

## BIOFUEL BLENDS WITH IMPROVED OXIDATION STABILITY AND LUBRICITY

**[0001]** The present disclosure generally relates to a renewable hydrocarbon blend for use as a biofuel. More specifically, the present disclosure relates to a renewable hydrocarbon blend of products derived from hydroprocessing of solid biomass and a liquid.

## BACKGROUND OF THE DISCLOSURE

**[0002]** The demand for energy is increasing as a result of worldwide economic growth and development. This increase in the demand for energy has contributed to an increase in the amount of greenhouse gases and the overall carbon footprint. In addition, with increasing demand for liquid transportation fuels, decreasing reserves of crude petroleum oil that may be accessed and recovered easily and increasing constraints on carbon footprints of such fuels, it may be desirable to develop routes to produce liquid transportation fuels from renewable resources in an efficient manner. Such liquid transportation fuels produced from biomass are sometimes also referred to as biofuels. Biomass offers a source of renewable carbon. Examples of suitable biomass include vegetable oils, oils obtained from algae and animal fats, deconstruction materials such as pyrolyzed recyclable materials and wood, among others. Therefore, when using fuels derived from renewable resources, it may be possible to achieve more sustainable CO<sub>2</sub> emissions over petroleum-derived fuels. For biofuels to replace all or at least a portion of the carbon-based fossil fuels, the biofuels should meet the required performance and emission specifications of the carbon-based fossil fuels.

**[0003]** One technique for producing liquid transportation fuels from renewable resources is hydroprocessing. However, certain hydroprocessing-based techniques produce hydrocarbon liquid products that do not meet specifications required for diesel and gasoline range products. For example, the hydrocarbon liquid products produced from hydroprocessing-based techniques may have an undesirable distribution of various classes or hydrocarbon compounds (e.g., aromatics, paraffins and naphthenes). As such, the hydrocarbon liquid products resulting from hydroprocessing-based techniques may have octane and cetane numbers for gasoline and diesel, respectively, that do not meet the required specifications for the location at which they will be used.

- 2 -

**[0004]** Additionally, certain properties of the hydrocarbon liquid products may render the hydrocarbon liquid products unsuitable for use as a transportation fuel. For example, based on the source of the biomass, the resultant hydrocarbon liquid products (e.g., biofuel) may be prone to oxidative degradation that deteriorates the quality of the hydrocarbon liquid products over time. Therefore, these products may not be suitable for use and long-term storage. Fuels, such as biofuels, undergo oxidation stability testing to determine if these fuels are suitable for market and use as transportation fuels. European standard EN 12205 is a reference stability test in automotive diesel standard for the European market (EN 590) that is used in determining the stability of diesel fuel towards oxidation. This test measures the amount of insoluble materials that is formed when a stream of pure oxygen is bubbled through a sample at 95°C for 16 hours. The reaction with oxygen triggers some decomposition processes that lead to the formation of high molecular weight species, which are mostly insoluble in the diesel sample. The higher the amount of these insoluble materials, the more unstable the fuel towards oxidation. During testing for oxidation stability according to the EN 12205 standard, the conditions at which certain biofuels (e.g., those having branched paraffins and/or aromatics) are tested at may result in oxidation stability performance that does not meet the specification set forth by the standard. As such, these off-spec biofuels may not be suitable for market and use as transportation fuels. Additionally, in certain instances, hydrocarbon liquid products (e.g., hydrotreated ester fatty acid (HEFA) and heavy gas oils) may not meet the required specification or have undesirable properties (e.g., oxidation stability, lubricity, cetane number/index) to be used as a suitable transportation fuel. Accordingly, the hydrocarbon liquid product(s) may either be used as a blending component in a fossil fuel, upgraded, or mixed with property enhancing additives in order to be used as the fuel itself.

**[0005]** Accordingly, to meet the increasing demand for fuels and/or fuel components derived from renewable resources and mitigate degradation, hydroprocessing-based processes used for producing biofuels may benefit from energy-efficient and economically suitable processing options that provide biofuels with desired product quality attributes (e.g., cold flow properties, oxidation stability, lubricity, and cetane number, in the case of a diesel boiling range fraction, or octane number, in the case of a gasoline boiling range fraction) without having to undergo a costly upgrading processes and incorporation of property enhancing additives. Such

- 3 -

processing options could be adapted as needed to meet changing end-product demands for renewable fuels, thereby maximizing overall value and process economics.

## SUMMARY

**[0006]** In an embodiment, a biofuel includes a mixture having a gasoil generated from hydropyrolysis and hydroconversion of a solid biomass containing lignocellulose and an isomerized hydroprocessed ester and fatty acid (HEFA) generated from hydrotreating a renewable resource having fats and oils. The gasoil has a cetane index less than 46 and at least 10 parts per million weight (ppmw) of a heteroatom and a cetane index of the biofuel is greater than 46.

**[0007]** In another embodiment, a process for producing a biofuel includes feeding a solid feedstock and hydrogen to a first stage hydropyrolysis reactor. The first stage hydropyrolysis reactor includes one or more deoxygenation catalysts and the solid feedstock includes biomass containing lignocellulose. The process also includes hydropyrolysing the solid feedstock in the first stage hydropyrolysis reactor to generate a product stream having partially deoxygenated hydropyrolysis product, H<sub>2</sub>O, H<sub>2</sub>, CO<sub>2</sub>, CO, C<sub>1</sub> - C<sub>3</sub> gases, char and catalyst fines, feeding at least a portion of the product stream to a second stage hydroconversion reactor having one or more hydroconversion catalysts, hydroconverting the partially deoxygenated hydropyrolysis product in the product stream to generate a vapor phase product having substantially fully deoxygenated hydrocarbon product, H<sub>2</sub>O, CO, CO<sub>2</sub>, and C<sub>1</sub> - C<sub>3</sub> gases, and condensing the vapor phase product to generate a deoxygenated hydrocarbon liquid comprising the substantially fully deoxygenated hydrocarbon product. The substantially fully deoxygenated hydrocarbon product includes a gasoil having a cetane index of less than 46 and at least 10 parts per million weight (ppmw) of a heteroatom. The process further includes mixing the gasoil with an isomerized hydroprocessed ester fatty acid (HEFA) to generate the biofuel, wherein a cetane index of the biofuel is greater than 46.

**[0008]** In a further embodiment, a process for producing a biofuel includes mixing a gasoil derived from hydropyrolysis and hydroconversion of a biomass containing lignocellulose with an isomerized hydroprocessed ester fatty acid (HEFA). The gasoil has a cetane index less than 46, at least 10 parts per million weight (ppmw) of a heteroatom, and a boiling point greater than 145 degrees Celsius (°C).

- 4 -

**[0009]** Additional features and advantages of exemplary implementations of the disclosure will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by the practice of such exemplary implementations. The features and advantages of such implementations may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features will become more fully apparent from the following description and appended claims, or may be learned by the practice of such exemplary implementations as set forth hereinafter.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** Advantages of the disclosure may become apparent upon reading the following detailed description and upon reference to the drawings in which:

**[0011]** FIG. 1 is a hydroprocessing system having a first stage and a second stage used to produce a gasoil (GO) from biomass used to generate a biofuel blend, in accordance with an embodiment of the present disclosure;

**[0012]** FIG. 2 is a hydroconversion system having a hydroconversion reactor used to produce a hydrotreated ester fatty acid (HEFA) used in combination with the GO of FIG. 1 to generate the biofuel blend, in accordance with an embodiment of the present disclosure;

**[0013]** FIG. 3 is a plot of oxidation stability in grams/cubic meter ( $\text{g}/\text{m}^3$ ) as a function of an amount of gasoil (GO) in volume % (vol%) in the biofuel blend in which the GO in the biofuel blend is from a distillation fraction having a boiling point  $>180^\circ\text{C}$ ; and

**[0014]** FIG. 4 is a plot of lubricity in micrometers ( $\mu\text{m}$ ) as a function of an amount of GO in vol % in the biofuel blend in which the GO in the biofuel blend is from a distillation fraction having a boiling point  $>150^\circ\text{C}$ .

#### DETAILED DESCRIPTION

**[0015]** One or more specific embodiments of the present disclosure will be described below. These described embodiments are examples of the presently disclosed techniques. Additionally, in an effort to provide a concise description of these embodiments, not all features of an actual implementation may be described in the specification. It should be appreciated that

- 5 -

in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions will be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such a development effort might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

**[0016]** When introducing elements of various embodiments of the present disclosure, the articles “a,” “an,” and “the” are intended to mean that there are one or more of the elements. The terms “comprising,” “including,” and “having” are intended to be inclusive and mean that there may be additional elements other than the listed elements. Additionally, it should be understood that references to “one embodiment” or “an embodiment” of the present disclosure are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

**[0017]** The terms “approximately,” “about,” and “substantially” as used herein represent an amount close to the stated amount that still performs a desired function or achieves a desired result. For example, the terms “approximately,” “about,” and “substantially” may refer to an amount that is within less than 10% of, within less than 5% of, within less than 1% of, within less than 0.1% of, and within less than 0.01% of a stated amount.

**[0018]** The terms “linear paraffins” and “normal paraffins” or “*n*-paraffins” as used herein are intended to denote long straight chain saturated hydrocarbons such as, for example, normal hexadecane (n-C16). The term “non-linear paraffins” as used herein is intended to denote saturated branched hydrocarbons such as, for example, secondary paraffins and tertiary paraffins. The term “iso-paraffins” as used herein is intended to denote secondary non-cyclic branched paraffins such as, for example, iso-hexadecane (i-C16). The term “unsaturated hydrocarbons” as used herein is intended to denote hydrogen deficient hydrocarbons such as, for example, olefins, naphthenes, cycloparaffins, and aromatics.

