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A COMPARATIVE ASSESSMENT OF CURRENT AND FUTURE FUELS FOR THE TRANSPORT SECTOR

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ABSTRACT: To facilitate the transition to a sustainable and less fossil dependent transport sector in the short to medium term, the current fuel mix needs to be enriched with renewable fuel alternatives. The present work aims to assess and highlight the opportunities for current and future biomass based fuels to be utilized. Seven fuels and fuel blends fulfilling the EN590 diesel fuel standard have been selected and are compared using qualitative and quantitative criteria covering technical, environmental and economic attributes of the fuels. Mature fuels such as dimethyl-ether (DME) and hydrotreated vegetable oils (HVO) are ranked higher in the assessment due to the increased possibility for environmental gains at moderate costs. For future fuels to be competitive stricter regulation in terms of GHG emissions savings are needed.

Keywords: transport sector, advanced biofuels, multi criteria assessment, decision making

1 INTRODUCTION

The world’s road vehicle fleet today is dominated by internal combustion engine (ICE) vehicles running on fossil fuels. About 95% of the European fleet is diesel or gasoline driven vehicles which makes the ICE the major technology for both passenger and freight transports for the coming years [1]. Even with technology improvements, increased fuel economy and reduced tailpipe emissions, the continuous use of fossil fuels, remains a non-sustainable strategy not only from a resource but also from a climate, health and environmental point of view. Especially for diesel engine vehicles the need of reducing emissions of particles and nitrogen oxides (NO_x) is still apparent as regulations for mitigating local air pollution become stricter.

Alternative fuel options based on renewable and biomass based feedstock are available, both for spark ignition (SI) and compression ignition (CI) engines. Such fuels are used either in blends or as neat fuels. From a climate perspective, the higher the renewable content in the fuel, the lower the fossil carbon dioxide (CO_2) emissions during the use phase of the vehicle. However, fuel quality, safety, combustion performance, and engine modification requirements are among the determining factors for the optimal share of the different constituents in a blend. Additional aspects such as fuel handling, storage and distribution options, feedstock availability, production cost and life cycle environmental performance, are expected to influence the overall acceptance and adoption of a fuel. It has been seen already that the need for powertrain modifications as well as the potential competition with food production have slowed down the large-scale expansion of certain types of biofuels [2].

The past years, great focus has been given on “second generation” or “advanced” biofuels to deal with some of the aforementioned drawbacks. Advanced biofuels can be produced from organic waste, crop or forest residues and are therefore considered as a more sustainable alternative in terms of feedstock [3, 4].

Research on fuel design has further assisted in understanding the fundamental properties of different fuels and their respective conversion pathways with the aim to develop customized or “tailor-made” fuels that combine improved combustion and production performance [5]. Specifically, for diesel engines a great variety of fuels is under investigation today.

As part of a national research project funded by the Swedish Energy Agency, alternative fuels that are tailored to offer improved combustion properties and life cycle sustainability performance, are being investigated. The focus is on “drop-in” alternatives that are possible to blend at high concentrations with conventional fuels and that require few modifications of current vehicle powertrain technology and fuel distribution infrastructure. A preliminary list of fuels has been identified in the initial phases of the project, and is currently under evaluation including long chain alcohols and ethers [6].

Similarly, other research groups have been focusing on different compounds with higher oxygen content than conventional fuels – mainly due to the beneficial effects on soot emissions in compression ignition engines [5].

The development state and information available on these alternatives varies significantly. Laboratory experiments and engines tests are continuously performed aiming to increase understanding on the performance characteristics of such novel fuels. Information of their environmental and socioeconomic performance is on the other hand scarce. To obtain a holistic view on the performance of such novel fuels and assist their adoption in the current transport fuel mix, a systematic review and comparison is needed. Further, a comparison to existing fuel options may provide insights on their benefits and limitations while also illustrate the factors that could increase the potential of future advanced fuels to be competitive.

The aim of the present work is therefore twofold:

- to provide the basis for a holistic and systematic comparison of different fuel options based on multiple factors that are expected to influence the performance and adoption of a fuel
- and by that to assist identification of possible future transport fuel alternatives that could enrich the renewable content of the current fuel mix as well as identification of hinders that need to be overcome to fully develop the potential of promising fuel alternatives.

Seven fuels have been considered in this comparative assessment. The list contains traditional biomass based fuels that are used already in diesel engine vehicles as well as more advanced biofuels that are of specific interest for the Swedish project. The studied fuels, whether neat or blends, have to meet the EN590 diesel standard. The selected fuels are then assessed based on a variety of criteria including technoeconomic and environmental aspects. To evaluate, compare and rank the selected fuels a multicriteria decision making model was applied.

Multi-criteria decision analysis (MCDA) tools are often used for managing complex decision problems. Selecting the optimal fuel mix for the transport sector given the variety of parameters and constraints that are involved is such a complex problem. Transport fuels and drivetrain solutions do not only need to be technologically superior but to also assist in mitigating climate and health impacts and at the same time being economically feasible to produce. In this work, the decision making model is based on the Analytical Hierarchy Process (AHP) developed by Thomas L. Saaty [7]. The AHP has been previously used in multicriteria assessments of bioenergy systems in general and transport applications in particular [8-12].

2 METHOD

The Analytical Hierarchy Process (AHP) is a decision support tool that can be used to assess and rank different alternatives given a variety of objectives or decision criteria. AHP is a three-stage approach (Fig. 1) starting with problem decomposition and structuring [13].

