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Feasibility of New Liquid Fuel Blends for Medium-Speed Engines

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Abstract: Several sustainable liquid fuel alternatives are needed for different compression ignition (CI) engine applications. In the present study, five different fuel blends were investigated. Rapeseed methyl ester (RME) was used as the basic renewable fuel, and it was blended with low-sulfur light fuel oil (LFO), kerosene, marine gas oil (MGO), and naphtha. Of these fuels, MGO is a circulation economy fuel, manufactured from used lubricants. Naphtha is renewable as it is a by-product of renewable diesel production process using tall oil as feedstock. In addition to RME, naphtha was also blended with LFO. The aim of the current study was to determine the most important properties of the five fuel blends in order to gather fundamental knowledge about their suitability for medium-speed CI engines. The share of renewables within these five blends varied from 20 to 100 vol.%. The properties that were investigated and compared were the cetane number, distillation, density, viscosity, cold properties, and lubricity. According to the results, all the studied blends may be operable in medium-speed engines. Blending of new, renewable fuels with more conventional ones will help ease the technical transitional period as long as the availability of renewable fuels is limited.

Keywords: alternative fuels; renewable energy; renewable naphtha; marine gas oil

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1. Introduction

The use of diesel or compression ignition (CI) engines in heavy-duty transportation, off-road machines, power generation, and shipment has spread all over the world. The engine technology is at an advanced level. CI engines are very reliable stand-alone prime movers, and they show the highest fuel conversion efficiency of all thermal prime movers within an output range of approximately 100 kW to 100 MW [1]. Most engines still burn conventional liquid petroleum-based fuels, and in the mentioned applications, liquid fossil fuels will most probably continue to dominate for the next few decades as well [2].

Nevertheless, the share of gaseous and renewable liquid fuels, or the share of alternative fuel options more generally, has increased rapidly because of the need to reduce greenhouse gas (GHG) emissions in the near future. Renewable, alternative fuels can reduce the usage of fossil fuels. Energy efficiency and sustainability must be continuously improved because it further promotes the reduction of GHG emissions [3]. The European Parliament has proposed three key targets to increase cleaner energy and enhance energy efficiency by the year 2030: to improve energy efficiency by 35%, to have at least 35% share for renewables in energy consumption, and to achieve at least 12% share of energy from renewable sources in transport [4].

The pollutant exhaust emissions of CI engines are already strictly limited. The most stringent standards concern on-road engines, but legislation relating to off-road and power plant engines is also very strict. Recently, the emission limits for marine engines have also become stricter. First, limitation were placed on oxides of nitrogen, but even the sulfur and particulate matter is now limited. For EU inland waterways, pollutant emissions must already be strongly reduced, including particulate number emissions [5]. The development of the emissions legislation therefore strictly guides engine development and simultaneously directs the transition from fossil fuels to more sustainable alternative fuels.

On the other hand, fuels must be cost-effective. As a result of low crude oil price, the price of alternative or renewable fuels is difficult to set to an attractive level [6]. Still, many countries and regions prefer local fuels to increase the self-sufficiency of their energy generation. The production of renewable electricity, such as wind or solar power, has increased globally, but it has generally been highly intermittent. The role of conventional energy production is to keep electricity grids in balance. Engine-driven power plants are extremely well suited for this task because the plants can be started, loaded, and stopped very quickly. Gas engines are also a favorable option, but the availability of gaseous fuels is still limited.

Several sustainable liquid fuel alternatives are therefore needed for different CI engine applications to reduce GHG emissions and ensure proper primary energy sources for the engines. The reduction of fossil reserves, together with the concern relating to emissions, has promoted research on alternative fuels in internal combustion engines (ICEs). In theory, these fuels are able to reduce emissions, and several advantageous results have already been obtained in practice. To ensure positive progress on energy security and sustainability, alternative fuels need to be increasingly available. The challenge in estimating sustainability and CO_2 emissions of renewable fuels is that the whole chain must be observed, from growing of the crops, proceeding through to harvesting and manufacturing of biofuels, and ending with the exhaust [6].

For CI engine applications, one possible solution is to use various blends of renewable and liquid fossil fuels until the availability of renewable fuels reaches sufficient levels. Together with special renewable fuels, fuel options originating from the circular economy can also be blended with conventional fuels. For instance, in Finland, the government is aiming to promote the circular economy. In fuel production, this means that waste greases and cooking oils as well as lubricating oils can be used as fuel raw material.

