An interesting case study is in the production of Canola in Australia. This is dominantly grown as an intermediate crop in the major wheat producing regions where it is grown between plantings of wheat or barley. Ploughing in the Canola stalks helps rejuvenate the soil. Because it is an intermediate crop, it is not considered as displacing food crops

(concern 1 above). Australia produces about 1 million tonnes of Canola seed per year. Half of this (500,000t/y) is exported to the EU for the production of biodiesel (FAME). Clearly swinging this to *B. Carinata* (say) for SAF would displace Canola for biodiesel production or food (cooking oil) production.

Oil Production

Turning to the economic considerations. Firstly we have to accept the fact that the rising price of crude oil has an impact on the price of vegetable oils and that farmers producing crops for fuel use will want to benefit from this. The case for Canola is illustrated in Figure 2.3 which shows the correlation between the recent price of Canola oil and the price of gas-oil (diesel).

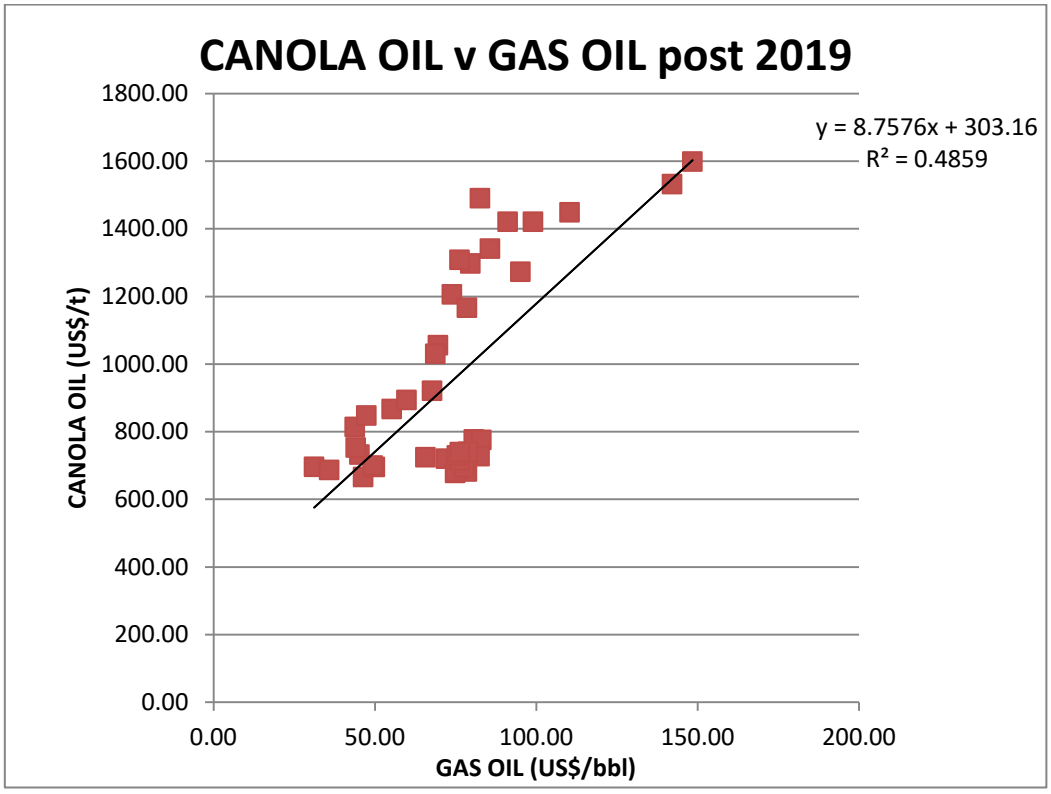


Figure 2.3: Correlation between the price of Canola Oil and Gas Oil since 2019[2]

So as the price of crude oil and hence conventional jet-fuel rises so will rise the cost of vegetable oils for the production of biofuels. An additional point is that oil production also produces meal as a by-product which will off-set some of the cost of oil production.

It has to be recognised that the oil producer will have the options to supply the SAF market, the biofuels market or the food market. Left to a free market this could have unforseen outcomes such as an impact on food supply.

Refinery Operations

The duty of the refinery is to covert the vegetable oil (or animal fats) into SAF. As noted above FAME is generally unsuitable as a SAF due to their relatively high melting points (e.g. methyl dodecanate m.p. -14^{o}C). However, there may be a role as a minor blend component in Jet-fuel when the major

[2] Canola data from the Canadian Canola Board, gas oil from Singapore spot prices reported by OPEC

portion of the fuel is compliant to the required specification. For drop-in SAF we are principally concerned with hydrogenation/decarboxylation and isomerisation of the oils and fats and separating the Jet-Fuel fraction by distillation. Materials falling outside the jet fuel fraction will generally be green diesel and green gasoline and a "green" tail-gas; the term green meaning production has not produced carbon dioxide emissions. These by-products would be expected to attract a price premium over conventional crude oil products.

The refining of the vegetable oil feedstocks could be conducted in a specific bio-refinery or be incorporated into the larger operations of conventional crude oil refineries. The technology is now well established.

The refining process requires hydrogen and this is a significant cost to the processing costs. The hydrogen demand is determined by the chemical processes involved particularly the removal of oxygen from the oil/fat feedstock. However, the hydrogen demand is increased by higher levels of olefins in the feedstock. Table 2.1 gives the iodine numbers of possible feedstock which reflect the level of olefins present. Note the high level of olefin content for *B. Carinata*.

Case Study

The following tables gives a cost estimate for producing SAF from *B. Carinata*. The general methodology is published elsewhere[3]. The case is for a process processing 1Mt/y of feedstock in a refinery aimed at maximising SAF. For this all material in the diesel and higher boiling ranges are recycled to extinction so that the only liquid products are green gasoline and SAF together with propane. The selectivity of the hydrogenation step is assumed to be 98% and the cracking step is 90%. The latter may be optimistic. The cracked gases (CH_4) are used to supply fuel to the plant and there are no other inputs.

Table 2.3A: *B. Carinata* fatty acid composition (wt.%)

C16:0	3.15
C17:0	0.00
C18:0	0.93
C18:1	9.30
C18:2	16.59
C18:3	20.09
C21:0	0.00
C22:0	0.00
C22:1	49.94
	100.00

[3] D. Seddon, "Petrochemical Economics" ICP Press 2010

Table 2.3B: Mass Balance

	kt/y	ML/y	MMbbl/y	kbbl/y
FEED	**1000.00**	**1089.32**	**6.86**	**18.78**
Hydrogen	**20.00**			
CH4	**85.18**			
Propane	**48.53**			
Gasoline	**381.84**	**535.32**	**3.37**	**9.23**
Jet	**384.80**	**521.74**	**3.28**	**9.00**
Diesel	**0.00**			
	900.35	**1057.06**	**6.65**	**18.23**

The capital cost is taken from recent bio-refinery operations producing green diesel. It is assumed no other significant capital items are required for the production of SAF. The capital cost is $903M (2018). The required return on capital is 13.6%. Hydrogen is priced at $3000/t

The results in Table 2.3C compares two scenarios. The first with crude oil at $50/bbl (Tapis) which gives jet fuel at $57/bbl. For this case feed is assumed to be available at $1000/t. Propane (green LPG) is sold at $600/t. Together this generates an estimated production cost of $184.9/bbl for the green gasoline and SAF product. Over three time the price from crude oil. The table also shows the result for crude oil at $100/bbl. Here the estimated cost of the feedstock is assumed to track that of Canola (see Figure 2.3) at $2,000/t and this results in a SAF cost of $333/bbl, treble conventional costs.

