Survey on Advanced Fuels for Advanced Engines

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Norbert Grope
Olaf Schröder
Jürgen Krahl

Franziska Müller-Langer
Jörg Schröder

Modified and presented by Ulrich Arnold, KIT, Germany

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Report structure

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2 Non-technical framework for advanced biofuels

- Political and legislative aspects on an international level
- Current development of biofuel markets and forecast scenarios for different biofuels
- Discussion of potentials and challenges of advanced fuels
- Requirements with regard to sustainability criteria

- Information on
  - *European Union*
  - *EU Member States:* Austria / Denmark / Finland / Germany / Italy / The Netherlands / Norway / Sweden
  - *Furthermore:* Australia / Brazil / Canada / China / Israel / Japan / New Zealand / South Africa / South Korea / Thailand / USA

2 Non-technical framework for advanced biofuels
Fact sheets | Example EU

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Topic	EU
Energy carrier – - RE mandates	Fixed in RED 2009/28/EG with 10% RE in 2020 and in FQD with 6% CO_2-eq reduction by 2020; No sector related targets for post-2020 (1990-2030: –40% GHG, 27% renewable energies, 27% improvement of energy efficiency)
- Legislation for biofuels / renewable fuels	RED: 7% cap for biofuels based on food crops, i/dLUC, sustainability criteria and methodology for GHG; min. 60% GHG reduction for new plants
- Incentives for advanced biofuels	Determined in RED amendment, subtargets for advanced biofuels
- Taxes for fuels	Energy Taxation Directive (ETD)
Energy infrastructure	Clean Power for Transport / Alternative Fuels Infrastructure Directive: CPD only marginal steering in favor of advanced fuels; AFID: Setting frame conditions and facilitate installation of infrastructure, mainly electric/hydrogen/natural gas, biofuels and reformulated fuels not a priori excluded
Vehicles – - Legislation for vehicle emission standards and fuel efficiency	CO_2 regulations 2020 on tank-to-wheel basis, fleet averages for manufacturers: 95 g/km passenger cars / 120 g/km for HDV EURO VI emission regulations HC, CO, NO_x, PM Possible inclusion of hitherto non-regulated pollutant parameters
- Incentives for purchasing ZEV / LEV	See individual tables for EU member countries (Tables 6 – 10)

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3+4 Fuel standards and fuel properties
Example: Physico-chemical & combustion data

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	HVO	XtL	Biodiesel	OME (OME3 / OME4)	DME	Methanol	Ethanol
Cetane number [-]	80-110	>74	47-66	78 / 90	55-60	5	8
Octane number Research [-]						106	107
Octane number Engine [-]						92	89
Density (15°C) [kg/m³]	~780	~780	883	1030 / 1070	667	791	789
Flash point [°C]	80-94	100-120	>150	54 / 88	-42	11	17
Lubricity (HFRR) [µm]	~420		320	534 / 465		1100	1057
Viscosity at 40°C [mm²/s]	2.9-3.0		~4.5	1.05 / 1.75 (25°C)	<0.1	0.58	1.13

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5 Liquid advanced biofuels for road transport

5.1 Hydrotreated vegetable oils (HVO) and hydroprocessed esters and fatty acids (HEFA)

5.2 Biomass-to-liquids fuels (BTL)

5.3 Dimethyl ether (DME)

5.4 Oxymethylene ether (OME)

5.5 Alcohols as fuels
5.5.1 Methanol
5.5.2 Lignocellulosic ethanol

5.6 Liquefied biomethane (Bio-LNG)

5.7 Biodiesel (FAME)

5.8 Fuel properties: tabulated analysis data

5 Liquid advanced biofuels for road transport
Biofuel fact sheets

- Typical feedstocks >> typical bio-based resources used today or under R&D
- Typical process characteristics >> most important technology issues and typical byproducts
- Examples for main technology providers for the related overall plant designs and plant operators
- Technology / fuel readiness level (TRL / FRL) according to the European Commission and CAAFI
- Typical fuel production costs (normalized to 2015) >> economic competitiveness >> highly depending on the respective TRL / FRL as well as plant design etc. and methodology used for cost calculation
- Typical GHG emissions for well-to-tank (WTT) >> competitiveness for climate friendliness including the notice that they are highly depending on the same factors like for fuel production costs as well as the methodology for their calculation (e.g. EU RED or US RFS)
- (Very brief) SWOT analyses with strength (S), weaknesses (W), opportunities (O) and threats (T) compared to conventional biofuels like biodiesel / FAME, ethanol based on sugar and starch and in terms of their general use for road application

