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Sourcing Hydrogen for the Production of Sustainable Aviation Fuels

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Abstract:

Sustainable aviation fuels (SAFs) are the near-term technological solution to decarbonize the aviation industry sector. There are several pathways to obtain biojet fuels, which can be classified into four main categories, namely oil-to-jet, alcohol-to-jet, gas-to-jet, and sugar-to-jet. All of them share the need for hydrogen to obtain a drop-in fuel that can be blended with petroleum-based jet fuel. The hydrogen input requirements affect the life cycle greenhouse gas emissions, increase the biojet fuel cost and hinder the construction of distributed processing plants. This study addresses the problem of hydrogen sourcing in the production of SAFs through a systematic literature review. Techno-economic studies of biojet fuel production using different feedstocks and conversion pathways are analyzed focusing on the methods of hydrogen provision. The technological options used to generate the required hydrogen within the conversion process itself as well as externally, along with the main strategies to reduce the hydrogen demand are identified. The production yields and the hydrogen consumption of several SAF production pathways are compared. The jet fuel yields reach values as high as 0.66 for hydroprocessing of vegetable oils with external hydrogen provision, while they drop to 0.10 for production from lignocellulosic biomass with internal hydrogen sourcing. The results of the analysis highlight the real potential of four among the most promising routes for the production of biojet fuels when the burden related to hydrogen demand is properly taken into account.

Keywords:

Aviation; Biofuels; Biojet fuel; Hydrogen; Hydroprocessing; Upgrading.

1. Introduction

Sustainable aviation fuels (SAFs) represent one of the main strategies to decarbonize the aviation sector. Very recently, one of the biggest aircraft companies announced a program aimed at the development of a hydrogen propulsion system for entry-into-service of a zero-emission aircraft by 2035 [1]. Nevertheless, there is general agreement that in the short/medium term the main strategy to abate the greenhouse gas (GHG) emissions in the aviation field is the use of jet fuels derived from biomass feedstocks, which are blended with petroleum-derived jet fuel. In this context, hydrogen still plays a key role since the vast majority of the biojet fuel production pathways require hydrogen to make a hydrocarbon end product from biomass and intermediates that contain oxygen. Large-scale hydrogen production is obtained from steam reforming of natural gas, which negatively affects the carbon footprint of the produced jet fuel. On the other hand, the use of green hydrogen obtained from the electrolysis of water would make the overall process economically prohibitive (see e.g. [2]). Thus, hydrogen sourcing from biomass-derived streams available within the boundaries of the production process can be considered a promising solution to strike a balance between economics and the environment.

Although the problem of hydrogen sourcing in the production of biojet fuels was often raised as part of several techno-economic studies, this important aspect has never been addressed in a standalone systematic study aimed at comparing the hydrogen provision routes and hydrogen requirements of different production pathways. This work aims to fill this gap for a meaningful set of biojet fuel production pathways. Besides the Hydroprocessing of vegetable/waste cooking oils, which is currently the most mature technology [3], the conversion of lignocellulosic feedstocks via Gasification-Fischer Tropsch, Alcohol-to-Jet and Pyrolysis-to-Jet are considered. These four biojet

fuel production processes are investigated focusing on the upgrading sections of vegetable oil/syncrude/alcohol/bio-oil, which require hydrogen. Block diagrams are built which highlight all the operational units/sub-units that require hydrogen as well as all the material streams which can be used for hydrogen sourcing. Relevant studies with integrated hydrogen production were found for each pathway to show the technological solutions proposed in the literature for producing hydrogen from the internal streams as well as their consumption to fulfill the hydrogen self-sufficiency. Finally, the fuel yields and hydrogen requirements for the selected production pathways are presented to allow for a performance comparison when the jet fuel is the main targeted product.

2. Production processes of sustainable aviation fuels

The four selected biojet fuel production processes are here presented focusing on the hydrogen inputs in the upgrading sections.

2.1. Hydroprocessing pathway

Fig. 1 shows a block diagram of the hydroprocessing route, which is adapted and further developed from [4] and [5]. Vegetable oil/waste cooking oil is sent to the hydroprocessing reactor with hydrogen gas. Hydrogenation, hydrogenolysis, and deoxygenation happen in the hydroprocessing reactor at around 380–400°C and 50–90 bar, as described below:

1) *Hydrogenation*. The reaction of hydrogenation converts the unsaturated tri-, di-, mono-glycerides, and fatty acids into saturated ones using hydrogen. The lower content of unsaturated fatty acids in the vegetable oil implies a lower hydrogen consumption.

2) *Hydrogenolysis*. The hydrogenolysis is carried out to form the free fatty acids (FFAs) by removing the propane backbone from the glycerides.