- 6 -

**[0019]** Hydroprocessing is a catalytic process that includes hydropyrolysis, hydroconversion and/or hydrotreating of certain carbon-containing materials to generate hydrocarbon fuels. Carbon-containing materials that may be used to generate hydrocarbon fuels via hydroprocessing include solid and/or liquid feedstocks from renewable resources such as, for example, biomass, waste plastics, and biorenewable fats and oils containing triglycerides, diglycerides, monoglycerides and free fatty acids or fatty acid esters. For example, a feedstock such as vegetable oil yields biofuels having desirable cetane indices (e.g., a cetane index greater than 46). However, due to the large amount of linear paraffins (e.g., saturated long chain hydrocarbons having at least 15 carbon atoms) present in the biofuel, the cold flow properties of the biofuel produced from highly saturated feedstock may be undesirable. For example, the biofuels having a high linear paraffinic content (e.g., greater than or equal to approximately 95 wt%) may have a cloud point (CP) or cold filter plugging point (CFPP) greater than 15 °C. Accordingly, biofuel derived from vegetable oil undergoes a hydroisomerization process to generate non-linear, which improves the CP and CFPP of the biofuel. The non-linear paraffins in the biofuel, however, may negatively affect the outcome of standardized test methods used to determine the oxidation stability of the fuel such as oxidation stability test standard EN 12205.

**[0020]** In contrast, solid biomass feedstock such as lignocellulosic materials (e.g., wood), among others, are highly cyclic (e.g., greater than 75 wt% of hydrocarbons are in rings). For example, the lignocellulosic materials include cyclic compounds such as aromatics, non-aromatics, and carbohydrates. As such, these highly cyclic feedstocks result in biofuels having non-linear and cyclic paraffins which results in cold flow properties suitable for cold climates (e.g., climates where ambient temperatures may fall below freezing temperature of water, 0 °C). Besides these cyclic paraffins or naphthenes, these biofuels also contain unsaturated cyclic compounds and aromatics. The aromatic content of these biofuels may be undesirable (e.g., aromatic content of greater than 25 wt%), resulting in a cetane index that is not within the required specification for commercial use. For example, the cetane index for biofuels resulting from hydroprocessing of solid biomass materials may be less than 46. Moreover, certain aromatic compounds in these biofuels may promote and/or facilitate oxidative degradation, thereby degrading the biofuel over time. Accordingly, these biofuels may undergo additional processing and/or include additives to

- 7 -

upgrade and yield commercially suitable transportation biofuels having the desired cetane index and/or oxidation stability.

**[0021]** For example, gasoils (GO) (e.g., diesel) generated via catalytic hydrothermal liquefaction and hydroconversion of solid biomass feedstock are generally dense (e.g., a density greater than approximately 845 kilograms (kg)/cubic meter ( $\text{m}^3$ )), and have a high unsaturated hydrocarbon content (e.g., greater than approximately 75% wt%) and a low amount of linear paraffinic compounds (e.g., less than approximately 25 wt%). The high aromaticity of the biodiesel results in low cetane indices (e.g.,  $< 46$ ), and in certain instances undesirable oxidation stability, thereby its quality and/or performance as a transportation fuel is undesirable and may not meet the specifications set forth by regulatory agencies. While the low amount of linear paraffinic compounds in these highly aromatic biodiesels results in desirable cold flow properties (e.g., cloud point and cold filter plugging point temperatures), the aromaticity results in low cetane indices (e.g., less than approximately 46) and undesirable oxidation stability. As such, these biodiesels generally undergo costly and extensive hydrotreating to reduce the aromaticity and increase the cetane index above approximately 46 and improve the oxidation stability. In certain instances, hydrotreating may not be enough to upgrade the biodiesel into a suitable transportation biofuel, and the hydrotreated biodiesel undergoes additional processing and is mixed with additives to improve its properties. Therefore, biodiesel fractions derived from solid biomass feedstock may be combined with cetane and/or oxidation stability improving additives and/or fossil-derived diesel or sold in markets without meeting specifications, thereby increasing the carbon footprint of these biodiesels. Accordingly, it may be desirable to develop biodiesel (GO) formulations that do not require upgrading or the use of additives (e.g., oxidation stabilizers) to improve the cetane index and/or oxidation stability.

**[0022]** Unlike hydroprocessing of solid biomass, hydroprocessing biorenewable fats and oils (e.g., vegetable oil) generates hydrotreated esters and fatty acids (HEFA) that have low aromaticity (e.g., less than or equal to approximately 1 wt%) and high linear paraffinic content (e.g., greater than or equal to approximately 95 wt%) compared to the biodiesel generated from hydrothermal liquefaction and hydroconversion of the solid biomass feedstock. The low aromaticity of the HEFA is desirable because it yields biodiesel having cetane indices greater than 46, which meet

- 8 -

regulatory specifications for commercial use. However, the high linear paraffinic content in the HEFA results in undesirable cold flow properties (e.g., cloud point and cold filter plugging point temperatures greater than 15 °C). Therefore, HEFA derived biodiesel may not be suitable for use in climates in which the temperatures are less than 0 °C. Accordingly, similar to the solid biomass-derived biodiesel, the HEFA derived biodiesel undergoes additional processing to hydroisomerize the *n*-paraffins to generate iso-paraffins, and improve the cold flow properties of the biodiesel. However, due to the iso-paraffinic content of the HEFA in isomerized HEFA-derived biofuels, these biofuels may show a high oxidative degradation tendency when tested according to oxidation stability test standard EN 12205 used to determine oxidation stability for biofuels in European and other markets. For example, not wishing to be bound by theory, the iso-paraffins present in isomerized HEFA biofuels form stable radicals due to factors such as, but not limited to, the presence of air, oxygen, elevated temperatures, metals, and combinations thereof. These radicals begin a chain reaction that may decompose other components in the biofuel formulation, such as esters and fatty acids present in the biofuel. Additionally, due to the very low content (e.g., less than 10 parts per million weight (ppmw) of heteroatoms (nitrogen (N), sulfur (S)), HEFA-derived biofuels may have undesirable lubricity.

[0023] Moreover, HEFA may have an undesirable low density. For example, isomerized HEFA biodiesel may have a density of between 760 and 800 kg/m<sup>3</sup>, which does not meet the minimum density specification of 825 kg/m<sup>3</sup> for ultra-low sulfur diesel (ULSD) in Europe. As such, diesel boiling range fractions (e.g., boiling point range 180-360 °C) derived from isomerized HEFA are combined with fossil-derived diesel having a higher density and, in certain instances, a lower cloud point compared to isomerized HEFA alone. Consequently, certain biodiesel may be low quality and/or have an undesirable oxidation stability and carbon footprint (e.g., when combined with fossil-derived fuels). Therefore, certain isomerized HEFA derived biofuel fractions may undergo additional processing to continue upgrading and improving the cold flow properties and quality of the biofuel. The degree of isomerization of the HEFA may depend on target use for HEFA derived biofuels.

[0024] Additional processing of biodiesel to upgrade and improve the cetane index/number, density, cold flow properties, oxidation stability, and/or lubricity may be

- 9 -

cumbersome, inefficient and costly. Addition of additives that improve these properties may also be costly. In addition, renewable and fossil-derived fuel blends have a higher carbon footprint/intensity compared to biofuels alone. Therefore, there is a current need to improve the quality of biofuels derived from renewable resources such that they may be used as transportation fuels without the need for additional costly processing and additives to upgrade the biofuels and/or blending with fossil-derived fuels. Accordingly, disclosed herein is a biodiesel blend having a mixture of an intermediate product produced from hydroprocessing of a solid biomass feedstock and isomerized HEFA. Surprisingly, as discussed in further detail below, the hydroprocessing intermediate products may be combined with the isomerized HEFA to yield biodiesel fuel blends having improved oxidation stability when tested according to oxidation stability test standard EN 12205 and lubricity compared to the respective biofuel alone. In addition, the biodiesel fuel blends have the desired cetane index/number and density. As such, by blending the hydroprocessing intermediate products with the isomerized HEFA, costly upgrading processes such as hydropolishing and additives may be omitted or reduced when producing commercially viable biodiesel fuels.

[0025] With the foregoing in mind, **FIG. 1** is a block diagram of an embodiment of a system **10** that may be used for hydroprocessing solid feedstocks (e.g., biomass and/or waste plastics/oils) to generate one or more hydrocarbon products (e.g., GO/diesel, gasoline, kerosene, etc.) used to generate at least a portion of the biofuel blend disclosed herein. As should be appreciated, the solid feedstock-derived hydrocarbon products disclosed herein may be generated by any suitable hydroprocessing technique such as those disclosed in U.S. Patent No. 9,447,328, which is hereby incorporated by reference in its entirety. In the illustrated embodiment, the system **10** includes a hydropyrolysis reactor **14** and a hydroconversion reactor **16**. As discussed in further detail below, the reactors **14**, **16** are used to convert a solid feedstock into an intermediate hydrocarbon fuel fraction (e.g., a GO/diesel fraction) that may be used in combination with a hydrotreated ester and fatty acid (HEFA) to generate a commercially viable biodiesel. As illustrated, the reactors **14**, **16** are disposed within one of two stages. For example, the system **10** includes a first stage **18** and a second stage **20**. The first stage **18** includes the hydropyrolysis reactor **14**, and the second stage **20** includes the hydroconversion reactor **16**. The reaction pressure in the first stage **18** and the second stage **20** may be varied to tailor the boiling point distribution

- 10 -

and composition of the resultant hydrocarbon product(s) generated by the second stage **18**. The ability to tailor the boiling point distribution and/or composition of the resultant hydrocarbon product by varying the reaction pressure may provide an efficient process for generating commercially viable hydrocarbon biofuels that meet the different requirements set forth by the location and/or market in which the hydrocarbon biofuel will be used. For example, when the reaction pressure is less than approximately 0.6 megapascals (MPa) the occurrence of undesirable olefin and/or aromatic saturation reactions may be decreased and cetane numbers for biodiesel and/or gasoline fractions may be increased compared to reaction pressures above 2.0 MPa. However, the cetane numbers may still not be at a desired level to meet specifications set forth for commercial biodiesel fuels. Therefore, the biodiesel fraction may need to undergo additional processing (e.g., hydropolishing) to upgrade the biodiesel and increase the cetane number above approximately 50. However, as discussed in further detail below, the biodiesel fraction may be combined with a HEFA such that upgrading the biodiesel fraction is not necessary to improve the cetane number.

