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Evaluation of the Applicability of Synthetic Fuels and Their Life Cycle Analyses

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Abstract: This paper summarizes the findings of a detailed assessment of synthetic, electricity-based fuels for use in aviation, shipping, and road transport. The fuels considered correspond to the most promising alternatives that were analyzed as part of the German research project BEniVer (Begleitforschung Energiewende im Verkehr—Accompanying Research for the Energy Transition in Transport) initiated by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Focusing on usage, infrastructure, and ecological analyses, several e-fuels were evaluated and compared to fossil fuels according to the specific sector. It turns out that for all sectors evaluated, the existing sustainable synthetic fuels are already compatible with current technology and regulations. In shipping and road transport, the use of advanced, sustainable fuels will allow for a more distinct reduction in emissions once technology and regulations are adopted. However, standard-compliant synthetic gasoline and diesel are considered the most promising fuels for use in road transport if the transition to electricity is not realized as quickly as planned. For the aviation sector, the number of sustainable aviation fuels (SAFs) is limited. Here, the current aim is the introduction of a 100% SAF as soon as possible to also tackle non-CO_2 emissions.

Keywords: synthetic fuels; e-fuels; PtL (power-to-liquid); SAF (sustainable aviation fuel); LCA (Life cycle assessment); aviation; road transport; maritime transport

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1. Introduction

To cope with global warming, the European Union aims to reduce greenhouse gas emissions by at least 55% by 2030 compared with 1990, which is considered a key milestone on the path to climate neutrality by 2050. Germany has set an even more ambitious target, aiming for climate neutrality by 2045 [1]. As part of the European 2030 Climate Target Plan, the share of renewable energy in the transport sectors—road, rail, aviation, and waterborne transport—should increase to 24% from 6% in 2015 [2]. In 2021, the German road sector contributed to 145 million metric tons of CO_{2eq} emissions, making up 19.3% of the total CO_{2eq} emissions [3,4]. Over 99% of these emissions are because of the combustion of fossil gasoline and diesel [4]. In order to achieve the ambitious targets stipulated in the federal climate protection act for the transport sector and become climate-neutral by 2045, fossil fuels must be gradually replaced. This requires technological solutions such as the use of more efficient battery electric vehicles or the use of synthetic and sustainable fuels.

For the aviation and maritime sectors, the emissions only for Germany are hard to quantify due to cross-border transport. But globally, the share of the radiative forcing and CO_2 emissions, respectively, is 5% for aviation and 2.9% for maritime transport (see Sections 3 and 4). Within these sectors, the use of renewable and low-carbon fuels (nearly all or most of the carbon dioxide (CO_2) that is released during the fuel's application is consumed during the fuel's production) such as advanced biofuels or further sustainable alternative fuels are identified as essential for the success of the energy transition; for details, see the ReFuelEU Aviation [5] and the Fuel-EU Maritime [6] initiatives. In addition to the reduction in the greenhouse gas CO_2, the usage of sustainable and synthetic fuels aims to reduce the emissions of nitrogen oxides (NO_x), sulfur, and soot particles since they not only affect the climate but are also harmful to human health and the environment as well [7,8]. It must be pointed out that the climate effect of non-CO_2 emissions is even more complex and ranges from an intensifying up to a cooling impact. This depends mainly on the kind of emission (e.g., as aerosol), the location of disposal (e.g., on the ground or in the upper atmosphere), and the persistence of the emissions. Since the differentiation between these different effects is not part of this work, the reader is referred to other studies, such as those given in the references [9–14].

To cope with these challenges synthetic fuels are needed. A limited number of biogenic fuels are available including hydrogenated vegetable oils (HVO) as diesel substitute and hydrogenated esters and fatty acids (HEFA) as synthetic kerosene (see below); methanol for shipping; ethanol and, in the U.S., also some C_4 alcohols for road transport; and biogas (especially in road transport).

Even though they are not commercially available, the so-called e-fuels have become of high importance due to the limitation of biomass for the production of advanced biofuels (ensuring no competition with food and/or forage production). E-fuels are produced using power-to-liquid (PtL) technology. As shown in Figure 1 [15], renewable energy such as wind or solar power is used to obtain green hydrogen (H_2) via the electrolysis of water. As a carbon source, CO_2 stemming either from biogas or direct air capture (DAC) is converted into carbon monoxide (CO). Biomass corresponding to the RED II criteria [16] can be used as a carbon source as well. The adjustment of the resulting syngas—a mixture consisting predominantly of H_2 and CO—depends on the specific process chain. For sustainable fuel production, two promising paths are discussed within this study: (I) direct fuel synthesis via the Fischer–Tropsch (FT) process and (II) the synthesis of methanol (CH_3OH) further converted to the fuel of interest [15].

Due to the different possible production processes, various types of renewable and sustainable fuels are available. These fuels can be used across different kinds of transport sectors, for example, in road and rail transport, aviation as well as maritime shipping. In particular, the road, rail, and maritime sectors offer a lot of possibilities for the usage of various sustainable fuels. In contrast, the possibilities for the use of sustainable aviation fuels (SAFs) are limited due to strong global regulations and requirements [17–19].

In order to evaluate the technical applicability of several different kinds of synthetic fuels as well as their ecological impact, the accompanying research project BEniVer (Begleitforschung Energiewende im Verkehr) on the funding initiative “Energy Transition in Transport” was initiated by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Within this funding initiative, the production and application of synthetic fuels have been studied, developed, and evaluated within the frame of 16 specific research projects. The overall aims of BEniVer were: (I) the evaluation and comparison of the results achieved within the specific research projects; (II) the development of a roadmap for guiding the further research and production as well as the market launch of synthetic fuels, and (III) to enable networking and communication between the different research projects.

An overview of the different types of fuels including their important fuel properties, as considered within the BEniVer project [20], is given in Table 1. From these fuel types, the studied synthetic diesel, synthetic gasoline, and synthetic kerosene are most similar to their conventional fossil-based fuel analogs since they consist of hydrocarbons only. The molecules with groups of ethers (DME and $OME_{3\text{-}5}$) and alcohols (methanol and higher alcohols) belong to oxygenated fuels, which are assumed to be possible alternative drop-in or neat fuels for road transport and maritime applications. The gaseous fuels—H_2, CH_4 (methane), and NH_3 (ammonia)—are alternative fuel options for the maritime and road transport sectors as well; however, they are more interesting for use in ship engines due to their handling and required storage capacity. More details about the possible synthetic fuels including an evaluation of their compatibility with regulations and standards are given by NormAKraft [21], a partner project within BEniVer.

Table 1. Overview of the alternative fuels considered within BEniVer [15]. Abbreviations: (I) fuels: DME—dimethyl ether, FT—Fischer–Tropsch, MtG—methanol-to-gasoline, MtJ—methanol-to-jet, $OME_{3\text{-}5}$—oxymethylene ether; (II) properties: CN—cetane number, FBP—final boiling point, FP—flash point, H_u—lower heating value, MN—methane number, (M/R)ON—(motor/research) octane number, T_b—boiling temperature, T_f—freezing point, ρ—liquid density at 15 °C and 1 bar.