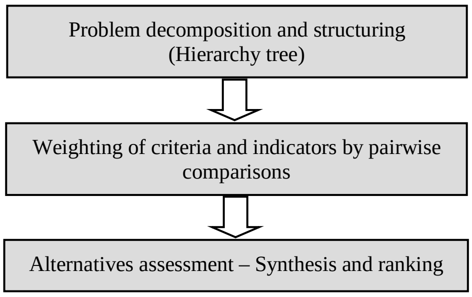

Figure 1: The AHP decision making process

The goal of the decision is defined and set on the top level of a conceptual decision-making tree. The intermediate levels represent the decision's criteria and sub-criteria followed by the alternatives considered which are often listed at the lowest levels [7]. The AHP tree considered in this assessment is illustrated in Fig. 2.

The AHP decision-making model is based on pairwise comparisons where the performance of each alternative for a given criterion or sub-criterion is assessed and scored against each other. Saaty [7] has defined a scoring system using a scale from 1 to 9; 1 indicating equal importance and 9 indicating that one option is clearly more important or preferred over another. The complete scale is shown in Table I. This scoring system is adopted in this study and used to perform the pairwise comparisons of the different fuels. To reduce the risk for judgments subjectivity, the performance of the different fuels for a given criterion is assessed first individually based on qualitative and quantitative data from the literature.

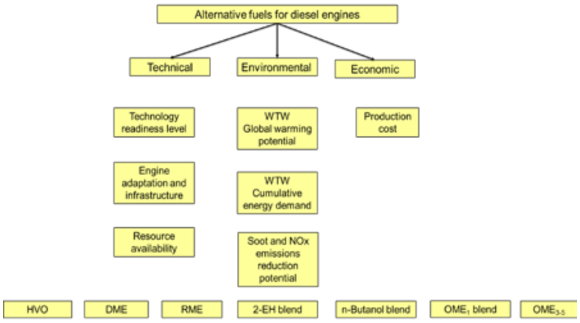

Figure 2: AHP tree showing the different criteria, sub-criteria and fuels considered in this assessment

Table I: Saaty's scale for pairwise comparisons using the AHP process [7]

Score	Description	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slight favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong plus	
7	Very strong importance	One activity is favored very strongly over another
8	Very very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
	Reciprocals of above	If activity i has one of the above non- zero numbers assigned to it when compared with activity j then j has the reciprocal value when compared with i.

An important feature of the decision-making process is to define the relative importance of the different criteria by assigning different weights to them. The AHP relies on experts judgements to derive priority scores [7]. The priority scores are given by using pairwise comparisons, i.e. assessing the relative importance of one criterion over another using the same scale described before (from 1-9). An alternative approach to define the relative importance of the studied criteria was followed in this work, based on the process adopted by Tsita and Pilavachi [9]. The weighting factors for the different criteria were given by the authors. A baseline scenario is considered in which the three criteria categories (technical, environmental, economic) obtained the same weight. Additional cases where also considered representing different scenarios and aiming to highlight different views of interests. Sub-criteria were assigned equal weight in all scenarios considered. A detailed explanation of the scenarios is provided in Section 3.4.

During the final synthesis step the overall score for each alternative is obtained by combining its overall performance with respect to the other alternatives.

Sensitivity analysis in relation to the weighting factors of the sub-criteria is also performed.

Section 3, describes the different criteria considered in this assessment as well as the weighting scheme applied. Section 4 describes the seven fuels assessed aiming to give insights on relevant properties, similarities and differences that have been considered during the scoring process. The analysis and synthesis of the results is presented and discussed in Section 5 followed by the conclusions of the study (Section 6).

3 ASSESSMENT CRITERIA

The evaluation of the fuel alternatives is performed from a technical, environmental and economic perspective. Within these three main categories different sub-criteria are identified and are briefly explained below. The different criteria and sub-criteria were selected by the authors aiming to include relevant aspects that are expected to influence the adoption of an alternative fuel in the transport sector. Previous studies have been reviewed for inspiration and consistency.

The goal at this stage, is to keep the number of criteria short, in order to be able to provide a comprehensive outcome, yet covering major sociotechnical constraints such as resource availability, emissions of pollutants, production cost etc.

Data for the assessment is collected through the literature as well as through project specific findings and own calculations of the authors. The level of information in relation to the different fuels varies and for this reason both qualitative and quantitative information is used.

3.1 Technical criteria

For reducing the impact of road transport in the short to medium term, alternative fuel solutions need to be accessible and to provide possibilities for the existing systems (engines or infrastructure) to be utilized. The technical aspects considered in this work aim to access the ease of adoption of the selected fuels as well as to provide the opportunity to foresee possible limitations. In total three sub-criteria are considered covering aspects related to their adoption from a systems perspective (i.e. technology maturity level, engine adaptation requirements, infrastructure adaptation) and to the fuel properties and production (i.e. supply availability and feedstock to fuel efficiency). The fuels are assessed in a qualitative manner using literature and experimental data for defining the performance of each fuel.

3.1.1 Technology readiness level (TRL)

This criterion aims to evaluate the development state of a fuel today and provide a conceptual roadmap of the maturity and readiness of a fuel towards full-scale production. The TRL scale from 1-9 is adopted (1 indicating an unproven concept while 9 indicating full scale commercial application) and used in this work as a first evaluation and ranking step of the fuels [14]. Although the more advanced fuels are under development today, for some of them a fossil alternative exists which is expected to make the transition to the biomass based production less complex and costly.

3.1.2 Engine adaptation and infrastructure

Engine adaptation and infrastructure refers to the compatibility of the different fuels assessed to the current systems aiming to evaluate the degree that existing diesel engines and fuel storage and distribution infrastructure can be utilized. The term “drop-in” is often used to describe fuels that can be used directly in the current systems without requiring extensive modifications. Such fuels are of great interest as they may contribute to the earliest adoption of renewable fuels. Due to the inherent properties of certain fuels however, adaptations of the engine system might be necessary to avoid damages and to also ensure better fuel combustion (thus performance).

Ageing aspects have also been considered here i.e. possible replacements of engine parts or filters, or deterioration of the fuel per se due to environmental conditions etc. Moreover, current fuel infrastructure might be affected in cases of gaseous fuels which could potentially delay the use or increase the cost of a fuel.

