Blending of pyrolysis oil, biodiesel and sustainable alcohols for application in maritime diesel engines.

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ABSTRACT: Goal of this research is to find a stable blend of Hydrotreated Vegtable Oil / Biomass-to-liquid biodiesel (BD) and pyrolysis oil (PO) for application in the maritime sector in order to reduce its greenhouse gas emissions. Three alcohols that have a (promising) sustainable production process are used to overcome the difference in polarity between PO and BD; ethanol, butanol and isopropanol. Fuel properties used to determine the fuels capability to replace fossil alternatives are viscosity and higher heating value (HHV). Additionally, it is checked whether these fuels meet several standards with regards to sulphur content. Two blends are found that have a HHV higher than 35 MJ/kg and a viscosity lower than 4.5 cP.

Key words: Biodiesel, pyrolysis oil, fuel blending, alcohol, maritime, miscibility

1 INTRODUCTION

Modern civilization relies heavily on energy generated from fossil fuels. Over the past decades, many researchers have claimed that fossil fuels would be depleted soon. Even though none of these claims were legitimate up to this point, it is fair to state that there is only a finite amount of fossil fuel present or attainable. The effort needed to collect fossil oil will only increase. The scarcity of fossil fuels also puts energy security at risk. Most countries rely on imported fuels for their energy generation and domestic transportation. [1]

Not only petroleum fuels are affected. Plastics, polymers and various composites are globally used for packaging and lightweight purpose. Plastics and polymers are created via petrochemical processes, meaning that they are derived from fossil resources at some point. This also connects almost all plastic products to the availability of fossil oil. [2] The depletion of fossil resources for plastics has been regarded as the most concerning impact for some plastics. [3] Being less dependent on fossil resources is a widespread challenge for modern civilization.

1.1 Global warming

Global warming is a widely accepted concept that describes the enhanced greenhouse effect as a result of the emission of greenhouse gasses (GHG). This human induced greenhouse effect causes a significant warming in the earth's surface and lower atmosphere,

with consequences for nature and society. [4] Of all GHGs, carbon dioxide (CO_2) accounts for around 50 percent of all the radioactive forcing in the atmosphere. Other GHGs, like methane (CH_4), nitrous oxide (N_2O) and various halocarbons are responsible for about 30 percent. Latter group of GHGs are typically more potent than CO_2, meaning they have significantly more global warming potential (factor 23-10 000 compared to CO_2). [5] Using these factors, emissions of all GHG emitting sectors can be compared and evaluated by expressing their GHG profile in CO_2-equivalent values (CO_2e).

1.2 Shipping and greenhouse gas emissions

The transport sector dominantly uses fossil fuels as energy source, due to its energy density and availability. Global transportation (including international aviation and maritime) was responsible for 23% of all CO_2 emissions in 2005. [6] The EU has created several policies that aim to bring down the emissions of the road transportation sector. International maritime transport long remained the only transport mode that was not included in the European emission reduction commitment. This while shipping accounted for 4% of all EU GHG emissions, or 2.5% of global GHG emissions. [7] The International Maritime Organization (IMO) has monitored and published the estimates of GHG emission from shipping. Depending on future economic and energy developments, shipping emissions are predicted to rise between 50% and 250% by 2050. [8] In July 2011 IMO's Marine Envi-

ronment Protection Committee (MEPC) had a break-through with the first obligatory global GHG reduction policy for the entire maritime sector. This policy was adopted in The International Convention for the Prevention of Pollution from Ships (MARPOL). [9]

1.3 Regulations

The EU opts for lower CO_2 emissions in various sectors via numerous policies. [10] For the maritime sector specifically the EU recently introduced more fuel quality standards. These are mostly with regards to sulphur and nitrogen emissions. This is because SO_x and NO_x emissions from the shipping sector correspond to 13% and 15% of global human induced pollution, receptively, as reported in the IPCC Fifth Assessment Report (AR5). [11] Relative to the overall GHG emission of the sector, NO_x and SO_x emissions are high.

These sulphur and nitrogen oxides form during or after combustion under influence of heat in the presence of air. Nitrogen is injected into combustion engines, since it is naturally present in atmospheric air. Nitrogen oxidation can be influenced by design changes to engines. For example Exhaust Gas Recirculation (EGR), which brings down the gas temperature in the cylinder and reduces the concentration of the oxygen concentration, realises substantial reduction in NO_x emissions in diesel engines. [12].