3) *Deoxygenation*. The deoxygenation reaction, which contains decarboxylation, decarbonylation and hydrodeoxygenation routes, converts FFAs into n-alkanes, with the removals of CO_2, CO and H_2O, respectively [4]. The decarboxylation reaction removes oxygen in the absence of hydrogen gas. The decarbonylation reaction uses one mole of hydrogen per mole of saturated fatty acid, whereas three moles of hydrogen are necessary for hydrodeoxygenation. Accordingly, the hydrogen required for the deoxygenation process is dependent on the selectivity between the three oxygen removal reactions. The conversions and selectivity are dependent on reaction conditions and selected catalysts [6].

The deoxygenated effluent is sent to a hydrocracking/hydroisomerization unit where n-alkanes are cracked and rearranged simultaneously into small and branched species. The purpose of this unit is to reduce the freezing point while maintaining a high flash point for the biojet fuel. The liquid product streams are separated by boiling point in a distillation column.
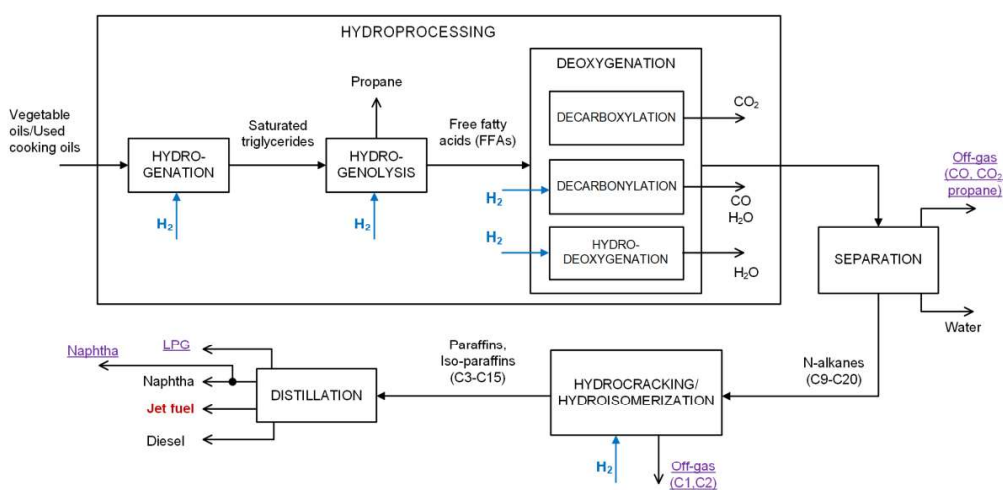

Fig. 1. *Hydroprocessing of vegetable oils/used cooking oils for the production of jet fuel. The hydrogen inputs are shown using light blue arrows, whereas the potential streams for hydrogen sourcing are underlined and highlighted in violet color. The block diagram is built from* [4] *and* [5].

2.2. Gasification and Fischer-Tropsch pathway

Fig. 2 shows a block diagram of the gasification-Fischer Tropsch route, which is adapted and further developed from [7], [8], [9] and [10]. In the pretreatment, process biomass is dried and ground according to the requirements of each gasification technology. In the gasification step, ground biomass is gasified using oxygen to produce raw syngas. Syngas is cooled and cleaned of undesired components. Clean syngas is mostly composed of hydrogen, carbon monoxide and carbon dioxide, but also contains some methane and light hydrocarbons. It is optionally sent to a steam reforming reactor to convert methane and light hydrocarbons. In the water gas shift (WGS) reactor the syngas hydrogen content is increased up to a H_2:CO molar ratio of 2.1 which is suitable for the subsequent Fischer-Tropsch (F-T) synthesis. The high CO_2 fraction in the syngas is optionally removed before admission to the F-T reactor because carbon dioxide is not a reactant in the F-T reaction but its presence negatively influences the C5+ selectivity [11]. The conditioned syngas enters the F-T reactor where the synthesis of hydrocarbons occurs. In the F-T reactor, high selectivity towards liquid products (i.e., longer hydrocarbons) should be combined with high conversion. The selectivity towards longer chain hydrocarbons can be controlled by the proper choice of the catalysts, the decrease of the reaction temperature and the increase of the partial pressure of reactants [11]. On the other hand, the conversion extent in the F-T reactor is limited. For instance, the single-pass fractional conversion of CO is less than 40% in a fixed bed F-T reactor, while it reaches 80% only using advanced liquid phase (slurry) reactors [7]. Thus, the unreacted hydrogen and carbon monoxide contained in the reactor product stream is recycled at the entrance of the F-T reactor. After water separation, the syncrude (i.e., the raw mixture of hydrocarbons) is sent to the upgrading section, which is composed by three main units: hydrogenation, primary distillation, and hydrocracking, as described below:

1) *Hydrogenation*. The syncrude is hydrogenated to saturate the olefins and reduce any oxygenates that might be present. The reactor effluent undergoes a high-pressure flash to recover the circulating hydrogen, which is mixed with make-up hydrogen and recycled to the reactor, and a lower pressure flash to remove the tail gases (C1-C3) that may have formed [12].