The extent that such changes are relevant for the studied fuels is assessed in a qualitative manner based on literature data.

3.1.3 Supply availability

Supply availability of a fuel refers to feedstock availability and is closely linked to reliable and sustainable supply. Although biomass is a renewable source, it is not unlimited thus feedstock security is an important factor when future fuels for the transport sector are selected. In terms of sustainable supply, biomass feedstocks shall not lead to land use changes or conflicts with other production systems (such as food). The assessment is based on qualitative information and literature data. As for most of the selected biomass based fuels, similar feedstock has been assumed, an indicator evaluating the feedstock to fuel production efficiency is used as extra input to the comparison as it directly impacts the amount of biomass feedstock needed for biofuel production.

3.2 Environmental criteria

Vehicles use a considerable amount of resources during their long use phase and are responsible for major problems related to human health, air pollution as well as climate change. Future transport fuels need to be less fossil fuel depended and provide possibilities to reduce GHG emissions. Especially for diesel engine fuels, criteria pollutants such as particles and NO_x need to be significantly reduced. The performance sub-criteria considered in this category aim to assess emission reduction potential of the different fuels along with an overall assessment of the primary energy needed for their production.

3.2.1 WTW Cumulative energy demand (CED)

The primary energy demand of the different fuels is assessed using the cumulative energy demand (CED) indicator [15]. CED considers all energy flows (renewable and non-renewable) on a primary energy level, thus providing a comprehensive analysis of the energy efficiency of the studied system. Fuels are compared from a life cycle perspective considering the stages of production or well to tank (WTT) and use of the fuel in the vehicle, tank to wheel (TTW). CED is expressed in MJ per km.

WTT data were obtained from the literature or estimated by the authors when no suitable data were available. To estimate the energy demand during the use phase of the vehicle the fuel consumption of an average distribution diesel truck was considered (8.9MJ/km) according to Romare and Hanarp [16]. Based on experimental data [17-19] the efficiency for biofuel blends only slightly differs from fossil diesel and therefore is considered being equal for all blends in this study.

3.2.2 WTW Global warming potential (GWP)

The impact of the different fuels on climate change is assessed using the global warming potential (GWP) indicator as applied in [20]. GWP in this study is expressed in gr of carbon dioxide equivalents (CO_{2eq}) per km including again the stages of production and use of the fuel in the vehicle. For the use phase the same vehicle type and performance as for the previous criterion have been assumed. Biofuels are often considered carbon neutral, thus CO_2 emissions from biofuel combustion is zero [3].

3.2.3 Soot and NO_x emissions reduction potential

Emissions of particles and soot is a major concern for internal combustion engine vehicles and especially for diesel engines. Soot contributes to air pollution and is harmful for human health. In addition, diesel engine vehicles cause high NO_x emissions which apart from human health, are responsible for other environmental impacts such as eutrophication, acidification and ozone depletion.

Soot is formed from unburnt carbon due to incomplete fuel combustion while NO_x is mainly formed because of high combustion temperatures. NO_x is usually reduced with the use of exhaust gas recirculation (EGR) systems which help to decrease the high temperatures. High EGR rates however, tend to reduce oxygen concentration in the combustion chamber thus leading to higher soot formation.

Research has shown that the presence of oxygen in biomass based fuels tends to reduce the soot and particle emissions from diesel fuels significantly [21, 22] while allowing for high EGR rates that simultaneously can lead to NO_x reductions.

Based on the above, the contribution of the studied fuels to lower emissions is assessed collectively. Data from experimental studies are used to evaluate the fuels. These data are only used to estimate the trend and not as absolute values due to different process design.

3.3 Economic criteria

Economic criteria are often ranked high in MCA studies [12]. The total price of a fuel is influenced by many different parameters such as feedstock cost, investment and production cost, regulation, taxes etc. and can be difficult to determine especially for fuels that are under development. For this reason and to reduce data uncertainties only production cost is considered in this assessment.

3.3.1 Production cost

The cost for producing the different fuels including feedstock price, is assessed in this work in a semi-quantitative manner. Relative costs to fossil diesel have been estimated based on literature data indicating the relationships among the different fuels which was further used to perform the pairwise comparisons.

3.4 Weighting scenarios

The priority scales of the selected criteria in this work were set by the authors aiming to cover different decision-making contexts and potential interests. The scenarios considered are listed in Table II. In the first scenario (S1), all criteria categories obtained equal weights. The remaining scenarios S2-S4 represent different situations where focus has been given on one main criterion (S2 focuses on technical aspects, S3 on environmental and S4 on economic). Sub-criteria were assigned equal weight in all scenarios considered.

Table II: Priority scales and scenarios considered in this assessment

Studied scenarios	Technical	Environmental	Economic
S1	0.33	0.33	0.33
Sub criteria*	(0.33)	(0.33)	(1)
S2	0.6	0.2	0.2
S3	0.2	0.6	0.2
S4	0.2	0.2	0.6

*All sub-criteria considered in the respective group are assigned equal weighting factors. These weighting factors remain constant in all four scenarios.

4 FUEL ALTERNATIVES FOR DIESEL ENGINES

Four advanced biomass based fuels and three existing biofuel options were considered in the assessment. The focus is on fuels that can be used in CI engines, fulfilling the diesel EN590 standard. Fuels were assessed as neat fuels or blends focusing on their properties and performance. The selected fuels are listed in Table III followed by a brief description.