Table 2.3C: Estimate of SAF production costs

TAPIS	JET	*B.Carinata*	Propane	SAF
$/bbl	$/bbl	$/t	$/t	$/bbl
50	56.8	1000.0	600.0	184.9
100	110.3	2000.0	900.0	333.1

3. SAF using the Fischer-Tropsch Process

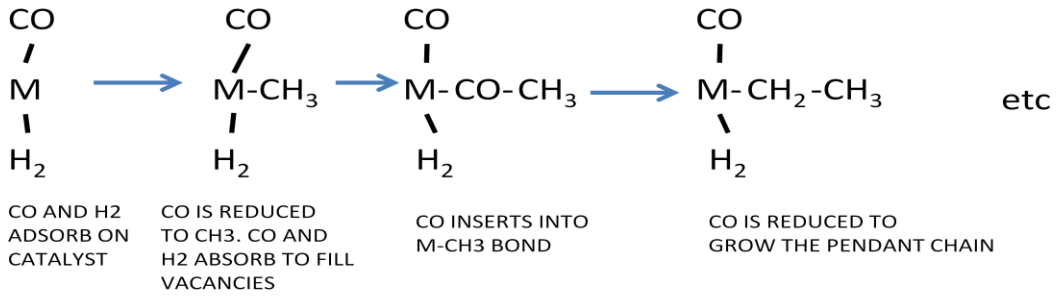
The Fischer-Tropsch (FT) process concerns the conversion of a mixtures of carbon monoxide and hydrogen (known as synthesis gas) into hydrocarbons and water. To produce SAF the problem is the production of carbon monoxide from sustainable sources; the hydrogen can be assumed to be obtained as green hydrogen via electrolysis or blue hydrogen involving geo-sequestration of carbon dioxide emissions. There are currently two general ideas (i) removing carbon dioxide from air or other sustainable source, or (ii) from agricultural wastes which are sustainably produced.

Removing carbon dioxide from air (recall carbon dioxide content in air is only 0.04%) is costly and at present this does not seem to be economically viable. The main problem is the energy cost of recycling the absorption medium. Sustainable carbon dioxide may be obtainable from other process operations, such as gasification of biomass. If such sustainable carbon dioxide is available, then the carbon monoxide for the synthesis gas can be obtained by the reverse water-gas-shift reaction:

$$CO_2 + H_2 = CO + H_2O$$

With appropriate adjustment of the stoichiometry, the optimum ratio of hydrogen to carbon monoxide can be produced; this is typically about $2H_2$:CO.

At its heart, the FT process is a polymeristion reaction where a CO moiety attached to a metal catalyst is reduced to an CH_2 group and adds another CO to grow the chain or desorb from the metal surface to form product; Figure 3.1. The chain growth can be mathematically modelled with a probability function - Alpha - which represents the probability of chain growth against desorption. High values of Alpha give high levels of high boiling products (wax) and low Alpha the products are dominated by light gases and naphtha. The Alpha value changes with operational variables such as the process temperature; high temperature favouring low Alpha values.



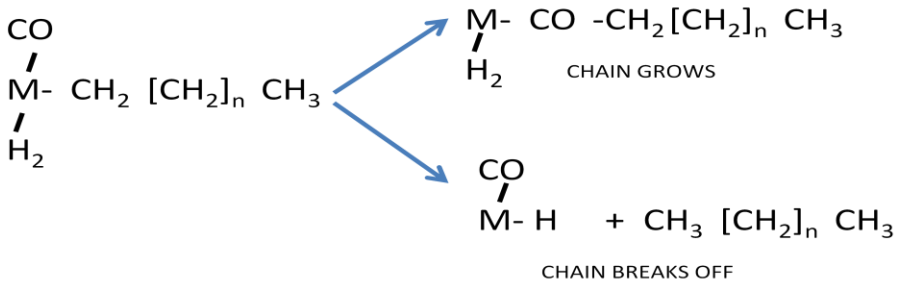


Figure 3.1: Highly abbreviated mechanism of the Fischer-Tropsch Process

Since its discovery in 1929, there have been developed many variants on the FT process but all can be characterised by the Alpha value. The process continues to be developed. In the modern version of the process the preference is for slurry reactors using cobalt catalysts operating at about 200^{o}C. This is a high Alpha value operation and the product slate is dominated by wax which is subsequently hydro-cracked into jet-fuel and diesel. The variation of product slate with alpha is illustrated in Figure 3.2 which also shows the Alpha value of some commercial operations.

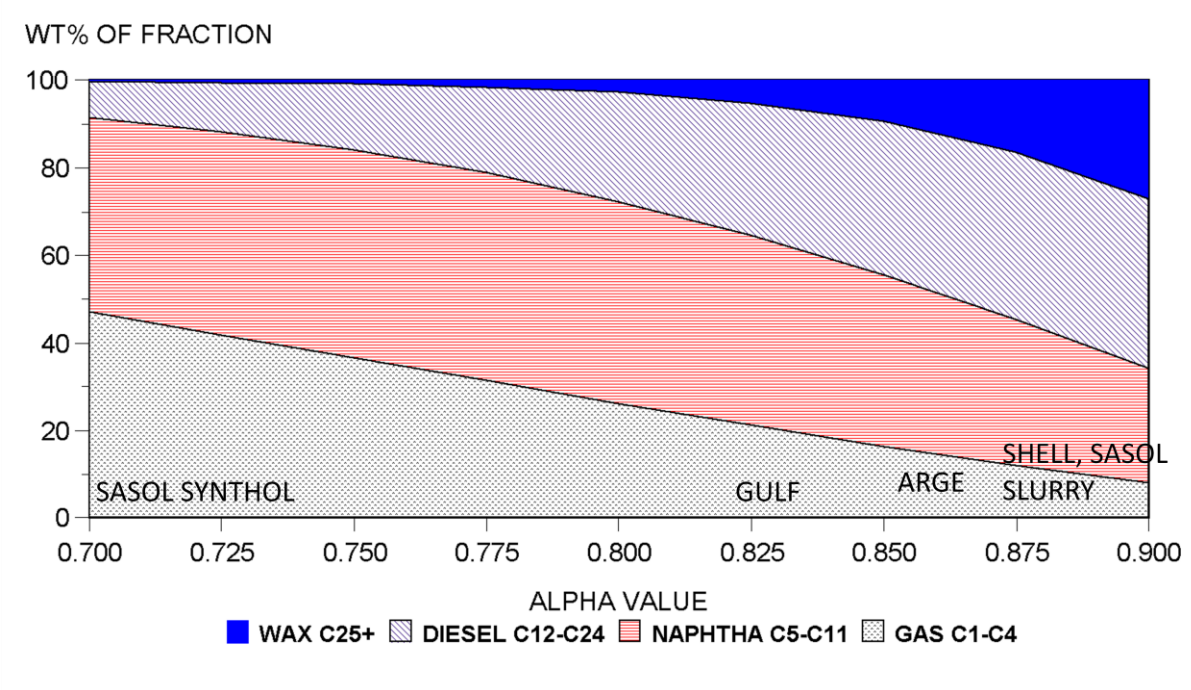


Figure 3.2: Variation of product slate of the FT Process with Alpha value.

The Sasol Synthol process is a high temperature process and operates at relatively low values of Alpha. This generates a lot of gas and naphtha products. However, these products have high levels of olefins which can be easily polymerised into jet-fuel and light diesel. The more recent approach is to operate at low temperatures and aim for a high Alpha value (more than 0.9) to give a wax product which can be selectively hydro-cracked to diesel.

FT operation at various levels of Alpha overlaid on typical refinery cut points is illustrated in Figure 3.3. From this illustration it can be seen that the quantum of straight-run jet-fuel changes little with alpha.