2) *Primary distillation*. The hydrotreated syncrude is sent to a fractionation unit with the production of a gaseous LPG fraction, liquid light naphtha and jet fuel, and bottoms made of wax and diesel fractions.

3) *Hydrocracking*. The wax and diesel fractions are sent to the hydrocracking process to increase the yield of paraffins in the aviation fuel range. Similarly to hydrogenation, the hydrocracker effluent firstly undergoes a high-pressure flash to recover circulating hydrogen and then a low-pressure flash to remove tail gases [12].

The degassed hydrocracked product is distilled in a fractionation unit into LPG, light naphtha, jet fuel, and a wax residue.
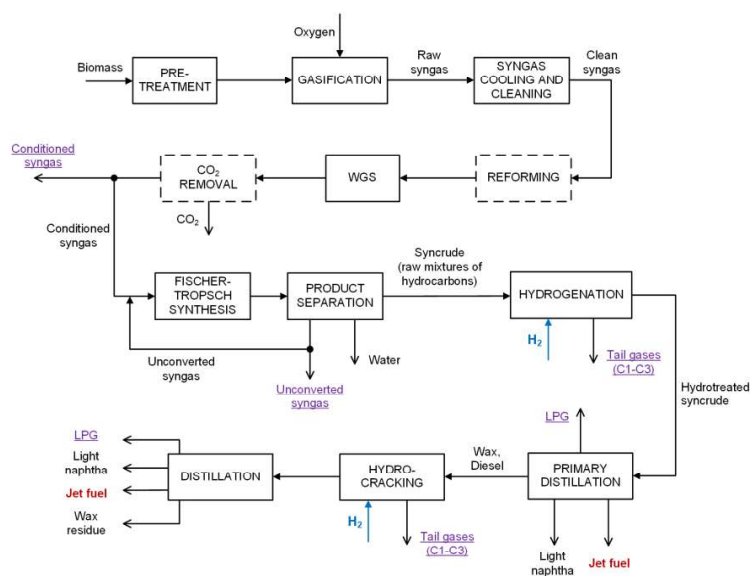
Fig. 2. Biomass gasification, Fischer-Tropsch synthesis and syncrude upgrading for the production of jet fuel. The hydrogen inputs are shown using light blue arrows, whereas the potential streams for hydrogen sourcing are underlined and highlighted in violet color. The block diagram is built from [7], [8], [9] and [10].

2.3. Alcohol to jet fuel pathway

Fig. 3 shows a block diagram of the alcohol-to-jet route, which is adapted and further developed from [13], [14] and [15]. In the pretreatment process, the size of the lignocellulosic biomass is reduced and chemicals are added to decompose the biomass into cellulose, hemicellulose and lignin. In the enzymatic hydrolysis, cellulose is converted into glucose, and hemicellulose is converted into various sugars (xylose, glucose, etc.) using enzymes. Lignin is separated whereas the sugars are sent to the fermentation process, which can be either the ethanol fermentation or the ABE (acetone, butanol, ethanol) fermentation. The fermentation beer undergoes a distillation step to produce high purity alcohol, which is sent to the upgrading section. The latter is composed of three main steps, namely alcohol dehydration, oligomerization and hydrogenation, which are described below:

1) *Dehydration*. In the dehydration step, ethanol is converted to ethylene whereas butanol/isobutanol is converted to butene/isobutene. The catalytic dehydration of ethanol to ethylene is a well-known industrial process with high ethanol conversion (approaching 100%) and high ethylene selectivity (99%). Even though the dehydration of higher alcohols has been less explored, high conversion and selectivity have been reported for isobutanol dehydration as well [15]. Water is generated during the dehydration reaction and must be completed removed from the dehydrated product before the oligomerization step. The stream of water and unconverted alcohol is recycled to the distillation unit.

2) *Oligomerization*. In the oligomerization step, the dehydrated alcohol is converted into olefins using homogeneous or heterogeneous catalysts. Among the homogeneous technologies for ethylene oligomerization, the two-step Ziegler process was selected in [14] targeting the production of jet fuel. An oligomerization reactor with heterogeneous catalyst and a recycle of the light olefins through the reactor was used in [15] to drive the reaction to the target carbon range. Four different processes have been recently compared in [12] for the oligomerization of ethylene. The authors showed that the heterogeneous catalyst used in the Heveling oligomerization process shows a low selectivity towards jet fuel since most of the hydrocarbons produced are in the range of LPG (C3-C5) and gasoline (C6-C8). They showed how the selectivity towards heavier olefins can be improved by adding a second reactor that operates the LPG oligomerization using a recycled stream of LPG. Another option consists in butene oligomerization which gives olefins that lie primarily in the jet fuel range. In such a case, butene can also be obtained from ethylene using a two-step oligomerization process [12].