Elemental sulphur is not present in atmospheric air, in contrast to nitrogen. Sulphur, which is present in diesel fuels as a pollutant, oxidises in a process similar to nitrogen oxides. The most common ways to reduce the emission of SO_x is via the use of low sulphur fuel or exhaust gas cleaning systems. The latter option requires the investment and installation of an exhaust gas cleaning system. This may decrease functional space and introduces maintenance. Using low sulphur fuel is less intrusive, but is generally more expensive. Considered an ultra-low sulphur diesel standard is the EN 590 fuel specification that, amongst other properties, dictates a maximum sulphur content of 10.0 mg/kg or 0.001 % - mass based. [13] This fuel standard complies with the MARPOL Annex VI for Emission Control Areas (ECAs). This is a more intense standard for the North Sea, Baltic Sea, North American ECA and Caribbean Sea ECA regarding SO_x and particulate matter (PM) pollution. Within these ECAs the maximum sulphur content is 0.10 w%, which is still more than the EN 590 norm. Outside the ECAs the maximum content of sulphur is 3.50w%, with the intention to reduce this to 0.50w% in 2020. [9]

1.4 Combustion

Currently, combustion engines are designed and optimized for fossil derived fuels. The properties of biofuels such as biodiesel or bio oil are quite different from those of fossil fuels. The use of biofuels in conventional diesel engines has consequences for the performance and emissions. The use of Fatty Acid Methyl Esther (FAME) biodiesel in several types of diesel engines showed significant decrease of Brake Thermal Energy (BTE) and increase of Brake Specific Fuel Consumption (BFSC). [14] These negative effects to performance are allocated to the higher viscosity and lower HHV of FAME biodiesel. The atomization of more viscus fluids is difficult. Because of this, the fuel-air mixture in the combustion chamber is suboptimal, leading to incomplete combustion. [15] [16] Marine diesel engines face similar issues when injecting highly viscous fuels. Poor atomization of the fuel, leads to poor combustion. [17] Marine engine systems might have multi-fuel systems that include preheating of the fuel in order to reduce viscosity. [18]

1.5 Pyrolysis oil

A promising technology to convert biomass to fuels is pyrolysis. This thermochemical process decomposes organic materials at high temperatures in absence of oxygen. This results in three main products; pyrolysis-oil, char and non-condensable gasses. The biochar can be burned amongst non-condensable gasses to generate heat for the pyrolysis process or drying the biomass. Even though pyrolysis processes are maturing rapidly, the properties of pyrolysis-oil still are very different from petroleum derived fuels. [19] Pyrolysis oil (PO) typically has high viscosity, low HHV, low oxidative stability and low PH (<3). [20] These characteristics deviate substantially from fossil fuel oil introducing implications for fuel atomization, filter clogging, etc. Fast pyrolysis - fast denoting the high temperature rates and short residence times - is an industrially realized technology. There are multiple working fast pyrolysis plants, of which the world leader in production volume (> 20 million liter, as of 2017) is located close to the University of Twente. [21] This is the Empyro pyrolysis plant of Biomass Technology Group B.V. located in Hengelo, The Netherlands. Their pyrolysis oil, produced with

sawdust as feedstock, was utilised in this research. Properties as specified by the producer of this woody oil are shown in table 1. Sulphur content was not specified. However, since woody biomass contains negligible amounts of sulphur, and looking at the data from other woody pyrolysis oil, it is estimated to be lower than 1w%. [22] Note the high water content in PO. Due to the fact that water is polar and thus solves with polar liquids, it can be concluded that PO is polar as well.

Table 1: Sawdust pyrolysis oil properties

Property	Unit	Value
Water content	w%	21.8
Carbon residue	w%	18.1
Ash content	w%	0.02
Sulfur content	w%	<1*
Density 15°C	kg/l	1.2
Carbon content	w%	42
Hydrogen content	w%	7.5
Nitrogen content	w%	0.1
HHV	MJ/kg	19

not specified by Biomass Technology Group B.V.

1.6 Biodiesel

Upgrading from bio oil to biofuels with the desired properties is possible, this is however costly, adds complexity and may reduce the sustainability of the pyrolysis oil. [23] Hydrotreated Vegetable Oil (HVO) or Biomass To Liquid (BTL) biodiesel, considered second generation biodiesels, are commercially available. For this research, contact was made with Den Hartog B.V. Who are located in Groot-Ammers, The Netherlands. The fuel they distribute is a CO_2 footprint reducing fuel for diesel engines, of which the properties are conform the EN 15940 regulation for synthetic and hydrotreated fuels. Properties of this fuel, as specified by Den Hartog (tested by Inspectorate Netherlands) are displayed in table 2. Note the very low water content (0.004 w%) compared to PO. This illustrates the non-polarity of this biodiesel very well.

Table 2: 'CO$_2$Fuel 100' HVO/BTL biodiesel properties

Property	Unit	Value
Water content	mg/kg	40
Carbon residue	w%	<0.10
Ash content	w%	<0.001
Sulfur content	mg/kg	<3
Density 15°C	0.7795	kg/l
FAME Content	v%	<7
HHV	MJ/kg	42*
Dynamic viscosity 40°C	cP	2.28

not specified by Den Hartog B.V.