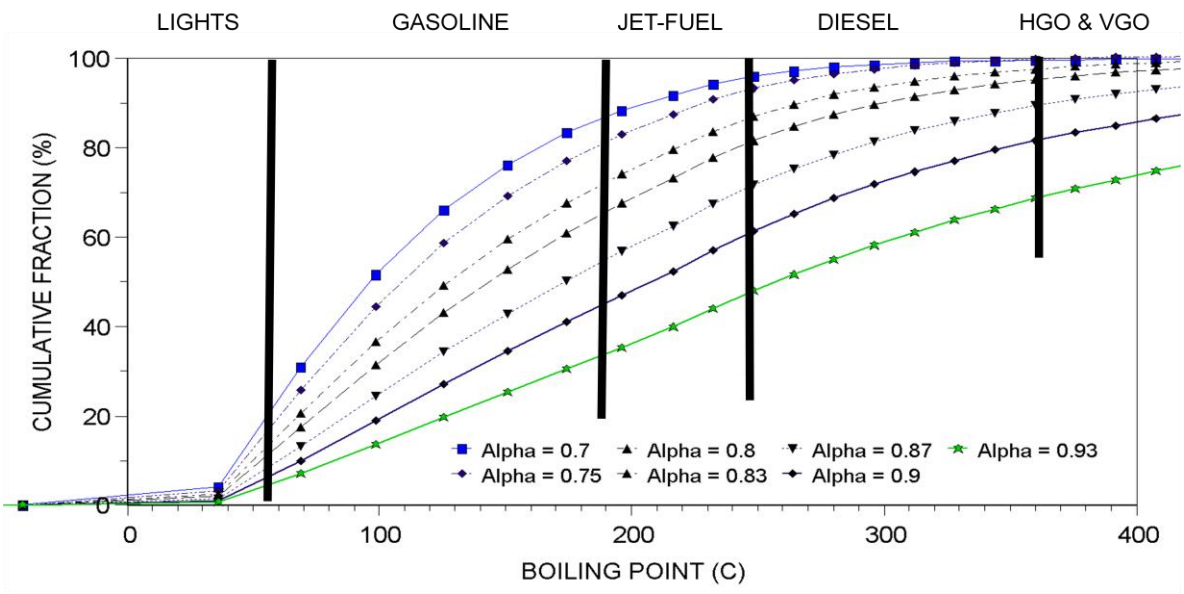


Figure 3.3: Fischer-Tropsch product slate and refinery cut-points

It is important to note the refinery cut points can be somewhat arbitrary and the jet cut can be maximised by including some of the heavy gasoline and light diesel with the limits of this action being controlled by the jet-fuel specification. The typical refinery jet-fuel cut is 195°C to 235°C when a refineries duty is to supply gasoline, jet and diesel markets. For maximum jet-fuel the lower cut point can be reduced to about 160°C (determined principally by the flash point limit; 38°C) and this is offset by increasing the higher cut point to about 290°C (determined by the FBP limit; 300°C)

To further maximise the jet-fuel cut the options are illustrated in Figure 3.4.

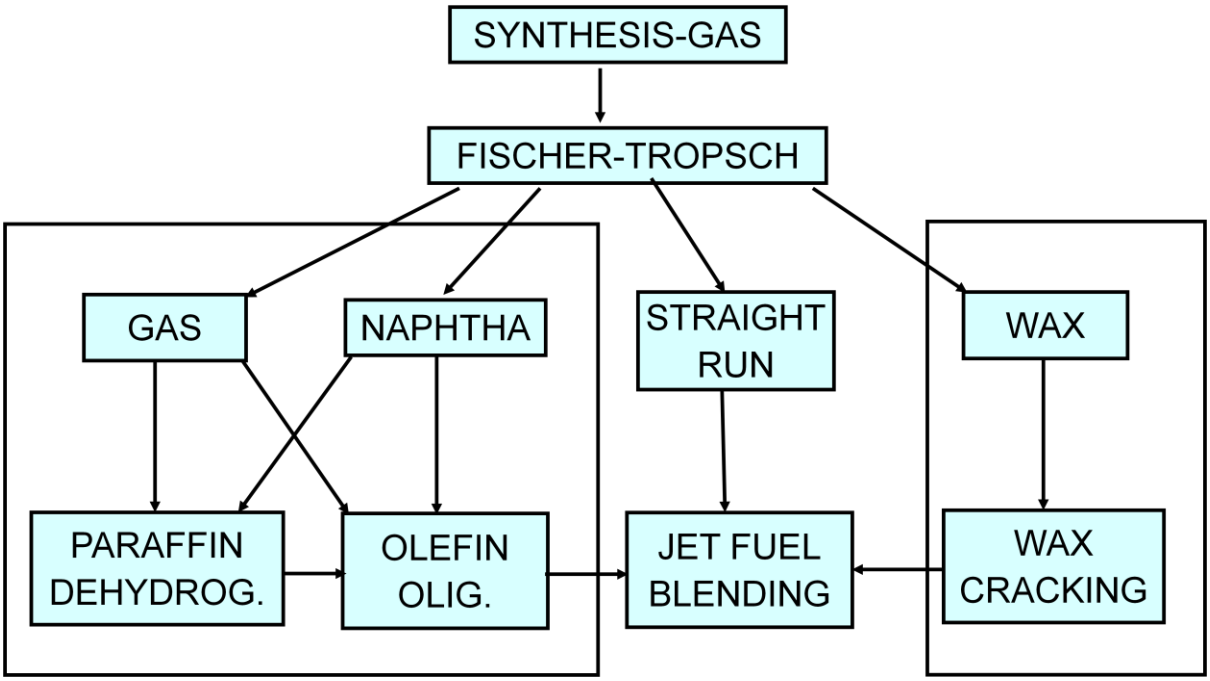


Figure 3.4: Options for maximising jet-fuel with the Fischer-Tropsch Process

The options are:

(i) Operate at low Alpha and supplement the straight-run jet-fuel by oligomerising the lower olefins in the naphtha cut into jet-fuel range product. Paraffins in the naphtha cut can be dehydrogenated to increase the olefins available for oligomerisation. This approach was practiced by Sasol in South Africa for many years.

(ii) Operate at very high Alpha value and crack the wax product into jet-fuel. This is the current approach taken by the new FT processes in Qatar for maximising the diesel cut (including jet-fuel). Whether or not this is the best route for the production of only the jet-fuel cut for SAF is not clear.

Finally the products are hydrogenated to remove any olefins and oxygenates and then isomerised to achieve the required cold flow properties.

Synthesis gas

The FT Process requires synthesis gas. The conventional ways of making synthesis gas are:

(i) by stream reforming of light hydrocarbons. For SAF this can be green methane recovered from appropriate sustainable processes including the use of methane from landfill gas. It can also be from hydrocarbons and oxygenates from the hydrogenation of biomass such as lignocellulose from waste forestry products.

(ii) by partial oxidation of the same where an appropriate sustainable fuel is combusted in a restricted atmosphere of oxygen.

(iii) by a combination of the above in gasification of any sustainable carbonaceous material.

There are many variations on these operations with the most important being the last since it is applicable to a wide variety of feedstocks, particularly feedstocks that are in relative abundant supply such as crop wastes (corn stover, bagasse), forestry waste, specifically grown feedstock (such as prairie grass or plantation forest) and municipal waste.

Biomass Logistics

The principal problems with biomass gasification is the nature of the feedstock. Raw (as received) biomass has very low specific energy, typically only 5 to 6 GJ/t. This is a consequence of the inherently high water (moisture) content of as received material . Drying of the as received biomass will lift the specific energy to about 12GJ/t but this is hardly sufficient to maintain the smooth operation of a gasifier and in many operations a supplementary fuel is added to raise the fuel specific energy higher. Adding natural gas is an obvious choice here and this is practiced in many large facilities for the gasification or incineration of urban waste, however, this defeats the object of producing a carbon emission free product.

Furthermore, biomass contains a lot of oxygen in the molecules that comprise it. Biomass is generally based on a poly-cellulose matter which has an oxygen content of about 55%. This bound oxygen cannot be removed prior to gasification.

One practical problem is storage. Biomass, as received or dry, can undergo putrefaction and spontaneous combustion brought about by bacteria and the like in the biomass (compost heap

combustion is familiar to most gardeners and horticulturalists) and the prevention of this increases costs.

Another issue is the variability of the biomass quality (specific energy), even dedicated biomass, according to season which affects downstream performance of the gasifier. This goes not to just the water content but the nature of the material making up the biomass. In addition dedicated biomass crops (prairie grass, forest waste) can be exposed to total loss through wild-fires and the like.

Many studies for bio-gasification assume that the biomass is available for free. This is not so. The use of biomass will inevitably lead to loss of soil carbon and essential minerals necessary for healthy growth. If the biomass is produced as a by-product to a cash crop, then the farmer (or forester) would want some form of compensation for this.

Finally the collection costs of transporting the biomass to a gasifier operation will be significant (typically $5 to $15/t). The logistics of transporting the biomass will incur some carbon emissions from fuel and also importantly there is a compromise of the distance from the gasifier of the biomass source as consequence of the cost of transport logistics. This will limit the size of the gasifier. This compromise limits the scale of bio-gasifiers when compared to the large scale gasification operations for coal or natural gas, i.e. full economy of scale is not realised.