5 Liquid advanced biofuels for road transport
5.1 HVO/HEFA

HVO / HEFA	Short description
Typical feedstocks	Vegetable oils (mainly palm oil, used cooking oil; for aviation jatropha, camelina) and fats; alternatively tall oil and (often under R&D&D) algae oils, tobacco, but also pyrolysis- and hydrothermal-based oils
Typical process characteristics	Multistep hydrotreating of the feedstocks with hydrogen (usually out of natural gas steam reforming or internal naphtha reforming), comparable to conventional refinery processes; Multiproduct plant: HVO / HEFA diesel or jet fuel, naphtha, propane/butane (and – if directly with annex oil mill in case of rape or soya also extraction meal as fodder)
Main technology providers (examples)	Single plant capacities about 0.1 to 0.8 mn t/a, regional focus EU, US, Indonesia Neste Cooperation (total capacities: 1.9 mn t/a), UOP / Eni (0.55 mn t/a), UOP / Galp Energia + Petrobras (0.22 mn t/a), Axens / TOTAL (0.5 mn t/a startup 2017), UPM (0.1 mn t/a), Preem / Sunpine (0.1 mn t/a), UOP / Diamond Green Diesel (0.27 mn t/a startup 2017), Dynamic Fuels (0.2 mn t/a)
TRL / FRL	9 / 9, currently clear focus on diesel fuel production; ASTM certified jet fuel as HEFA-SPK (only in batches as requested by costumers), ASTM certification for HEFA Diesel+ expected for 2017
Typical fuel production costs	19 to 47 USD/GJ Mainly due to the feedstock price, specific TCI about 360 to 495 USD/kW fuel
Typical GHG	5 to 76 kg CO_2-eq/GJ (according RED)
S | Strength	Higher fuel quality compared to biodiesel. Can be blended up to about 100 vol.% (but usually limited by 20 to 30 vol.% due to density given by fuel standards); high ignition quality (cetane number) and such fuels do not contain aromatics, enabling low emission combustion; material compatibility, storage stability and calorific value comparable to conventional diesel fuel
W | Weaknesses	Competition with biodiesel / FAME regarding vegetable oils and used cooking oils or animal fats as feedstocks and therewith part of the debate on feedstocks availability and impact on d/iLUC; especially in context of palm oil use; low density disabled high blending rate given by fuel standards
O | Opportunities	Increasing installed capacities worldwide and a change to so called advanced feedstocks (like algae-based oils, biooils from pyrolysis or hydrothermal processes) possible
T | Threats	Limited availability of renewable hydrogen for the hydrotreating processes