To be able to promote the transition from conventional fossil fuels to renewable alternatives, a great deal of additional research on various alternative fuels, in particular their blends with conventional fuels, is required. Before experiments on engines, a lot of new information has to be gathered about the blend properties through fuel analyses [6]. Another important issue is the compatibility of the present and new additives that are used to enhance the properties of fuels and fuel blends. This is not dealt with in the present study, but the compatibility of the studied blends with lubricity improvers, deposit control additives, cold flow improvers, and stability improvers should be studied. Lubricity improvers are usually fatty acids, esters, and amides. Blends containing high contents of biodiesel (fatty acid methyl esters, FAME) will not need this additive. Usually, deposit control additives are based on succinimide chemistry. The product consists of a polar head that has affinity for metal surfaces and a hydrocarbon tail. The effect is partly based on preventing agglomeration of deposit precursors and partly on making a film on metal surfaces. Cold flow improvers are based on vinyl ester copolymers, such as ethylene vinyl acetate (EVA), low molecular-weight polymers, olefin–ester copolymers, and dispersants (in combination with EVA). Stability improvers are generally long-chain and cyclic amines. The additive interferes with the acid–base reactions, thereby preventing sediment formation [7,8].

In the present study, five different fuel blends were thoroughly investigated. Rapeseed methyl ester (RME) was used as the basic renewable fuel, and it was blended with low-sulfur light fuel oil (LFO), kerosene, marine gas oil (MGO), and naphtha. Of these fuels, MGO is a circulation economy fuel, manufactured from used lubricants. Naphtha is renewable as it is a residue of a renewable diesel production process using tall oil as feedstock [9]. The blend of RME and naphtha is therefore fully renewable. In addition to RME, naphtha was also blended with LFO. The B20 blend, consisting of 20 vol.% FAME and 80 vol.% fossil diesel fuel, is commonly used as fuel and is also standardized [10].

The blending ratios (presented in Table 1) were chosen to determine if FAME B20 blends with MGO and kerosene are feasible. Naphtha, due to its low viscosity, cannot yet be added in large portions to medium-speed engines. This was the reason for choosing 20 vol.% naphtha content for naphtha blends.

The main aim of the current study was to determine the most important properties of these blends in order to gather fundamental knowledge about their suitability, particularly for medium-speed CI engines. Certain properties of fuel have certain effects on the fuel system and engine performance, and these properties are therefore standardized for different kind of fuels [10–12]. For this reason, the measured and analyzed properties in the present study were the cetane number (CN), distillation curve, density, kinematic viscosity, cold properties, and lubricity. Important additional information could have been gathered from combustion experiments, such as experiments using prevaporized fuel, droplets, or sprays, but these were not investigated in this study. The engine performance and emissions of the LFO–naphtha blend and neat RME and MGO have been further studied in Hissa et al. and Ovaska et al. [13,14].

Even though the primary focus was on the blend suitability for marine and power plant engines, the results can, for the most part, also be exploited when selecting sustainable options for off-road engine applications. All the studied blends may be operable in marine, power plant, and off-road applications when the target of 35% renewable share of total energy consumption must be reached.

2. Materials and Methods

2.1. Fuels

RME was obtained from ASG Analytik-Service Gesellschaft mbH, Germany. It contained 1000 mg kg^{-1} of butylated hydroxytoluene (BHT) as antioxidant, and it was delivered in January 2017. RME fulfilled the requirements of European Standard, EN 14214:2012 [13].

Naphtha was obtained from UPM, Finland. It is a residue of the manufacturing process for renewable diesel based on wood and forest residues via tall oil. Naphtha was delivered in February 2017.

LFO was obtained from Oy Teboil Ab, Finland. It is a sulfur-free, winter-grade diesel, and it was delivered to the Univerisity of Vaasa, UV, in September 2016. LFO fulfilled the requirements of Standard EN 590:2013 [14].

Kerosene was obtained from Neste, Finland. It was delivered in September 2016.

MGO was obtained from of STR Tecoil, Finland. It is a marine fuel produced from recycled lubricating oils, and it was delivered in September 2016.

Table 1 shows the studied fuel blends and their blending ratios. The blending ratio for LFO, kerosene, and MGO blends (consisting of 20 vol.% of FAME) were chosen to represent common blending ratio of FAMEs. Due to naphtha's high volatility and due to some results obtained in engine laboratory, the content of naphtha in naphtha blends was chosen to be 20 vol.%. The blends were prepared based on their volumes. Table 2 shows the analyses of neat fuels received from the suppliers.