The fuel is completely made from sustainable feedstocks, according to Den Hartog B.V. Unfortunately, what sources of biomass are used is unknown. The biodiesel is actually a blend and consists of three different fuels; a small part FAME (<7w%) and an unknown fraction of HVO biodiesel and BTL diesel. HVO diesel is described as a paraffinic biofuel, which can be synthesized from various vegetable oils. This process hydrogenates the triglycerides of the feedstocks and breaks them down into various intermediates. These are then formed into alkanes of the desired length. These processes take place above about 300°C and at a pressure of at least 3 MPa. [24] As side-products propane, carbon mono- and dioxide and water are formed. The result is a energy dense, very stable, high cetane and pollutant free fuel. The downsides of HVO reside mainly in its demand for a high capital investment, compared to FAME biodiesel. Processing costs and feedstock flexibility are reported to improve with HVO. [24] BTL will yield a fuel with properties closely resembling those of HVO. [25] The process has a higher flexibility with regards to the input biomass, as it may also use gasification (present during pyrolysis) followed by a Fischer-Tropsch (like) synthesis. Pyrolysis oil can also be upgraded via a similar catalytic hydroprocess, therefore classifying as a biomass-to-liquid. [26]
The HHV of this particular biodiesel blend is unknown, and is therefore estimated based on its chemical composition in relation to known biodiesels. Due to its high quality, the HHV will be high for biodiesel. Based on this, a conservative estimate of 42 MJ/kg should provide enough precision to estimate the HHV of the blends later in this research. [27] [28] There

have been cases where researchers reported HVO biodiesel to have a higher HHV than petroleum diesel; 44 versus 43 MJ/kg, respectively. [25]

1.7 Bio alcohols as solvents

This research aims to use sustainable alcohols (bio alcohols) as solvents between PO and BD. The particular BD used is of high quality and very similar to fossil diesel. Because of the negligible water content in BD compared to PO, and the fact that it is insolvable in water, it is concluded that this BD is non-polar, like fossil diesel. It is no surprise that PO and BD are unable to form a stable blend in any fraction, as shown in figure 1, due to their difference in polarity.

Table 3: Overview of three alcohols [29]

Alcohol	n in C_n-H_{2n+1}-OH	Molar weight [g/mol]	HHV [MJ/kg]
Ethanol	2	46.07	29.8
Isopropanol	3	60.10	31.0
Butanol	4	74.12	37.3

Alcohols are aliphatic hydrocarbon compounds, meaning they do not contain aromatic groups and are composed of carbon and hydrogen molecules. Alcohol contains a polar hydroxyl group (-OH) and a non-polar carbon chain (C_nH_{2n+1}) of which the length is dependent on the order (n) of alcohol. Table 3 shows the molar weight and HHV of the three alcohols, which correlate with an increase in hydrocarbons due to the longer carbon chain. Liquids are able to form a stable blend and thus solve if the intermolecular attraction of the solvent-solute are greater than the attraction of the solute-solute (in this case PO or BD) and solvent-solvent (in this case alcohols). These intermolecular forces are a result of the properties of the solutes and the solvent . There are multiple distinctive forces that influence the molecule interaction. In this specific situation; hydrogen-bonding, dipole-dipole and dipole-induced dipole interaction. The latter is of importance for blending polar and non-polar molecules. [30] As the non-polar chain of the alcohol increases in length, the polarity of the alcohol decreases overall. This allows the alcohol to solve with the non-polar fluid (BD) via dipole-induced dipole interaction. The hydroxyl group allows blending with

the polar fluid (PO) via dipole-dipole interaction and hydrogen bonding. A stable blend will form when these interactions find a balance, which is a function of the ratio of the three fluids in the blend. Therefore it can be stated that the potential of the alcohol as solvent also increases with a higher n.
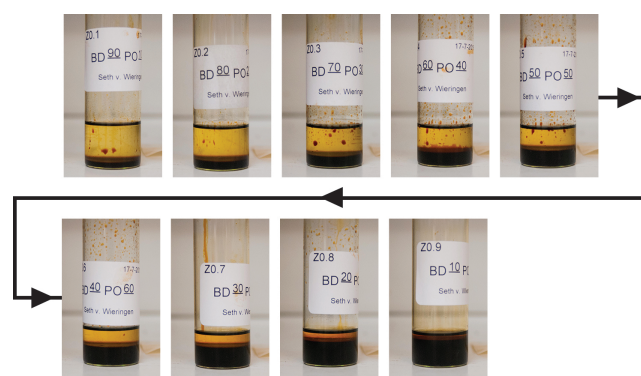

Figure 1: 9 blends of different fractions of PO and BD, with a concentration interval of 10 w%. Left to right, top to bottom the concentration of PO increases. The clear fluid on top is BD.