#### First Stage

[0026] In the illustrated embodiment, a solid feedstock **24** having biomass (e.g., lignocellulose) and/or waste plastics and molecular hydrogen (H<sub>2</sub>) **28** are introduced into the hydrolysis reactor **14**. The hydrolysis reactor **14** contains a deoxygenation catalyst that facilitates partial deoxygenation of the solid feedstock **24**. For example, in the hydrolysis reactor **14**, the solid feedstock **24** undergoes hydrolysis, producing an output **30** having char, partially deoxygenated products of hydrolysis, light gases (C<sub>1</sub> - C<sub>3</sub> gases, carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and H<sub>2</sub>), water (H<sub>2</sub>O) vapor and catalyst fines. The hydrolysis reactor **14** may be a fluidized bed reactor (e.g., a fluidized bubbling bed reactor), fixed-bed reactor, or any other suitable reactor. In embodiments in which the hydrolysis reactor **14** is a fluidized bed reactor, the fluidization velocity, catalyst particle size and bulk density and solid feedstock particle size and bulk density are selected such that the deoxygenation catalyst remains in the bubbling fluidized bed, while the char produced is entrained with the partially deoxygenated products (e.g., the output **30**) exiting the hydrolysis reactor **14**. The hydrolysis step in the first stage **18** employs a rapid heat up of the solid feedstock **24** such that a residence time of

- 11 -

the pyrolysis vapors in the hydropyrolysis reactor **14** is preferably less than approximately 1 minute, more preferably less than approximately 30 seconds and most preferably less than approximately 10 seconds.

**[0027]** The solid feedstock **24** used in the disclosed process may include a residual waste feedstock and/or a biomass feedstock containing lignin, lignocellulosic, cellulosic, hemicellulosic material, or any combination thereof. Lignocellulosic material may include a mixture of lignin, cellulose and hemicelluloses in any proportion and also contains ash and moisture. Such material is more difficult to convert into fungible liquid hydrocarbon products than cellulosic and hemicellulosic material. It is an advantage of the present process that it can be used for lignocellulose-containing biomass. Therefore, the solid feedstock **24** used in the disclosed process preferably contains lignocellulosic material. Suitable lignocellulose-containing biomass includes woody biomass and agricultural and forestry products and residues (whole harvest energy crops, round wood, forest slash, bamboo, sawdust, bagasse, sugarcane tops and trash, cotton stalks, corn stover, corn cobs, castor stalks, *Jatropha* whole harvest, *Jatropha* trimmings, de-oiled cakes of palm, castor and *Jatropha*, coconut shells, residues derived from edible nut production and mixtures thereof), and municipal solid wastes containing lignocellulosic material. The municipal solid waste may include any combination of lignocellulosic material (yard trimmings, pressure-treated wood such as fence posts, plywood), discarded paper and cardboard and waste plastics, along with refractories such as glass, metal. Prior to use in the process disclosed herein, municipal solid waste may be optionally converted into pellet or briquette form. The pellets or briquettes are commonly referred to as Refuse Derived Fuel in the industry. Certain feedstocks (such as algae and lemna) may also contain protein and lipids in addition to lignocellulose. Residual waste feedstocks are those having mainly waste plastics. In a preferred embodiment of the process disclosed herein, woody biomass, preferably wood, is used as the source of the biomass.

**[0028]** The solid feedstock **24** may be provided to the hydropyrolysis reactor **14** in the form of loose biomass particles having a majority of particles preferably less than about 3.5 millimeters (mm) in size or in the form of a biomass/liquid slurry. However, as appreciated by those skilled in the art, the solid feedstock **24** may be pre-treated or otherwise processed in a manner such that larger particle sizes may be accommodated. Suitable means for introducing the

- 12 -

solid feedstock **24** into the hydrolysis reactor **14** include, but are not limited to, an auger, fast-moving (greater than about 5 minutes (m)/second (sec)) stream of carrier gas (such as inert gases and H<sub>2</sub>), and constant-displacement pumps, impellers, turbine pumps or the like. In an embodiment of the present disclosure, a double-screw system having a slow screw for metering the solid feedstock **24** followed by a fast screw to push the solid feedstock **24** into the reactor without causing torrefaction in the screw housing is used for dosing. An inert gas or hydrogen flow is maintained over the fast screw to further reduce the residence time of the solid feedstock **24** in the fast screw housing.

**[0029]** The hydrolysis step is carried out in the hydrolysis reactor **14** at a temperature in the range of from approximately 350 Celsius (°C) to approximately 600 °C and a pressure in the range of from approximately 0.1 megapascal (MPa) to approximately 0.6 MPa (approximately 1-6 bar). The heating rate of the solid feedstock **24** is preferably greater than about 100 watts/meter<sup>2</sup> (W/m<sup>2</sup>). The weight hourly space velocity (WHSV) in grams (g) biomass/g catalyst/hour (h) for the hydrolysis step is in the range of from approximately 0.2 h<sup>-1</sup> to approximately 10 h<sup>-1</sup>, preferably in the range of from approximately 0.3 h<sup>-1</sup> to 3 h<sup>-1</sup>.

**[0030]** The hydrolysis step may operate at a temperature between approximately 300 °C and 650 °C. The temperatures used in hydrolysis rapidly devolatilize the solid feedstock **24**. Thus, in a preferred embodiment, the hydrolysis step includes the use of an active catalyst (e.g., a deoxygenation catalyst) to stabilize the hydrolysis vapors. The activity of the catalyst used herein remains high and stable over a long period of time such that it does not rapidly coke. Catalyst particle sizes, for use in the hydrolysis reactor **14**, are preferably in the range of from approximately 0.3 millimeter (mm) to approximately 4.0 mm, more preferably in the range of from approximately 0.6 mm to approximately 3.0 mm, and most preferably in the range of from approximately 1 mm to approximately 2.4 mm.

**[0031]** Any deoxygenation catalyst suitable for use in the temperature range of the hydrolysis process may be used. Preferably, the deoxygenation catalyst is selected from sulfided catalysts having one or more metals from the group consisting of nickel (Ni), cobalt (Co), molybdenum (Mo) or tungsten (W) supported on a metal oxide. Suitable metal combinations include sulfided NiMo, sulfided CoMo, sulfided NiW, sulfided CoW and sulfided ternary metal

- 13 -

systems having any 3 metals from the family consisting of Ni, Co, Mo and W. Monometallic catalysts such as sulfided Mo, sulfided Ni and sulfided W are also suitable for use. Metal combinations for the deoxygenation catalyst used in accordance with certain embodiments of the present disclosure include sulfided NiMo and sulfided CoMo. Supports for the sulfided metal catalysts include metal oxides such as, but not limited to, alumina, silica, titania, ceria and zirconia. Binary oxides such as silica-alumina, silica-titania and ceria-zirconia may also be used. Preferably, the supports include alumina, silica and titania. In certain embodiments, the support contains recycled, regenerated and revitalized fines of spent hydrotreating catalysts (e.g., fines of CoMo on oxidic supports, NiMo on oxidic supports and fines of hydrocracking catalysts containing NiW on a mixture of oxidic carriers and zeolites). Total metal loadings on the deoxygenation catalyst are preferably in the range of from approximately 1.5 weight percent (wt%) to approximately 50 wt% expressed as a weight percentage of calcined deoxygenation catalyst in oxidic form (e.g., weight percentage of Ni (as NiO) and Mo (as MoO<sub>3</sub>) on calcined oxidized NiMo on alumina support). Additional elements such as phosphorous (P) may be incorporated into the deoxygenation catalyst to improve the dispersion of the metal.

**[0032]** The first stage of the process disclosed herein produces the output **30** having a partially deoxygenated hydropyrolysis product. The term “partially deoxygenated” as used herein denotes a material in which at least 30 weight % (wt%), preferably at least 50 wt%, more preferably at least 70 wt% of the oxygen present in the original solid feedstock **24** (e.g., lignocelluloses-containing biomass) has been removed. The extent of oxygen removal refers to the percentage of the oxygen in the solid feedstock **24** (e.g., biomass), excluding that contained in the free moisture in the solid feedstock **24**. This oxygen is removed in the form of water (H<sub>2</sub>O), carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) in the hydropyrolysis step. Although it is possible that nearly 100 wt% of the oxygen present in the solid feedstock **24** is removed, generally at most 99 wt%, suitably at most 95 wt% will be removed in the hydropyrolysis step.