3) *Hydrogenation*. The hydrogenation step consists in hydrotreating and hydroisomerization [14]. In the hydrotreating process, the olefins' double bonds are saturated using hydrogen and a catalyst and producing paraffins. In the hydroisomerization process, the normal paraffins are converted to their isomers using a catalyst and a negligible amount of hydrogen. The product gas stream of hydrogenation (mainly excess hydrogen feed) enters a PSA unit that separates, purifies and recycles the hydrogen to the reactor [14]. A simpler direct gas recycle is considered in [15].

In the fractionation process, the resulting paraffins are fractionated into light paraffins and gasoline, jet, and diesel range fuels.
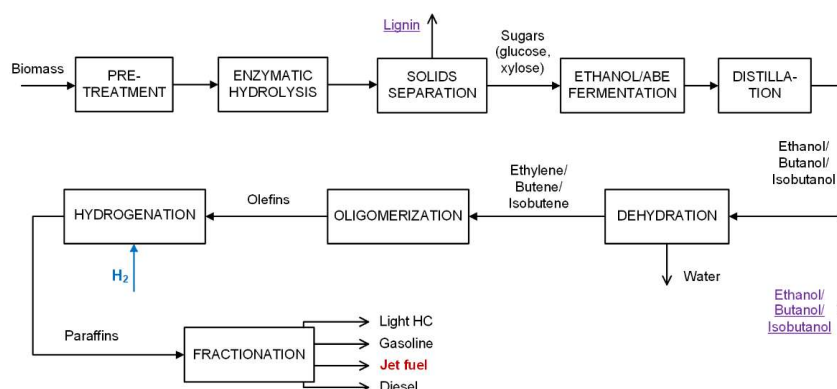

Fig. 3. *Production of alcohol from lignocellulosic biomass and conversion of alcohol to jet fuel. The hydrogen inputs are shown using light blue arrows, whereas the potential streams for hydrogen sourcing are underlined and highlighted in violet color. The block diagram is built from* [13]*,* [14] *and* [15]*.*

2.4. Pyrolysis to jet fuel pathway

Fig. 4 shows a block diagram of the fast pyrolysis to jet route, which is adapted and further developed from [16], [17], [18] and [19]. In the pretreatment, biomass is dried and ground before feeding into a pyrolyzer. In the fast pyrolysis, biomass is rapidly heated to 500°C and then rapidly cooled to stop the reaction. The fast pyrolysis products are a liquid bio-oil (composed of organic compounds and water), a solid char mixed with biomass ash, and non-condensable gases. In the hydrotreating step the bio-oil is deoxygenated by catalytic hydrotreating at elevated pressures using hydrogen. Three fixed bed reactors are typically used with a staged increase in processing severity to reduce overall coking [17], as described below:

1) *Stabilizer*. The filtered bio-oil product from the pyrolysis unit is pumped to high pressure (~80 bar), then combined with compressed hydrogen and preheated in a stabilization bed at mild conditions (140–180°C).

2) *First stage hydrodeoxygenation reactor*. The liquid effluent from the stabilizer is further pumped to around 140 bar, mixed with hydrogen and hydrodeoxygenated at medium temperature (180–250°C).

3) *Second stage hydrodeoxygenation reactor*. The effluent from the previous reactor is heated to 350–425°C and hydrotreated under the most severe conditions.

The effluent from the last hydrotreating stage is separated into a gas product (C1-C4 and CO_2), a stable hydrocarbon oil, and an aqueous phase. In the reference configuration, shown in [17], the hydrocarbon oil is sent to the fractionation unit where gasoline, diesel, and a heavy fraction (wax) are produced. The heavy fraction is sent to a hydrocracking unit to improve the yield in the gasoline and diesel range. A similar layout was proposed in [19] targeting the production of jet fuel, which is shown in Fig. 4. Instead, different placement of the hydrocracking unit before fractionation was considered to improve the jet fuel yield and the cold flow properties in [18].
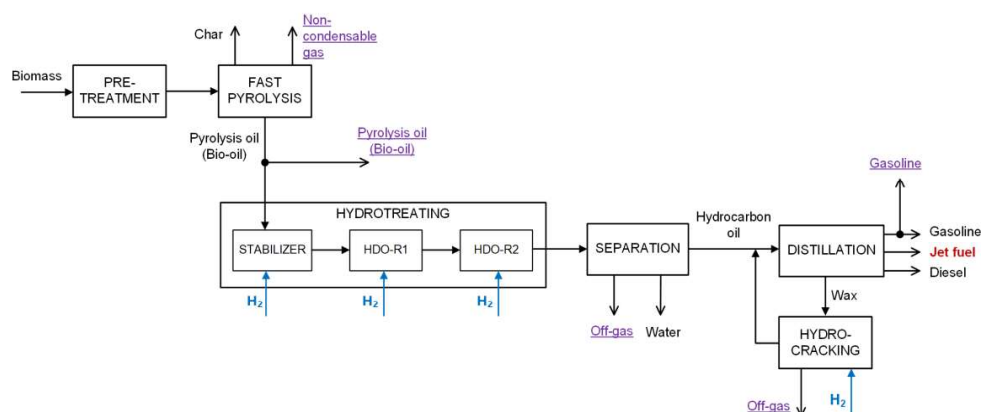

Fig. 4. *Fast pyrolysis of biomass and bio-oil upgrading for the production of jet fuel. The hydrogen inputs are shown using light blue arrows, whereas the potential streams for hydrogen sourcing are underlined and highlighted in violet color. The block diagram is built from* [16], [17], [18] *and* [19].