Biomass quality

Zhou et alia[4] have compiled proximate and ultimate analysis of materials constituting municipal waste, some of which are presented in Table 3.1 along with the analysis for corn stover and prairie grass. These are compared to lignite and a typical black coal used for thermal power generation.

As received, municipal waste has a specific energy of typically 5 to 6GJ/t. After drying, vegetable matter, bone and paper have specific energies of about 15 to 17GJ/t. Dry wood has a specific energy of nearly 20GJ/t. On a dry ash-free basis (DAF), these materials have typically 55% carbon plus hydrogen. The exception is bone matter which has over 65% carbon plus hydrogen. The main other element is oxygen which is typically over 40% of the total. Vegetable matter and bone have relatively high levels of nitrogen and sulphur.

As received biomass such as wood, corn stover, prairie grass have high moisture content. This encourages bacterial attack in storage and degrades the efficiency of the gasifier. For optimum performance this moisture is removed prior to storage and gasification, typically by steam driers using excess steam produced in the gasification process.

[4] Hui Zhou,1 Aihong Meng,1,2 Yanqiu Long,1 Qinghai Li,1 and Yanguo Zhang, *Journal of the Air & Waste Management Association* 64 (2014) 597–616

Table 3.1: Analysis for some biomass materials of interest

	Specific Energy (GJ/t)	Water %	Ash %	C %	H%	O%	N%	S%	
Vegetable	16.8			44.9	5.5	45.4	3.6	0.6	DAF[a]
Bone	15.7			58.0	7.2	25.4	8.7	0.74	DAF
Paper	15.1			45.5	6.3	47.7	0.2	0.2	DAF
Dry wood	19.6			50.5	5.9	43.4	0.11	0.03	Pine - DAF
Wood	12.6	28.6	28.6	37.8	4.5	28.4	0.07	0.0	As received
Corn stover	12.6	20.0	6.0	35.0	4.4	34.1	0.5	0.01	As received
Prairie grass	14.6	15.0	6.2	39.5	4.8	33.8	0.7	0.08	As received
Lignite	15.6	64.7	7.4	18.7	1.3	7.7	0.14	0.07	Victoria
Black Coal	25.3	8.7	13.5	60.6	3.8	11.6	1.33	0.44	Queensland

(*a*) Dry Ash Free

The moisture content of as received biomass is generally lower than lignite, a widely used fossil fuel for power generation and gasification. Lignite from the La Trobe Valley in Victoria, Australia has a moisture content over 60% and is used as a power generation fuel. Lignite used to fuel the Dakota Coal Gasification Company operation has a moisture content of about 25 to 40%. However, lignite (brown coal) have lower fixed oxygen content than biomass giving them a higher calorific value measured on a dry ash-free basis.

Compared to biomass and lignite, black coal has a much lower as received moisture content and lower fixed oxygen which gives the product a high specific energy. The value in the table is for export quality thermal coal from Queensland, Australia.

Process Flow Sheet for Biomass Gasification

The process flow-sheet to produce liquid products from biomass is illustrated in Figure 3.5.

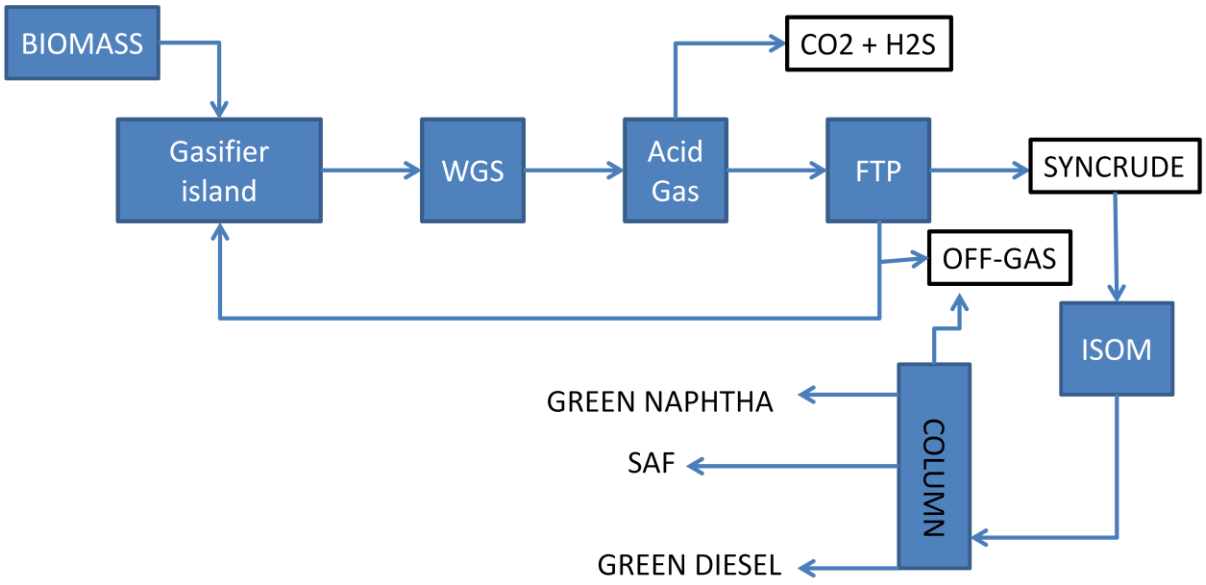


Figure 3.5: Process flow for biomass to SAF

The gasifier island (shown in more detail in Figure 3.6) converts the biomass into synthesis gas (a mixture of carbon oxides and hydrogen). The high temperature water-gas-shift (WGS) process converts most of the carbon monoxide into more hydrogen so as to obtain the correct stoichiometric ratio for the Fischer-Tropsch Process (FTP); typically about 2/1 [H2]/[CO]. This is passed to the acid gas plant which strips out the carbon dioxide and hydrogen sulphide making them available for geo-sequestration. For biomass feedstock geo-sequestration of the carbon dioxide would not necessarily require disposal (geo-sequestration or carbon credit purchase), however, many approaches embrace mixing the biomass with a fossil fuel in a co-firing operation in which case, for zero carbon emission, a disposal mechanism for some or all of the carbon dioxide would be required. The synthesis gas exiting the acid-gas plant would pass to the FTP to produce a synthetic crude oil product (SYNCRUDE). Tail gas would be recycled to the gasifier with a small quantity flared to extract inert gases (nitrogen, argon) and prevent build up in the recycle loop.

The FTP produces paraffinic products of high linearity. These would have to be isomerised to give the SAF cut the required cold flow properties. Distillation of the product would produce green naphtha (green gasoline), SAF and green diesel.

As discussed above to maximise SAF the FTP may operate at high Alpha value and the isomerisation be replaced with a hydro-cracking/isomerisation unit to maximise SAF. Alternately if an FTP operating with low Alpha value the syncrude would be distilled, olefins separated and passed to a polymersation unit to maximise SAF. Paraffinic material could be dehydrogenating to increase the olefins available for polymerisation to SAF (Figure 3.4).