	Synthetic Diesel	**Synthetic Gasoline**		**Synthetic Kerosene**		**Ether**		**Alcohols**		**Gases**		
	FT-Diesel *	**FT Gasoline**	**MtG ****	**FT Kerosene**	**MtJ**	**DME**	**$OME_{3\text{-}5}$**	**Methanol**	**Higher Alcohols**	**H_2**	**CH_4**	**NH_3**
Standard	EN 15940 [22] (EN 590 [23])	EN 228 [24]		ASTM D7566 [19]	--	ISO 16861 [b] [25]	--	ASTM D5797 [c] [26]	ASTM D7862 [c,d] [27]	EN 17124 [28]	EN 16723-2 [29] +	--
Appl.‡	Heavy-duty vehicles	Passenger cars		Aviation		Heavy-duty vehicles, shipping		Road transport, shipping		Road transport, shipping		
T_b (°C)	360 [e] (FBP)	210 [e] (FBP)		205...300 [e]	[g]	−24.8 [e]	105...280 [h]	65 [f]	99.5...117.7 [d,e]	−253 [f]	−162 [f]	−33.4 [f]
T_f (°C)	−40...6 [f]	−90.5...−95.4 [f]		≤−40 [e]	[g]	≈−140 [h]	−70... 48 [h]	−98 [f]	−89.5...−114.7 [d,e]	−259 [f]	−182 [f]	−77.7 [f]
ρ (kg/m³)	765–810 [e] (800–845 [e])	720–775 [e]		730–770 [e]	[g]	gaseous	961–1100 [h]	792 [h]	801–810 [d,e,j]	0.084 [f]	0.671 [f]	0.720 [f]
FP (°C)	≥55 [e]	≤−35 [f]		≥38 [e]	[g]	−42.2 [f]	54–115 [h]	9 [f]	24...35 [d,e]	--	--	--
CN	≥51 [e]	--		--	--	>55 [e]	63–100 [h]	5 [h]	17–25 [d,h]	--	--	--
ON	--	≥95 [e] (RON) ≥85 [e] (MON)		--	--	--	--	109 [i] (RON) 89 [i] (MON)	96–113 [d,e] (RON) 78–94 [d,e] (MON)	--	≥65 [f] (MN)	--
H_u (MJ/kg)	≈44 [h]	--		≥42.8 [e]	[g]	27.60 [h]	17.5–20.3 [h]	--	--	120 [k]	50 [k]	18.6 [k]
H_u (MJ/l)	--	30–33 [i]		--	[g]	18.44 [h]	19.5–19.7 [h]	15.8 [i]	26–27 [d,i] 31.1 [a,i]	8.5 [k]	22 [k]	12.7 [k]

[a] Refers to 1-octanol (n-octanol). [b] Deals with physical properties and does not give any requirements for application. [c] The U.S. standard is not valid in Germany or the European Union. [d] Refers to 1-butanol (n-butanol), 2-butanol (sec-butanol), and 2-methyl-1-propanol (iso-butanol). [e] Taken from the standard mentioned in Table 1. [f] Taken from [30]. [g] No information is available; however, the properties are expected to be similar to FT kerosene. [h] Taken from [31]. [i] Taken from [32]. [j] Temperature not specified in ASTM D7862 [27]. [k] Taken from [33]; values are given for liquified fuels. * Information belongs to applications in road transport; for the maritime sector, ISO 8217 [34] has to be considered. ** The values given in the table are requirements. Pure MtG does not match EN 228 but MtG E10 (MtG with $10\%_{vol}$ ethanol). + Refers to automotive applications; for maritime transport, EN ISO 23306 [35] has to be considered. ‡ Application; for details see Sections 3–5.

Within the accompanying BEniVer research project, the selected relevant chemical and physical properties of PtL fuels were not only evaluated but also compared with those of biofuels and fossil fuels (depending on the considered sector). Also, the compatibility with the current fuel infrastructure as well as with existing standards was analyzed. Moreover, the emissions connected with the production and usage of these fuels were evaluated by a Life Cycle Assessment (LCA).

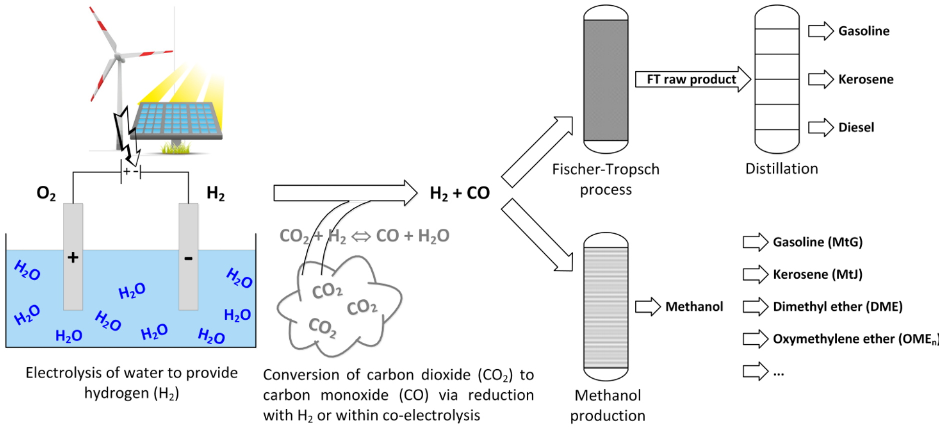

Figure 1. Illustration of e-fuel production via the power-to-liquid (PtL) process including (I) water electrolysis, (II) syngas production, and (III) fuel production via the Fischer–Tropsch (FT) process or the methanol production process. Methanol can be processed into further sustainable fuels [15]. Abbreviations: DME—dimethyl ether, MtG—methanol-to-gasoline, MtJ—methanol-to-jet, OME_n—oxymethylene ether.

2. Methodology of the Evaluation

Within the BEniVer project, 29 different evaluation criteria have been defined for analyzing the different fuels with regard to their ability to be integrated into the energy and transport system, their production efficiency and costs [36,37], their chemical and physical properties, and their ecological impact, acceptance, and market introduction mechanisms. In the present work, the focus is set on the fuel's properties and requirements as well as on their application and ecological aspects when using different synthetic fuels within specific transport sectors. In order not to go beyond the scope of this paper, only the most important results of the criteria are summarized and described qualitatively. For a comprehensive discussion of the further aspects, as well as the quantitative results of all the assessed fuels and all the 29 different evaluation criteria, see the BEniVer Roadmap [20].

2.1. Evaluation Criteria: Fuel Properties and Requirements for the Application of New Fuels

In order to compare the applicability of different synthetic fuels, the considered fuels were evaluated regarding (i) their ecological properties, (ii) their energy content, (iii) their safety and handling aspects as well as their (iv) compatibility with current standards and/or regulations, and (v) their technology.

With respect of the ecological properties, different kind of emissions being caused during the usage by combustion and/or handling itself were considered: carbon monoxide (CO), unconverted hydrocarbons, soot and particulate matter, nitrogen oxides (NO_x), and sulfur-containing components including sulfur oxides (SO_x). Moreover, the amount of carbon dioxide (CO_2) emission is taken into account as a measure of fuel consumption. Also, the possibility of the formation and emission of further pollutants like ketones and aldehydes, dinitrogen oxide (N_2O), and methane (due to methane slip) is incorporated in the evaluation. For the energy content, gravimetric and volumetric energy densities as well as the physical density were considered. Aspects of safety and handling were evaluated using typical relevant physical fuel properties as parameters. These include the boiling point or range, the vapor pressure, the freezing point, ignition properties (temperature, limits, octane/cetane/methane number), hygroscopic properties, oxidation stability, diffusivity (only relevant for gaseous fuels containing hydrogen), surface tension, and viscosity. In addition to the physical properties, the risk exposure by improper use was also taken into account.

The evaluation of the compatibility with current standards and regulations was carried out together with the project NormAKraft, a partner project of BEniVer focusing on standards and regulations for alternative and sustainable fuels [21]. To assess these criteria, we determined if a registration for the specific fuel in the ECHA (European Chemical Agency) database [38] already exists; if existing standards or standards are under development; and if there are acts or regulations that have to be respected for the usage of sustainable fuels. For technological compatibility, the following four indicators were used: the possibility of modifying and retrofitting in terms of costs and effort, the compatibility with materials, the ability for use as a drop-in fuel, and to what extent the usage of a new fuel is known or comparable to existing fuels.

2.2. Evaluation Criteria: Integration into the Transport System and Fuel Infrastructure

The following section mainly focuses on the methodology used to assess the road transport sector. Analogous to this assessment, the aviation and shipping sectors are also analyzed. However, due to a lack of data, the assessment can only be carried out qualitatively in some cases, so it differs to some extent from the assessment of the road sector. In order to assess the feasibility of integrating certain synthetic fuels into the transport system, three evaluation criteria were defined as follows: (i) the cost of vehicle maintenance, (ii) the refueling process, and (iii) the refueling infrastructure.

The costs of vehicle ownership consider acquisition costs and fuel costs over the entire service life of a vehicle. The minimum and maximum values are derived from the upper and lower limits of the evaluated generic fuel paths. The costs are calculated in each case excluding value-added tax (VAT) and energy tax (energy tax), so that comparability among the fuel types, some of which are taxed differently, is ensured.