3. Sourcing hydrogen for the production of jet fuel

The various options for sourcing hydrogen from the biomass-derived internal streams are here presented for the four production pathways.

3.1. Hydrogen sourcing in the hydroprocessing route

Most of the studies in the literature on hydroprocessing of vegetable oils or fats consider an external supply of hydrogen, which is either purchased or produced on-site via steam methane reforming. The significant hydrogen demand implies high GHG emissions in the fuel production process, which even exceed those in feedstock cultivation [20]. It is shown in [21] how the GHG emissions can be markedly reduced by internal production of hydrogen. The streams available for hydrogen production are the off-gases (C1-C3 and CO) produced in the hydroprocessing and hydrocracking/isomerization and two co-products (LPG and naphtha), as described below:

- *Hydrogen production from off-gas, LPG and naphtha.* In the integrated scenario investigated in [21], hydrogen was produced from off-gas, LPG and naphtha, which replaced NG as the steam reforming feedstock. In [22] the hydrogen required was generated by steam reforming of a fraction (29%) of the naphtha product along with

the light fraction (i.e., LPG) from the distillation unit. Hydrogen was recovered from the off-gases and the reformed gas using two PSA units.

3.2. Hydrogen sourcing in the gasification Fischer-Tropsch route

The hydrogen required in the hydrogenation and hydro-cracking steps can be produced from the gaseous streams available within the process. In particular, hydrogen can be produced from an intermediate (syngas), a co-product (LPG), and waste gas (tail gas and unconverted syngas):

- *Hydrogen separation from syngas using PSA*. At the admission of the F-T reactor, the syngas already shows a high hydrogen content due to the WGS reaction and the CO_2 separation. To obtain high purity hydrogen, a PSA unit can be installed before the F-T reactor. In this configuration, a small fraction (1.5–2%) of syngas is diverted through the PSA process, while the remaining syngas and PSA off-gas are sent to the F-T reactor. This solution was proposed in [8] in combination with both fluidized bed and entrained flow-type gasifiers. A similar choice was taken in [22] where hydrogen was produced in a PSA unit fed by a fraction (1.7%) of clean syngas.

- *Hydrogen separation from unconverted syngas*. The gaseous effluent from the F-T reactor is mainly composed of hydrogen and carbon monoxide. Depending on the applied F-T technology a fraction of unconverted syngas is recycled to the reactor, whereas the remaining part is purged and typically used as a fuel, e.g. to produce power [8]. However, hydrogen can be recovered from the unconverted syngas in a PSA unit, as proposed in [10].

- *Reforming of LPG*. In [12] the LPG produced by the primary and secondary distillation is combined with the tail gases (C1-C3) released from the effluents of the hydrogenation and hydrocracking reactors for producing the hydrogen required. The steam reforming of liquefied petroleum gas is widely reported (see e.g. [23]). The tail gas can be used as fuel gas for the steam reformer furnace.

3.3. Hydrogen sourcing in the alcohol to jet fuel route

The hydrogen required in the hydrogenation step can be produced using intermediate streams or derivative products. Two main internal sources of hydrogen have been considered for the alcohol-to-jet process, namely lignin gasification and alcohol reforming, as described below:

- *Lignin gasification.* The gasification of lignin, rather than of the whole biomass, was investigated in [2] as a potential source of hydrogen. The lignin feedstock was first dried, preheated and gasified using steam as a gasification medium. After cleaning, the syngas was sent to two water gas shift (WGS) reactors to convert carbon monoxide and steam into hydrogen and carbon dioxide. The resulting gases with 70% hydrogen purity were then cooled before entering a pressure swing adsorption (PSA) unit. The purity of the hydrogen produced by the PSA unit was 99.9%, in connection with a recovery rate of hydrogen equal to 85%. The authors pointed out that there is still little information on lignin gasification, also because lignin is typically burned to produce process heat or steam. Due to the particular biorefinery concept, which used acetic acid as an intermediate, the gasification of lignin could supply only 75% of the required hydrogen.

- *Alcohol reforming.* In [22] the hydrogen demand of the alcohol-to-jet process was fulfilled by steam reforming a fraction (less than 4%) of ethanol. The composition of the reformed gas was adjusted in a WGS reactor followed by hydrogen recovery in a PSA unit. Similarly, in the case of an ABE fermentation scenario, the steam reforming of a fraction of butanol/isobutanol followed by WGS and PSA could be applied to fulfill the hydrogen demand of the upgrading process. The steam reforming of butanol was reviewed in [24], also in association with ABE fermentation [25].