5 Liquid advanced biofuels for road transport
5.2 BTL-fuels: Fischer-Tropsch fuels

BTL: FT-fuels	Short description
Typical feedstocks	Wood (industrial wood, waste wood, short rotation coppice), stalk materials (mainly straw, triticale whole plants, miscanthus), wood-based black liquor, US: also municipal waste
Typical process characteristics	Mechanical treatment of biomass (e.g. grinding, crushing), thermal pretreatment (e.g. pyrolysis, drying, smoldering), gasification, conditioning of the resulting synthesis gas (e.g. scrubber, filter, absorption, reforming, shift-reaction), Fischer-Tropsch synthesis and product work-up (e.g. hydrocracking, distillation, isomerization); Multiproduct plant: BTL diesel or jet fuel, waxes, naphtha, heat and power
Main technology providers (examples)	Regional focus EU, US BioTfueL consortium (Avril, Axens, Total, Thyssen Krupp, IFP and others with 3 t/h feedstock; IFP 2016), Fulcrum Bioenergy / Tesoro (0.2 mn t/a feedstock), Red Rock Biofuel / Velocys; small-scale: e.g. Velocys, Ineratec, Bioenergy2020+ / TU Vienna
TRL / FRL	5-6 / 5
Typical fuel production costs	18 to 62 USD/GJ Mainly determined by capital investment and feedstock costs, specific TCI about 2,600 to 4,260 USD/kW fuel
Typical GHG	7 to 100 kg CO_2-eq/GJ (according RED)
S | Strength	Higher fuel quality compared to biodiesel. Can be blended up to about 100 vol.% (but usually limited by 20 to 30 vol.% due to density given by fuel standards like EN 15940); high ignition quality (cetane number) and no aromatics in the fuel, enabling low-emission combustion; material compatibility, storage stability and calorific value comparable to conventional diesel fuel
W | Weaknesses	Comparably low overall efficiency and the production of a wide range of different aliphatic hydrocarbons, which makes intensive product separation and treatment necessary for the production of applicable fuels; therefore comparably cost intensive; low density disabled high blending rate given by fuel standards
O | Opportunities	Well-known handling and applications of FT fuels from GTL processes, and FT fuels are of interest for different road and aviation applications (production of bio jet fuel that already is ASTM certified)
T | Threats	Ongoing delay of commercialization along innovative chain for FT fuels and the challenge to be competitive with HVO / HEFA which show similar fuel properties

5 Liquid advanced biofuels for road transport
5.3 Dimethyl ether (DME)

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DME	Short description
Typical feedstocks	Wood, wood-based black liquor and solid organic wastes (wood, municipal solid organic waste, straw), biogas
Typical process characteristics	Mechanical pretreatment of biomass (crushing), drying, fast pyrolysis (in case of decentral collecting for better transportation), gasification, synthesis gas conditioning (sulphur removal, CO_2/water removal, water gas shift reaction) and indirect synthesis, which means methanol synthesis + methanol dehydration, or direct DME synthesis followed by product purification (distillation)
Main technology providers (examples)	Regional focus: EU, US Chemrec / LTU (black liquor - pilot plant/out of operation), KIT (solid organic waste - pilot plant), Oberon Fuels (biogas / natural gas - pilot plant, offers commercial small scale units)
TRL / FRL	4-6 / 5
Typical fuel production costs	16 to 30 USD/GJ
Typical GHG	1 to 72 kg CO_2-eq/GJ (according RED)
S | Strength	Low soot emission, established synthesis technologies
W | Weaknesses	Low energy density (around 50% of fossil diesel), DME is a gas under ambient conditions, low viscosity and poor lubricity, material compatibility of fuel-carrying components not assured
O | Opportunities	Potential replacement of LPG (LPG/DME blends already used in different regions like in Asia) and the use as an alternative fuel for diesel engines
T | Threats	The related OME fuels are liquids and seem to be more favorable (methanol/DME-derived, also low soot emission, diesel-like handling)

5 Liquid advanced biofuels for road transport
5.4 Oxymethylene ether (OME, PODE, POMDME)

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OME	Short description
Typical feedstocks	Wood and solid organic wastes (wood, municipal solid organic waste, straw)
Typical process characteristics	Regarding the thermo-chemical pathway: Mechanical pretreatment of biomass (crushing), drying, gasification, conditioning of the resulting synthesis gas (water gas shift reaction, sulphur removal, CO_2/water removal), methanol synthesis, intermediate synthesis from methanol (formaldehyde, methylal, trioxane), OME synthesis, purification (distillation)
Main technology providers (examples)	There are some plants in China for commercial OME production as well as research activities especially in China and Germany, e.g. by KIT (OME from methanol, DME and formaldehyde sources); There are also several patents held by BP, BASF and Chinese companies
TRL / FRL	3-4 / 3
Typical fuel production costs	33 to 50 USD/GJ (estimated for non-renewable OME) Mainly capital investment, methanol price
Typical GHG	Estimated currently and will be available soon
S | Strength	Clean combustion with almost no soot and NO_x emissions; Properties are very similar to conventional diesel and cetane numbers are very high
W | Weaknesses	Low heating values and material compatibility of fuel-carrying components has to be improved (similar to DME)
O | Opportunities	High fuel quality and comparatively simple production from methanol
T | Threats	Production from renewable resources is not state of the art and there could be a strong competition with other diesel fuels