1.7.a Bio ethanol

The best known and widely established bio alcohol is bio ethanol. Defined as the production of ethanol from renewable sources, bio ethanol is mostly produced via low-cost fermentation of lignocellulosic or high starch biomass. During this process, celluosic sugars or starches are hydrolysed using enzymes. Before enzymatic hydrolysis feedstocks may be pretreated mechanically or chemically in order to increase its susceptibility to enzymes. In North America and Europe most bio ethanol was fermented based on starch, such as grains and corn. [31] Since its introduction it has matured to also processing waste product from various sources; such as waste water and fruit processing wastes. [32] [33]

1.7.b Bio isopropanol

Isopropanol is one specific configuration of C3 alcohol, which is different from 1-propanol. Chemically, these alcohols are produced differently. Isopropanol is made through a hydration reaction between water and propene, while 1-propanol is produced from ethane, carbon monoxide and hydrogen. In recent years the interest for producing these chemicals from renewable resources has grown. It is possible to develop microbes, through genetic engineering, for producing various types of chemicals, including

isopropanol. Several microbial systems for production of isopropanol have been reported. [34] When using a sustainable feedstock as input chemicals, such as glucose from sugar cane waste water, this biobased production has great sustainable potential. Chemical producers have announced their construction plans for C3 platform production, using hardwood or wheat straw as their feedstock. [35]

1.7.c Bio butanol

The same microbial production has been reported for butanol, amongst other C4 compounds. [34] When comparing fermentation derived butanol to ethanol, the yields from corn or switchgrass are approximately halved. This is a serious disadvantage of butanol to ethanol, as feedstock costs is an important parameter for the fuel price. [36] For butanol specifically, thermochemical processing of macroalgae (seaweeds) seems promising. Macroalgae are gasified to syngas, cleaned and used for mixed alcohol production. Alcohols are later separated. [37]

1.8 Desired fuel properties of blend

Various methods exist to allow the use of diesel and alcohol in compression ignition engines, such as dual injection, alcohol-diesel fuel emulsions, and alcohol-diesel fuel blends. Of these methods, the least intrusive option is the use of stable blends. Blends are more stable than emulsions and can be used in diesel engines, if the properties of the blend are close enough to those of fossil diesel fuel.

The interest to blend pyrolysis oil, biodiesel and renewable alcohols arises due to the fact that promising results were achieved when blending PO with fossil diesel. Using alcohol as solvent, researchers of the University of Twente were able to achieve fossil diesel/pyrolysis oil blends with properties which were suitable for use in turbines. [38] The use of FAME biodiesel, considered a first generation biodiesel, has a higher moisture content; improving blending with pyrolysis oil. In this research HVO/BTL biodiesel is used, which has chemical and physical properties very close to fossil diesel.

Based on existing and future regulations, both in the EU and internationally, and based on findings of other researchers, desired fuel properties have been set. These are shown in table 4. Even though preheating is a technique used in marine engines, it is disregarded due to pyrolysis oil poor thermal stability. Temperatures above 80°C can lead to polymerization

reactions and an increase of viscosity.

Table 4: Desired fuel properties

Property	Unit	Value
Dynamic viscosity 20°C	cP	<4.5
HHV	MJ/kg	>35
Sulphur content	w%	0.10-3.50

In addition to these properties, it can be stated that the aim is to obtain a stable blend that has the highest fraction of PO and lowest fraction of alcohols. This is found most likely to improve the sustainability and costs of the fuel. A higher concentration in BD will improve the HHV but will decrease the sustainability as this is an upgraded fuel. [23]

Goal of this research is to find a stable blend of three liquid fuels for application in the maritime sector in order to reduce its GHG emissions. The main focus will be reducing or minimizing the CO_2 footprint by utilising second generation biodiesel and pyrolysis oil as main fuel components. Three alcohols that have a (promising) sustainable production process will be used as solvents; ethanol, butanol and isopropanol. Further analysis of the miscible solutions should point out whether the fuel is admissible for application in shipping. Factors used to determine the fuels capability to replace fossil alternatives are viscosity and specific energy or higher heating value (HHV). [14] Additionally, it is checked whether these fuels meet EU and IMO fuel standards with regards to sulphur content, which has become mandatory for shipping (EN 590 and Regulation 14 of the MARPOL Annex VI, respectively).

2 METHODS

2.1 Blending

The blends of PO and BD were prepared in tall glass sample tubes of 50 millilitre, with a total weight of 10 gram fuel per sample. Samples were prepared at room temperature. For measuring a KERN PLS 1200 laboratory balance was used, with a readability of 1 milligram and error of ±3 milligrams. All samples were prepared within an error of +50 milligram. In perspective, a single pipetted droplet weighs between 20-35 milligram. The PO droplets are noteworthy heavy

when compared to alcohols and BD, due to the high density and high surface tension. For each of the three alcohols a full ternary mesh was filled, with a resolution of 10 w% concentration intervals. This yields a total of 56 samples per ternary diagram. Throughout the three blends the 11 samples without alcohol (shown in figure 1) remained the same. After carefully pipetting a sample, it was shaken vigorously in a linear up and down motion for 15 seconds. The samples were stored for approximately one day at room temperature in the laboratory, free of major vibrations. Through optical inspection of the samples, their miscibility was assessed. After the boundary of blending was found, another set of samples was created for the three alcohol solvents. This sample set consisted of a certain number of samples forming a more acurate boundary along the 10 w% datapoints. This sample set had an interval of 5 w%.