3.4. Hydrogen sourcing in the pyrolysis to jet fuel route

The hydrogen demand of the bio-oil upgrading process can be fulfilled using streams available within the pyrolysis to jet fuel process. The main sources considered in the literature consist of the non-condensable gases released in the fast pyrolysis process, a fraction of the pyrolysis oil, the off-gases produced in the hydroprocessing and a fraction of the gasoline product, as described below:

- *Steam reforming of pyrolysis gases.* The non-condensable gases produced in the fast pyrolysis typically represent around 15 weight% of the pyrolysis products. These gases are mainly composed of carbon monoxide, carbon dioxide, hydrogen and light hydrocarbons. In [17] the pyrolysis gases were treated in a steam reformer, followed by a WGS and a PSA unit to produce hydrogen. Additional natural gas was used to obtain sufficient hydrogen production.

- *Steam reforming of hydroprocessing off-gases.* The off-gases are those separated from the effluent of the last hydrotreating stage and the hydrocracking unit. In [17] a fraction of off-gases was steam reformed (together with the pyrolysis gas), whereas the remaining fraction was used as a fuel to fire the reformer. The different

end-use of the off-gases was considered in [18] where hydrogen was externally supplied and the off-gases were used to produce propane.

- *Steam reforming of bio-oil.* In [26] a significant fraction (38.5%) of bio-oil was sent to a steam reformer followed by a PSA unit to generate the hydrogen required by the upgrading process of the remaining bio-oil. The state-of-the-art of steam reforming of pyrolysis oil was recently summarized in [27].
- *Steam reforming of gasoline.* In [19] use approximately 10% of the gasoline product was required to fulfill the hydrogen demand. The gasoline along with the pyrolysis gases and the off-gases were sent to a pre-reformer which was employed to produce a mixture of syngas (CO and H2) and methane from the hydrocarbons. This unit was followed by a reformer, a WGS and a PSA unit.

4. Results

This Section shows the fuel yields and specific hydrogen demand obtained from the literature for the four biojet fuel production pathways considered.

The fuel yield is defined as the ratio between the main fuel product/s and the feedstock (kg/kg). The main fuel product is jet fuel in most of the studies considered in this work, yet it is specified in the following Tables due to the inclusion of a few significant studies targeting the production of other fuels (e.g. gasoline) featuring similar conversion and upgrading processes. As for the feedstock we considered both a fuel yield based on the dry biomass and a fuel yield based on a specific intermediate product (vegetable oil, syncrude, alcohol, bio-oil).

The specific hydrogen demand is defined as the ratio between the hydrogen required in the upgrading process and the aforementioned intermediate products (kg/ton). For a systematic comparison between different pathways the specific hydrogen demand has also been calculated based on the jet fuel product.

4.1. Fuel yield and hydrogen demand with the hydroprocessing route

Table 1 shows the fuel yield and the hydrogen demand for different feedstocks taken from selected studies in the literature targeting the production of jet fuel. Except for [20], the jet fuel yield from vegetable/used cooking oils varies in the range 0.48–0.66. It appears from [4] that the yield is higher for fats compared to vegetable oils, even though a lower yield was reported for chicken fat in [28]. It is also interesting to note that the use of waste feedstock, like used cooking oil, does not affect the yield. The hydrogen demand is high and varies in the range 20–46 kg of hydrogen per ton of oil, which corresponds to 30–92 kg of hydrogen per ton of jet fuel. The lowest values of hydrogen demand are obtained when decarboxylation is assumed as the main conversion route in the deoxygenation process, whereas the highest values are obtained with hydrodeoxygenation. For instance, in [6] the extent of reaction was set equal to 0.68 for decarboxylation, 0.03 for decarbonylation, and 0.29 for hydrodeoxygenation, with overall oil conversion equal to 1. Furthermore, the kind of vegetable oil/fat impacts the hydrogen demand due to the different fatty acid profiles of different feedstocks.

Table 1. Yield of jet fuel from vegetable oils and fats, and hydrogen demand for the hydroprocessing pathway.

Feedstock (Vegetable Oil*/Fat)	Jet fuel yield (kg jet fuel/kg oil)	Hydrogen demand (kg H_2/ton oil)	Hydrogen demand (kg H_2/ton jet fuel)	Ref.
Rapeseed oil, Algae oil, Jatropha oil, Salicornia oil	0.578–0.599	21–45	37–75	[29]
Soybean oil	0.494	40	81	[30]
Soybean, Palm, Rapeseed, Jatropha, Camelina oil	0.74–0.76	22–30	30–40	[20]
Camelina oil	0.66	22	33	[31]
Vegetable oil (generic)	0.480	40**	84**	[22]
Camelina, Carinata, Used cooking oil	0.529–0.537	26–30	48–56	[6]
Jatropha, Camelina, Pennycress, Castor oils, Yellow grease	0.487–0.614	N.A.	N.A.	[32]
Camelina	0.665	20	30	[33]
Jatropha, Palm, Algae, Soybean, Rapeseed, Castor, Corn oils	0.511–0.609	39–46	64–86	[4]
Yellow/Brown grease, Edible/Inedible tallow, Lard	0.650–0.653	39–40	59–61	[4]
Used cooking oil	0.580	35	61	[34]
Chicken fat	0.475	44	92	[28]
Used cooking oil	0.568	40	70	[35]

* Vegetable oil yields (ton oil/dry ton oil seeds): 0.21–0.46 depending on the feedstock [20]; **internal hydrogen production.