Table III: Fuel alternatives for diesel engines included in the assessment [17-19, 23-25]

Fuel group	Fuel	Feed-stock	Assessed as	LHV (MJ/kg)	Oxygen content (%)	Cetane number (CN)
Alcohols	**2-EH**	Forest residues	blend with 50% HVO and 7% RME	41.2	6.0	52.1
	n-Butanol	Forest residues	blend with 40% HVO and fossil 40% diesel	41.3	4.4	50.3
Ethers	**OME$_1$**	Forest residues	blend with 65% fossil diesel	35.9	15.0	51.0
	OME$_{3-5}$	Forest residues	neat fuel	21.0	48.8	71
	DME	Forest residues	neat fuel	28.8	35	55.0
Vegetable oils	**HVO**	Tall oil	neat fuel	44.0	-	87.8
	RME	Rapeseed	neat fuel	37.3	10.0	53.4

4.1 2-Ethyl hexanol (2-EH)

2-Ethyl hexanol (2-EH) is an oxo-alcohol, produced currently from n-butyraldehyde via fossil propylene and syngas [26]. 2-EH can also be produced from renewable feedstock (e.g. wood based biomass) through a variety of conversion pathways and platform chemicals based on thermochemical and biochemical processes [27].

The use of 2-EH as a transport fuel is at early stages. Research, however, shows that it can be considered a promising fuel alternative [18, 19]. The combustion performance of 2-EH has been investigated in different studies and in drop-in blends that range from 30 to 45vol% 2-EH [18, 19, 23]. The remaining share consists of fossil or bio-diesel. As shown, 2-EH blends tend to reduce soot and carbon monoxide (CO) emissions. Emissions of hydrocarbons (HC) and NO_x did not seem to vary in comparison to fossil diesel while for certain load points in the tests, even slightly increased [18].

For consistency reasons and as limited information is available, the blend tested by Preuss et al [18] is selected for this assessment which consists of 43% 2-EH and 57% biodiesel (50% HVO and 7% RME). Neat 2-EH has not been tested so far due to the low cetane number (around 23) and heating value of the fuel which are expected to lead to inferior fuel quality.

Data on the environmental performance of 2-EH are provided by Poulikidou et al [28] and Heyne et al [6]. Among the different production pathways assessed, gasification of forest residues to produce 2-EH resulted in the lower GHG emissions and primary energy demands partly due to low energy demands of the process and partly due to substitution potential of the co-products obtained. The total CED and GWP of the blend was estimated based on the energy fraction and contribution of all constituents.

4.2 n-Butanol

N-Butanol is a heavy alcohol and a promising fuel alternative for diesel engines. Butanol can be produced from fossil based feedstock (naphtha) although biomass based production pathways are also developed. It can be produced from wood through ethanol oxidation into acetaldehyde followed by condensation and hydrogenation to form butanol [29].

Butanol has a high heating value, slightly lower than diesel but still better compared to lighter alcohols. The low cetane number of neat butanol can be compensated with the use of biodiesel offering a highly renewable content in the blend [19]. The performance of n-butanol in diesel engines has been investigated in various studies [19, 30, 31]. Results indicate that n-butanol blends lead to decrease of particle and soot emissions while leaving NO_x emissions almost unchanged.

The n-butanol blend considered in this study, consists of 20% n butanol, 40% HVO and 40% fossil diesel according to [19]. The environmental performance of n-butanol was estimated by the authors based on data from Royne et al [29] and Olofsson et al. [32]. Similar to the previous case, the total CED and GWP of the blend was estimated based on the energy fraction and contribution of all constituents.

4.3 Poly (oxymethylene) dimethyl ethers (OME)

Increased oxygen content in fuels leads to considerable reductions of soot emissions. Oxygenated fuels such as poly (oxymethylene) dimethyl ethers (POMDME or OME) are therefore seen as very promising renewable fuel candidates [21, 33].

OMEs can be produced from renewable methanol at different chain lengths. Their general structure is $CH_3\text{-O-}(CH_2\text{-O})_n\text{-}CH_3$. In this comparison two different fuels are considered. OME_1, that is characterized by one $CH_2\text{-O}$ group and $OME_{3\text{-}5}$ a mix of n=3,4,5.

OMEs can be used as neat fuels or blends in diesel engines requiring moderate or no modifications. OME_1 is normally used as blend. In this study a blend of 35% OME_1 and 65% fossil diesel is considered based on the experimental data for optimal OME_1 blends provided by Omari et al [22]. Experimental data by Omari et al [22] and Deutz et al [17] showed the potential of the OME_1 blend for simultaneous reduction of soot and NO_x due to the inherent properties of the fuel (high oxygen content) and the possibility for high EGR rates. As the authors suggest the commonly discussed trade-off among the two pollutants can be circumvented.

$OME_{3\text{-}5}$ can be used as neat fuel, thus a 100% renewable fuel is considered in this study. Data regarding the combustion performance of $OME_{3\text{-}5}$ in diesel engines is provided by [24, 33]. The respective soot emissions savings remain high for this fuel according to the experimental results while NO_x emissions are also reduced when EGR rates are increased.

OMEs are formed via condensation of methanol and formaldehyde. Methanol is formed through syngas via gasification of wood based biomass. Inventory data for OME_1 production was obtained from Deutz et al [17]. Data for $OME_{3\text{-}5}$ was obtained from Schmitz et al [34]. In both calculations methanol production data was obtained from the JEC WTW study [25].

4.4 Dimethyl-Ether (DME)

Dimethyl-Ether (DME) is a synthetic fuel produced from syngas via thermochemical conversion. It can be produced from a variety of feedstocks including renewable (biomass based) and non-renewable (natural gas or coal) sources. In this study, DME is produced from wood waste following the production pathway described in the JEC WTW study [25].

DME is typically a gaseous fuel although it can be liquified and handled as liquid fuel at moderate pressures [35]. As such DME can be used as neat fuel in conventional diesel engines. DME has shown good combustion performance resulting in low engine out emissions such as NO_x, particles and CO and HC [35, 36]. It has been considered a promising fuel although moderate adaptations of the fuel injection system are required. Similarly, to liquified petroleum gas (LPG), DME requires storage pressures more than 5 bar to maintain the fuel in a liquid state. Additional adaptations of the storage and refueling system are needed in order to be compatible to DME [25].