#### Char Removal

**[0033]** As discussed above, the output **30** produced from the hydropyrolysis step in the hydropyrolysis reactor **14** includes a mixed solid and vapor product that includes char, ash, catalyst fines, partially deoxygenated hydropyrolysis product, light gases (C<sub>1</sub> - C<sub>3</sub> gases, CO, CO<sub>2</sub>,

- 14 -

hydrogen sulfide (H<sub>2</sub>S), ammonia (NH<sub>3</sub>) and H<sub>2</sub>), H<sub>2</sub>O vapor, vapors of C<sub>4+</sub> hydrocarbons and oxygenated hydrocarbons. Char, ash and catalyst fines are entrained with the vapor phase product. Therefore, between the hydropyrolysis and hydroconversion steps, the first stage **18** and the second stage **20**, respectively, char and catalyst fines are removed from the vapor phase product (e.g., the partially deoxygenated hydropyrolysis product). Any ash present may also be removed at this stage.

**[0034]** In certain embodiments, the hydropyrolysis reactor **14** may include solid separation equipment (e.g., cyclones), for example above a dense bed phase, to mitigate the entrainment of solid particles above a certain particle size. In addition, or alternatively, the solid separation equipment may be positioned downstream from the hydropyrolysis reactor **14** that removes the char and other solids in the output **30** to generate a vapor phase product **34**. For example, as illustrated in **FIG. 1**, the output **30** is fed to a solid separator **36** that separates/removes the solids (e.g., char, ash and catalyst fines **38**) from the output **30**. The char and catalyst fines **38** may be removed from the output **30** by cyclone separation, filtering, electrostatic precipitation, inertial separation, magnetic separation, or any other suitable solid separation technique and combinations thereof. In one embodiment, the solid separator **36** includes one or more cyclones. For example, char may be removed by filtration from the vapor stream (e.g., the output **30**) or by way of filtering from a wash step-ebullated bed. Back pulsing may be employed in removing char and other solids from the filters as long as hydrogen used in the disclosed process sufficiently reduces the reactivity of the pyrolysis vapors and renders the char free-flowing.

**[0035]** In other embodiments, the solid separator **36** includes one or more filters or a combination of cyclones, filters and other suitable solid separation equipment to remove the entrained solids from the output **30**. For example, the char **38** and other solids may be removed by cyclone separation followed by hot gas filtration. The hot gas filtration removes fines not removed in the cyclones. In this embodiment, the dust cake caught on the filters is more easily cleaned compared to the char removed in the hot filtration of the aerosols produced in conventional fast pyrolysis because the hydrogen from the hydropyrolysis step stabilizes the free radicals and saturated the olefins. In accordance with another embodiment of the present disclosure, cyclone separation followed by trapping the char and catalyst fines **38** in a high-porosity solid adsorbent

- 15 -

bed is used to remove the char and catalyst fines **38** from the output **30**. By way of non-limiting example, high-porosity solid adsorbents suitable for trapping the char and catalyst fines **38** include alumina silicate materials. Inert graded bed and/or filter materials may also be used to remove the char and catalyst fines **38** from the output **30** to generate the vapour phase product **34**.

**[0036]** The char and catalyst fines **38** may also be removed by bubbling the first stage product gas (e.g., the output **30**) through a re-circulating liquid. The re-circulated liquid includes a high boiling point portion of a finished oil from this process (e.g., from the second stage **20**) and is thus a fully saturated (hydrogenated), stabilized oil having a boiling point above approximately 370 °C. In certain embodiments, the finished oil may be a heavy oil generated in a separate process. The char or catalyst fines **38** from the first stage **18** are captured in this liquid. A portion of the liquid may be filtered to remove the fines **38** and a portion may be re-circulated back to the hydropyrolysis reactor **14**. By using a re-circulating liquid, the temperature of the char-laden process vapors from the first stage **18** is lowered to a temperature suitable for the hydroconversion step in the second stage **20**, while also removing fine particulates of char and catalyst. Additionally, employing liquid filtration avoids the use of hot gas filtration.

**[0037]** In accordance with another embodiment of the present disclosure, large-size NiMo or CoMo catalysts, deployed in an ebullated bed, are used for char removal to provide further deoxygenation simultaneous with the removal of fine particulates. Particles of this catalyst should be large, preferably in the range of from 15 to 30 mm in size, thereby rendering them easily separable from the fine char carried over from the hydropyrolysis reactor **14**, which is generally less than 200 mesh (smaller than 70 micrometers (μm)).

#### Second Stage

**[0038]** Following removal of the char and catalyst fines **38**, the vapor phase product **34** (e.g., the partially deoxygenated hydropyrolysis product) together with the H<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, and C<sub>1</sub> - C<sub>3</sub> gases from the hydropyrolysis step (e.g., the first stage **18**) are fed into the hydroconversion reactor **16** in the second stage **20** and subjected to a hydroconversion step. The hydroconversion step is carried out at a temperature in the range of from approximately 300 °C to approximately 600 °C and a pressure in the range of from approximately 0.1 MPa to approximately 0.6 MPa. As should be noted, pressures higher than 0.6 MPa may be used to tailor the boiling point distribution

- 16 -

and composition of the resultant hydrocarbon product based on the desired specifications of the hydrocarbon fuel produced by the hydroprocessing. The weight hourly space velocity (WHSV) for this step is in the range of approximately  $0.1 \text{ h}^{-1}$  to approximately  $2 \text{ h}^{-1}$ . The hydroconversion reactor **16** is a fixed bed reactor. However, in certain embodiments, the hydroconversion reactor **16** may be a fluidized bed reactor. The vapor phase product **34** undergoes hydroconversion in the presence of a hydroconversion catalyst to generate a fully deoxygenated hydrocarbon product **42**. The term “fully deoxygenated” as used herein denotes a material in which at least 98 wt%, preferably at least 99 wt%, more preferably at least 99.9 wt% of the oxygen present in the original solid feedstock **24** (e.g., lignocelluloses-containing biomass) has been removed. The hydrocarbon product **42** contains light gaseous hydrocarbons, such as methane, ethane, ethylene, propane and propylene, naphtha range hydrocarbons, middle-distillate range hydrocarbons, hydrocarbons boiling above  $370 \text{ }^{\circ}\text{C}$  (based on EN ISO 3405/ASTM D86), hydrogen and by-products of the hydroconversion reactions such as  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{S}$ ,  $\text{NH}_3$ ,  $\text{CO}$  and  $\text{CO}_2$ .

**[0039]** The solid feedstock **24** used in the disclosed processes may contain metals such as, but not limited to, sodium (Na), potassium (K), calcium (Ca) and phosphorus (P). These metals may poison the hydroconversion catalyst used in the second stage **20**. However, these metals may be removed with the char and ash products (e.g., the char and catalyst fines **38**) in the first stage **18**. Accordingly, the hydroconversion catalyst used in the hydroconversion step is protected from Na, K, Ca, P, and other metals present in the solid feedstock **24** which may otherwise poison the hydroconversion catalyst. Moreover, by hydrothermal treatment of the solid feedstock **24** in the first stage **18**, the hydroconversion catalyst is advantageously protected from olefins and free radicals. The conditions under which hydrothermal treatment occurs in the first stage **18** stabilize free radicals generated during high temperature devolatilization of the solid feedstock **24** (e.g., biomass) by the presence of hydrogen and catalyst, thereby generating stable hydrocarbon molecules that are less prone to, for example, coke formation reactions which may deactivate the catalyst.

**[0040]** The hydroconversion catalyst used in the hydroconversion step includes any suitable hydroconversion catalyst having a desired activity in the temperature range of the disclosed hydroconversion process. For example, the hydroconversion catalyst is selected from sulfided catalysts having one or more metals from the group consisting of Ni, Co, Mo or W

- 17 -

supported on a metal oxide. Suitable metal combinations include sulfided NiMo, sulfided CoMo, sulfided NiW, sulfided CoW and sulfided ternary metal systems having any three metals from the family consisting of Ni, Co, Mo and W. Catalysts such as sulfided Mo, sulfided Ni and sulfided W are also suitable for use. The metal oxide supports for the sulfided metal catalysts include, but are not limited to, alumina, silica, titania, ceria, zirconia, as well as binary oxides such as silica-alumina, silica-titania and ceria-zirconia. Preferred supports include alumina, silica and titania. The support may optionally contain regenerated and revitalized fines of spent hydrotreating catalysts (e.g., fines of CoMo on oxidic supports, NiMo on oxidic supports and fines of hydrocracking catalysts containing NiW on a mixture of oxidic carriers and zeolites). Total metal loadings on the catalyst are in the range of from approximately 5 wt% to approximately 35 wt% (expressed as a weight percentage of calcined catalyst in oxidic form, e.g., weight percentage of nickel (as NiO) and molybdenum (as MoO<sub>3</sub>) on calcined oxidized NiMo on alumina catalyst). Additional elements such as phosphorous (P) may be incorporated into the catalyst to improve the dispersion of the metal. Metals can be introduced on the support by impregnation or co-mulling or a combination of both techniques. The hydroconversion catalyst used in the hydroconversion step may be, in composition, the same as or different to the deoxygenation catalyst used in the hydropyrolysis step (e.g., first stage **18**). In one embodiment of the present disclosure, the hydropyrolysis catalyst includes sulfided CoMo on alumina support and the hydroconversion catalyst includes sulfided NiMo on alumina support.