5.5.1 Methanol

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Methanol	Short description
Typical feedstocks	Wood, wood-based black liquor and solid organic wastes (wood, municipal solid organic waste, straw), alternatively glycerol or biogas
Typical process characteristics	Mechanical pretreatment of biomass (crushing), drying, gasification, synthesis gas conditioning (water gas shift reaction, sulphur removal, CO_2/water removal), methanol synthesis, product purification (distillation) Another option is steam reforming of biogas for syngas production
Main technology providers (examples)	Regional focus: US, CN, EU Enerkem (methanol as byproduct, 0.001 mn t/a), BioMCN, Air Liquide, Haldor Topsøe, Mitsubishi Hitachi
TRL / FRL	4-6 / 5
Typical fuel production costs	14 to 54 USD/GJ Mainly consisting of capital investment and the feedstock price
Typical GHG	2 to 58 kg CO_2-eq/GJ (according RED)
S | Strength	High knock resistance (ROZ, octane number) enabling a higher compression ratio and a higher efficiency of the engine; methanol is free of aromatic compounds with a high oxygen content and thus, a reduction of exhaust gas emissions is also possible
W | Weaknesses	Toxicity; material compatibility of fuel-carrying components sometimes not assured; lower heating value compared to conventional gasoline; low vapor pressure and high evaporation heat cause poor ignition characteristics at low temperatures; hygroscopic
O | Opportunities	Efficient synthesis and several different applications (e.g. as an intermediate for the production of gasoline or diesel substitutes like DME or OME), direct application in fuel cells; alternative fuel component for diesel and gasoline engines
T | Threats	Toxic properties of methanol, blend walls and its acceptance as a fuel compared to ethanol as fuel, methanol derived fuels (DME, OME)

5 Liquid advanced biofuels for road transport
5.5.2 Lignocellulosic ethanol

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Lignocellulosic ethanol	Short description
Typical feedstocks	Several types of lignocellulose (primarily straw, corn stover, bagasse, wood, switch grass); in case of syngas fermentation also organic (municipal) waste, industrial waste gas streams
Typical process characteristics	Regarding fermentation: pretreatment (thermal, acid etc.), hydrolysis, saccharification, C6/C5 fermentation, distillation and final dehydration with byproducts like lignin or lignin-based by-products, pentoses, stillage products such as fertilizer, biogas / biomethane, technical CO_2 Regarding syngas fermentation: gasification and gas conditioning, fermentation, distillation and separation of byproducts depending on process conditions: alcohols, organic acids technical CO_2
Main technology providers (examples)	Single plant capacities about 0.01 to 0.1 mn t/a, regional focus US, China, EU, Brazil In the case of fermentation: Clariant, Inbicon, Peot-DSM, Biochemtex, Raizen, Abengoa and Borregard In the case of syngas fermentation: Lanzatech, Ineos Bio and Synata Bio (former Coskata, focus chemicals)
TRL / FRL	7-8 / 7 for fermentation
Typical fuel production costs	21 to 46 USD/GJ for fermentation Mainly capital investment and feedstock price as well as revenues for byproducts, specific TCI about 2,030 to 3,160 USD/kW fuel
Typical GHG	4 to 32 kg CO_2-eq/GJ (according RED) for fermentation
S | Strength	Use of lignocelluosic residues, multifunctional applications (e.g. for ETBE, ATJ, ethylene) and a high knock resistance (ROZ, octane number) enabling a higher compression ratio and a higher efficiency of the engine; free of aromatic compounds; reduction of limited exhaust raw emissions because of high oxygen content
W | Weaknesses	Competition with conventional ethanol in already large capacities worldwide; material compatibility of fuel-carrying components sometimes not assured; lower calorific value compared to conventional gasoline; low vapor pressure and high evaporation heat cause poor ignition characteristics at low temperatures; hygroscopic
O | Opportunities	Improved value chain with regard to thin stillage use for biogas/biomethane and technical CO_2 (e.g. for industry or as renewable resource for synthetic power-to-fuels like discussed in the EU); also the alternative use as a diesel fuel (e.g. ED95 with 95% ethanol and 5% ignition improver)
T | Threats	Blend limitations (walls to E5/E10/E20 in most of the regions)