2.2 Viscosity

After obtaining the results of the mixture testing, the viscosity was determined for a certain set of samples. This was done only for the stable blends with the lowest possible concentration of alcohols, which forms the border of blending. Also, all fuels were measured without blending; PO, BD, ethanol, isopropanol and butanol. The dynamic viscosity was determined using the Brookfield DV-II+Pro viscometer with the CPE-40 spindle. This spindle provides a measurement range from 0.15 to 1065 cP. The accuracy of this viscometer is ±1%, according to the manufacturer. To ensure accurate results, the viscometer was allowed to complete a series of rotations after a period of stabilization. All measurements were conducted at 20°C. In order to control the temperature of the samples, the samplecup was cooled using a Jubalo FP35-HL water bath with a temperature stability of ±0.01°C. To make sure that the sample had actually cooled down, the internal temperature sensor of the viscometer was used, which has a accuracy of ±1°C. After each measurement the cup and spindle were dismantled and cleaned twice with isopropanol and disposable cleaning paper. After cleaning, some time was reserved to allow the remainder of isopropanol to evaporate. Samples were circulated through the pipette to make sure the measured viscosity represented the average of the sample, as heavier and parts of the blend may have parted slightly.

2.3 HHV and sulphur content

As both HHV and sulphur content are mass based properties, their values can be calculated because the samples are created on a mass ratio. This ratio of PO, BD and alcohol linearly correlates to the HHV and sulphur content. A MatLab script was written to calculate these values, based on their mixing ratios. To this end, the values as shown in table 1, 2 and 3 are used. It is assumed that the alcohols are free of pollutants and thus contain insignificant amounts of sulphur.

3 RESULTS AND DISCUSSION

3.1 Blending

Most samples showed clear boundaries between the fuels. They formed layers based on density, most of the times resulting in the formation of a clear layer of BD on top of the PO. Blending is shown in the ternary diagrams. Figure 3 shows the blending of the ethanol solvent based blends. Note that ethanol poorly solves both PO and BD; only above 80 w% ethanol stable blends are found. This can be allocated to the polarity of ethanol, which makes it hard to blend with the non-polar BD.

Figure 4 shows the blending of the isopropanol solvent based blends. As expected the minimum concentration for stable blends is pushed back further by using a longer alcohol chain. Stable blends form in all fractions along 70 w% isopropanol. For lower concentrations of isopropanol, equal fractions of PO/BD seem to impede blending; only low concentrations of PO relative to BD - and vice versa - remained stable.

Figure 2 shows the blending of the butanol solvent based blends. This alcohol with an even longer carbon chain again lowers the boundary, this time to 60 w% in all fractions. At 50 w% butanol solves in a 10:40 fraction of PO to BD. The inverse however does not blend.