Table 1. Fuel blends and their blending ratios.

Fuels	Blending Ratio (vol.%)
LFO + RME	80:20
Kerosene + RME	80:20
MGO + RME	80:20
RME + Naphtha	80:20
LFO + Naphtha	80:20

Table 2. Analyses of the neat fuels and requirements of European automotive fuel standard EN 590.

Parameter	Method	RME	LFO	Naphtha	Kerosene	MGO	EN590
Density (15 °C), kg m^{-3}	EN ISO 12185	883.2	826.7	722.1	787.3	842.5	820.0–845.0
Kinematic viscosity (40 °C), mm^2s^{-1}	EN ISO 3104	4.49	1.84	0.50	0.94	7.69	2.00–4.50
Flash point, °C	EN ISO 2719	179	63	20	38	110	>55
CFPP, °C	EN 116	−14	−45			−13	+5...−44 *
Sulfur content, mg kg^{-1}	EN ISO 20884/EN ISO 20846	<5	8.3		1000	<100	<10
Cetane number	EN 15195	53	52	34	41	68	>51
Sulfated ash (775 °C), % (m m^{-1})	ISO 3987	<0.001		0.005	0.001	<0.001	<0.01
Water content, mg kg^{-1}	EN ISO 12937	<30	68		35	22	<200
Total contamination, mg kg^{-1}	EN 12662:1998	20	1.5				<24
Copper strip corrosion	EN ISO 2160	1	1a			1a	1
Oxidation stability, h	EN 14112	12					>20
Oxidation stability, g m^{-3}	EN ISO 6245		1			5	<25
Phosphorus content, mg kg^{-1}	EN 14107	<4					
Alkali content (Na + K), mg kg^{-1}	EN 14538	1					
Metal content II (Ca + Mg), mg kg^{-1}	EN 14538	1					
Cloud point, °C	EN 23015	−3	−29	<−20	<−20	−10	
Acid value, mg KOH g^{-1}	EN 14104	0.49			0.002		
Iodine value gI 100 g^{-1}	EN 16300	110.8					
Ester content, % (m m^{-1})	EN 14103:2015	98.5					
Linolenic acid content, % (m m^{-1})	EN 14103:2015	8.7					

Note: * denotes "Climate-dependent".

2.2. Methods

Several properties were determined, and the results were obtained (discussed in Section 3) for the selected fuel blends in order to assess how suitable they are for CI engines. Certain properties of fuels have certain effects on the fuel system and engine performance. For this reason, assessments on the feasibility of the blends can be made according to the results of this study. The conclusions of this study were made based on the results achieved from these analyses. Below is a description of the properties examined in this study.

Cetane number: The cetane number describes the ignition quality of the fuel [1,8]. In this study, cetane numbers were analyzed using ignition quality tester (IQT) according to Standard EN15195 [15].

Oxidation stability: Oxidation stability index (OSI) is one of the most important properties for biofuels. FAME oxidizes easily compared to petroleum diesel fuel. The test methods for petroleum diesel fuel, FAMEs, and their blends differ [8,16]. In this study, the oxidation stability was measured by a Biodiesel Rancimat 873 instrument. The method is described in Standard EN 15751:2014. According to this standard, the maximum induction period is 48 hours [17]. The OSI was not measured for the LFO + naphtha blend.

Cold properties: The cold flow performance of a diesel fuel depends on its composition. It is described by different critical temperatures based on the formation of wax crystals as the fuel is cooled during the test. The wax can block fuel lines and filter and cause malfunction at low temperatures [1]. The cold flow properties are evaluated by three different methods: cloud point, pour point, and cold filter plugging point (CFPP). In this study, the cloud points, pour points, and CFPPs were measured according to American Standards ASTMD7689, ASTMD7346, and European standard EN116, respectively [18–20].

Distillation: The distillation curve describes the temperature range where the mixture of hydrocarbon vaporizes when the mixture is heated slowly at atmospheric pressure [8]. In this study, the distillation was produced according to Standard EN ISO 3405 [21].

Density: The air–fuel mass ratio is the determining value in the combustion chamber. A minimum value for the fuel density is given to ensure a sufficient maximal power from an engine that has a volume-based fuel flow control. A maximum value of density is given to help avoid smoke formation at full load. Smoke would result from an increase in the average equivalence ratio in the combustion chamber as smoke is formed by incomplete combustion. The density is dependent on the temperature [8,16].