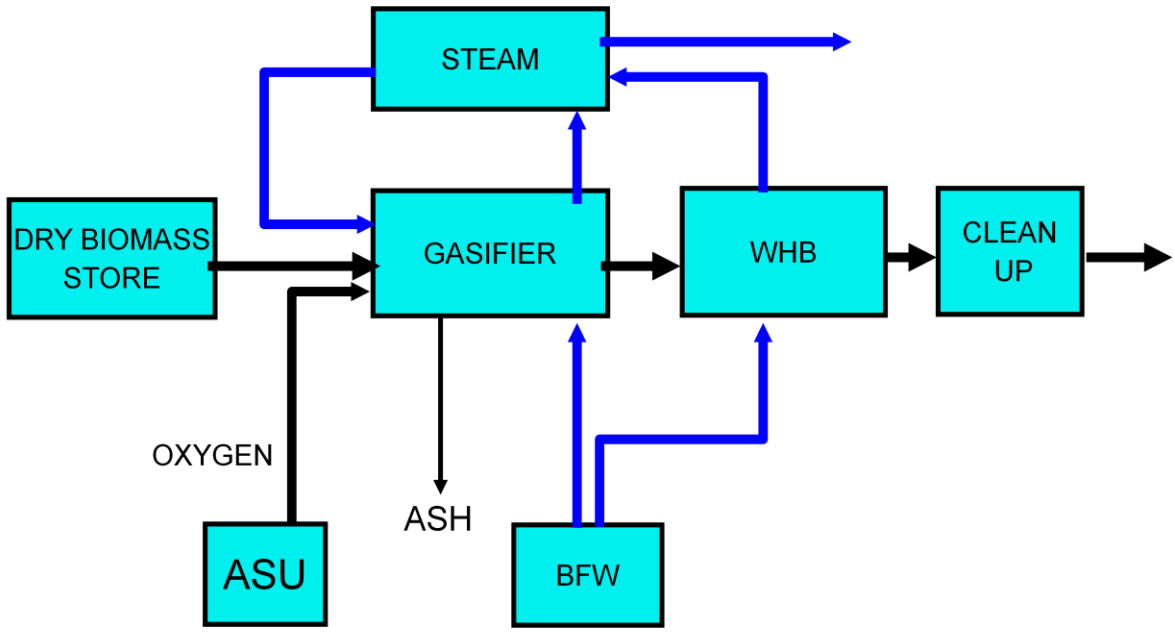


Figure 3.6: Gasifier island for biomass gasification

The gasifier island (Figure 3.6) comprises a several unit operations. It may be best practice that the biomass is pre-dried and stored with an inert gas environment. This may be avoided if storage is minimal and the gasifier is of a type that it can accomplish the drying duty.

The gasifier is supplied with oxygen from an air separation unit (ASU) and boiler feed water (BFW) for cooling and generating process steam. The raw synthesis gas passes to a waste heat boiler (WHB) which cools the gas prior to clean-up. Note the ASU is a high capital cost unit and the cost of this can be outsourced to a merchant gas producer.

There have been many approaches to the design of gasifiers for biomass. The properties of biomass (high water content, high fixed oxygen content and suitable scale of operation) reduces the selection of the types available. The gasifier design based on moving bed gasifier[5] and the fluid-bed gasifier[6] have been most popular for biomass - they are relatively small and well proven for this type of feedstock - Figure 3.7.

In the moving-bed gasifier, the design can accommodate a drying section above the gasifier bed. This performs the duty of removing excess moisture from the biomass prior to gasification. Fluid-bed type has been proposed, after milling and sizing, the unit can be used for biomass gasification. In this case to avoid excessive burning of feedstock in the gasifier to generate the heat required to remove the moisture, this type may benefit from pre-drying the raw biomass.

One of the major problems with biomass gasification is that the fixed oxygen content and consequential low specific energy results in a relatively low temperature operation, even with pure oxygen rather than air as the oxidant supplied by an air separation unit (ASU). This produces excessive tars and pyrolysis liquids in the synthesis gas so that clean-up cannot be simply achieved with filter systems. Washing the raw gas with a solvent (such as methanol) is widely recommended. One of these processes (Rectisol^{TM}) can handle the full range of impurities found in the pyrolysis gases and can be used to extract carbon dioxide, unfortunately it is capital intensive and operationally complex.

[5] A.A.C.M. Beenackers, *Renewable Energy*, 16, January-April, 1180 (1999)
[6] P.J. van den Enden and E. S. Lora, *Biomass & Bioenergy*, 26 (2004) 281

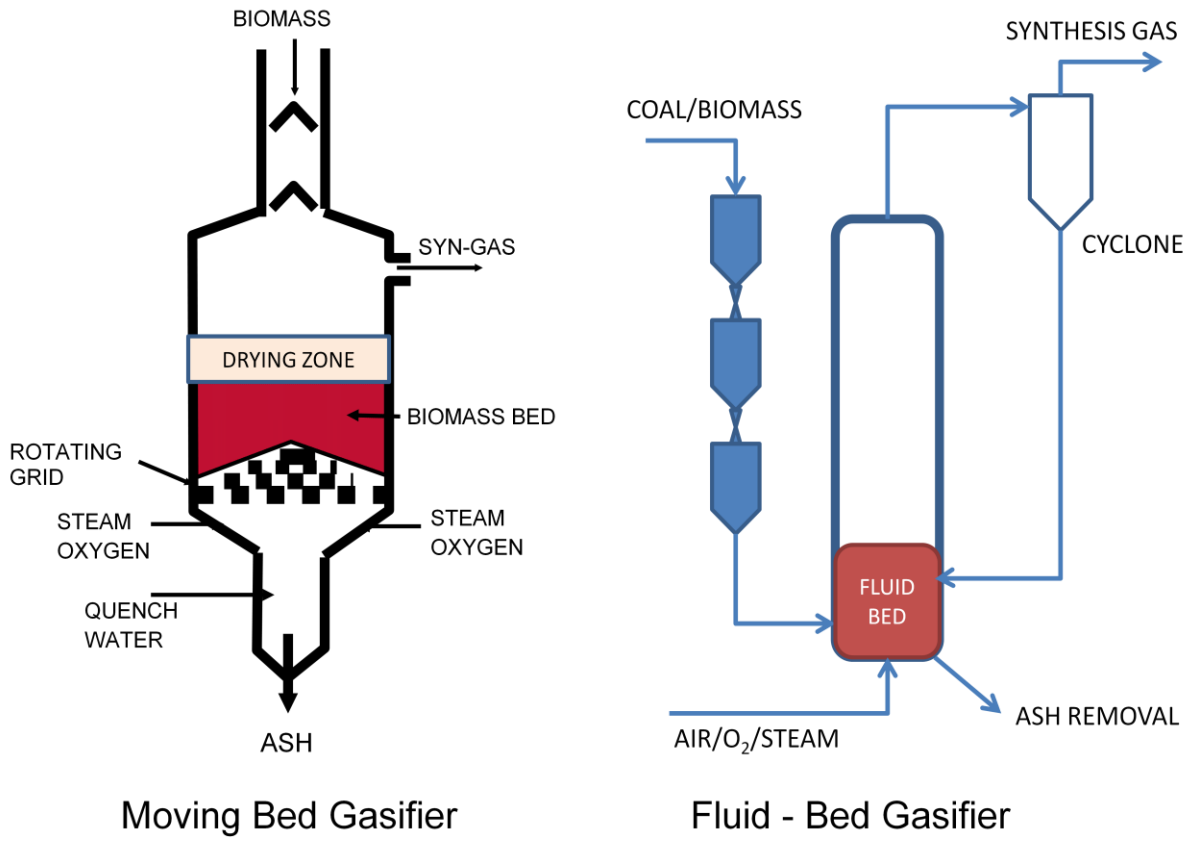


Figure 3.7: Gasifiers for biomass feedstock

Sustainability and Economics

From the foregoing discussion it is evident that SAF via the FT process is capital intensive and that obtaining the maximum economy of scale will be important. However, there will be severe restrictions on this due to the availability of feedstock. Some of the possibilities are:

- Waste from large scale agricultural crops, for example sugar cane bagasse and corn stover. These are available in large quantities in the growing areas. Some may already be productively utilised, for example bagasse is used as a fuel to power sugar mills.
- Waste from forestry operations. Especially in northern Europe and America large scale forestry operation leave a great deal of debris which could be collected and used.
- Dedicated feedstock plantations and in particular wood which could be dedicated to fuel production as opposed to alternatives such as paper manufacture or as a sustainable fuel for power generation.
- Feedstock from large areas of grass land such as prairie grass which is generally unused.

As noted earlier the size limit is often determined by the distance the feedstock has to be carried to the gasification facility i.e. the fuel required and the cost of the transport logistics.

Economics

The conversion of biomass to transport fuels by the Fischer-Tropsch process has been extensively studied and these studies lay out the main issues for the conversion of biomass into SAF. The production of liquid products requires biomass gasification to synthesis gas, water-gas-shift followed

by the Fischer-Tropsch conversion to liquids. These studies also address the issue of biomass collection and logistics and hence the size of the facility.