The refueling criteria are used to evaluate the time and effort of refueling the vehicle from the vehicle owner's perspective. The focus here is primarily on the frequency and duration of the refueling process. It results in equal parts from the individual evaluation of the refueling time and the range per refueling.

Finally, the refueling infrastructure is evaluated by the ability to use the current infrastructure for the corresponding synthetic fuel without adaptation and investment costs of converting or constructing new refueling infrastructure if needed. It is calculated from the quotient of the current number of filling stations for the respective fuel (e.g., there are approx. 6000 LPG filling stations currently in Germany [39,40]) and the current number of filling stations for petrol (approx. 14,000 [41]). The assessment of the refueling infrastructure is then derived equally from the individual assessment of the current availability of refueling stations and investment costs required for a sufficient expansion of the infrastructure.

2.3. Evaluation Criteria: Ecological Analysis (LCA)

To evaluate the ecological impact of the fuels and their application, a Life Cycle Assessment (LCA) is conducted. The whole life cycle of the fuels from resource supply and fuel production to the use of the fuels is considered. All results refer to the functional unit of one kilometer driven. It is assumed that production and use take place in Germany. Therefore, no transport routes are included, and the German electricity mix is used as the electricity source for the electricity supply of electrolysis, CO_2 capture, and synthesis. The data used for the calculations are either based on generic assumptions or project-specific data. The exact data sources for the generic values and the life cycle inventory data can be found in the LCA methodology guide [42]. Fuel consumption during the use phase of the vehicle is based on data from the literature as described in Pichlmaier et al. [42]. In addition to this foreground data from the methodology guide, the LCA database "ecoinvent" is used for the background data. For example, data records for the production of materials or energy sources are taken from this database. The LCA is conducted for the life cycle impact category global warming potential (GWP) for two different points in time: (i) 2018—to represent actual conditions and (ii) 2045—to include a future perspective. For 2045, the efficiency of plants and the efficiency during the use of vehicles are adapted as well as the German electricity mix. The future assumptions for the efficiency of plants and vehicles are described in Pichlmaier et al. [42]. For the adaptation of the electricity mix to future scenarios, the results from the MuSeKo project [43] are used. A conservative assumption was made for the background data, which are not adjusted to future developments.

3. Sustainable Aviation Fuels (SAFs)

The climate impact of the aviation industry is mainly caused by two impacts: (i) CO_2 as a greenhouse gas and (ii) the effect of other exhaust gas components like soot, aerosol, and NO_x, which are summarized as non-CO_2 effects. In total, the share of the aviation sector on radiative forcing is about 5%, with two-thirds resulting from non-CO_2 effects like the particle-induced formation of contrail cirrus [44,45].

Up to now (January 2024), eight different SAFs have been approved for use as a drop-in fuel in blends with a fossil jet fuel, up to an admixture of $50\%_{vol}$ [19]. One of these fuels is paraffinic FT-kerosene, which is called FT-SPK (synthetic paraffinic kerosene). "Paraffinic" means that this fuel has no aromatic components that are important precursors for the formation of soot particles. In addition to FT-SPK, the other SAF considered within the BEniVer project is methanol-to-jet (MtJ), which is not yet certified although very similar to alcohol-to-jet SPK (AtJ-SPK) in terms of the production process. AtJ-SPK is produced by the oligomerization of ethanol or *iso*-butanol, respectively, and allowed to be used as drop-in fuel according to ASTM D7566. In the MtJ process chain, methanol is used as feedstock for the oligomerization, thus ultimately leading to paraffinic kerosene as well. However, methanol is not yet included as an alcohol feedstock that is allowed to be processed within the ASTM D7566, with the consequence of not being allowed to fly with an AtJ-SPK that was produced via the MtJ path.

In contrast to fuels for the maritime sector as well as road transport fuels, oxygenated fuels are not an option for use as aviation fuel, and thus, consequently, as SAFs because any aviation fuel must consist of C and H atoms not less than $99.0\%_{mass}$. Molecular bonded oxygen in C-O could lead to lower storage stability and an increased risk of water contamination due to its hygroscopic nature. Furthermore, within the aviation sector, a significant reduction in soot emissions is only achievable by keeping the percentage of aromatics within jet fuel as low as possible [7,8,46]—but not by oxygenated fuels having no C-C bonds, as reported in the transport sector.

3.1. Requirements for the Application of SAFs

Without the integration of any aromatization and cyclization processes in fuel production, SAFs like FT-kerosene and MtJ consist of linear and/or branched paraffin only. However, as mentioned above, the ASTM D7566 standard defines $50\%_{vol}$ as the maximum of SAFs blended with fossil fuels. This strict limit results from the specification of the fuel properties and composition with the share of aromatics being historic fuel components due to their natural occurrence in fossil oil. Without aromatics in jet fuel, the risk of leakages cannot be excluded since these components lead to a (desired) swelling of seals [47]. Due to this, a share of min. $8\%_{vol}$ aromatics [19] is required within the specification; thus, the blending of an SAF with a fossil jet fuel is currently mandatory. Nevertheless, test flights with 100% SAF have demonstrated that the use of neat paraffinic kerosene as aviation jet fuel is possible [48]. As a consequence, it seems realistic that future specifications and standards might allow for the use of completely non-aromatic jet fuels. It is worth mentioning that additional benefits regarding a reduction in non-CO_2 effects—playing a major role within the global aviation effective radiative forcing [45]—could be realized as well because of the reduced emission of particles.

3.2. Usage and Infrastructure for SAF

For the aviation sector, an SAF blend of $50\%_{vol}$ FT-SPK with conventional jet fuel and a pure, i.e., 100%, SAF FT-SPK was considered and compared with a crude oil-based Jet A-1. Due to the requirements defined by the ASTM D7566, the physical properties of the SAF blend as well as of the 100% SAF are identical to the conventional Jet A-1. Hence, the way of handling an SAF is the same as that for Jet A-1 and, consequently, the existing infrastructure could be used for both types of the considered SAFs. Solely, a 100% SAF does not contain aromatics. As mentioned above, this fuel is not yet approved. The challenges of material compatibility and risk of leakages resulting from the missing aromatic components could be overcome with the replacement of, e.g., (critical) seals and valves during regular or additional (if necessary) inspections. In the case that a single aircraft is allowed to use 100% SAF, a parallel fuel infrastructure at airports might be necessary. Also, the higher fuel costs and/or a possible obligation to provide evidence for the usage of SAF may require a separate fueling system or infrastructure.

The main difference between the considered types of jet fuels results from the emissions. With the 100% SAF, the exhaust gas contains no sulfur components or SO_x, respectively, and the amount of soot particles as well as of unconverted hydrocarbons and CO are distinctly reduced. This is due to the absence of aromatics and the resulting cleaner and more efficient combustion of pure synthetic fuel. With the reduction in soot particles, pure SAFs will also reduce aviation's impact on climate change because of the reduction in non-CO_2 effects including the particle-induced formation of contrail cirrus [44,45] resulting from the emissions mentioned above. In contrast, the reduction in the climate impact using the $50\%_{vol}$ FT-SPK blend is not as much as that using pure SAF due to the fossil component.

3.3. Ecological Analysis (LCA)

Figure 2 shows the results of the LCA of the SAF, the SAF $50\%_{vol}$ blend, and fossil kerosene. It turns out that the emissions for the synthetic fuel and the blend in 2018 were significantly higher than those for fossil kerosene. This is mainly due to the high contribution of electrolysis and thus, is caused by the emissions from electricity production according to the current German electricity mix. However, the share of emissions from hydrogen production will be significantly reduced in a renewable energy system in 2045. If the negative emissions from CO_2 capture are taken into account, the total emissions from synthetic fuels in this year (2045) will be lower than those from fossil references.