The primary energy demand and GHG emissions of biomass based DME was obtained from the JEC WTW study assuming similar performance to wood based methanol [25].

4.5 Rapeseed methyl-ester (RME)

Rapeseed methyl-ester (RME) is a liquid fuel used in CI engines. It belongs to the group of fuels that originate from vegetable oils or animal fats, namely fatty acid methyl-ester, or FAME fuels. FAME fuels are produced through transesterification of fatty acids and methanol [37]. Rapeseed is the most common feedstock for biodiesel in Europe making RME a widely applied alternative for diesel engines. A mix of 7% FAME fuel with diesel is acceptable and can be used as drop-in. For higher blends and neat RME, an approval from the vehicle manufacturer may be required to ensure compatibility. RME has the advantage of reducing oil change intervals (including filters) to half the time compared to fossil diesel. It is however, a biodegradable fuel and therefore it cannot be stored for long periods of time.

Johansson et al [38] investigated the combustion performance of neat RME as well as RME blends with conventional diesel. The results showed that neat RME has the potential to reduce soot emissions by up to 90% compared to diesel. Emissions of HC and CO are also reduced. A trade-off with regard to engine out NO_x emissions was observed which tend to be higher for higher RME blends than for fossil diesel.

The environmental performance of RME in terms of CED and GWP is based on literature data [25, 39]. RME is the only renewable fuel included in the study that is based on energy crops. As such feed stock availability concerns relate to land use requirements and associated impacts from intense rapeseed agriculture especially when assuming that production volumes increase [40].

4.6 Hydrotreated vegetable oil (HVO)

Hydrotreated vegetable oils (HVO) represent and alterative group of biodiesel fuels. The difference with FAME fuels lies in the vegetable oil processing step that are hydrotreated (instead of esterification) as indicated by the fuels name.

HVO has a chemical composition that is similar to diesel and can be therefore used as a blend or up to 100% pure fuel without engine adaptations. It has been shown, however, that for the full potential of the fuel to be exploited (in terms of efficiency and emissions reductions) certain adjustments in the engine are needed [41]. HVO contains no aromatics, sulfur, or oxygen. During combustion, HVO exhibits lower emissions of soot and particles compared to diesel (25-30% lower). NO_x emissions are also reduced but to a much lower extent [42, 43].

The environmental and sustainability performance of HVO from a life cycle perspective, is determined by the type of feedstock material used. Feedstock connected to deforestation or land use changes such as palm oil is not considered as a long term sustainable option. Among the accepted sources of HVO today, at least in Europe, include vegetable or animal waste oils, tall oil or animal fats. In this study, HVO from tall oil is included. Tall oil is a byproduct of the pulp and paper industry and therefore fulfills the sustainability criteria for biofuels [3]. The environmental performance of HVO in terms of CED and GWP is based on information provided by Becker et al [44]. Data from life cycle inventory databases were also used to model background processes such as electricity and energy demands.

5 RESULTS AND ANALYSIS

In this section the performance of the fuels according to the criteria considered in the assessment is presented first (section 5.1). This information was used to perform the pairwise comparisons and to rank the fuels during the multicriteria analysis. The final ranking is then presented and discussed in section 5.2.

5.1 Fuels performance under the different criteria

5.1.1 Technical criteria

The performance of the fuels under the three technical criteria is summarized in Table IV. Positive signs (+) indicate favorable performance while negative signs (-) indicate potential limitations of the respective fuel.

Table IV: Fuels performance under the technical sub-criteria [17-19, 22, 27, 34, 37, 42, 43, 45, 46]

Fuel	**TRL assessment**	**Engine adaptation and infrastructure**	**Supply availability**
2-EH blend	7	++	+
n-Butanol blend	8	++	-
OME_1 blend	5	+	--
OME_{3-5}	5	+	+
BioDME	8	---	++
HVO	9	+++	+
RME	9	--	-

With regards to TRL, DME, HVO and RME are considered as mature fuels and have therefore obtained higher rates. 2-EH and OMEs obtained a lower rate. As already presented above although large scale production for their fossil alternatives exist, the biomass based pathways are less developed.

In terms of engine and infrastructure adaptations, HVO obtained the highest rate. As the fuel has similar properties to fossil diesel, no changes are expected to the existing systems. The studied alcohol blends (2-EH, n-butanol) are also compatible alternatives to the current diesel engines and fueling systems although potential effects on materials are less known at the moment. Among the least compatible options are DME and RME. DME requires special storage and distribution infrastructure that would need to be developed. Although with RME modest engine adaptations and even reduced oil change intervals are expected, the main drawback of this fuel is the short storage time and cold climate limitations.

Availability of supply was assessed based on two parameters. First considering the type of feedstock used and second considering the conversion process efficiency i.e. the feedstock to fuel efficiency. With the exception of HVO and RME the remaining fuels assessed in the study are produced from forest residues at an average conversion rate of 50%. From a Swedish perspective, sustainable supply of forest residues is estimated to be about 20-28 TWh/y with a potentail increase of 18–22 TWh/y [47]. As the domestic demand for forest based biofuels is also expected to increase, this may cover 70% of the needs in 2030 and less than 60% in 2050 [47].

HVO production is based on tall oil, assuming 52% conversion efficiency [44]. The annual global production of tall oil today is estimated to be around 1.8 million tons from which biofuels production uses 230 000 tons i.e. 13% of the market [46]. In Sweden domestic tall oil supply potential reaches 2.5 TWh which corresponds to 1.7 TWh HVO [45]. To fulfill total HVO demand however, Sweden imports more than 90% of the feedstock used for HVO production [48]. Despite increased supply potential availability concerns because of an increased fuel demand remain of high relevance and therefore HVO rates slightly lower in comparison to forest biomass based biofuels where domestic feedstock capacity is considerably higher.