Viscosity: The kinematic viscosity of the fuel depends on the fuel density, and factors affecting the fuel viscosity are similar to those affecting density. It is important to remember that even when the fuel is modified to adjust the viscosity, it must still meet the viscosity specifications [1,8]. In the present study, the densities and viscosities were measured by a Stabinger SVM 3000 rotational viscometer according to Standard ASTM D7042 [22,23].

Flash Point: The flash point is a minimum temperature where a fuel forms a flammable mixture with air under a fixed condition [1,8]. The flash points were measured according to Standard ASTM D93-A [24].

Lubricity: Diesel fuel needs to have sufficient lubricity to ensure integrity of the fuel system. The lubricity is measured by the size of the wear scar in a high-frequency reciprocating rig (HFRR) test [1]. In this study, the lubricity was measured according to Standard EN ISO 12156-1 [25].

3. Results

The results of the analyses are presented in Table 3.

The lubricity of neat naphtha was not able to be measured due to naphtha's high volatility.

Table 3. Analyses of neat fuels and requirements of automotive fuel standard EN 590.

Sample	Blending Ratio	Flash Point, °C	OSI, h	Density, kg m^{-3}	Kinematic Viscosity, $mm^2\ s^{-1}$	CFPP, °C	Cloud Point, °C	Pour Point, °C	Cetane Number	Lubricity, HFRR, µm 60 °C^{-1}
		ASTM D93-A	EN 15751	ASTM D7042	ASTM D7042	EN116	ASTMD 7689	ASTMD 7346	EN 15195	ENISO 12156-1
RME + Naphtha	80:20	20	15	850	2.75	−19	−9	−18	52	174
LFO + Naphtha	80:20	20	-	805	1.37	−32	−29	−50	51	391
LFO + RME	80:20	67	42	837	2.24	−29	−21	−39	53	171
Kerosene + RME	80:20	43	69	807	1.26	−29	−30	−72	44	170
MGO + RME	80:20	125	42	853	6.83	−8	−5	−18	64	169
RME		170	13	883	4.51	−14	−5	−15	54	196
Standard EN590		>55	>20	820.0–845.0	2.00–4.50	+5...−44 *	−10...−34 *		>51	<460

Note: * denotes "Climate-dependent".

3.1. *Blend of Naphtha and RME*

Distillation for the RME–naphtha blend started at below 100 °C. For this blend, it could be clearly seen that the fractions of naphtha (20 vol.%) first distilled below 350 °C, and the rest were heavier fractions of RME. The lubricity of neat naphtha is most probably excessively high (i.e., poor) for engines, and it may be assumed that it would cause problems in the entire engine fuel system. Still, this RME–naphtha blend showed good lubricity of 174 µm at 60 °C. When using naphtha as CI engine fuel, additives or blending could be the means to reduce lubricating problems.

While RME improved the lubricity of the blend, adding 20 vol.% naphtha into RME enhanced the cold properties (e.g., CFPP of the blend was −19 °C, whereas it was −14 °C for neat RME) and the OSI (from 13 to 15 h) of the blend compared to neat RME. The cetane number stayed quite high at 52, and the density and viscosity (850 kg m^{-3} and 2.8 mm^2 s^{-1}) were at an acceptable level, although the viscosity was still relatively low. However, the volatility of naphtha lowered the flash point under the detection limit of the method, approximately down to 20 °C. The safety properties of naphtha are therefore relatively low, and its storage and distribution may demand particular actions. If these actions are taken into account, the blend of naphtha and RME is suitable for medium-speed engines.

3.2. Blend of Naphtha and LFO

The distillation for the LFO–naphtha blend started at below 100 °C. The curve shape of naphtha–LFO was more even than that of naphtha–RME, most probably due to the lower fractions of LFO compared that of RME. Despite the poor lubricity of neat naphtha, the lubricity for this blend was at an acceptable level at 391 µm 60 $°C^{-1}$. The cold properties of the LFO–naphtha sample were good; CFPP was −32 °C, which was the lowest of all the samples measured. The OSI was not measured for this sample. The cetane number stayed quite high at 51, and the density and viscosity (805 kg m^3 and 1.4 s^{-1}) were relatively low. This may cause power losses if the engine has a volume-based fuel flow control and leakages in the injection system. As for the other naphtha blend, another shortcoming of this fuel is its low flash point (20 °C), and its storage and distribution may therefore demand particular actions. Despite of this shortcoming, the blend of naphtha and LFO seems to be feasible for medium-speed engines.