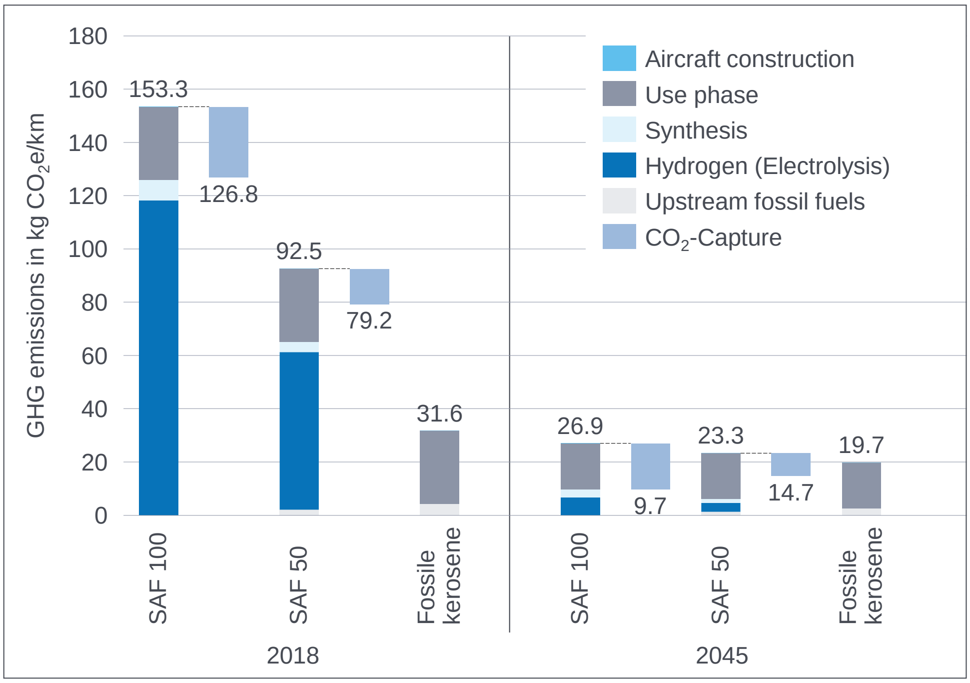

Figure 2. Results of the life cycle analyses (LCAs) for a 100% SAF, a 50% blend, and fossil kerosene.

3.4. High-Potential Synthetic Fuels for Use in Aviation

Table 2 compares and summarizes the application of the considered $50\%_{vol}$ blend SAF and a 100% SAF, as studied within the BEniVer project. Indeed, FT-SPK was the focus SAF; these findings apply to the other SAFs being approved by the ASTM D7566. Another promising SAF option could be MtJ, although it has not yet been approved (see Section 3.2). However, due to the production process, MtJ allows for more possibilities regarding fuel design and higher product yields.

Table 2. Overview of the evaluation of generic, electricity-based fuel options in aviation with FT-SPK as the SAF component * (+ advantageous, • unbeneficial, – disadvantageous). Abbreviation: SAF—sustainable aviation fuel.

	SAF 50%$_{vol}$ Blend	100% SAF
Fuel production	– Complex production process. – Side products.	– Complex production process. – Side products.
Infrastructure availability	+ Present infrastructure can be used. • Open question if the unlimited use of infrastructure is possible, e.g., due to costs.	+ Present infrastructure can be used. • Open question if the unlimited use of infrastructure is possible, e.g., due to costs → parallel infrastructure at airports may be necessary.
Applicability (drop-in/blend/engine customization)	+ Comply with ASTM D7566 → completely compatible with existing fleet and technology. – Higher fuel costs.	+ Regarding the technical point of view, compatible with existing fleet. + Higher efficiency in combustion. + If replacement of seals, fittings, valve, et cetera, is necessary, this can take place during regular inspections/maintenance. • Possibly inspections/maintenance is more often necessary to secure the compatibility with the material. – No approval according to ASTM D7566. – Higher fuel costs.
Pollutant emissions from usage	• Less emissions compared with pure fossil jet fuel.	• Significant reduction in emissions, including non-CO_2 effects.
GHG balance over the entire life cycle	• Less emissions in future scenario compared with fossil fuel.	+ Less emissions in the future scenario compared with the SAF 50%$_{vol}$ blend.
R&D requirements	❖ Handling and logistics of large quantities of SAF from different sources. ❖ Availability of resources (feedstock) for biogenic SAF. ❖ "Fuel design" [49].	❖ Handling and logistics of large quantities SAF from different sources. ❖ Availability of resources (feedstock) for biogenic SAF. ❖ "Fuel design" [49].

* The generic fuel paths listed here represent a selection of the fuel types researched by the supported EiV research projects. In addition, various other fuels were considered and described in the BEniVer Roadmap [20].

Currently, there are only two other power unit systems for aviation under discussion including (i) the use of hydrogen as fuel and (ii) electrically powered aircraft. The latter is out of scope for commercial aviation due to the low energy density of batteries compared with liquid fuels. The application may be only for short-distance flights (max. 500 km) and limited to 50 passengers. Compared with the worldwide aviation industry, the energy consumption in this specific area is less than 1%.

For distances up to 2800 km and a capacity of up to 250 passengers, the use of hydrogen-powered aircraft is a realistic option in the aviation sector. This segment has a share of about 50%, so a significant impact on aviation and its climate effect has to be expected by the introduction of hydrogen as fuel; however, currently, the market introduction is not foreseen to occur before 2035. This means that SAFs will be needed for the entire aviation industry, also distinctly beyond 2035.

3.5. Conclusions

The aviation sector is extremely challenging in terms of strict safety issues and requires a long time for the development of a new aircraft design including new power unit systems.

Additionally, non-CO_2 effects have also to be reduced in addition to those of GHG emissions. The grade of distance to fly will determine if fossil kerosene can be replaced and how fast this will be realized worldwide.

Recently, it has become apparent that for long-distance flights (>2800 km) with high passenger capacity, liquid fuels will still be the fuel of choice in 2035 and beyond due to the required high energy density. Several synthetic kerosenes, being approved for 50 $\%_{vol}$ blend with fossil kerosene, will allow a drastic reduction of the unwanted GHG emissions if they can be produced in sufficient amounts worldwide. However, non-CO_2 effects can only be reduced efficiently by the use of 100% SAF, a sustainable synthetic kerosene. Fortunately, the prospective for the large-scale and mid-time production of such innovative synthetic fuels—with FT-SPK and also MtJ—is promising.

Also, for mid-term distances (up to 2800 km) with a capacity of up to 250 passengers, hydrogen-powered aircraft will not be available before 2035. Furthermore, it is expected that for short-distance flights (max. 500 km) and limited passengers (up to 50), electrically powered aircraft will enter the market starting in 2030. Consequently, SAFs will be needed for the entire aviation industry in the mid-term and even longer, distinctly beyond 2035.

4. Synthetic Fuels for Maritime Transport

Currently, the use of heavy fuel oil (HFO)—which is still common with a share of 79% of the total fuel consumption—is the main reason for emissions stemming from the marine industry. Together with marine gas oil (MGO), the share of these marine fuels is about 97% of the total fuel consumption in maritime transport. Here, the most important and dominant part is the international navy due to the transport of wares and goods. Regarding global CO_2 emissions, the maritime sector has a share of 2.9%, of which 87% are caused by international shipping, leading to a share of 2.5% [50].

In contrast to the aviation sector, different synthetic fuels are discussed for use in the maritime transport sector, with electrically powered ships not being considered. These fuels include FT-diesel, methanol, $OME_{3\text{-}5}$, liquified natural gas (LNG), hydrogen (H_2), and, quite recently, ammonia (NH_3).

4.1. Requirements for the Application of Synthetic Maritime Fuels

For the fuels mentioned above, it is expected that no special requirements will be set for the use of FT-diesel and LNG, reflecting the estimation that these two fuels can be used without any major modification in current engines that are fueled with MGO/HFO or natural gas, respectively. If FT-diesel is designed for use in the maritime sector, this specific diesel will also cover the standard ISO 8217, defining MGO as well as HFO. The difference between these fuels mainly results from the viscosity, density, and boiling range. Depending on the composition, it may be necessary to heat HFO in order to enhance the flow properties.