Case Study

Clearly the optimisation for an SAF facility is complex. In order to overcome some of the complexities the case for the production cost of straight-run SAF is considered. The following economic descriptive has been adapted from a study by Kreutz et alia[7] for the conversion of 1Mt/y of corn stover into Fischer-Tropsch liquids (a mixture of gasoline and diesel - syncrude) . A proximate and ultimate analysis for the corn stover is given in Table 3.2. On a dry basis the stover had a specific energy of 18.7 GJ/t (HHV).

Table 3.2: Proximate and ultimate analysis of the corn stover feedstock

Corn Stover	Mt/y	1
Proximate	as received	
Fixed C	wt%	18.10%
Volatile matter	wt%	61.60%
Ash	wt%	5.30%
Moisture	wt%	15.00%
Total		100.00%
LHV	MJ/kg	14.509
HHV	MJ/kg	15.935
Ultimate	dry basis	
Carbon	wt%	46.96%
Hydrogen	wt%	5.72%
Oxygen	wt%	40.18%
Nitrogen	wt%	0.86%
Sulphur	wt%	0.09%
Ash	wt%	6.19%
Total		100.00%
HHV	MJ/kg	18.748

Feedstock and product flow rates are given in Table 3.3. The result of the simulation is that 1Mt/y of corn stover are converted into about 5,500bbl/d of syncrude.

[7] T. G. Kreutz, E. D. Larson, G. Lui, R.H. Williams; 25th Annual Pittsburgh Coal Conference 2008

Table 3.3: Feedstock and product flow rates

Stover as received	t/d	3581
dry	t/d	3044
DAF	t/d	2822
	MW LHV	601
	MW HHV	660
Oxygen	t/d	59
Purity	mass%	99.54%
Pure oxygen	t/d	58
Syncrude	t/d	551.2
	kt/y	187.4
	bbl/d	5,475.0

A power balance for the system is given in Table 3.4. The steam and power system is capable of producing about 66MW of power of which 27MW are used within the facility. The use is dominated by the power demand of the air separation unit (ASU) and the attached oxygen compressor (total 21MW). The synthesis gas clean-up (Rectisol^{TM}) consumes about 4MW.

These is an excess of power generation over the demand of nearly 49MW which is exported from the facility.

Table 3.4: Power balance for biomass to syncrude facility

Production	MW	65.99
Use		
Biomass	MW	0.41
Lock hopper	MW	0.35
Rectisol	MW	3.86
Fuel gas comp	MW	0.08
Steam cycle	MW	1.27
ASU	MW	14.78
O2 Compressor	MW	6.55
Total consumption	MW	27.3

The capital cost breakdown is given in Table 3.5. The cost estimates for 2007 have been escalated to 2018 values in the final column. The capital cost estimate is $1,178.8M for 2018 construction.

Table 3.5: Capital cost breakdown for a biomass to synfuel plant

		2007	2018
Land	$M	$ 5.00	$ 6.78
Gasifier	$M	$ 266.00	$ 360.81
Rectisol & WGS	$M	$ 58.00	$ 78.67
ASU	$M	$ 94.00	$ 127.50
FTP	$M	$ 126.00	$ 170.91
Power Island	$M	$ 64.00	$ 86.81
Naphtha	$M	$ 26.00	$ 35.27
		$ 639.00	$ 866.75
Engineering	15%	$ 95.85	$ 130.01
Contingency	10%	$ 63.90	$ 86.68
Start up, spares	6%	$ 38.34	$ 52.01
Offsites	5%	$ 31.95	$ 43.34
TOTAL	$M	$ 869.04	$ 1,178.79

Using the above statistics for a biomass to syncrude facility, the estimate for the production cost is developed in Table 3.6. It is assumed that the facility will take three years to build and require a 10% discounted cash flow return, operating for 20 years and paying a 2% capitalised royalty will require a return on capital (ROC) of 14.6%. Working capital cost assumes 30 days product storage at $100/bbl.

Non feedstock operating costs are $76.6 million/year. The feedstock (1Mt/y) is assumed to cost $10/t to cover collection and delivery costs. The total annual costs of $203.5 million are reduced by $15.8 million/year from the sale of by-product electricity at $50/MWh. The net production costs are $233.3 million/year. This generates a synthetic crude production cost of $125.7/bbl which can be taken as the production cost of straight-run SAF. If wax cracking units or olefin oligomerisation units are added to boost SAF yield, the average SAF production cost will rise accordingly.

This estimate is very near the cost of jet-fuel with crude oil at $100/bbl. But this is very dependent on obtaining feedstock at on $10/t. Woodchips are widely used for power generation in N.America and Europe. These typically sell at $30/t and if this value is used the production cost rises to $142/bbl for straight-run SAF. If the cost of the feedstock is in the $100/t range (covering collection, pre-drying, storage) the estimate rises to $175/bbl.

For maximising SAF, to these costs are to be added any costs associated with converting olefins to SAF or wax cracking and hydro-cracking. This will increase the overall average for the production cost of SAF, possibly by $25/bbl.

Table 3.6: Estimate for the production cost of Straight-Run SAF from Biomass

2018 CAPEX	$M	$ 1,178.79
ROC (20y, 10% DCF 3y build)	%	13.70%
	$M/y	$ 161.44
Working Cap	$M/y	1.65
OPEX	% Capex	
labour	1%	$ 11.79
maintenance	3.00%	$ 35.36
insurance	1.50%	$ 17.68
catalysts and chemicals	1%	$ 11.79
		$ 76.62
Fixed costs	$M/y	$ 239.72
Feedstock	Mt/y	$ 1.00
Feedstock cost	$/t	$ 10.00
Feedstock costs	M$/y	$ 10.00
Total annual costs	$M/y	$ 249.72
Byproduct electricity	MW	38.69
	MWh/y	315710.4
	$/MWh	$ 50.00
	$M/y	$ 15.79
NET Cost	$M/y	$ 233.93
Syncrude unit cost	**$/bbl**	125.67

4. SAF from Alcohols - Ethanol

It is possible to produce SAF from ethanol. Ethanol is widely used as a gasoline additive in many jurisdictions and there is a major international trade in fuel ethanol. Ethanol is widely produced, mostly from sugar or similar high carbohydrate products such as corn syrup by fermentation. The ethanol market comprises several sectors:

(i) Ethanol for beverages (beer, wines, spirits) is possibly the largest sector and highest valued sector. It is highly regulated and is highly taxed in many jurisdictions.

(ii) Industrial ethanol is produced either by fermentation or by hydration of ethylene produced by the petrochemical industry. There is extensive regulation to prevent low cost industrial ethanol being used for beverages.

(iii) Fuel ethanol produced by fermentation for gasoline blending. A 10% ethanol blend is common and many jurisdictions are proposing higher ethanol blending rates (15% or 25% is common).

Ethanol can be easily dehydrated to ethylene (reverse of industrial ethanol production). This has been practiced in the past but nowadays ethylene production is dominated by cracking of naphtha and light hydrocarbon gases. The bio-derived ethylene can be converted into higher (jet-fuel) hydrocarbons using commercially proven technology. There are several alternative approaches including the Shell Higher Olefins Process (SHOP) which was an early version.

The SHOP process aims to produce high valued olefins in the C_{10}-C_{14} carbon range. These materials are sought for the production of high value detergents. The carbon range can be easily extended to cover C_{10} - C_{15} hydrocarbons. In outline the process is shown in Figure 4.1.