3.3. Blend of MGO and RME

The blend of MGO and RME started to distillate at quite a high temperature of 264 °C. The distillation end was at 368 °C. This blend showed good lubricity of 169 µm at 60 °C. The cold properties of the MGO–RME sample were rather weak; CFPP was −8 °C, which was the highest of all the samples measured. The OSI was, however, at a decent level at 42 hours. The blend also showed a high cetane number of 64. The density was 853 kg m^{-3}, and the viscosity was 6.8 mm^2 s^{-1}. The density was a decent level. The marine standard sets a maximum limit of 890 kg m^{-3} for the lightest MGO quality but, according to the standard, the viscosity should not exceed 6.0 mm^2 s^{-1}. The MGO–RME blend seemed safe to handle as its flash point was as high as 125 °C. According to these results, the blend of MGO and RME is usable in medium-speed engines.

3.4. Blend of Kerosene and RME

The blend of kerosene and RME started to distillate at a rather low temperature of 150 °C, and the end point was at 201 °C. The lubricity of this blend was 170 µm at 60 °C. The blend's cold properties were, however, relatively favorable, even for northern areas, as its CFPP was −29 °C. The blend also showed relatively good oxidation stability as the OSI result was 69 hours, which is clearly above the highest given detection value (48 h) set in Standard EN 15751. Kerosene contained 0.1 m.% (1000 ppm) of sulfur, which may enhance its oxidation stability [26,27]. The cetane number was the lowest of all the blends at 44. The density was 807 kg m^{-3}, and viscosity was 1.3 mm^2 s^{-1}. The flash point was rather low at 43 °C.

3.5. Blend of RME and LFO

The distillation of the LFO–RME sample started at 179 °C, rose evenly, and ended at 341 °C. The lubricity of FAME blends is usually at a decent level, and this was true for this study as well, with the lubricity being 171 µm at 60 °C. The cold properties were at an acceptable level, e.g., the

CFPP was −29 °C. The OSI, which often restricts the commercialization of FAMEs and their blends, was at a good level of 42 hours. The cetane number (53) was appropriate. The density was 837 kg m^{-3}, and the viscosity was 2.2 mm^2 s^{-1}. The rather high flash point (67 °C) indicated that the fuel is safe to use. The blend of LFO and RME is suitable for medium-speed engines. The properties of the LFO–RME blend fulfilled all the requirements set in Standard EN 590, which is the diesel standard for automotive applications.

4. Discussion

The blends studied here are pioneering. There have been no other published studies on renewable naphtha and RME blend or naphtha and LFO blend. The blend of renewable naphtha and RME and the blend consisting of circulation economy product MGO and RME are relatively new and have not been studied before. Based on the results, both of them can be used as alternative fuels. In terms of the measured properties, these blends may be feasible in marine, power plant, and off-road applications when the target of 35% renewable share of total energy consumption must be reached. The naphtha and RME blend is an interesting addition to the biofuel category as it is 100% renewable. RME had a positive effect on naphtha's viscosity, as the viscosity of neat naphtha was 0.5 mm^2 s^{-1} compared to the viscosity of 2.8 mm^2 s^{-1} for the blend. RME also improved the lubricity to an acceptable level.

For both the naphtha blends, i.e., naphtha–RME and naphtha–LFO, the cold properties of neat biodiesel and LFO were enhanced when naphtha was added. The cetane number of neat naphtha was only 34, whereas it was above 50 for both the naphtha blends. These blends have really low flash points, which means that the safety aspects should be assured in their storage and usage.

Hissa et al. studied the effect of various alternative fuels on combustion, especially in-cylinder combustion. In their study, the naphtha-LFO blend showed overall combustion performance comparable to that of LFO, which was used as a reference fuel [11].

Ovaska et al. studied how different alternative off-road engine fuels affect the exhaust particle size distributions of a high-speed engine. In their study, the naphtha–LFO blend was successfully used as the power source of a high-speed engine. The behavior of this blend was beneficial as it reduced the particle numbers above 50 nm at rated and intermediate speeds, similar to neat RME [12].