$OME_{3\text{-}5}$ is a possible oxygenated blending component for diesel; this approach will allow for a considerable reduction in soot emissions [51], but it might require the modification of sealing materials. Moreover, there is currently no standard allowing the use of $OME_{3\text{-}5}$ in ship engines. The same is true for the use of the other fuel options including methanol, H_2, and NH_3. These fuels also have the potential to reduce greenhouse gas emissions considerably; however, the important drawback is that a modification of the engine or even the enforcement of new engine technologies is required, which may afford considerable costs. In the case of oxygenated fuels, at least other materials are necessary, whereas, for H_2 and NH_3, not only adjusted power units are required but also modified fuel storage and supply systems.

In addition to the technological and regulative requirements, further requirements regarding emissions have to be ensured. Here, in particular, when burning more (synthetic) LNG or ammonia, methane slip as well as the formation and emission of N_2O must be prevented since the greenhouse gas effect of methane or of N_2O is much higher compared with CO_2, by 25 times and 273 times, respectively [52].

4.2. Usage and Infrastructure of Synthetic Maritime Fuels

For the assessment of the usability of possible future maritime fuels, four different synthetic fuels were considered (FT-diesel, methanol, synthetic LNG, and ammonia) and compared to today's maritime fuels, fossil LNG, and MGO. Regarding the ecological properties of the use case, ammonia and methanol are the best options. When using ammonia, carbon-containing emissions are of course avoided; however, the drawback is that increased NO_x and/or N_2O emissions might occur. By the use of methanol, carbon emissions are distinctly reduced although not completely prevented. On the other hand, the energy density of both ammonia and methanol is lower compared with synthetic diesel, which might lead to a reduced cargo capacity since larger tanks are required.

Concerning the safety and handling aspects, the use of ammonia comes along with another drawback—high toxicity. Due to this, ammonia is currently seen only as fuel for freighters and bulk carriers but not for maritime passenger transport (cruise, ferry). Also, synthetic LNG and methanol have some drawbacks in their handling. For LNG, cryogenic tank fueling systems are necessary; methanol has less stability due to the oxygen in the molecule. So, regarding safety and handling, FT-diesel is the most beneficial fuel. FT-diesel could directly replace MGO as well as HFO since it is highly compatible with the current technology and also complies with the standard ISO 8217 for maritime fuels. Hence, the existing infrastructure allows for the use of FT-diesel—(extensive) modifications are not of relevance.

In addition to the fact that synthetic LNG is more or less methane, it fulfills the standard EN ISO 23306. And since LNG-powered ships are already established, synthetic LNG can be directly used today in ships and infrastructure as well. Unfortunately, the share of LNG ships is only approximately 3%. All other ships that are going to use the future maritime fuels are currently only single solutions or in the status of research; thus being the case for technological development as well as for standards regulating properties and daily usage of these fuels. Moreover, especially for methanol and ammonia, an extension of the infrastructure of harbors worldwide is required.

If fuel costs are considered, ammonia has advantages compared with other synthetic fuels. Additionally, the ammonia production process itself—the Haber–Bosch process—has been established on a large scale for decades. In the Haber–Bosch process, green hydrogen can easily replace fossil-based hydrogen. Of course, green hydrogen that is needed for the other synthetic fuels must be available in large amounts.

4.3. Ecological Analysis (LCA)

Including the CO_2 credit, the synthetic sustainable fuels are below the fossil references in 2045, as shown in the results of the LCA for the considered maritime fuels in Figure 3. Syncrude-based diesel produces higher GHG emissions than methane and methanol. Compared with the other fuels, ammonia produced total emissions in 2018 of a similar magnitude to methane and methanol. In 2045, the emissions from the use of ammonia will be slightly higher than those stemming from the use of methane and methanol.

4.4. High Potential Synthetic Fuels for Use in Maritime Transport

The different fuel options for maritime transport are compared in Table 3. FT-diesel can replace HFO and MGO immediately and reduce the impact on the environment significantly. The effect of the replacement with alternative fuels would be even more if oxygenated or non-carbon fuels (e.g., ammonia) are used. Here, methanol is the most promising alternative since there are already ships operating with methanol on the market [53], whereas the usage of hydrogen and/or ammonia is in the research stage. For hydrogen, a few demonstrator ships are known, e.g., [54–56]. Regarding the use of ammonia, increased emissions of NO_x have to be avoided due to their toxicity, in particular, N_2O, which has a factor of 273 and a much higher greenhouse gas potential than CO_2 [52].

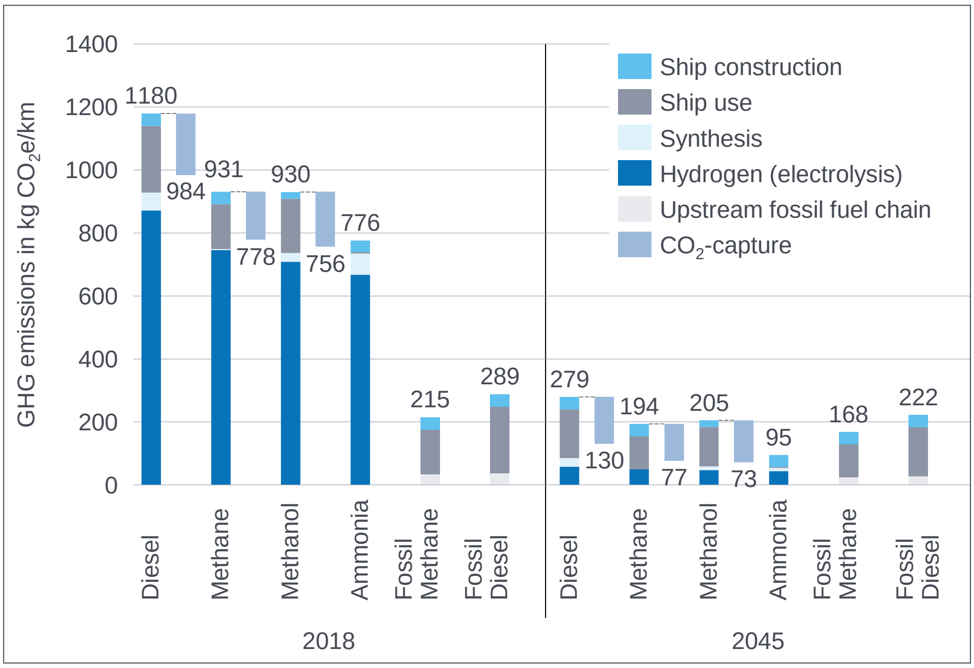

Figure 3. Results of the life cycle analyses (LCAs) for maritime fuels.

Table 3. Overview of the evaluation of generic, electricity-based fuel options in the shipping industry * (+ advantageous, • unbeneficial, – disadvantageous). Abbreviations: DAC—direct air capture, HFO—heavy fuel oil, LNG—liquified natural gas, LOHC—liquid organic hydrogen carrier, OME—oxymethylene ether, MGO—marine gas oil.

	FT-Diesel	Methane (LNG)	Methanol	OME	Hydrogen	Ammonia
Fuel production	– Complex production process. – Side products.	+ Fewer costs. + Production without side products possible. + CO_2 active process. + Maximum energy content per C atom.	+ Production without side products is possible. + CO_2 active process. • Energy content per C atom not as high as for diesel or LNG due to partially oxidized C atom.	• Production via methanol → additional process steps.	+ No DAC or other carbon source necessary.	+ No DAC or other carbon source necessary.
Infrastructure availability	+ Present infrastructure can be used.	• Global infrastructure partially existent. • Up to now, fueling was only possible via bunker vessel, LNG terminals necessary.	• Global infrastructure partially existent; expansion for maritime sector necessary.	– Not present; usage within existing systems depends on the amount of the admixture.	– Global infrastructure partially existent; expensive expansion for maritime sector necessary.	• Global infrastructure partially existent; expansion for maritime sector necessary.
Applicability (drop-in/blend/engine customization)	+ Replacement for MGO/HFO (90% of all ships). • Adjustment of engine control may be necessary. – Higher fuel costs.	+ Replacement for fossil LNG. + Fewer fuel costs than FT-diesel. • Share of LNG ships <10%. • Usage competition with the energy sector. – Modifications of MGO/HFO engines necessary. – Lower energy density than diesel → larger tank necessary (would reduce capacity) or less range.	+ Development of methanol ships is technically matured; single ships are already in use. + Promotion by global players. – Currently, no standard, only single permits. – Energy density half as much as diesel → larger tank necessary (would reduce capacity) or less range. – Nearly no existing ships; modification of MGO/HFO ships necessary.	– Maximum share of the admixture up to 15% due to compatibility with materials.	• Single test cases but no technically mature ships. – Low energy density → low range. – Currently, no standard.	• Usage competition with chemical industry, esp. fertilizer. – No compatibility with current engines and technology. – Currently, the technology is in development → no market-ready ships. – Toxic → application for cargo ships only. – Currently, no standard.