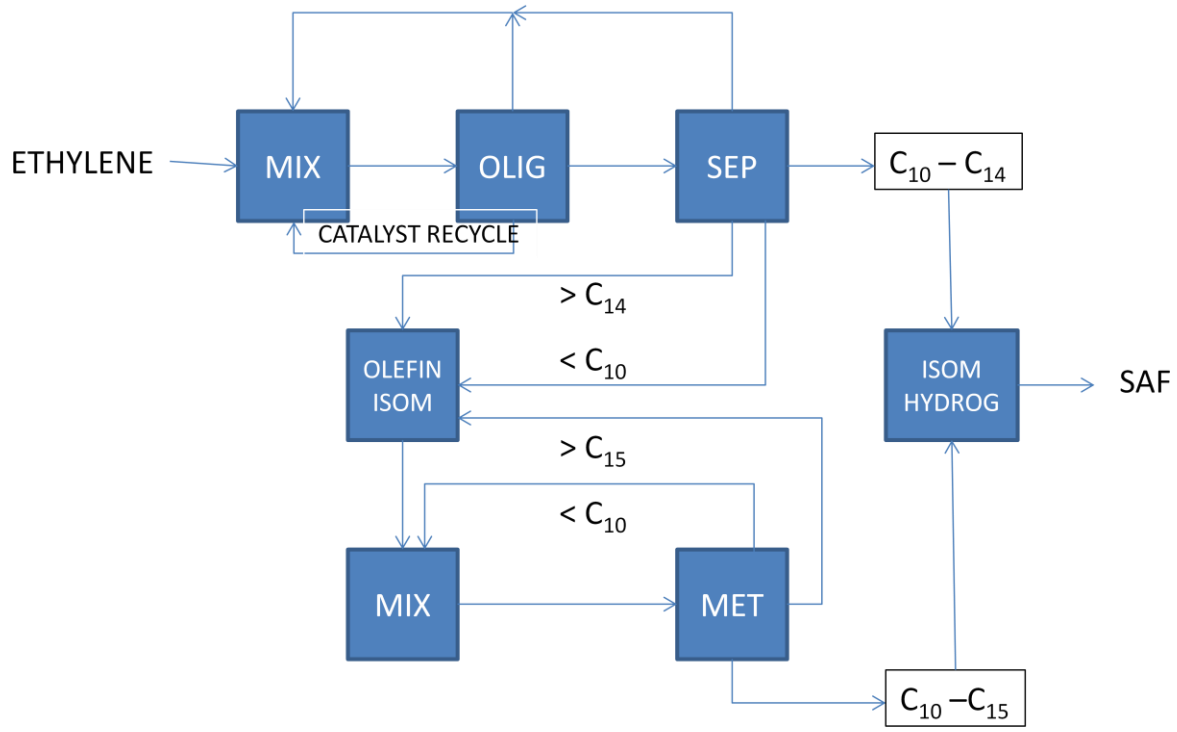


Figure 4.1: Possible use of the SHOP process for producing SAF.

Ethylene is added to a mixing tank where catalyst is added along with recycle materials. This passes to the oligomerisation vessel (OLIG) where ethylene is polymerised into higher olefins typically in the range C_4 to C_{20} olefins. A separation unit separates unconverted ethylene and lighter olefins for recycle, the C_{10} - C_{14} fraction. The fraction lower than C_{10} and higher than C_{14} are passed to an olefin isomerisation unit. The duty of this unit is to isomerise the alpha-olefins produced in the ethylene oligomerisation unit into internal olefins prior to metathesis (MET). The internal olefins produced are then mixed with recycle streams and passed to the metathesis unit. This unit breaks the olefins at the double bond and recombines them with similar moieties from other olefins to reform an olefin with an internal double bond. The chain lengths of the olefins are scrambled.

One point to note is that oligomerisation produces olefins with an even number of carbon atoms but after metathesis there is an even distribution of chains with even and odd numbers.

For SAF, the olefins of pertinent chain size (C_{10} - C_{15}) are separated and other olefins recycled as appropriate. The SAF precursors are hydrogenated and isomerised to the SAF properties required.

Another approach to the production of SAF using olefins is the Mobil Olefins to Gasoline and Distillate (MOGD) process[8]; now proposed by Exxon-Mobil. This has been adapted to more focus on production of the jet-fuel cut[9]; the scheme is outlined in Figure 4.2.

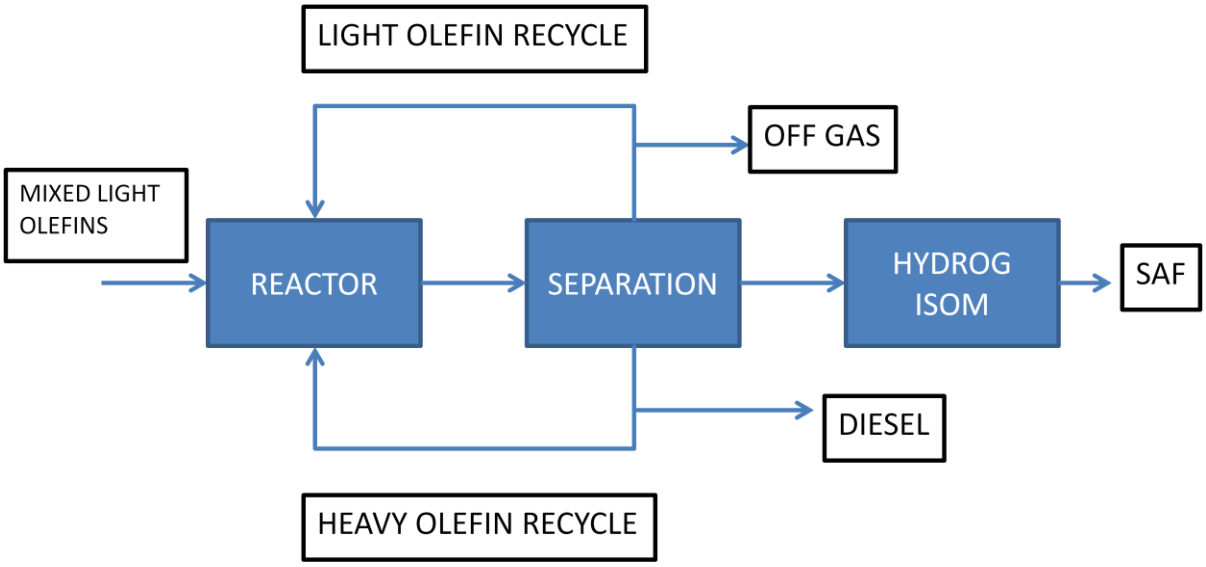


Figure 4.2: SAF by Exxon-Mobil Process

Mixed light olefins (C_2 to C_5) produced in a sustainable manner, enter the reactor system and are oligomerised to higher olefins boiling in the gasoline to diesel range. This is passed to a separation (distillation) section. Light olefins are recycled to the reactor with a purge to remove cracked gases. The jet-cut is hydro-isomerised to produce the specification SAF. Heavy olefins are also recycled but are slow to react so part of this stream is drawn off to produce green diesel.

The main issue with this approach is the production of the mixed olefin feedstock. Ethylene is slow to react to the preferred olefins which are propylene and higher olefins. This mixture can be

[8] W.E. Garwood and W. Lee US Patent 4,227,992 October 14, 1980 (to Mobil Oil Corporation)
[9] J.H. Beech Jr. H Owen, M.P. Ramage and S.A. Tabak, US Patent 5,073,351, Dec. 17 1991 (To Mobil Oil Corporation)

produced using the Mobil Methanol to Olefins Process with the methanol being green methanol produced by steam reforming of glycerol (a by-product of biofuel production) or steam reforming of other light hydrocarbons produced from biomass. In theory ethanol could be used but this generally reacts slower than methanol and has not been demonstrated.

Sustainability

This route to SAF places suitable arable land in competition with land for food crops (corn, beet and sugar) and land for fuel (gasoline). The concern with the amount of land needed for fuel crops has caused several jurisdictions to limit land use for fuel crops and promote the conversion of non food biomass into ethanol. This mainly involves the conversion of lignocellulose from forestry products and the like into ethanol. This requires new fermentation media and there has been some progress in this field but it has been slow.

To quote Wikipedia[10]:

> *Although the global bioethanol market is sizable (around 110 billion liters in 2019), the vast majority is made from corn or sugarcane, not cellulose. In 2007, the cost of producing ethanol from cellulosic sources was estimated ca. USD 2.65 per gallon (€0.58 per liter), which is around 2–3 times more expensive than ethanol made from corn. However, the cellulosic ethanol market remains relatively small and reliant on government subsidies. The US government originally set cellulosic ethanol targets gradually ramping up from 1 billion liters in 2011 to 60 billion liters in 2022. However, these annual goals have almost always been waived after it became clear there was no chance of meeting them. Most of the plants to produce cellulosic ethanol were cancelled or abandoned in the early 2010s. Plants built or financed by DuPont, General Motors and BP, among many others, were closed or sold. As of 2018, only one major plant remains in the US.*

The conclusion is that at this time SAF routes requiring ethanol will be in competition with fuel ethanol and food (corn and sugar).