**[0041]** Following the hydroconversion step, the fully deoxygenated hydrocarbon product **42** is fed to one or more condensers that condenses the hydrocarbon product **42**. The condensed hydrocarbon product **42** is fed to a gas-liquid separator **50** to provide a liquid phase product **52** having substantially fully deoxygenated C<sub>4</sub><sup>+</sup> hydrocarbon liquid and aqueous material. The term “substantially fully deoxygenated” is used herein to denote a material in which at least 90 wt% to 99.5 wt% of the oxygen present in the original lignocellulose containing biomass (e.g., the solid feedstock **24**) has been removed. Accordingly, the resulting liquid phase product **52** (e.g., the substantially fully deoxygenated hydrocarbon C<sub>4</sub><sup>+</sup> liquid) contains less than 2 wt%, preferably less than 1 wt%, and most preferably less than 0.2 wt% oxygen. The substantially fully deoxygenated C<sub>4</sub><sup>+</sup> hydrocarbon liquid is compositionally different from bio-oil that is generated using other low pressure hydroprocesses. For example, the oxygen content of bio-oil is greater (e.g., between

- 18 -

approximately 5 wt% to 15 wt%) compared to the liquid phase product **52** (e.g., less than 2 wt%). Therefore, due, in part, to the lower oxygen content of the liquid phase product **52**, an amount of acid components (as measured by total acid number) and polar compounds is decreased compared to the bio-oil. By way of non-limiting example, the acid components include carboxylic acids, phenols and mixtures thereof.

[0042] The liquid phase product **52** undergoes a separation process in the gas-liquid separator **50** that separates and removes the aqueous material from the substantially fully deoxygenated C<sub>4+</sub> hydrocarbon liquid. Any suitable phase separation technique may be used to separate and remove the aqueous material from the substantially fully deoxygenated C<sub>4+</sub> hydrocarbon liquid, thereby generating the liquid phase product **52** having the substantially fully deoxygenated C<sub>4+</sub> hydrocarbon and non-condensable gases **54**. The non-condensable gases **54** includes mainly H<sub>2</sub>, CO, CO<sub>2</sub> and light hydrocarbon gases (typically C<sub>1</sub> to C<sub>3</sub> and may also contain some C<sub>4+</sub> hydrocarbons).

[0043] In certain embodiments, the non-condensable gases **54** are fed to a gas clean-up system **58**. The gas clean-up system **58** removes H<sub>2</sub>S, NH<sub>3</sub> and trace amounts of organic sulfur-containing compounds, if present, as by-products of the process, thereby generating a hydrocarbon stream **60** having CO, CO<sub>2</sub>, H<sub>2</sub> and the light hydrocarbon gases. The gas clean-up system **58** includes one or more process units that remove H<sub>2</sub>S **62** and NH<sub>3</sub> **64** from the non-condensable gases **54** as by-products of the process. The hydrocarbon stream **60** may be sent to a separation, reforming and water-gas shift section **68** where hydrogen **28** is produced from the light hydrocarbon gases in the hydrocarbon stream **60** and renewable CO<sub>2</sub> **70** is discharged as a by-product of the process. A fuel gas stream may be recovered as a by-product of this process. The produced hydrogen **28** may be re-used in the process. For example, the hydrogen **28** may be recycled to the hydropyrolysis reactor **14** in the first stage **18**. Sufficient hydrogen is produced for use in the entire process disclosed herein. That is, the quantity of the hydrogen **28** produced by the separation, reforming and water-gas shift section **68** is equal to or greater than the hydrogen required to maintain fluidization and sustain chemical consumption of hydrogen in the process.

[0044] The liquid phase product **52** recovered from the gas-liquid separator **50** is fed to a product recovery section **72**. In the product recovery section **72**, aqueous product **74** is removed

from the liquid phase product **52** to generate an intermediate liquid phase product **80**. The intermediate liquid phase product **80** may undergo distillation to separate the substantially fully deoxygenated C<sub>4+</sub> hydrocarbon liquid into fractions according to ranges of the boiling points of the liquid products contained in the intermediate liquid phase product **80**. For example, the substantially fully deoxygenated C<sub>4+</sub> hydrocarbon liquid in the intermediate liquid phase product **80** includes naphtha range hydrocarbons, middle distillate range hydrocarbons (e.g., gasoil, diesel) and vacuum gasoil (VGO) range hydrocarbons.

**[0045]** For the purpose of clarity, “middle distillates” as used herein are hydrocarbons or oxygenated hydrocarbons recovered by distillation between an atmospheric-equivalent initial boiling point (IBP) and a final boiling point (FBP) measured according to standard EN ISO/ASTM distillation methods. EN ISO 3405/ASTM D86 initial boiling point of middle distillates may vary from between approximately 150 °C to approximately 220 °C. Final boiling point of middle distillates, according to EN ISO 3405/ASTM D86 distillation, may vary from between approximately 350 °C to approximately 380 °C. “Naphtha” as used herein is one or more hydrocarbons or oxygenated hydrocarbons having four or more carbon atoms and having an atmospheric-equivalent final boiling point that is greater than approximately 90 °C but less than approximately 200 °C. A small amount of hydrocarbons produced in the process (approximately less than 3 wt% of total C<sub>4+</sub> hydrocarbons, and preferably less than 1 wt% of total C<sub>4+</sub> hydrocarbons) boil at temperatures higher than those for the middle distillates as defined above. That is, these hydrocarbons have a boiling range similar to vacuum-gasoil produced by distillation of petroleum. Gasoline is predominantly naphtha-range hydrocarbons and is used in spark-ignition internal combustion engines. In the United States, ASTM D4814 standard establishes the requirements of gasoline for ground vehicles with spark-ignition internal combustion engines. Gasoil (GO)/diesel is predominantly middle-distillate range hydrocarbons and is used in compression-ignition internal combustion engines. In the United States, ASTM D975 standard covers the requirements of several grades of diesel fuel suitable for various types of diesel engines.

**[0046]** Accordingly, in the illustrated embodiment, the intermediate liquid product **80** is fed to a distillation unit **82** to recover gasoline product **84** and a distillate product **86** (e.g., a middle distillate). In certain embodiments, kerosene/jet fuel **88** are recovered as separate streams from

- 20 -

the distillation unit **82**. The distillate product **86** (e.g., the middle distillate) contains gasoil (GO), for example biodiesel, and is substantially fully free from oxygen, sulfur and nitrogen. In certain embodiments, the oxygen content of the distillate product **86** is less than approximately 1.50 wt %. For example, the oxygen content may be approximately 1.40 wt %, 1.25 wt %, 0.50 wt %, or less. In one embodiment, the sulfur content is less than 100 ppmw. For example, the sulfur content may be approximately 75 ppmw, 50 ppmw, 25 ppmw, or less. Accordingly, the biodiesel obtained from the distillate product **86** may be considered as an ultra-low sulfur diesel (ULSD), if this distillate contains less than 10 ppmw sulfur. However, in certain embodiments, the distillate product **86** may not be desulfurized in a manner that reduces the sulfur content to less than 100 ppmw. Regarding the nitrogen content, in certain embodiments, the nitrogen content of the substantially fully deoxygenated C<sub>4+</sub> hydrocarbon liquid is less than 1000 ppmw. For example, the nitrogen content may be approximately 750 ppmw, 500 ppmw, 250 ppmw, 100 ppmw, 75 ppmw, 50 ppmw, 25 ppmw, or less. The presence of oxygen, nitrogen, and/or sulfur in the distillate product **86**, while low, may improve the lubricity of HEFA-derived biofuels when the distillate product **86** is mixed with the HEFA-derived biofuel.

[0047] As discussed above, hydrocarbon liquid products such as the distillate product **86** generated from hydroprocessing of solid biomass feedstock (e.g., the solid feedstock **24**) generally requires additional processing and/or additives to upgrade and improve product properties such as cetane number, oxidation stability, reduced density, reduced sulfur and/or nitrogen content, reduced benzene content (e.g., as a result of selective saturation), among others, and facilitate tailoring the overall hydrocarbon product to certain location and market specifications, among other benefits. However, the additional processing to upgrade the distillate product **86** introduces complexity to the process, while also increasing the overall cost of producing commercially viable biodiesel fuels having the desired specifications set forth by various fuel regulations. However, it has been recognized that by blending the distillate product **86** with a hydrotreated ester and/or fatty acid (HEFA), the product properties (e.g., cetane number, density, and oxidation stability) are improved without requiring additional processing and/or additives to upgrade the distillate product **86**. Therefore, in accordance with an embodiment of the present disclosure, the distillate product **86** is mixed with HEFA-derived biodiesel **90** to yield a commercially viable biodiesel blend **92** that does not require upgrading via complex and costly processing. As discussed in further detail

below, the HEFA-derived biodiesel **90** may be generated from hydroprocessing renewable fats and oils. The HEFA-derived biodiesel **90** may be non-isomerized HEFA (e.g., HEFA **128**), isomerized HEFA (e.g., isomerized HEFA **134**) or a combination of non-isomerized and isomerized HEFA.

**[0048]** As discussed above, blending the distillate product **86** with the HEFA-derived biodiesel **90** may provide biodiesel formulations having improved cetane number, oxidation stability, lubricity, and density, among other properties, compared to biodiesel fuel formulations made up of the distillate product **86** and the HEFA-derived biodiesel **90** alone. For example, by blending the distillate product **86** with the HEFA-derived biodiesel **90**, the aromaticity of the distillate product **86** may be decreased, thereby increasing the cetane number of the biodiesel blend **92** compared to the distillate product **86**. Moreover, the density of the biodiesel blend **92** may have a lower density compared to the density of the distillate product **86**. Additionally, it has been surprisingly found that when blending heavy distillate product (e.g., gas oil (GO) having a boiling point at or greater than 180 °C) with the HEFA-derived biodiesel (e.g. the HEFA-derived biodiesel **90**), the oxidation stability of the heavy distillate product was improved by approximately more than 95% compared to the heavy distillate product alone (see, e.g., Table 1). Therefore, by blending the distillate product **86** with the HEFA-derived biodiesel **90**, the resultant biodiesel blend **92** may not only have the desired cetane number and density to meet regulatory specifications, but also a desired oxidation stability without having to subject the distillate product **86** to additional processing used to upgrade the distillate product **86**. Moreover, the amount of additives added to the biofuel blend **92** that are typically used for improving properties such as oxidation stability may be omitted or reduced compared to an amount of additives used in biofuels made up of the individual components in the blend.