Table 3. *Cont.*

	FT-Diesel	Methane (LNG)	Methanol	OME	Hydrogen	Ammonia
Pollutant emissions from usage	+ Less soot emissions compared with MGO/HFO. + No emissions of SO_x. • Reduction in emissions not as much as for other synthetic fuels.	+ Significant reduction in emissions, e.g., complies with limits for NO_x. + No emissions of SO_x. – Risk of methane slip → has to be avoided.	+ Significant reduction in emissions, eventually, no exhaust gas treatment will be necessary. + Largest potential for a reduction in soot emissions in the group of carbon containing fuels. + No emissions of SO_x.	+ Reduction in SO_x and soot emissions when used as a blending component.	+ No carbon containing emissions → no CO_2 emissions. + No emissions of SO_x.	+ No carbon-containing emissions → no CO_2 emissions. + No emissions of SO_x. – Increased NO_x emissions and emissions of N_2O possible.
GHG balance over the entire life cycle	• Slightly higher GHG emissions.	+ Relatively less GHG emissions. – CH_4 emissions possible.	+ Relatively less GHG emissions.	• Slightly higher GHG emissions.	+ No carbon-containing emissions.	+ No carbon-containing emissions. – Emissions of N_2O possible.
R&D requirements	❖ Exhaust gas treatment. ❖ Engine control. ❖ Lubricating properties.	❖ Minimization and prevention of methane slip. ❖ Further development of modifications for MGO/HFO-fueled ships toward pure CH_4 → integration of tanks without losings cargo capacity.	❖ Further development of modifications for MGO/HFO-fueled ships toward pure CH_4 → integration of tanks without losings cargo capacity. ❖ Technical components (engine, tank, and fuel-injected systems). ❖ Material (esp. metallic → corrosion).	❖ Technical components (engine, tank, and fuel-injected systems). ❖ Material (esp. sealings made from plastics).	❖ Kind of application (direct combustion or fuel cell). ❖ Storage (liquid, gaseous, LOHC). ❖ Technical components (engine, tank, and fuel-injected systems). ❖ Material.	❖ Minimization and prevention of NO_x and N_2O emissions. ❖ Exhaust gas treatment. ❖ Kind of application (direct combustion or fuel cell). ❖ Storage (liquid, gaseous). ❖ Technical components (engine, tank, and fuel-injected systems). ❖ Material. ❖ Actions in case of damage.

* The generic fuel paths listed here represent a selection of the fuel types researched by the supported EiV research projects. In addition, various other fuels were considered and described in the BEniVer Roadmap [20].

To accelerate the use of alternative fuels, increased production capacities are necessary in order to decrease fuel costs. Here, research is needed for the optimization of fuel production and improvement of the product yield, especially regarding FT-diesel, methanol, and H_2 production. Also, an improvement in engine technology is required for more efficient combustion processes. Since ships have lifetimes of 20, 30, or even more years, there is also a demand for research regarding engine modification and retrofitting, e.g., to replace HFO engines with a methanol- or hydrogen-powered engine unit. Furthermore, power units with fuel cells using H_2 or NH_3 are currently under consideration as well.

4.5. Conclusions

The application of sustainable alternative fuels in maritime shipping reveals a large similarity to the challenges existing in the aviation sector, with a long time required for the development of the design of a new cargo ship or bulk carrier, including new power unit systems and the combination of long-distance, heavy mass, and worldwide availability.

The perspectives for a successful transition are promising. Options that are effective in reducing GHG emissions already exist. Among them, FT-diesel in particular allows for the replacement of fossil liquid fuels that are used today overwhelmingly (HFO and MGO) with an immediate and significant reduction in GHG. GHG emissions might be further reduced by using green methanol, the most appropriate representative of oxygenated fuels. This technology already exists today, with the first ships operating on the market. In the future, GHG emissions may be avoided almost totally by using ammonia and hydrogen, the most prominent representatives of the so-called non-carbon fuels. Currently, their application and adaptation for shipping is in the research stage, with the first realization shown.

Of course, it must be ensured that introducing new fuels will not open the door to additional emissions of molecules (like N_2O and CH_4) that are even more harmful to the environment than CO_2. Given the bundle of appropriate and sustainable fuels identified in the maritime sector, activities should focus on increased production capacities and lower fuel costs to realize their effective introduction into the market.

5. Synthetic Fuels for Road Transport

E-fuels, as an option for de-fossilization, offer the advantage of being able to store energy at about the same high density as fossil fuels, thus enabling long vehicle ranges. A number of e-fuels also have the potential to be integrated seamlessly into the existing infrastructure (vehicles, fuel depots, service stations, distribution structures, etc.). This is particularly important for the de-fossilization of the existing fleet. For example, on 1 January 2023, 59 million vehicles with combustion engines were registered in Germany [57]. Emission measurements by project partners within the funding initiative "Energy Transition in Transport" [20] have shown that e-fuels tend to cause fewer local pollutant emissions during combustion in the engine than fossil fuels [58–60]. There is also considerable development potential in this field if fuel properties are improved by optimizing the manufacturing processes.

5.1. Requirements for the Application of Synthetic Fuels in Road Transport

Fuels offered as blends or pure fuels at service stations in Germany must meet the requirements of fuel standards in Germany. In addition to meeting the product standard, the sale of any fuel must also be approved by the German legislature. This is regulated in the 10th ordinance for the implementation of the Federal Immission Control Act (10th BImSchV, as of February 2023). Therefore, only the following fuels may be placed on the market: gasoline (DIN EN 228), diesel fuels (DIN EN 590), biodiesel (DIN EN 14214), ethanol fuel E85 (DIN EN 15293), autogas (DIN EN 589), natural gas and biogas (DIN EN 16723-2), vegetable oil fuels (rapeseed oil, DIN EN 51605), and hydrogen (for fuel cell vehicles, DIN EN 17124). Consequently, paraffinic fuels, for example—for which a fuel standard already exists (DIN EN 15940)—are not tradable as pure fuels at German service stations. However, this will change because of a resolution proposed by the government fractions of the German Bundestag [61]. This resolution calls for the inclusion of the DIN EN 15940 in the 10th BImSchV and is to be implemented in the near future.

For the use of new fuels outside the common fuel standard DIN EN 228 [24] or DIN EN 590 [23], the approval of the vehicle manufacturer is also important (e.g., when using 100% paraffinic diesel). In the case of existing vehicles, the manufacturer or importer can subsequently approve the fuel's use (as was necessary, for example, in the case of the introduction of E10). If a fuel will be used by the vehicle's owner but this fuel has not been approved by the manufacturer, it is not possible to invoke the warranty in the event of vehicle damage.

5.2. Integration into the Road Transport System and Fuel Infrastructure

Due to the large differences in application, purpose, requirements, and energy consumption among the various sectors, the freight transport and passenger transport sectors were considered separately within the project BEniVer. In the field of freight transport, the focus is primarily on long-haul heavy commercial vehicles with a gross vehicle weight of 40 tons.