5.6 Biomethane

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Bio-LNG	Short description
Typical feedstocks	Agriculture and forest residues (straw, wood chips) and solid municipal wastes (landfill waste gas)
Typical process characteristics	Regarding the biochemical pathway: pretreatment, anaerobic digestion, CO_2 removal (e.g. by pressure swing adsorption, membrane or crygenic separation of CH_4 and CO_2) and compression / liquefaction (less relevant yet) thermo-chemical pathway via synthetic natural gas: pretreatment (crushing, drying), gasification, gas treatment (reforming, water gas shift, sulphur removal, CO_2/water removal), methane synthesis, purification, liquefaction
Main technology providers (examples)	Bio-LNG Wijster in the Netherlands (Rolande LNG and partners), Osomo, French CRYO-PUR®, Norwegian Campi AS / Wärtsila, Waste Managment / Linde (US, landfill waste gas)
TRL / FRL	7-9 / 7
Typical fuel production costs	13 to 16 USD/GJ For biowastes and landfill gas as biogas resource
Typical GHG	11 to 21 kg CO_2-eq/GJ for biowastes and landfill gas as biogas resource (according RED)
S | Strength	Use of established technologies; reduction of harmful emissions like NO_x or PM and reduction of CO_2 emissions; free of aromatic compounds; high knock resistance (ROZ, octane number) enable higher compression ratio and efficiency of spark ignition engines; Bio-LNG use without blending or to improve the quality of fossil LNG
W | Weaknesses	High energy demand for liquefaction and high methane slip; high material stress because of no use of additives and high combustion temperature
O | Opportunities	Transportation to areas without gas grid and upcoming marine LNG engines; Could also be used as an alternative fuel for gasoline and diesel engines
T | Threats	Competition with different sectors (depending on policies often CHP)

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Example: Relative Emissions of HVO and HVO-blends