**[0049]** In certain embodiments, the HEFA-derived biodiesel **90** may be highly *n*-paraffinic (e.g., having linear long chain hydrocarbon having 15 carbon atoms or more). As discussed above, the cloud point (CP) and cold flow pour point (CFPP) of certain *n*-paraffinic HEFA compositions, are undesirable due to the *n*-paraffinic content. Therefore, these *n*-paraffinic HEFA compositions generally undergo hydroisomerization to isomerize *n*-paraffins, thereby generating shorter chain hydrocarbons (e.g., iso-paraffins) and decreasing the CP and CFPP temperatures. For example, the *n*-paraffinic HEFA composition is hydroisomerized such that the amount of iso-paraffinic

- 22 -

compounds in the HEFA composition results in a desirable cloud point (CP). However, while the CP of the isomerized HEFA-derived biofuel is improved compared to non-isomerized HEFA-derived biofuels, the oxidation stability of the isomerized HEFA-derived biofuel is undesirable when tested according to the oxidation stability test standard EN 12205. Without wishing to be bound by theory, the undesirable oxidation stability test results obtained on the isomerized HEFA-derived biofuels may be due, in part, to the non-linear/branched paraffins. For example, the non-linear/branched paraffins may form stable radicals that catalyze radical chain reactions in the presence of air, oxygen, and elevated temperatures or combinations thereof. However, as it has been surprisingly found, by blending the isomerized-HEFA derived biofuel with GO derived from biorenewable feedstocks (e.g., the distillate product **86**), the oxidation stability result obtained according to oxidation stability test standard EN 12205 is improved compared to that of the isomerized-HEFA biofuel alone obtained according to the same oxidation stability test standard. For example, blending the isomerized HEFA-derived biofuel with the gas oil may improve the oxidation stability test result by at least approximately 85%. Additionally, it was surprisingly found that the lubricity of the HEFA-derived biofuels is also improved compared to biofuels having the isomerized HEFA as the only component. For example, the lubricity of the isomerized HEFA-derived biofuel may be improved by at least approximately 40%.

**[0050]** The HEFA-derived biodiesel **90** may be generated by any suitable hydroprocessing technique such as those disclosed in U.S. Patent No. 8,912,374, which is hereby incorporated by reference in its entirety. By way of non-limiting example, **FIG. 2** is a block diagram of a system **100** that may be used for hydroprocessing renewable fats and oil to generate the HEFA-derived biodiesel **90**. The system **100** includes a hydrotreating reactor **102** having one or more catalyst beds **104**. Each catalyst bed **104** may be on a catalyst support grid with a distribution/redistribution tray placed above each catalyst bed **104**. The hydrotreating reactor **102** may also include quench mixing devices having quench fluid inlets **106** on an outer wall of the hydrotreating reactor **102**.

**[0051]** In the illustrated embodiment, a renewable feedstock **108** having a renewable fat or oil (e.g., vegetable oil) is introduced into the hydrotreating reactor **102** along with hydrogen ( $H_2$ ) gas **112**. The  $H_2$  gas **112** may be from any suitable source. In certain embodiments, the  $H_2$  gas **112** may be a “green hydrogen,” which may be generated by electrolysis of water powered from

- 23 -

wind and/or photovoltaic energy. While in the hydrotreating reactor **102**, the renewable feedstock flows through and contacts the hydrotreating catalyst in the one or more catalyst beds **104**. The hydrotreating catalyst facilitates hydrogenation, hydrodeoxygenation, hydrodenitrogenation, and hydrodesulfurization reactions in the hydrotreating reactor **102**. The hydrotreating reactor **102** may be a fluidized bed reactor, fixed-bed reactor or any other suitable reactor.

[0052] The renewable feedstock **108** used in the hydrotreating reactor **102** may include vegetable oils, oils obtained from algae and animal fats having triglycerides, diglycerides, monoglycerides and free fatty acids or fatty acid esters. In certain embodiments, the renewable feedstock **108** may include deconstructed materials such as pyrolyzed recyclable materials or wood. By way of non-limiting example, the renewable feedstock **108** may include fatty acid methyl esters, fatty acid ethyl esters, algal oil, brown grease, canola oil, carinata oil, castor oil, coconut oil, colza oil, corn oil, cottonseed oil, fish oil, hempseed oil, jatropha oil, lard, linseed oil, milk fats, mustard oil, olive oil, palm oil, peanut oil, rapeseed oil, sewage sludge, soy oils, soybean oil, sunflower oil, tall oil, tallow, train oil, used cooking oil, yellow grease, the like and combinations thereof. In certain embodiments, the renewable feedstock **108** may be pretreated prior to feeding to the hydrotreating reactor **102** to remove impurities and other undesirable components. The renewable feedstock **108** is provided to the hydrotreating reactor **102** via any suitable means such as via a pump.

[0053] Hydroprocessing the renewable feedstock **108** is carried out in the hydroprocessing reactor **102** in the presence of hydrogen (e.g., the hydrogen gas **112**) at a pressure in a range of between approximately 1.0 MPa to approximately 20 MPa and at a temperature in a range of from approximately 200 °C to 410 °C. Preferably, the pressure is selected from 2.0 MPa to 15 MPa, and the temperature is in the range of from 200 to 400°C, more preferably from 240 to 390°C, most preferably from 260 to 385°C. The liquid hourly space velocity is in a range of from approximately 0.3 m<sup>3</sup>/m<sup>3</sup>.h to 5 m<sup>3</sup>/m<sup>3</sup>.h based on fresh feed. In certain embodiments, the total feed entering the hydrotreating reactor **102** may have approximately 50-20000 ppmw, preferably 1000-8000 ppmw, most preferably 2000-5000 ppmw of sulfur, calculated as elemental sulfur. The term “total feed” is intended to denote the total of fresh feed and any optional diluting agent(s).

- 24 -

The ratio of the hydrogen gas **112** to the renewable feedstock **108** (excluding diluent) supplied to the hydrotreating reactor **102** is in a range of from approximately 200 to 10,000 normal L (at standard conditions of 0 °C and 1 atm (0.101 MPa)) per kg of the renewable feedstock **108**, preferably from approximately 500 to 8,000 NL/kg, more preferably from approximately 800 to 3,000 NL/kg.

**[0054]** Hydrotreating of the renewable feedstock **108** in the hydroprocessing reactor **102** is an exothermic process. Therefore, to control any temperature increase in the catalyst bed **104**, a staged supply of the renewable feedstock **108** and/or the hydrogen **112** may be applied. In certain embodiments, the renewable feedstock **108** may be diluted, preferably by recycling a portion of a hydrotreated liquid stream. Alternatively, a quench fluid (e.g., a hydrotreated liquid stream and/or recycle gas) may be fed to the hydroprocessing reactor **102** between each catalyst bed **104** via the quench fluid inlets **106**.

**[0055]** Each catalyst bed **104** includes a catalyst suitable for hydrotreating. The hydrotreating catalyst includes metals of Group VIII and/or Group VIB. In certain embodiments, the metals are in sulfided form rather than in the oxide form. By way of non-limiting example, the hydrotreating catalyst active metal includes sulfided nickel, sulfided cobalt, sulfided molybdenum, sulfided tungsten, sulfided CoMo, sulfided NiMo, sulfided MoW, sulfided NiW, and combinations thereof. In certain embodiments, the catalyst may have a mixture of two types of catalysts. In other embodiments, successive catalyst beds **104**, including stacked beds, may have the same or different catalysts and/or catalyst blends. When using a sulfided hydrotreating catalyst, a sulfur source will typically be supplied to the hydrotreating catalyst in order to keep the catalyst in sulfided form during the hydrotreating step. The hydrotreating catalyst may be sulfided in-situ or ex-situ. In-situ sulfiding may be achieved by supplying a sulfur source, usually H<sub>2</sub>S or an H<sub>2</sub>S precursor (i.e. a compound that easily decomposes into H<sub>2</sub>S such as, for example, dimethyl disulfide, di-tert-nonyl polysulfide or di-tert-butyl polysulfide) to the hydrotreating catalyst during operation of the process. The sulfur source may be supplied with the feed, the hydrogen stream, or separately. An alternative suitable sulfur source is a sulfur-containing hydrocarbon stream boiling in the diesel or kerosene boiling range that is co-fed with the feedstock. In addition, added

sulfur compounds in hydrotreating feed facilitate the control of catalyst stability and reduce hydrogen consumption.

**[0056]** The hydrogenation catalyst may be used in bulk metal form or the metals may be supported on a carrier. Suitable carriers include refractory oxides, molecular sieves and combinations thereof. Examples of suitable refractory oxides include, but are not limited to, alumina, amorphous silica-alumina, titania, silica, and combinations thereof.

**[0057]** Hydrotreating the renewable feedstock **108** in the hydrotreating reactor **102** produces an effluent **116** having a hydrotreated liquid and a vapor phase having hydrogen, H<sub>2</sub>S, CO<sub>2</sub>, carbon monoxide and light hydrocarbons. The effluent **116** is separated into one or more liquid streams and one or more offgas streams. For example, in the illustrated embodiment, the effluent **116** is fed to a separation system **120** that separates the effluent **116** into one or more liquid streams and one or more offgas streams **126**. The offgas stream **126** may be fed to one or more treatment systems for desulfurization. The hydrotreating process may also generate additional streams such as, but not limited to, a hydrogen-enriched stream, a CO-enriched stream and a HEFA **128**.