RME, despite high conversion efficiency, obtained lower scores due to higher risk for supply limitations. Similarly, fuels containing fossil diesel are also rated lower.

5.1.2 Environmental criteria

Table V presents the results from the WTW assessment of the different fuels in terms of cumulative energy demands (CED) and climate impact (GWP). Fuels containing fossil diesel (the n-butanol blend and the OME_1 blend) have lower primary energy demands but result in higher GHG emissions. Although the neat renewable fuels are more energy intense the main contributor is the biomass used as feedstock for their production. As biofuels are emission free during the use phase of the vehicle their impact on GWP is associated to the emissions resulting during the fuels production stage. Among the studied fuels, forest based DME performs good from a life cycle perspective both in terms of CED and GWP followed by HVO, OME_{3-5} and the 2-EH blend. RME results in increased GWP due to high emissions during cultivation stages [25].

Table V: Life cycle CED and GWP of the studied fuels [6, 16, 17, 25, 28, 29, 32, 34, 39, 44]

Fuel	CED (MJ/km)	GWP (gr CO2 eq. /km)
2-EH blend	26	77.5
n-Butanol blend	19	461
OME_1 blend	15	623
OME_{3-5}	30	52
BioDME	18	12.5
HVO	23	60
RME	17	415

The comparison of the performance of the fuels in relation to NO_x and soot emission is performed in a qualitative manner based on experimental data provided in literature. The assessment takes into consideration potential emission reductions relative to fossil diesel. The results are summarized in Table VI. As expected highly oxygenated fuels performed better since they exhibit high potential for simultaneous NO_x and soot reductions. The NO_x emissions reduction potential of the studied alcohols was less obvious.

Table VI: Fuels assessment with regard to NO_x and soot emissions reduction potential [17-19, 24, 30, 35, 38, 41-43]

Fuel	Performance	Motivation
2-EH blend	-	Lower soot but similar NO_x compared to diesel.
n-Butanol blend	--	Lower soot – slightly higher NO_x compared to diesel.
OME_1 blend	++	Simultaneous soot and NO_x emissions reduction can be achieved when high EGR rates are used.
OME_{3-5}	++	Simultaneous soot and NO_x emissions reduction can be achieved when high EGR rates are used.
BioDME	++	Simultaneous soot and NO_x emissions reduction can be achieved when high EGR rates are used.
RME	-	Reduced soot but NO_x could be increased for higher RME blends.
HVO	+	Lower soot and slightly lower NO_x compared to diesel.

5.1.3 Economic criteria

Fig. 3 illustrates the performance of the different fuels in terms of production cost which is estimated relative to fossil diesel. For the comparison among the different fuels the average values have been considered.

According to the figure, OME_{3-5} is the most expensive fuel primarily due to the fact that it involves the most conversion steps among the alternatives considered. Among the more mature and developed fuels, RME was the less costly while DME and HVO were at similar levels according to the information provided by Volvo Trucks [49]. The n-butanol blend exhibits low production cost partly due to its constituents (HVO and fossil diesel).

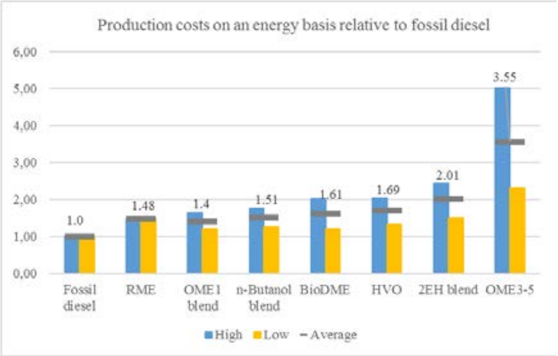

Figure 3: Production cost of the different fuels and blends considered in the assessment. Production costs are presented relative to fossil diesel [34, 49-51]

5.1.4 Overall performance based on pairwise comparisons

Based on the information presented above, pairwise comparisons were performed using Saaty's scoring scale from 1-9, in order to estimate the performance of each fuel relative to the others. The overall performance of the fuels under the different sub-criteria considered in this work is shown in Fig.4. Detailed tables containing the applied scoring scheme are found in the Appendix of this paper.

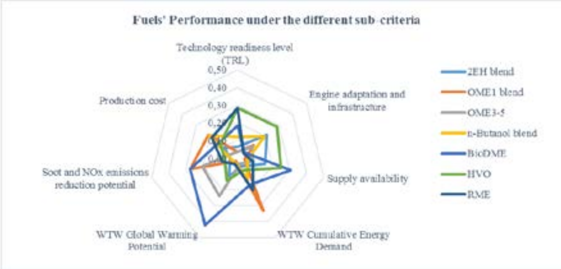

Figure 4: Illustration of the performance of the fuels under the different sub-criteria selected for the study and after the pairwise comparisons and scoring.

By linearly applying the weighting factors of the sub-criteria and criteria to the first order priorities of the fuels, their final ranking was obtained and is discussed in Section 5.2.

5.2 MCA results

The ranking order of the studied fuels for the four scenarios studied are shown in Fig 5 to Fig.8. In Fig. 5 the three criteria categories (technical, environmental and economic) obtained equal weighting factors. The first three best performing fuels are illustrated in colors. Moreover, fuels containing fossil diesel as a blend are marked with black dots.