4.2. Fuel yield and hydrogen demand with the gasification F-T route

Table 2 shows the yield of the intermediate (syncrude) and the fuel yield along with the hydrogen demand of the syncrude upgrading section. The double conversion process (gasification and F-T synthesis) implies that the syncrude yield is only approximately 0.2. The use of an entrained flow bed gasification technology results in a higher yield compared to the fluidized bed one, as shown in [8]. The liquid transportation fuels produced in the upgrading process represent a significant fraction of the syncrude, as high as 0.89. Overall, the dry biomass to jet fuel conversion reaches values in the range 0.10–0.15. It should be noticed that these fuel yields are obtained with internal hydrogen production. The hydrogen demand of the upgrading section is higher when jet fuel (rather than diesel) is the desired product due to the hydrocracking step. Note that in [10] the high hydrogen demand of the upgrading process is more than offset by the hydrogen production from the unconverted syngas in a second PSA unit.

Table 2. Intermediate and product yields and hydrogen demand for the Gasification-FT to jet fuel pathway.

Feedstock	Syncrude yield (kg syncrude/ kg dry biomass)	Fuel yield (kg fuel/ kg syncrude)	Fuel yield (kg fuel/ kg dry biomass)	Main fuel product/s	Hydrogen demand* (kg H_2/ton syncrude)	Hydrogen demand* (kg H_2/ ton jet fuel)	Ref.
Corn stover	0.166	0.885	0.147	Naphtha, Diesel	10.3	/	[8]
Corn stover	0.214		0.189				
Switchgrass	N.A.	N.A.	0.137	Gasoline, Diesel	N.A.	/	[7]
Lignocellulose	N.A.	N.A.	0.102	Jet fuel	N.A.	30	[22]
Rice husk	0.208	0.735	0.153	Jet fuel	82	111	[10]

*Internal hydrogen production in all studies.

4.3. Fuel yield and hydrogen demand with the alcohol to jet route

Table 3 shows the yields of alcohols (i.e, the intermediate), the fuel yields, and the hydrogen demand of the upgrading process for selected studies in the literature. It appears that the alcohol yield is roughly two times higher when ethanol, rather than butanol, is produced through fermentation. In this context, a systematic comparison is carried out in [13] between the conventional ethanol fermentation and the ABE fermentation by regular or genetically modified microorganisms, where the latter can convert a higher fraction of xylose. On the other hand, the advantage of the higher alcohols (i.e., butanol, isobutanol) becomes visible when considering the alcohol to fuel conversion. The fuel yield raises from 0.45–0.50 for ethanol-to-jet to around 0.7 for butanol-to-jet. Overall, the biomass to jet fuel yield is higher using ethanol rather than butanol/isobutanol as intermediate. Except for the study by [13], the hydrogen demand appears moderate with values lower than 10 kg per ton of alcohol. Accordingly, the penalty in jet fuel yield can barely be noticed for those processes (e.g. in [22]) where hydrogen is generated internally rather than being purchased.

Table 3: Intermediate and product yields and hydrogen demand for the alcohol to jet fuel pathway.

Feedstock	Alcohol yield (kg alcohol/ kg dry biomass)	Alcohol	Fuel yield (kg fuel/kg alcohol)	Fuel yield (kg fuel/kg dry biomass)	Main fuel product/s	Hydrogen demand (kg H_2/ton alcohol)	Hydrogen demand (kg H_2/ton jet fuel)	Ref.
Corn stover	0.260	Ethanol	0.489	0.127	Jet fuel	N.A.	N.A.	[14]
Generic	N.A.	Ethanol	0.43	N.A.	Jet fuel	6.8	15.8	[15]
		Isobutanol	0.67			8.4	12.6	
Eucalyptus wood	0.184	Ethanol	0.497	0.091	Jet fuel	26.5	53	[13]
	0.074– 0.106	Butanol	0.71	0.053– 0.074		37.7	53	
Lignocellulose	0.192	Ethanol	0.52	0.100	Jet fuel	7.1*	13.7*	[22]
Generic	N.A.	Ethanol	0.45– 0.51	N.A.	Jet fuel, gasoline, Diesel	6.5–11.1	24–53	[12]

*internal hydrogen production.