Throughout all blends, the alcohols seem to prefer PO for blending. This statement is based on the fact that insolvable mixtures showed a clear fluid on top, of approximately the same size as the fraction BD in those mixtures. Even in higher concentrations of alcohol, the clear fluid correlated to the concentration of BD.
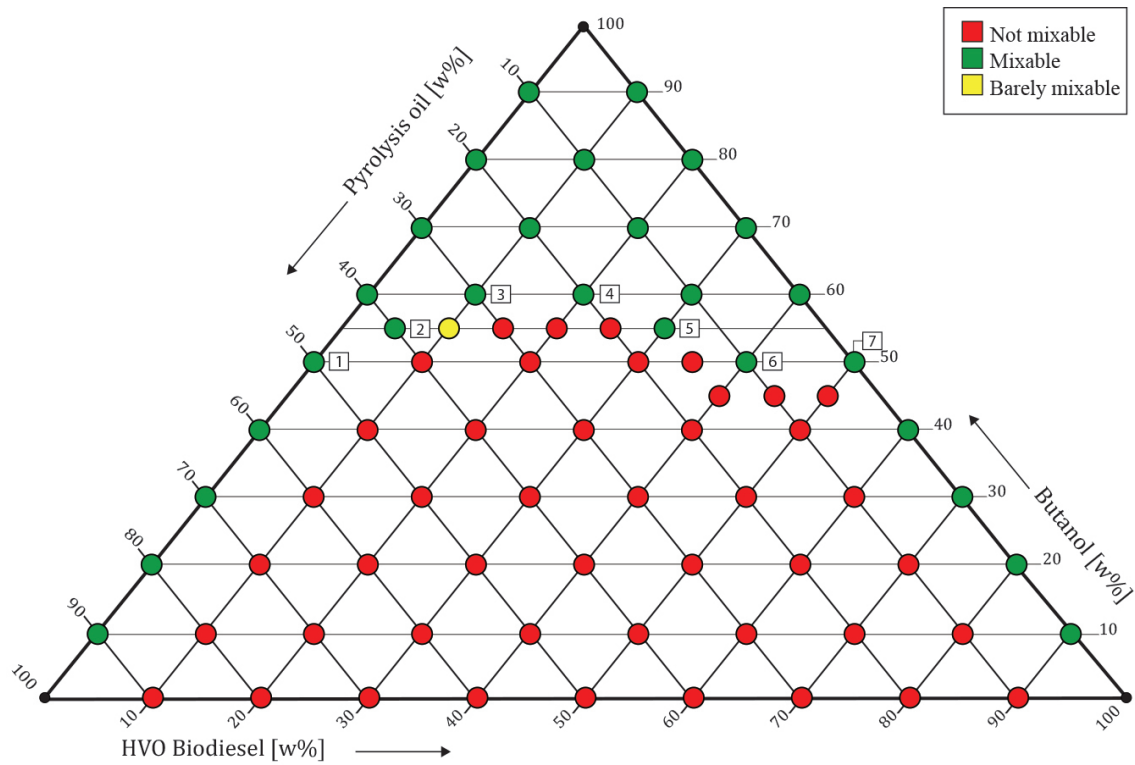
Figure 2: Ternary diagram of PO, BD and butanol. The boxes connected to the data points show the numbering of the samples on the boundary of mixing. These are later used to display viscosity and HHV.
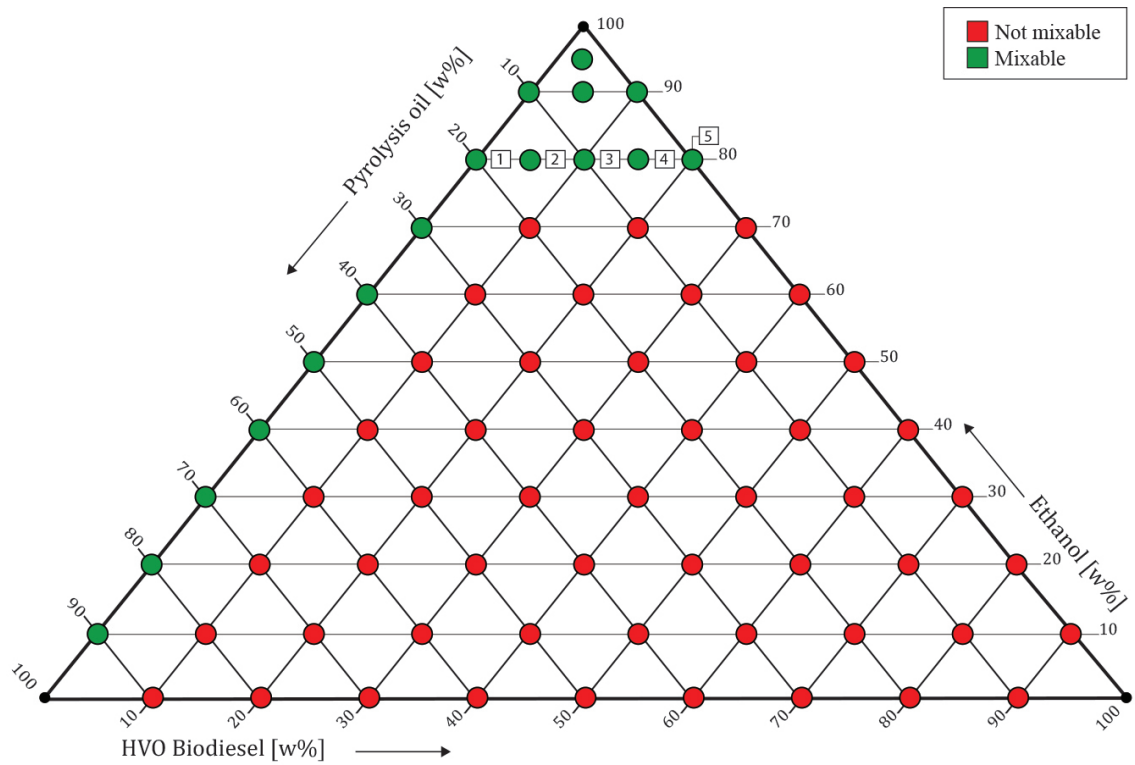