Economics

For this route there are several competing products to SAF which will influence the cost. Figure 4.3 illustrates the overall course of feed stocks from sugar or corn to SAF.

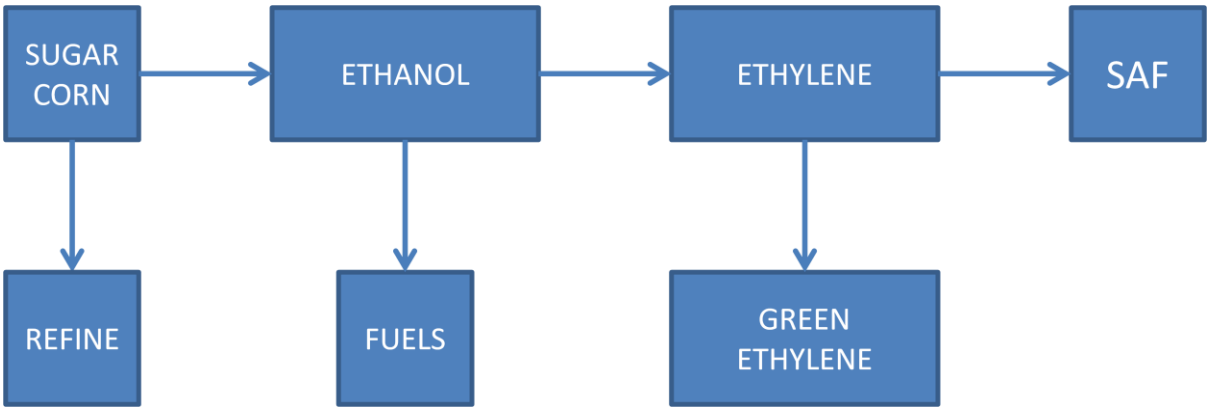


Figure 4.3: Route from Sugar/Corn to SAF

The main source of ethanol is sugar or corn. So at this stage the cost of the feedstock is determined by the market demand for sugar or corn syrup for the food and beverage markets. Relative to fuel

[10] Wikipedia "Cellulosic Ethanol" downloaded 13/07/2022

these are high value markets. Upon conversion to ethanol the facility owner has the option to supply the existing fuel market, that is as a blendstock to gasoline. This market is increasing in size due the various jurisdictions increasing the mandates for using renewable fuels in their domestic vehicle fleets. Because the ethanol is used as a gasoline blendstock, the value of the ethanol is related to the prevailing price of gasoline, hence crude oil.

The conversion of ethanol to ethylene is a facile process. Once made the ethylene would be classified as "green ethylene" meaning it was produced sustainably from non fossil fuel sources. Ethylene is easily converted into commodity plastics such as HDPE which could also be classified as "green HDPE". Although "green ethylene" would have a production cost of about 60% higher than fossil fuel derived ethylene, the demand for green-HDPE could justify this premium against using it as a feedstock for SAF production.

Case Study

The following Table 4.1 gives an estimate for the production cost of SAF.

Table 4.1: Estimate for producing 300kt/y SAF from ethylene produced via ethanol from sugar/corn fermentation

2018 CAPEX	$M	125.11
ROC (3,10,20)	% Capec	14.60
ROC (3,10,20)	$M/y	18.27
WC 30 days	kt	25.00
$/t		200.00
WC	$M	5.00
ROWC (10%)	$M/y	0.50
OPEX	% Capex	$M/y
Maintenance	3.00%	3.75
Labour	2.00%	2.50
Insurance	1.50%	1.88
Catalysts		9.9
NON FEED OPEX		18.03
NON FEED COSTS	$M/y	36.80
Hydrogen	kt/y	4.29
	$/t	3000
	$M/y	12.86
SUB TOTAL	$M/y	49.65
Selectivity	%	86.4%
Feed (Ethylene)	kt/y	347.22
Ethylene cost	$/t	1373.41
Feed Costs	$M/y	476.88
TOTAL COSTS	$M/y	526.53
	$/t	1755.10
	$/bbl	219.38

This table shows with crude oil at the $100/bbl mark and jet fuel at $110/bbl, the production cost for this route is about $220/bbl.

CONCLUSIONS

- SAF production is feasible but competition from other demands on land and bio-crops will limit its production. It is highly doubtful if current jet-fuel demand could be replaced by SAF without seriously compromising food and other biofuel production.
- SAF production cost is higher than conventional jet-fuel and will remain so. This is because the basic feedstock for SAF rises and falls in tandem with the price of crude oil.
- The cost of production from bio-crop is at least double that for conventional jet-fuel.
- The most competitive route to SAF appears to be the Fischer-Tropsch route using gasified biomass. The advantage lies in a low cost of feedstock carbon - forestry or agricultural waste. Plantation wood may be an option but there will be competition for this feedstock from renewable power generators supplying power to high value markets (cities).
- Government and major airline targets for 100% SAF by 2050 are pie in the sky without significant curtailing of flights.

For a successful business opportunity in making SAF:

- Target the biomass/FT route
- Identify and obtain control or agreement for the biomass feedstock (aim for less than $50/t delivered).
- Identify a purchaser of SAF willing to pay a premium for SAF
- Avoid MOUs which limit the price as being competitive to conventional jet - this will never happen.

HOWEVER, IN THIS BIG WIDE WORLD THERE ARE ALWAYS NICHE MARKET OPPORTUNITIES!

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ACADEMIC QUALIFICATIONS AND HONOURS

1967-1970 B.Sc. Special Hons. (First Class), Chemistry; University of Sheffield, U.K.
1970-1973 Ph.D. (Sheffield)
1973-1974 Personal Fellow of the Science Research Council at Imperial College, London.
1987 Fellow of the Royal Australian Chemical Institute.

EXPERIENCE

2000 - to date: Principal, Duncan Seddon and Associates Pty. Ltd.
Consultancy services to energy intensive and related industries. Expertise on fuels and refinery and petrochemical operations. Presenter of Master-classes on petrochemical and refinery economics, Gas to Liquids and Coal to Liquids technology and economics. Promotion of small scale GTL projects. Books "Gas Usage and Value", PennWell, 2006; "Petrochemical Economics", ICP Press, 2010."Hydrogen Economy", 2022, *in press*

1988-2000 Managing Director of Hindsford Pty. Ltd. Mount Eliza, Victoria, Australia.
Promotion of the development of natural-gas conversion opportunities. Expertise on geological and economic analysis of gas production and field development and gas utilisation. Consultants to oil and gas industry groups on the development of un-utilised gas fields. Advice and courses covering all aspects of the petroleum refining and petrochemical industries. Detailed economic and technical appraisals of Fischer-Tropsch, Methanol to Gasoline and MTBE technologies. Publication of monographs detailing the production economics of methanol, ethylene, MTBE and LPG.

1982-1987 Broken Hill Proprietary Co. Ltd, 140 William Street, Melbourne, Australia.
Coordinator of gas conversion research team at the Company's Melbourne Research Laboratories; responsible for the ongoing technical development of the project and extensive liaison and management of joint research with CSIRO and a wide range of University groups.

1974-1982 ICI PLC (Petrochemicals Division), The Headquarters, Wilton, Cleveland, United Kingdom.
Research into the fundamental properties of polymerisation catalysts; Project Leader for development of catalysts for the aromatics business - technical, commercial analysis and legal activities; Energy Manager, (Oil Works, Billingham). 1980, seconded to ICI (Australia) Pty. Ltd., 1 Nicholson Street, Melbourne, Australia in order to build a team aimed at research and evaluation of new routes to petrochemicals from natural gas. .

Professional Activities

Fellow of the Royal Australian Chemical Institute; Member Australian Institute of Energy and Society of Petroleum Engineers. Served as a member of the Biological Committee of the AusIndustry *START* program. Member of GLG consultancy panel. Dr. Seddon has over 180 publications covering books, book chapters, refereed papers, patents and conference papers and general articles. Peer reviewer for *Journal of Catalysis*.