4.4. Fuel yield and hydrogen demand with the pyrolysis to jet route

Table 4 shows the yield of the intermediate (bio-oil), the fuel yield, and the hydrogen demand of the pyrolysis to jet process. Except for [18], which considered a higher fraction of non-condensable gases among the pyrolysis products, the bio-oil yield is slightly above 0.6. The bio-oil to transportation fuels (gasoline and diesel) yield is 0.42 when hydrogen is purchased, while it drops to 0.26 when hydrogen is produced internally by using a fraction of bio-oil [26]. A bio-oil to jet fuel yield of 0.16 was obtained in [19] where jet fuel was the desired product. A higher bio-oil to jet fuel yield was calculated in [18], presumably due to the particular configuration of the upgrading process. Considering the overall conversion process, the dry biomass to jet fuel yield is around 0.1. It appears that the bio-oil upgrading process is highly demanding in terms of hydrogen requirements, therefore the most convenient options for sourcing hydrogen should be selected.

Table 4. Intermediate and product yield and hydrogen demand for the pyrolysis to jet fuel pathway.

Feedstock	Bio-oil yield (kg bio-oil/kg dry biomass)	Fuel yield (kg fuel/kg bio-oil)	Fuel yield (kg fuel/ kg dry biomass)	Main fuel product/s	Hydrogen demand (kg H_2/ton bio-oil)	Hydrogen demand (kg H_2/ton jet fuel)	Ref.
Corn stover	0.63	0.42	0.26	Gasoline and Diesel	40	/	[26]
Corn stover	0.63	0.26	0.16	Gasoline and Diesel	40*	/	[26]
Rice husk	0.29	0.34	0.10	Jet fuel	60	180	[18]
Forest residue	0.61	0.16	0.10	Jet fuel	60*	370*	[19]

*internal hydrogen production

5. Discussion of the results

The dry biomass to jet fuel yield for the three conversion pathways which use lignocellulosic biomass is typically low, in the range 0.10–0.15, due to the double conversion process (i.e., biomass-to-intermediate and intermediate-to-jet fuel). In the case of the Gasification-FT pathway, there are even two intermediates (syngas and syncrude). Any jet fuel yield increase relies upon an improvement of both the upgrading section (e.g. the hydrocracker) and the production of the intermediate (e.g. choice of the gasifier, FT reactor, ethanol versus butanol fermentation, etc.). For the Hydroprocessing pathway, the vegetable oil yields appear quite constrained, whereas there are chances to further improve the oil to jet fuel yield, which currently shows values approaching and exceeding 0.6 also from waste cooking oils.

The hydrogen demand is highly dependent on the selected production pathway. While the hydrogen requirement of the Alcohol-to-Jet route is quite low, the intermediate hydrogen demand of the Gasification-Fischer Tropsch process could be easily satisfied by taking advantage of the syngas intermediate stream. Instead, the hydrogen consumption is high for both the Hydroprocessing and Pyrolysis to Jet routes, reaching values up to 45–60 kg of hydrogen per ton of vegetable oil/bio-oil. The high hydrogen demand of these two routes implies a significant penalty on the jet fuel yield when hydrogen is internally sourced, which could be alleviated using the waste streams available within the boundary of the production process for its generation. In case of external hydrogen provision, a green hydrogen supply appears mandatory to limit the GHG emissions in the jet fuel production process.

6. Conclusions

This work has shown that multiple options are potentially available to fulfill the hydrogen demand in the biojet fuel production processes using either intermediate products, co-products or waste products of the conversion process as well as a combination of them. All production pathways share the use of off-gases generated in the upgrading process which can be fed to a reforming reactor or used as fuel in the reforming furnace as a substitute of natural gas. Furthermore, most of them use the lightest fraction of the distillation (LPG, naphtha or even gasoline) for additional hydrogen production via steam reforming. For some production pathways, the use of an intermediate can be preferred over the use of a co-product for hydrogen sourcing. For instance, in the Gasification-Fischer Tropsch pathway, the clean syngas or unconverted syngas can be used for hydrogen production using a pressure swing adsorption unit. Similarly, the steam reforming of a fraction of alcohol and a fraction of bio-oil were considered in the Alcohol-to-Jet and Pyrolysis-to-Jet pathways, respectively. Also, the waste streams typically used to provide process heat/steam, such as lignin or pyrolysis gases were considered as potential sources of hydrogen via gasification and steam reforming, respectively.

In order to use sustainable aviation fuels some challenges need to be considered including feedstock availability, compatibility of alternative fuels with conventional fuels, environmental issues, and production and distribution

concerns. The use of new production technologies can improve the production process, while the use of locally available feedstock will also bring out regional development. Recent interest from the government and international organizations will enable scale-up, commercialization, and supply chain infrastructure to a large extent. Furthermore, it will provide new job opportunities and will help to maintain the sustainability of the fuel production and distribution. Finally, feedstock costs can be alleviated by the use of waste materials from various sources that are widely available as feedstock.

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