Within the scope of the collaborative research activities, an extensive examination was conducted on a range of fuels and fuel blends suitable for heavy-duty transportation encompassing diesel, methanol, OME, and DME. In the interest of facilitating meaningful comparisons, fuels such as FT-diesel, synthetic liquefied methane (comparable to fossil LNG), and methanol were viewed as generic fuels within the framework of the BEniVer project. The analyzed fuels of the truck sector, including the most relevant results of the collaborative research, are summarized in Table 4. In the truck sector, only diesel and LNG currently have existing infrastructure and will therefore be drop-in-capable. Compared with methanol, OME, and DME, synthetic diesel scores mainly with its high energy density. The oxygenated fuels, on the other hand, promise, above all, more soot-free combustion due to the oxygen they contain. However, analyses by research associations have also shown that CO, soot, and HC emissions can also be reduced when synthetic diesel is used in comparison with the respective emissions of the fossil fuel pendent. Even though the production costs for synthetic methane are the lowest, the storage of this gas is challenging [36,37]. Currently, the liquefaction of methane and its transport in cryogenic tanks is state-of-the-art. However, this is energy-intensive; even with liquified methane, the same ranges cannot be achieved as with diesel vehicles. Furthermore, the problem of methane slip must be further investigated and prevented; see also the presented discussion in the maritime sector.

For the passenger car sector, a comprehensive investigation of FT-gasoline and MtG, methanol, methane, OME, and DMC as well as methyl formate and hythane blends (mixture of hydrogen and methane) was conducted as part of the collaborative research initiatives. In order to improve comparability, FT-gasoline, synthetic methane (comparable to the fossil CNG), methanol, and hythane were also identified as generic fuels within the framework of the BEniVer project. To prevent duplications in the passenger car sector, the focus of the BEniVer project was placed on the gasoline pathway; consequently, diesel, OME, and DME are not discussed here, even though these fuels can also be used in the passenger car sector. Table 5 shows the most important results. Due to its lower carbon content, methane is less expensive to produce than gasoline. Both fuels are drop-in capable and can thus directly de-fossilize the vehicle fleet (in the case of MtG, DIN EN 228 can be achieved by adding octane boosters). Methanol promises a very clean combustion process and also an increase in efficiency in newly developed, optimized engines due to its high knock resistance. However, there is currently almost no infrastructure existing and, moreover, it may not be sold as a fuel in Germany due to its absence from the 10th BImSchV.

5.3. Ecological Analysis (LCA)

Figure 4 shows, similar to the other sectors, that in 2018, the studied synthetic fuels produced significantly more GHG emissions than their fossil references. Similarly, emissions from syncrude-based diesel are higher than those from other synthetic fuels. However, the differences between the fuels are much higher in 2018 than in 2045, in which the differences between diesel, DME, and methanol, for example, would be marginal. Due to the lower emission factor of electricity, the differences in the efficiency of the production itself do not have such a significant impact on the final result.

5.4. Outlook for the Use of Synthetic Fuels in Heavy-Duty Transport

Among the spectrum of synthetic fuels under consideration, synthetic diesel and synthetic methane have emerged as the most promising alternatives for deployment in long-haul heavy-duty vehicles. It should be noted that 100% synthetic diesel, although offering substantial advantages, falls short of meeting the DIN EN 590 [23] standard for diesel fuel primarily because of its relatively low density. Nevertheless, numerous contemporary and forthcoming engine iterations have obtained approvals for the use of paraffinic fuels like synthetic diesel. As already described, however, the current lack of integration of EN 15940 [22] into the 10th BImSchV represents a substantial barrier to the immediate introduction of pure synthetic diesel in Germany. However, upon its incorporation into the regulatory framework, this fuel could become a viable option, maintaining compatibility with the existing refueling station infrastructure.

Table 4. Overview of the evaluation of generic, electricity-based fuel pathways for heavy-duty vehicles (40t gross vehicle weight) * (+ advantageous, • unbeneficial, – disadvantageous). Abbreviations: DME—dimethyl ether, LNG—liquified natural gas, OME—oxymethylene ether.

	FT-Diesel	Methane (LNG)	Methanol	OME	DME
Fuel production	– High fuel costs.	+ Low fuel costs. + Very pure production possible.	• Low fuel costs, but low calorific value.	– Moderate fuel costs and low calorific value.	• Moderate fuel costs and moderate heating value.
Infrastructure availability	+ Already partly available as blend (R33) [a]. • Currently, (still) no existing fueling infrastructure for pure paraffinic diesel (EN 15940) in DE. + Required infrastructure can be set up with low capital expenditure.	• Currently, only approx. 100 LNG refueling stations are available.	– Currently, no existing fueling infrastructure.	– Currently, no existing fueling infrastructure.	– Currently, no existing fueling infrastructure.
Applicability (drop-in/blend/engine customization)	+ Compliant with standards as a blend (R33) and can therefore be used in all diesel vehicles without conversion. • Vehicles must be approved by the manufacturer for operation with pure paraffinic diesel (DIN EN 15940). + Many current engine generations are already approved, e.g., from Scania, Volvo, Mercedes, MAN, and others [62].	+ Direct replacement for fossil LNG. + LNG production vehicles available. • Share of LNG SNF in the vehicle fleet <1%.	• Individual test applications, but no production vehicles with EU approval are available yet. – Low energy density (shorter range).	• Currently, only individual research applications. – Low energy density (shorter range).	• Currently, only individual research applications. – Low energy density (shorter range).
Pollutant emissions from vehicle use	+ Reduced CO, soot, and HC emissions compared with conv. Diesel.	+ Reduced CO and soot emissions compared with conv. Diesel. – Methane slip must be avoided.	+ Reduced CO, soot, and HC emissions compared with conv. Diesel.	+ Reduced soot emissions compared with conv. Diesel.	+ Reduced soot emissions compared with conv. Diesel.
GHG balance over the entire life cycle	• GHG balance slightly higher due to the increased expenditure for fuel production.	+ Lowest GHG footprint compared with electricity-based fuels, but high uncertainties due to methane slip.	+ Relatively low GHG footprint compared with electricity-based fuels.	+ Relatively low GHG footprint.	+ Relatively low GHG footprint compared with electricity-based fuels.
R&D requirements	❖ Integration of DIN EN 15940 into the BImSchV [b]. ❖ Safeguard the use of paraffinic diesel within the existing fleet. ❖ Approval and optimization of future engine generations for paraffinic diesel.	❖ Minimization and mitigation of methane slip.	❖ Challenges with regard to engine lifetime due to corrosion and cavitation.	❖ Durability of injection components. ❖ Development of engines with diesel/OME mixed operation.	❖ Corrosion tendency and material compatibility of the fuel.

* The generic fuel paths listed here represent a selection of the fuel types researched by the supported EiV research projects. In addition, various other fuels were considered and described in the BEniVer Roadmap [20]. [a] Composition: 7%$_{vol}$ biodiesel, 26%$_{vol}$ HVO, 67%$_{vol}$ fossil diesel fuel (see: AVIA R33—diesel, Shell R33 Blue Diesel); [b] BImSchV: Bundes-Immissionsschutzverordnung (Federal Immission Control Act).

Moreover, synthetic diesel presents a promising prospect for light commercial vehicles given their predominant reliance on diesel. Additionally, the transition to synthetic methane can be a direct, drop-in solution for existing LNG vehicles, although this transition may be limited by the current relatively small fleet of LNG vehicles.

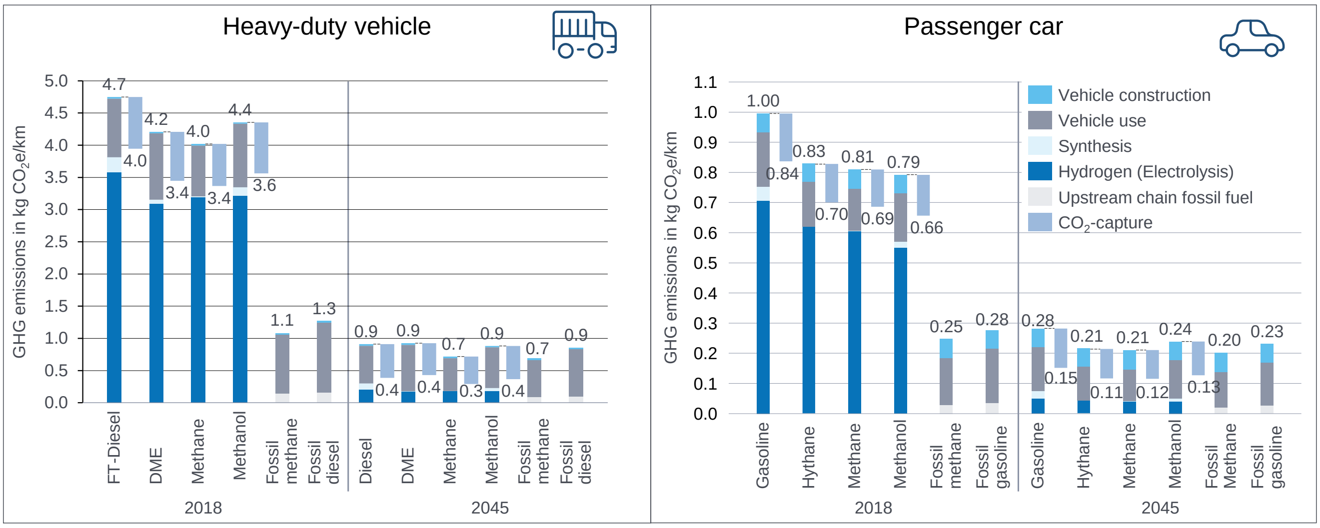

Figure 4. Results of the life cycle analyses (LCAs) for the fuels considered in road transport (heavy-duty and passenger transport).