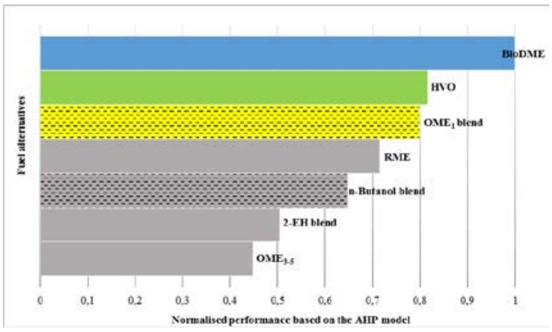

Figure 5: Final ranking order under S1: Criteria categories obtained equal weighting factors

According to this first scenario, biomass based DME is the fuel that scores highest followed by HVO and the OME_1 blend. Although DME would require engine and fuel storage modifications (reflected by the lower score in S2 – Fig. 6), it offers a competitive advantage in terms of clean and efficient combustion at a modest production cost. The newly developed n-butanol blend, 2-EH blend and OME_{3-5} were ranked lower. These fuels could be easily adapted into the current systems and lead to higher GHG emissions savings from a life cycle perspective. Their overall score however, is lower due to higher primary energy demand and production cost.

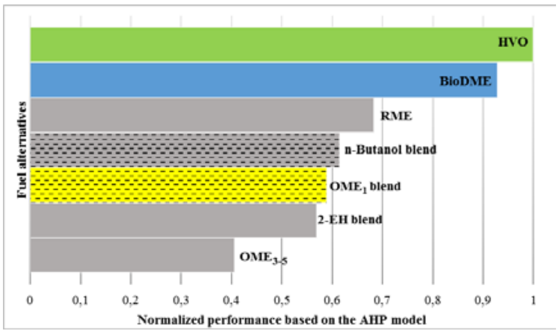

Figure 6: Final ranking order under S2: Focus on technical criteria

As technical criteria were ranked higher in the second scenario (S2) the more mature and easily accessible fuels were favored. An additional change in S2 compared to S1 was the higher-ranking order obtained for RME.

In S3 (Fig. 7) where environmental criteria such as primary energy demands, climate impact and soot and NO_x emissions obtained higher weights, again DME, HVO and the OME_1 blend were ranked among the three best fuels. Both DME and the OME_1 blend resulted in lowest soot and NO_x emissions and energy demands. In terms of GWP however, OME_1 was the worst performing fuel due its fossil content. Despite this, and based on its overall performance, it was ranked in the second place in S2.

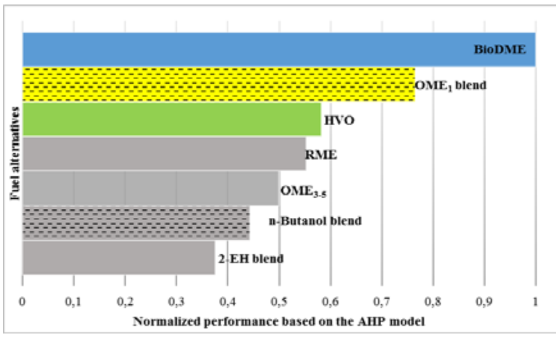

Figure 7: Final ranking order under S3: Focus on environmental criteria

Finally, when production cost was weighted higher (S4 - Fig.8), again DME the OME_1 blend scored higher together with RME. As already seen in Fig. 3 these three were the fuels with the lower production cost together with the n-butanol blend.

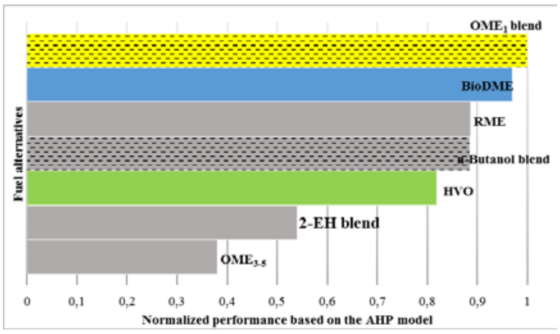

Figure 8: Final ranking order under S4: Focus on economic criteria

Overall the results of the study, favor mature and less costly fuels to be used in the short to medium term. These fuels however, may require additional infrastructure changes, what - if seen as a major constraint - may affect the ranking order of the selected fuels. In addition, if stricter environmental legislation is in place or with more ambitious climate goals (a scenario that was tested as sensitivity analysis), fuels relying only on renewable feedstock, will outperform the ones containing fossil diesel even if productions costs are higher.

The two main limitations regarding the more advanced and tailor-made fuels (such as 2-EH and OMEs) were related to primary energy efficiency and costs. These may be overcome or at least be improved over time and as technologies mature.

The final ranking order of the studied fuels depends on the selected criteria and assigned weights. The situation where all criteria are considered of equal importance (given equal weights), is less likely in practice. Different stakeholders may have different interests which are expected to affect the strength of each criterion and consequently the parameters that will define the overall potential of a fuel.

6 CONCLUSIONS

The environmental impact of the transport sector needs to be reduced and this could be achieved by using existing technologies at least in the short to medium term.

The overall aim of this work is therefore to assist the identification of possible fuel alternatives for diesel engines and discuss their strengths but also potential hinders that need to be overcome.

Based on a systematic and holistic comparison using technical, environmental and economic criteria, this work shows that a wide range of biomass based fuel alternatives is available. The study concludes that fuels with low production costs and good environmental performance are more attractive than fuels with high potential for emission reduction and environmental performance improvements but high associated production costs and energy demand.

As a continuation of this work and to reduce uncertainties in relation to the most relevant performance criteria and their associated impact on the adoption of renewable fuels, transport related stakeholders (including policy makers, transport providers, fuel and vehicle producers) are invited to the decision-making process.

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APPENDIX A

This section contains information on the scoring scheme applied during the pairwise comparisons of the fuels under the different criteria and sub-criteria considered in the study.