Figure 3: Ternary diagram of PO, BD and ethanol. The boxes connected to the data points show the numbering of the samples on the boundary of mixing. These are later used to display viscosity and HHV.
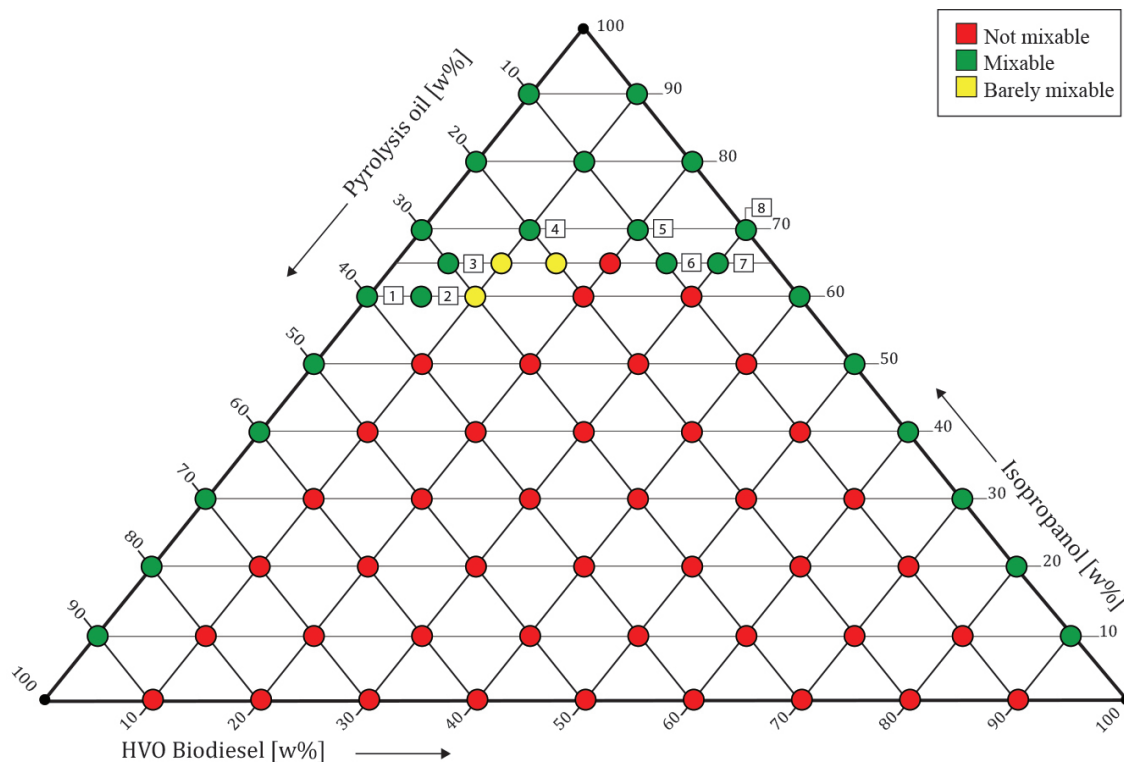
Figure 4: Ternary diagram of PO, BD and isopropanol. The boxes connected to the data points show the numbering of the samples on the boundary of mixing. These are later used to display viscosity and HHV.

3.2 Viscosity and HHV

As visible in the ternary diagrams (figures 3-2) the samples that form the discrete boundary are labelled. These samples have been tested for their viscosity. An overview of the viscosity, HHV and sulphur content; as well as the mixing ratios of all boundary samples, are shown in table 5 in the appendix. The values of viscosity and HHV are visually represented in figures 5-7. In all figures, the desired properties of HHV and viscosity are plotted as reference. Samples plotted from left to right decrease in pyrolysis oil content. Overall it can be concluded that higher concentration of PO causes a lower HHV and higher viscosity, while the opposite is true for BD. This was expected due to the superior fuel properties of the BD. Both the viscosity and the HHV increase with a longer alcohol. This can be explained through the intermolecular interaction of the alcohols. Longer chains lead to higher energy density as well as higher internal attraction, attributing to the higher viscosity.
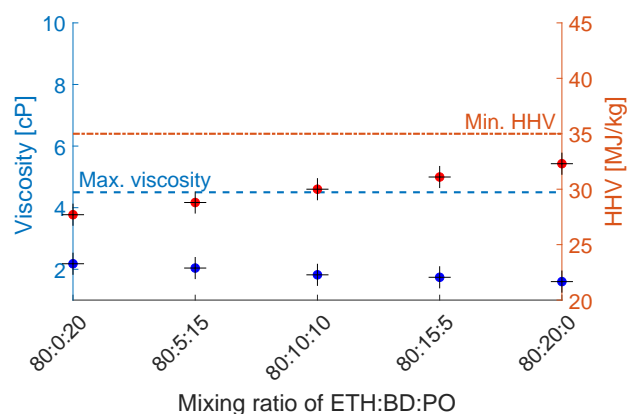

Figure 5: Viscosity and HHV of 5 samples from the ethanol/PO/BD mixing boundary. Note the low viscosity, attributed to high concentration ethanol and its low viscosity. Downside to this is the low HHV, which is nowhere near the minimum.

3.3 Sulphur content

The sulphur content is shown in the table 5 in the appendix. All fuel blends are below the maximum level of MARPOL Annex VI outside of ECAs, currently (<3.5w%) and the 2020 goal (<0.5w%). Only 3 fuel blends meet the standard for inside ECA's, containing

at most 0.1w% sulphur. However, on the other criteria the fuel blends fail. None of the fuel blends meet the required sulphur contents of the EN 590 fuel standard (<0.001w%). It must be noted that the author considers it very likely that the sulphur content is actually lower than calculated due to the conservative estimate regarding the PO sulphur content.
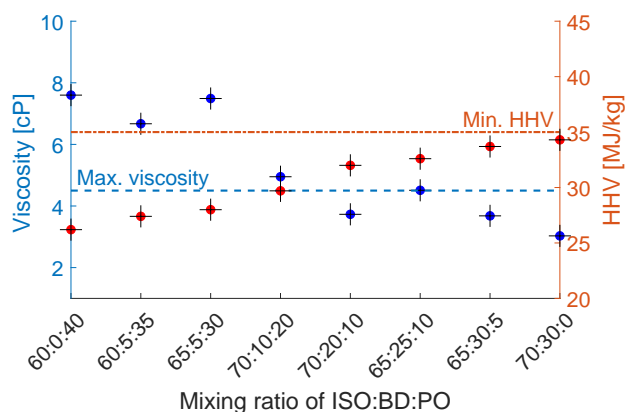