Table 5. Overview of the evaluation of generic, electricity-based fuel pathways for passenger cars * (+ advantageous, • unbeneficial, – disadvantageous). Abbreviations: CNG—compressed natural gas, FT—Fischer–Tropsch, MtG—methanol-to-gasoline.

	Gasoline (FT/MtG)	Methane (CNG)	Methanol
Fuel production	– High fuel costs.	+ Low fuel costs. + Very pure production possible.	+ Low fuel costs. • Low calorific value.
Infrastructure availability	+ Compliant with DIN EN 228. → Existing infrastructure can be used.	• Currently, only approx. 850 CNG filling stations are available.	– Currently, no existing fueling infrastructure.
Applicability (drop-in/blend/engine customization)	+ FT gasoline as a pure fuel is standard-compliant with DIN EN 228 and thus 100% drop-in-capable.	+ Synth. methane as a pure fuel is standard-compliant with DIN EN 16723-2 and thus 100% drop-in-capable.	• Individual test applications, but no production vehicles with EU approval are available yet.
Pollutant emissions from vehicle use	+ Predominantly reduced NO_x, CO, soot, and HC emissions compared with conv. gasoline. + Fuel behaves neutrally in application.	+ Reduced CO and soot emissions compared with conv. gasoline. – Methane slip must be avoided.	+ Reduced CO, soot, and HC emissions compared with conv. gasoline. + Effectiveness degree increase possible.
GHG balance over the entire life cycle	• GHG balance slightly higher due to increased expenditure for fuel production.	+ Relatively low GHG emissions, but high uncertainties due to methane slip.	+ Relatively low GHG emissions.
R&D requirements	❖ Compliance with the quality requirements of DIN EN 228. ❖ Safeguard the use of FT gasoline (and also MtG) within the existing fleet. ❖ Analysis of the influence of different fuel compositions by additives and octane boosters on cold start capability and soot formation potential.	❖ Minimization and mitigation of methane slip.	❖ Challenges with regard to engine lifetime due to corrosion and cavitation. ❖ Development of dual-fuel vehicles that can run on methanol or gasoline.

* The generic fuel paths listed here represent a selection of the fuel types researched by the supported EiV research projects. In addition, various other fuels were considered and described in the BEniVer Roadmap [20].

5.5. High-Potential Synthetic Fuels for Use in Passenger Transport

Among the electricity-based fuels under examination, synthetic gasoline has emerged as one of the most promising options for passenger vehicle applications. This is primarily due to its drop-in compatibility, which obviates the need for vehicle modifications or additional purchase costs. Furthermore, the pre-existing fueling station infrastructure can be utilized, maintaining parity in terms of vehicle range and refueling time compared to conventional fossil gasoline. The only disadvantage is the slightly higher fuel costs compared with methane and methanol.

Due to its simpler chemical structure, the production costs of synthetic methane are lower than those of gasoline. The transition to synthetic methane also offers a "drop-in" solution for existing CNG vehicles, although the effect may be limited by the current relatively small CNG vehicle fleet.

Methanol has also been the subject of developmental projects for use in modern direct-injection gasoline engines. These projects have demonstrated efficiency and emission advantages over conventional gasoline [21,59]. Nonetheless, challenges persist in terms of engine durability, for example, due to corrosion and cavitation, as well as the cold-start capabilities of these engines. One interesting approach would be the development of vehicles that can run on both methanol and petrol.

Regarding the other synthetic fuels considered in the collective research, namely, methyl formate, DMC, 2-butanol, and 1-octanol, there is presently no market presence in the field of road vehicles. These fuels are not compatible with existing vehicles, and no standardization initiatives or promising combustion engine development projects have been identified. Nonetheless, the imperative to decarbonize road transportation necessitates the availability of drop-in compatible fuels.

5.6. Conclusions

Considering the current market-specific and technical framework conditions, drop-in capable synthetic fuels have been identified as the most promising fuels for the road transport sector. This is mainly caused by the long lifespan of conventional vehicles with internal combustion engines, which will still be on the roads in 2045 and years beyond, making the use of non-fossil fuel alternatives such as synthetic fuels necessary. The corresponding fuels must therefore be standardized and also drop-in-capable in order to be allowed to be blended into the existing fleet. Consequently, standard-compliant synthetic gasoline (FT or MtG) and FT-diesel are seen as the most promising fuels for use in road transport. Methane, among the synthetic fuels under consideration, ranks as the most cost-effective, leveraging a somewhat developed infrastructure and existing vehicles. However, the current CNG and LNG fleets are notably small, and an increasing number of manufacturers are withdrawing from the development of natural gas vehicles. The operation of vehicles with synthetic methanol is also slightly more economical than that of electricity-based gasoline vehicles; however, the volumetric energy density, the lack of infrastructure, and the lower durability when used in modern direct injection engines pose challenges. Both methane and methanol therefore trail behind drop-in capable synthetic gasoline and diesel fuels.

There are further potential applications for electricity-based fuels in the field of road transport, but also—beyond that—particularly in certain niche applications like fire brigades, rescue, military, or disaster control as well as sectors such as agriculture and construction machinery. Although these sectors have been touched within the scope of the research initiative, an in-depth analysis of the various potential fuels for these sectors has yet to be carried out.

6. Concluding Remarks and Outlook

It is essential to concentrate efforts on a rapid and drastic reduction in worldwide GHG emissions in order to combat the harmful effects of global warming on the environment and thus, mankind as well. In this context, synthetic sustainable fuels offer several possibilities to drastically reduce carbon emissions in aviation, shipping, and road transport. Currently, it seems that the best way to eliminate fossil fuels in global air travel and maritime shipping by 2045 is by using synthetic fuels. Reflecting the existing needs and legal restrictions that must be met in a specific sector—such as, for example, specific standards and approval procedures—as well as the interconnection among application, acceptance, costs, and realization, this multi-criteria challenge will lead to different approaches depending on the respective mobility economy and behavior. In order to cope with the described challenge, the funding initiative “Accompanying Research for the Energy Transition in Transport (BEniVer)” was initiated by the German Federal Ministry for Economic Affairs and Climate

Action (BMWK). Here, different synthetic sustainable fuels were evaluated regarding their applicability and ecological effects.

To sum up, for global air travel and maritime shipping the most promising way to achieve a fast and drastic reduction in GHG emissions seems to be by using synthetic fuels by 2045 and eliminating fossil fuels. For this, the production capacity of synthetic fuels, especially PtL fuels, has to be increased drastically. This would not only enable sufficient availability but also a reduction in fuel costs, which is currently one of the major obstacles to the market introduction. If the required quantities of e-fuels cannot be provided, more measures are required for a comprehensive mobility transition (e.g., transport relocation, demand reduction, etc.). This could reduce the need for synthetic fuels in the transport sector and, on the other hand, increase the options for de-fossilization in other sectors like the chemical, steel, and building industries as well as the power supply industry. Also, those sectors are aiming to reduce their GHG emissions using renewable energy and synthetic fuels as well. Here, the development of synergies in the transport sectors is required to avoid competition for the sustainable energy supply.

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