**[0058]** The separation system **120** may include, for example, gas/liquid separators, including hot high- and low-pressure separators, intermediate high- and low-pressure separators, cold high- and low-pressure separators, strippers, integrated strippers and combinations thereof. Integrated strippers include strippers that are integrated with hot high- and low-pressure separators, intermediate high- and low-pressure separators, cold high- and low-pressure separators. It will be understood by those skilled in the art that high-pressure separators operate at a pressure that is close to the pressure of the hydrotreating reactor **102**, suitably between approximately 0 and 1 MPa below the reactor outlet pressure, while a low-pressure separator is operated at a pressure that is lower than the pressure of the hydrotreating reactor **102** or high-pressure separator, between approximately 0 and 1.5 MPa. Similarly, the hot-separator is operated at a temperature that is close to the temperature of the hydrotreating reactor **102**, which is, for example,  $\geq 20$  °C, preferably  $\geq 10$  °C above the water dew point and greater than salt deposition temperatures (e.g.,  $\geq 20$  °C, preferably  $\geq 10$  °C, above the salt deposition temperature), while intermediate- and cold-separators are at a reduced temperature relative to the temperature of the hydrotreating reactor **102**. For

- 26 -

example, a cold-separator is generally at a temperature that can be achieved via an air cooler. An intermediate temperature will be understood to mean any temperature between the temperature of a hot- or cold-separator.

[0059] As discussed above, the separation system **120** separates the vapor phase from the hydrotreated liquid to generate the HEFA **128** and the offgas stream **126**. The HEFA **128** is made up of mostly linear paraffinic compounds (*n*-paraffins) and has a low amount of aromatic compounds if any. Therefore, the cetane number of the HEFA **128** is greater than 50, which is desirable for commercially viable diesel fuels. However, due to the large content of *n*-paraffins in the HEFA **128**, properties such as cloud point (CP) and cold flow pour point (CFPP), are undesirable. Therefore, the HEFA **128** undergoes a hydroisomerization process to decrease the *n*-paraffinic content of the HEFA **128** and generate isomerized HEFA **134** having shorter chain isomers (iso-paraffins) of the *n*-paraffins. For example, at least a portion of the HEFA **128** is fed to a hydroisomerization reactor **130** to reduce the content of *n*-paraffins and generate the isomerized HEFA **134** having a greater amount of iso-paraffins than *n*-paraffins. For example, the hydroisomerization reactor **130** may have one or more hydroisomerization catalysts that facilitate isomerization of the *n*-paraffins in the HEFA **128** to iso-paraffins. The hydroisomerization catalyst may be any suitable catalyst including, but not limited to, Group VIII metals. In particular, the hydroisomerization catalyst may be platinum (Pt) and/or palladium (Pd) metal supported on a refractory oxide and/or molecular sieve. The resultant isomerized effluent may be fed to other processing systems (e.g., separators, strippers, distillation units, etc.) that separate the isomerized HEFA **134** from gases and other reaction byproducts generated during the hydroisomerization process. In this particular embodiment, the HEFA **128** within the hydroisomerization reactor **130** undergoes a reduced hydroisomerization to lower the cloud point from between approximately 15 °C and approximately 30 °C to between approximately -30 °C and 0 °C. The degree of hydroisomerization of the HEFA **128** may be less than between approximately 10% and approximately 90%, such that a volume ratio of iso-paraffins to *n*-paraffins in the hydroisomerized HEFA **128** is between approximately 1:9 and 10:1, respectively.

[0060] The isomerized HEFA **134** may be combined with the distillate product **86** to generate the biodiesel blend **92**. In other embodiments, the isomerized HEFA **134** is combined

- 27 -

with the HEFA **128** and the distillate product **86**. In one embodiment, the HEFA **128** is not subjected to the hydroisomerization process. In this particular embodiment, the HEFA **128** is combined with the distillate product **86** to generate the biodiesel blend **92**. As discussed in further detail below, biodiesel blends having the isomerized HEFA (e.g., the isomerized HEFA **134**) surprisingly had oxidation stability and lubricity that were better than the isomerized HEFA and distillate product (e.g., the distillate product **86**) alone, indicating that isomerized HEFA, such as the isomerized HEFA **134**, and biodiesel derived from solid feedstock, such as the distillate product **86**, may be used to improve the oxidation stability and lubricity of isomerized HEFA and the distillate product without requiring extensive hydroisomerization and/or hydropolishing, respectively, of the biodiesels derived from renewable resources. In addition, additives generally used to improve the oxidation stability and lubricity of the biofuels may be omitted or the concentration of these additives in the biodiesel blends disclosed herein may be reduced compared to biofuels that do not have both the HEFA-derived biofuel and the distillate product.

#### EXAMPLES

**[0061]** As discussed above, combining biodiesel products derived from different renewable resources (e.g., solid biomass and renewable fats and oils) improves the result from the oxidation stability test EN 12205 and lubricity of the biodiesel. Set forth below are experiments illustrating the improved oxidation stability and lubricity of the biodiesel blends disclosed herein. Each hydrocarbon blend was tested according to EN ISO 12205 standard for oxidation stability and ISO 12156 standard for measuring lubricity. For example, the blends used in the oxidation stability experiments below in Table 1 were each prepared and tested by aging approximately 400 milliliters (mL) of a pre-filtered biodiesel blend sample in an oxidation cell at 95 °C for 16 hours while bubbling oxygen through the biodiesel blend sample. Following the aging step, the biodiesel blend sample is cooled to approximately room temperature after which it is filtered. Filter residue remaining on the filter is weighed to obtain an amount of filterable insoluble. The oxidation cell is washed with 400 mL of a mixture of acetone, toluene, and methanol. The washing mixture is removed from the oxidation cell via evaporation and the remaining residue in the oxidation cell after evaporation is weighed to obtain an amount of adherent insoluble. The total insolubles of the sample is determined by taking the sum of both filterable and adherent insolubles. The blends used for the lubricity experiments in Table 2 were prepared and tested by adding approximately 2

- 28 -

mL to a test reservoir and immersing a test ball made up of a fixed steel ball held in a vertically mounted chuck and forced against a horizontally mounted stationary steel plate with an applied load into the sample in the test reservoir. The test ball is oscillated at a fixed frequency and stroke length while the interface with the plate is fully immersed in the sample. The wear scar generated on the test ball is measured in microns ( $\mu\text{m}$ ) and taken as a measure of the sample lubricity. The isomerized HEFA component in each blend was prepared from the biodiesel fraction resulting from the hydrotreatment of tallow oil according to a process similar to the process discussed above with reference to **FIG. 2**. The GO (gasoil) component in each blend was prepared from the biodiesel fraction resulting from hydropyrolysis and hydroconversion of pinewood chips according to a process similar to the process discussed above with reference to **FIG. 1**.

**[0062]** The effects of the amount of HEFA and GO in the hydrocarbon blends on the oxidation stability and lubricity were investigated. The results for binary HEFA/GO hydrocarbon blends are provided in Tables 1 and 2, and **FIGS. 3** and **4**, which are plots of the oxidation stability and lubricity as a function of the amount of GO in the hydrocarbon blend. The cetane index calculations used to determine the cetane index listed in Tables 1 and 2 were done according to EN ISO 4264/ASTM D4737, which has been developed for standard gasoil composition; the cloud point (CP) of isomerized HEFA in the tested blends is  $-28\text{ }^{\circ}\text{C}$ ; and the boiling point range of the GO in the blends is either at or above  $150\text{ }^{\circ}\text{C}$  or at or above  $180\text{ }^{\circ}\text{C}$ .

**TABLE 1. ISOMERIZED HEFA & GASOIL (GO) FUEL BLEND OXIDATION STABILITY**

|                                              |                    | <b>EXP.<br/>1</b> | <b>EXP.<br/>2</b> | <b>EXP.<br/>3</b> | <b>EXP.<br/>4</b> | <b>EXP.<br/>5</b> | <b>EXP.<br/>6</b> | <b>EXP. 7</b> |
|----------------------------------------------|--------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|---------------|
| <b>HYDROCARBON BLEND (vol%)</b>              | HEFA isom (CP -28) | 100               |                   | 96                | 78                |                   | 96                | 78            |
|                                              | GO 150+            | -                 | 100               | 4                 | 22                |                   |                   |               |
|                                              | GO 180+            | -                 | -                 | -                 | -                 | 100               | 4                 | 22            |
| <b>DENSITY (kg/m<sup>3</sup>)</b>            |                    | 774.1             | 904.5             | 779.8             | 803.3             | 922.2             | 780.5             | 806.9         |
| <b>CETANE INDEX</b>                          |                    | >100              | 30                | 94                | 75                | 28                | 94.3              | 74.6          |
| <b>OXIDATION STABILITY (g/m<sup>3</sup>)</b> |                    | 44                | 9                 | <2                | 5                 | 134               | 3                 | 5             |

**[0063]** As shown by the data in Table 1 and **FIG. 3**, the oxidation stability measured according to the oxidation stability test standard EN 12205 of isomerized HEFA/GO binary blends was improved by approximately 44% and approximately 98% percent compared to isomerized

- 29 -

HEFA and GO alone. Surprisingly, when the heavy GO (e.g., GO 180+) was mixed with isomerized HEFA, the improvement in the oxidation stability test result was between approximately 96% and approximately 98%. Table 2 below illustrates the relative % improvement in oxidation of the biofuel blends disclosed herein relative to the individual components. According to the oxidation stability specs indicated in the paraffinic fuels standard EN 15940, the maximum limit for the amount of insolubles measured via oxidation stability test standard EN 12205 is 25 g/m<sup>3</sup>. As shown in Table 1, the biodiesel blends disclosed herein are below the target value indicating that these biodiesel blends have desirable oxidation stability, unlike the individual blend components. The synergy between the hydrocarbon composition of each component (e.g., HEFA and GO) in the biodiesel blends disclosed herein is such that the formation of stable radicals is reduced or inhibited compared to biodiesel having only one of the two components. Due, in part, to the reduced or inhibited radical formation in these HEFA-GO biodiesel blends, the oxidation stability test result is significantly improved such that these biofuel blends meet the oxidation stability standards for biofuels and may be effectively used as a suitable transportation fuel.