Figure 6: Viscosity and HHV of 8 samples from the isopropanol/PO/BD mixing boundary. The higher viscosity on the left side of this figure is attributed to the concentration of PO, which can be higher with isopropanol as solvent. None of the samples however reach the desired properties.
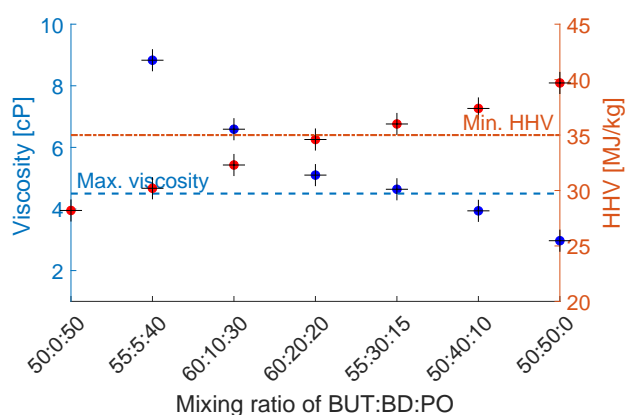

Figure 7: Viscosity and HHV of 7 samples from the butanol/PO/BD mixing boundary. The higher viscosity is again attributed to the concentration of PO, which can be even higher with butanol. Two samples meet the demands, one sample has too high viscosity with sufficient HHV.

4 CONCLUSIONS

Two pyrolysis oil and HVO/BTL biodiesel blends are found that have a HHV higher than 35 MJ/kg and a viscosity lower than 4.5 cP. One blend had promising HHV (36 MJ/kg) but a viscosity exceeding the set perimeter (4.64 cP). These blends are mixed using butanol as solvent. The highest concentration of pyrolysis oil is 15 w%. This fraction of pyrolysis has potential to reduce costs, if it were not for the very high fraction of butanol needed to blend it with HVO/BTL biodiesel. The results obtained are very similar to the blending of pyrolysis oil with fossil diesel. [38]

Eventhough the HHV is lower than typical, it has potential for use in compression engines. Albeit at a lower brake thermal energy and a higher brake specific fuel consumption. Combustion tests in a conventional diesel engine should reveal this. Otherwise, some blends showed promising properties for use in turbines, which have a greater tolerance with regards to HHV and viscosity. Turbines powered with these mixtures have the potential to lower the footprint of power generation substantially.

Also, the very low sulphur content of all blends is notable. It can be stated that synthetic fuels have great potential to meet current fuel standards, as well as future fuel standards. If the fuels are upgraded from pyrolysis oil, via BTL, the sustainability and feedstock flexibility is promising.

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5 APPENDIX B - DATA TABLE

Table 5: Viscosity, HHV and sulphur content of all blends and pure fuels.

		Blend by part			Tested	Calculated	
	Property →	Alc.	BD	PO	**Viscosity**	**HHV**	**Sulphur**
	Unit →	w%	w%	w%	cP	MJ/kg	w%
↓ Category	**↓ Sample number**						
Ethanol	[-]	100	0	0	1.28	29.8	-
	1	80	0	20	2.18	27.7	0.20
	2	80	5	15	2.04	28.8	0.17
	3	80	10	10	1.82	30.0	0.13
	4	80	15	5	1.74	31.1	0.10
	5	80	20	0	1.60	32.3	0.06
Isopropanol	[-]	100	0	0	2.38	31.0	-
	1	60	0	40	7.60	26.2	0.40
	2	60	5	35	6.67	27.4	0.37
	3	65	5	30	7.49	28.0	0.32
	4	70	10	20	4.95	29.7	0.23
	5	70	20	10	3.73	32.0	0.16
	6	65	25	10	4.51	32.6	0.18
	7	65	30	5	3.68	33.7	0.14
	8	70	30	0	3.03	34.3	0.09
Butanol	[-]	100	0	0	2.90	37.3	-
	1	50	0	50	12.00	28.2	0.50
	2	55	5	40	8.83	30.2	0.42
	3	60	10	30	6.59	32.3	0.33
	4	60	20	20	5.10	34.6	0.26
	5	55	30	15	4.64	36.0	0.24
	6	50	40	10	3.94	37.4	0.22
	7	50	50	0	2.97	39.7	0.15
Pyrolysis oil	[-]	0	0	100	150.00	19.0	1.00
Biodiesel	[-]	0	100	0	3.42	42.0	0.30