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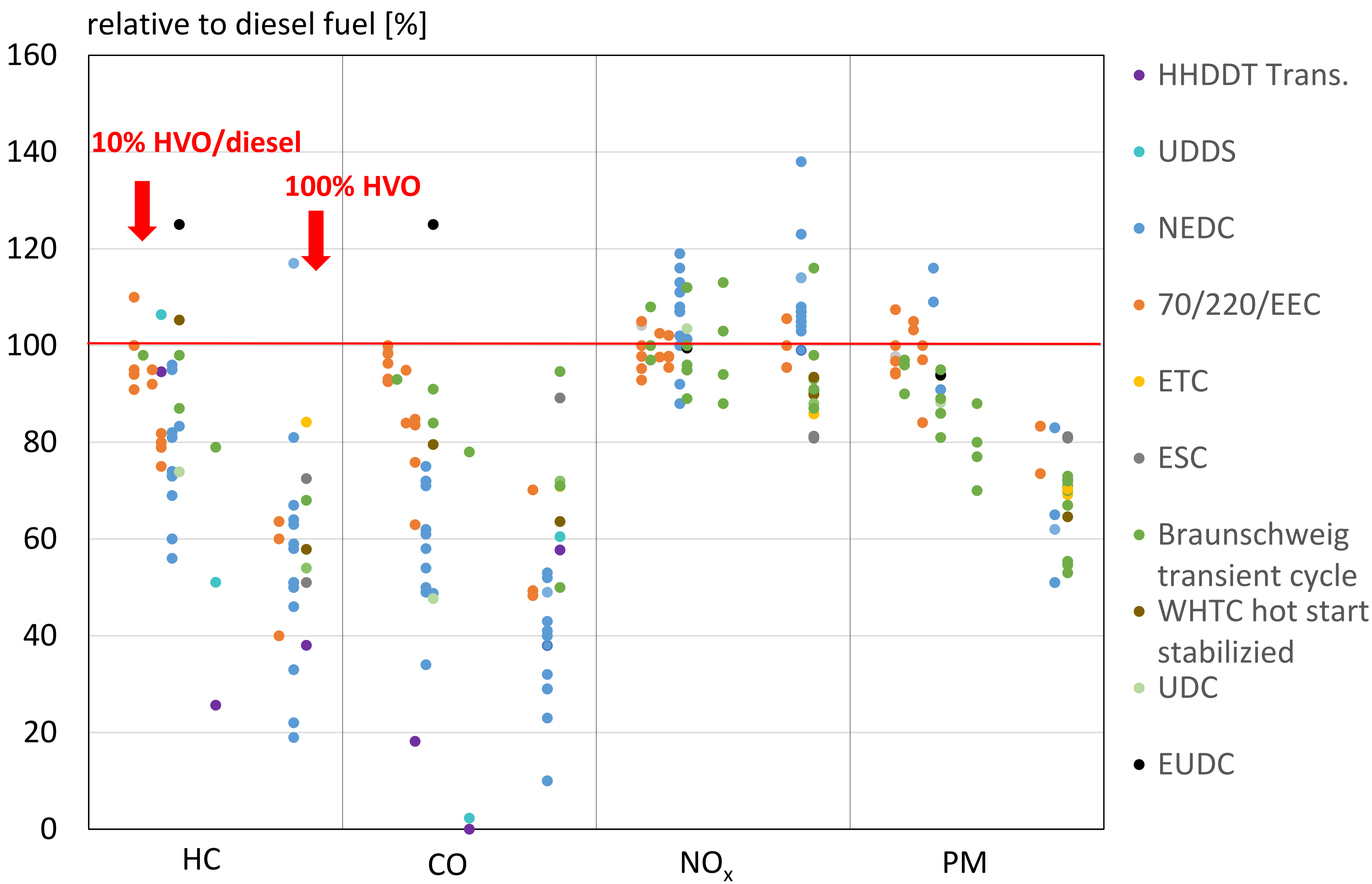

Conclusions

Fuel	Production technique	Raw material base	Drop-in fuel	Engine technique	Emissions
HVO	++	–	++	++	+
BtL	0	+/++	++	++	+
OME	+	Electricity +/++ (Biomass)	+	+	++
DME	0	+	– –	0	++
Lignocellulosic Ethanol	+	+	+	+	0
Methanol	0	Electricity +/++ (Biomass)	–	0	0
Biogas	++	0	++	++	0 (++)

++ Very favorable → – – Hardly feasible

Outlook and recommendations

Short- and mid-term

- Diversity of feedstocks and fuels will increase
- Drop-in fuels should be preferred
- All types of advanced fuels should be taken into consideration
- Political framework is essential for the success of advanced fuels

Long-term

- Changes in the mobility behavior and more BEV lead to a lower fuel demand
- Internal combustion engines cannot be completely replaced in the short-term, therefore advanced fuels are necessary to reduce CO_2 emissions
- GHG reduction targets will help to introduce advanced fuels

Survey on Advanced Fuels for Advanced Engines

Your feedback is welcome!

Olaf Schröder | +49-9561-317-640 | olaf.schroeder@tac-coburg.de

Jörg Schröder | +49-341-2434-522 | joerg.schroeder@dbfz.de
Franziska Müller-Langer | +49-341-2434-423 | franziska.mueller-langer@dbfz.de