The MGO–RME blend appears to be a good option as a marine fuel in large regions globally, except for arctic areas, where the restricted cold properties may limit its feasibility. MGO is a high-quality fuel for reducing sulfur emissions in ships. The studied circulation economy MGO contained less than 100 ppm of sulfur. As a comparison, heavy fuel oil in Finland is allowed to contain a maximum sulfur level of 1.00 m.%, which is equal to 10,000 ppm [28]. Adding non-sulfur RME to MGO decreases the blend's sulfur content even further. Moreover, the lubricating oil is a viable raw material for marine fuel. However, the volumes of RME and MGO may still be limited, thereby restricting the availability of this blend. According to Ovaska et al., neat MGO generated high total particle number (TPN) at all loads at rated speed in engine experiments, most likely due to the higher fuel sulfur content. MGO is thought favorable in terms of CO and HC emissions. The same result was achieved when neat RME was tested [12]. Favorable emissions of MGO were also found in the study by Hissa et al. According to their study, MGO's high viscosity may increase the combustion duration by hindering mixture formation, and this may also be taken into consideration if MGO is blended with RME, although an engine experiment of the RME–MGO blend was not studied [11].

The RME–kerosene blend, which was also studied, showed extremely good oxidation stability, and kerosene could perhaps be used to enhance the oxidation stability of FAMEs. This should, however, be studied in more detail. The neat kerosene contained 1000 ppm of sulfur. Based on the blending ratio, the sulfur content of the blend was approximately 800 ppm. According to the results obtained in earlier studies [26,27], the high sulfur content may have improved the oxidation stability of the kerosene–RME blend. Kerosene blended with FAME was also studied by Hüseyin, who conducted engine experiments with blends of kerosene and FAME–fossil diesel. According to Hüseyins results, the addition of kerosene to biodiesel is a feasible solution to overcome the challenges of biodiesel usage [29]. The same results were obtained by Bayındır et al. [30].

Regarding alternative fuels, the diversity is one of the complications. When the properties of renewable blending components are known, some conclusions can be drawn about the blend properties. When fuels are new and have not been studied before, there is a need for detailed study of certain properties to determine their feasibility for CI engines. In this study, RME would not be considered as a new fuel and neither would the RME–LFO blend. The kerosene–RME blend has also been studied before [29,30] as has waste-oil-based marine diesel [31,32], but the results of naphtha and MGO blends are pioneering. The results of the study provide valuable and fundamental new knowledge and understanding for engine research and development. Kerosene, however, is still an interesting and important fuel to study, especially because of the Single Fuel Concept introduced by the North Atlantic Organization (NATO). Yang et al. studied the performance and emissions of kerosene and its blends with fossil diesel. They stated that kerosene gives higher maximum output and lower CO emissions than fossil diesel [33].

The blending of new, renewable fuels with more conventional ones eases the technical transitional period as long as the availability of renewable fuels is limited. Fuel blending and decisions on which fuels could be used need to be made on a case-by-case basis. The main parameters are the applications for which the fuel is used and the fuel options for blending. For this reason, it is important to know all information about different blends and their properties. The diversity of alternative fuels is large and makes engine development demanding, but there are also several simple options for medium-speed engine fuels.

5. Conclusions

The main aim of the current study was to determine the most important properties of certain renewable–fossil fuel blends in order to gather fundamental knowledge about their suitability, particularly for medium-speed CI engines.

The share of renewables within the five blends examined in this study varied from 20 vol.% to 100 vol.%. RME was blended with renewable naphtha in a ratio of 80 vol.% RME and 20 vol.% naphtha. This fuel blend is 100% renewable and has not been studied before. Moreover, naphtha was blended with LFO in a ratio of 20 vol.% naphtha and 80 vol.% LFO. RME was also blended with LFO, kerosene, and circulation economy fuel MGO in a ratio of 20 vol.% RME and 80 vol.% fossil fuel. The properties that were investigated and compared were the cetane number, distillation, density, viscosity, cold properties, and lubricity.

According to the results obtained, the following conclusions can be drawn:

- All the studied blends may be operable in marine, power plant, and off-road applications when the target of 35% renewable share of total energy consumption must be reached.
- The 100% renewable naphtha–RME blend is an interesting addition to the biofuel category.
- For the two naphtha blends, the cold properties of neat biodiesel and LFO were both enhanced when naphtha was added. These blends have really low flash points, which means that safety aspects should be assured in their storage and usage.
- The MGO-RME blend appears to be a good option as a marine fuel in large regions globally, except for arctic areas, where the unfavorable cold properties may limit its feasibility. However, the volume of these two fuels may still be limited, thereby restricting the availability of this blend. Nevertheless, MGO is a high-quality fuel for reducing sulfur emissions in ships.
- The RME–kerosene blend showed extremely good oxidation stability, and kerosene could perhaps be used to enhance the oxidation stability of FAMEs. This should, however, be studied in more detail.
- The blending of new, renewable fuels with more conventional ones eases the technical transitional period as long as the availability of renewable fuels is limited.

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