Technical criteria

Table A1: Pairwise comparison matrix for the technical sub-criterion: technology readiness level (TRL)

	2-EH blend	**n-Butanol blend**	**OME$_1$ blend**	**OME$_{3-5}$**	**BioDME**	**HVO**	**RME**	**Priorities**
2-EH blend	1	1/3	3	3	1/4	1/5	1/5	**0.06**
n-Butanol blend	3	1	4	4	1/2	1/3	1/3	**0.12**
OME$_1$ blend	1/3	1/4	1	1	1/5	1/6	1/6	**0.03**
OME$_{3-5}$	1/3	1/4	1	1	1/5	1/6	1/6	**0.03**
BioDME	4	2	5	5	1	1/2	1/2	**0.18**
HVO	5	3	6	6	2	1	1	**0.28**
RME	5	3	6	6	2	1	1	**0.28**
								λmax= 7.22 CR=0.03

Table A2: Pairwise comparison matrix for the technical sub-criterion: fuel adaptation and infrastructure

	2-EH blend	**n-Butanol blend**	**OME$_1$ blend**	**OME$_{3-5}$**	**BioDME**	**HVO**	**RME**	**Priorities**
2-EH blend	1	1	2	2	4	1	4	**0.2**
n-Butanol blend	1	1	3	3	3	1/4	4	**0.19**
OME$_1$ blend	1/2	1/2	1	1	3	1/3	4	**0.12**
OME$_{3-5}$	1/2	1/3	1	1	2	1/3	4	**0.1**
BioDME	1/4	1/3	1/3	1/2	1	1/5	1	**0.05**
HVO	1	3	3	3	5	1	4	**0.28**
RME	1/4	1/4	1/4	1/4	1	1/4	1	**0.04**
								λmax=7.35 CR=0.043

Table A3: Pairwise comparison matrix for the technical sub-criterion: supply availability

	2-EH blend	**n-Butanol blend**	**OME$_1$ blend**	**OME$_{3-5}$**	**BioDME**	**HVO**	**RME**	**Priorities**
2-EH blend	1	4	4	2	1/3	1/3	3	**0.16**
n-Butanol blend	1/4	1	2	1/2	1/4	1/4	1/2	**0.06**
OME$_1$ blend	1/4	1/2	1	1/3	1/4	1/4	1/3	**0.04**
OME$_{3-5}$	1/2	2	3	1	1/4	1/4	1	**0.09**
BioDME	3	4	4	4	1	2	3	**0.3**
HVO	3	4	4	4	1/2	1	3	**0.25**
RME	1/3	2	3	1	1/3	1/3	1	**0.09**
								λmax=7.3 CR=0.04

Environmental criteria

Table A4: Pairwise comparison matrix for the environmental sub-criterion: WTW cumulative energy demand

	2-EH blend	**n-Butanol blend**	**OME$_1$ blend**	**OME$_{3-5}$**	**BioDME**	**HVO**	**RME**	**Priorities**
2-EH blend	1	1/3	1/4	3	1/4	1/3	1/4	
n-Butanol blend	3	1	1/3	4	1/2	3	1/2	
OME$_1$ blend	4	3	1	5	3	4	3	
OME$_{3-5}$	1/3	1/4	1/5	1	1/4	1/3	1/4	
BioDME	4	2	1/3	4	1	3	1/2	
HVO	3	1/3	1/4	3	1/3	1	1/3	
RME	4	2	1/3	4	2	3	1	
								λmax= 7.5 CR=0.06

Table A5: Pairwise comparison matrix for the environmental sub-criterion: WTW global warming potential

	2-EH blend	**n-Butanol blend**	**OME$_1$ blend**	**OME$_{3-5}$**	**BioDME**	**HVO**	**RME**	**Priorities**
2-EH blend	1	5	8	1/3	1/5	1/2	5	**0.11**
n-Butanol blend	1/5	1	3	1/8	1/9	1/6	1/2	**0.03**
OME$_1$ blend	1/8	1/3	1	1/9	1/9	1/8	1/3	**0.02**
OME$_{3-5}$	3	8	9	1	1/4	3	8	**0.24**
BioDME	5	9	9	4	1	5	9	**0.4**
HVO	2	6	8	1/3	1/5	1	5	**0.14**
RME	1/5	2	3	1/8	1/9	1/5	1	**0.04**
								λmax= 7.6 CR=0.07

Table A6: Pairwise comparison matrix for the environmental sub-criterion: soot and NOx emissions reduction potential

	2-EH blend	**n-Butanol blend**	**OME$_1$ blend**	**OME$_{3-5}$**	**BioDME**	**HVO**	**RME**	**Priorities**
2-EH blend	1	2	1/5	1/5	1/5	1/3	1/3	**0.04**
n-Butanol blend	1/2	1	1/5	1/5	1/5	1/3	1/3	**0.04**
OME$_1$ blend	5	5	1	2	1	4	4	**0.27**
OME$_{3-5}$	5	5	1/2	1	1/2	4	4	**0.21**
BioDME	5	5	1	2	1	4	4	**0.27**
HVO	3	3	1/4	1/4	1/4	1	1/2	**0.07**
RME	3	3	1/4	1/4	1/4	2	1	**0.08**
								λmax= 7.4 **CR=0.05**

Economic criteria

Table A7: Pairwise comparison matrix for the economic sub-criterion: production cost

	2-EH blend	**n-Butanol blend**	**OME$_1$ blend**	**OME$_{3-5}$**	**BioDME**	**HVO**	**RME**	**Priorities**
2-EH blend	1	1/2	1/2	4	1/2	1/2	1/2	**0.09**
n-Butanol blend	2	1	1	4	2	2	1	**0.21**
OME$_1$ blend	2	1	1	5	2	2	1	**0.21**
OME$_{3-5}$	1/4	1/4	1/5	1	1/4	1/4	1/4	**0.04**
BioDME	2	1/2	1/2	4	1	1	1	**0.14**
HVO	2	1/2	1/2	4	1	1	1/2	**0.13**
RME	2	1	1	4	1	2	1	**0.19**
								λmax=7.16 **CR=0.02**