**TABLE 2. RELATIVE % IMPROVEMENT IN OXIDATION STABILITY OF BLENDS**

| Biofuel Component   | Exp 3 | Exp 4 | Exp 6 | Exp 7 |
|---------------------|-------|-------|-------|-------|
| HEFA isom (CP - 28) | 95    | 89    | 93    | 89    |
| GO 150+             | 78    | 44    | -     | -     |
| GO 180+             | -     | -     | 98    | 96    |

**[0064]** In addition to the improved oxidation stability of the biofuel blends disclosed herein, certain blends were also evaluated for lubricity. As shown in Table 3 and **FIG. 4**, the lubricity of the isomerized HEFA was improved by between approximately 12% and approximately 45% by adding between approximately 4 vol% and approximately 22 vol% GO 150+. According to the lubricity specs indicated in the paraffinic fuels standard EN 15940, the maximum limit for the wear scar diameter measured via method EN ISO 12156 is 450 micrometers (μm). As shown in **FIG. 4**, adding at least approximately 7 vol% and up to approximately 60 vol% of the GO results in a lubricity of 450 μm or less for the biofuel blends disclosed herein. The improvement in lubricity stabilizes (e.g. plateaus) above 60 vol% of the GO. Unlike the HEFA

- 30 -

component, GO component (e.g., the GO 150+ and the GO 180+) contains a measurable amount (e.g., at least 10 ppmw of oxygen, sulfur, nitrogen, or any combination thereof) of heteroatoms. By way of non-limiting example, the GO component may have up to approximately 1 wt% oxygen, 100 ppmw sulfur, and/or 100 ppmw nitrogen. The heteroatoms in the GO are similar to the heteroatoms present in additives used to improve the lubricity of fuels. Therefore, without wishing to be bound by theory, the heteroatoms in the GO appear to play a role in improving the lubricity of the HEFA. As such, the GO may be blended with the HEFA component to improve the lubricity without having to add lubricity additives. By blending the HEFA with the GO, not only is the oxidation stability improved, but also the lubricity compared to the HEFA component alone. It has been recognized that to improve both the oxidation stability and the lubricity in the biofuel blends disclosed herein, between approximately 10 vol% and 35 vol% of the GO will need to be present in these biofuel blends. The relative improvement in the lubricity of HEFA/GO biofuel blends disclosed herein is between approximately 13% and approximately 45% compared to biofuels having HEFA as the only biodiesel fuel component.

**TABLE 3. ISOMERIZED HEFA & GO FUEL BLEND LUBRICITY**

|                                   |                     | <b>EXP. 8</b> | <b>EXP. 9</b> | <b>EXP. 10</b> | <b>EXP. 11</b> |
|-----------------------------------|---------------------|---------------|---------------|----------------|----------------|
| <b>HYDROCARBON BLEND (vol%)</b>   | HEFA isom (CP - 28) | 100           | -             | 96             | 78             |
|                                   | GO 150+             | -             | 100           | 4              | 22             |
| <b>DENSITY (kg/m<sup>3</sup>)</b> |                     | 774.1         | 904.5         | 779.8          | 803.3          |
| <b>CETANE INDEX</b>               |                     | >100          | 30            | 94             | 75             |
| <b>LUBRICITY (μm)</b>             |                     | 576           | 281           | 502            | 315            |

**[0065]** The technical effects of combining non-upgraded (e.g., GO not subjected to hydropolishing and having a cetane index less than 46) GO with HEFA-derived biodiesel improves the oxidation stability and lubricity, in particular the cetane index, oxidation stability, lubricity and handling of these HEFA-GO-derived biodiesel blends compared to the individual HEFA and GO components. For example, certain HEFA-derived biodiesels generally have undesirable oxidation stability, when determined according to oxidation stability test standard EN 12205, and lubricity due to their paraffinic composition, which may make it difficult to store and distribute these biofuels. However, by combining these HEFA-derived biodiesels with non-upgraded GO derived from solid biomass, as discussed above with reference to **FIG. 1**, the oxidation stability test results

- 31 -

and the lubricity of these HEFA-derived biodiesel fuels are improved without the need of adding oxidation stability and lubricity additives and/or upgrading and/or adding additives to improve the cetane number of the non-upgraded GO biodiesel. Therefore, by combining non-upgraded GO biodiesel with HEFA-derived biodiesel (e.g., non-isomerized or isomerized HEFA), the non-upgraded GO and HEFA may be used without having to undergo costly and complex upgrading processes or using oxidation stability/lubricity additives to generate a commercially viable biodiesel. Moreover, it may not be necessary to combine the non-upgraded GO with fossil-derived diesel, thereby decreasing the carbon footprint of biodiesel fuels.

**[0066]** The present disclosure may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the disclosure is, therefore, indicated by the appended claims rather than by the foregoing description. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

## CLAIMS

We claim:

1. A biofuel, comprising:

a mixture having a gasoil generated from hydropyrolysis and hydroconversion of a solid biomass containing lignocellulose and an isomerized hydroprocessed ester and fatty acid (HEFA) generated from hydrotreating a renewable resource comprising fats and oils, wherein the gasoil has a cetane index less than 46 and at least 10 parts per million weight (ppmw) of a heteroatom, and wherein a cetane index of the biofuel is greater than 46.

2. The biofuel of claim 1, wherein the gasoil is present in an amount less than the HEFA.
3. The biofuel of claim 1, wherein the gasoil is present in an amount of from between approximately 5 volume % (vol%) and 60 vol%.
4. The biofuel of claim 3, comprising a lubricity of less than approximately 450 micrometers ( $\mu\text{m}$ ).
5. The biofuel of claim 4, comprising an oxidation stability of less than 25 grams/cubic meter ( $\text{g}/\text{m}^3$ ).
6. The biofuel of claim 1, wherein the gasoil has an initial boiling point greater than 145 °C.
7. The biofuel of claim 1, wherein the at least one heteroatom is nitrogen, sulfur, or both.
8. The biofuel of claim 1, wherein the gasoil is generated by a hydroprocess comprising:

hydropyrolysing the solid feedstock in the first stage hydropyrolysis reactor to generate a product stream comprising partially deoxygenated hydropyrolysis product,  $\text{H}_2\text{O}$ ,  $\text{H}_2$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{C}_1$  -  $\text{C}_3$  gases, char and catalyst fines;

feeding at least a portion of the product stream to a second stage hydroconversion reactor comprising one or more hydroconversion catalysts; and

hydroconverting the partially deoxygenated hydropyrolysis product in the product stream to generate a vapor phase product comprising substantially fully deoxygenated hydrocarbon product,  $\text{H}_2\text{O}$ ,  $\text{CO}$ ,  $\text{CO}_2$ , and  $\text{C}_1$  -  $\text{C}_3$  gases;

- 33 -

condensing the vapor phase product to generate a deoxygenated hydrocarbon liquid comprising the substantially fully deoxygenated hydrocarbon product having one or more heteroatoms, wherein the substantially fully deoxygenated hydrocarbon product comprises the gasoil.

9. A process for producing a biofuel comprising:

feeding a solid feedstock and hydrogen to a first stage hydropyrolysis reactor, wherein the first stage hydropyrolysis reactor comprises one or more deoxygenation catalysts, and wherein the solid feedstock comprises biomass containing lignocellulose;

hydropyrolysing the solid feedstock in the first stage hydropyrolysis reactor to generate a product stream comprising partially deoxygenated hydropyrolysis product, H<sub>2</sub>O, H<sub>2</sub>, CO<sub>2</sub>, CO, C<sub>1</sub> - C<sub>3</sub> gases, char and catalyst fines;

feeding at least a portion of the product stream to a second stage hydroconversion reactor comprising one or more hydroconversion catalysts;

hydroconverting the partially deoxygenated hydropyrolysis product in the product stream to generate a vapor phase product comprising substantially fully deoxygenated hydrocarbon product, H<sub>2</sub>O, CO, CO<sub>2</sub>, and C<sub>1</sub> - C<sub>3</sub> gases;

condensing the vapor phase product to generate a deoxygenated hydrocarbon liquid comprising the substantially fully deoxygenated hydrocarbon product, wherein the substantially fully deoxygenated hydrocarbon product comprises a gasoil having a cetane index of less than 46 and at least 10 parts per million weight (ppmw) of a heteroatom; and

mixing the gasoil with an isomerized hydroprocessed ester fatty acid (HEFA) to generate the biofuel, wherein a cetane index of the biofuel is greater than 46.

10. The process of claim 9, wherein the isomerized HEFA is produced by hydroprocessing a renewable resource comprising fats and oils.

11. The process of claim 9, wherein the gasoil is present in an amount less than the HEFA.

12. The process of claim 9, wherein mixing the gasoil with the isomerized HEFA comprises adding between approximately 10 volume (vol) % and 35 vol % of the isomerized HEFA to the gasoil.

- 34 -

13. The process of claim 9, wherein a lubricity of less than approximately 450 micrometers ( $\mu\text{m}$ ) and an oxidation stability of less than approximately 25 grams/cubic meter ( $\text{g}/\text{m}^3$ ).
14. The process of claim 9, wherein the heteroatom is nitrogen, sulfur, or both.