Synthetic Fuels in Transport, Aviation, and Shipping – Opportunities and Challenges

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BEniVer
Begleitforschung Energiewende im Verkeh

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

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Motivation

Reducing global warming below 2 °C (better: 1.5 °C) and effects of climate change

Reducing emission of greenhouse gases – goals:

- European Union (EU):
  - Reduction of CO_2 to 55% by 2030 compared to 1990
  - Net zero greenhouse gas emission by 2050
- Germany:
  - Reduction of CO_2 to 65% by 2030
  - Climate neutrality by 2045

Reducing emission of greenhouse gases – How?

- European 2030 Climate Target Plan: Increasing share of renewable energy in transport sector to 24%
- Renewable Energy Directive (RED III): 2.6% RFNBO in 2030
- ReFuelEU Aviation → aspired minimum shares:
  - 2% SAF in 2025 (in Germany: 0.5% PtL in 2026)
  - 5% SAF in 2030 with 0.7% PtL (in Germany: 2%)
  - 63% SAF in 2050 with 28% PtL

  ⇒ Plans to increase these shares (possibly up to 100% SAF in 2050)
- Shipping: Efforts in EU to define shares for PtL fuels

RFNBO – Renewable liquid and gaseous transport Fuels of Non-Biological Origin
SAF – Sustainable Aviation Fuels

Overview

- **Motivation**
- **Synthetic Fuels from renewable energy**
- **Synthetic Fuels in Road Transport**
  - Synthetic diesel and gasoline
  - Oxygenated fuels
  - Gaseous fuels
- **Sustainable Aviation Fuels**
  - Fischer-Tropsch (FT) kerosene
  - Methanol-to-Jet (MtJ)
- **Synthetic Maritime Fuels**
  - Synthetic diesel and LNG
  - Oxygenated fuels (methanol and oxymethylene ether)
  - Ammonia and hydrogen
- **Summary and Conclusions**

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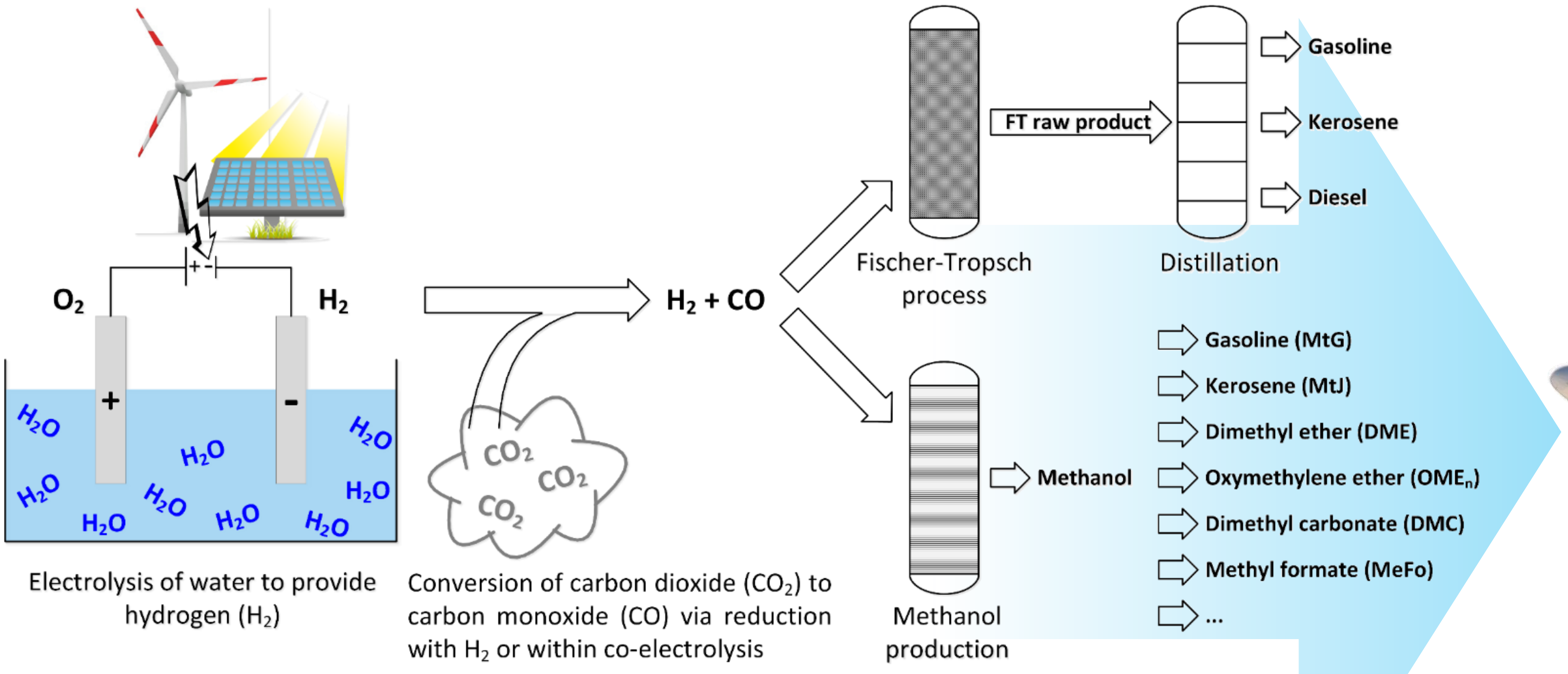
Synthetic Fuels from renewable energy



Focus on PtL fuels ⇒ Part of project "BEniVer"

Other option: advanced biofuels from waste materials
(used cooking oils / fats, residues from agriculture / forestry)

Richter et al., Proc. 13th ICF 2021

Synthetic Fuels from renewable energy

BEniVer
Begleitforschung Energiewende im Verkehr

BEniVer ("Begleitforschung Energiewende im Verkehr")

Research project accompanying the funding initiative "Energy transition in transport" of the German Federal Ministry of Economic Affairs and Climate Action (BMWK)

- Funding initiative comprises 17 research projects focusing on the production and usage of synthetic fuels made via the Power-to-Liquid process
- Projects cover the different transport sectors of road transport, aviation, and shipping as well as power generation
- BeniVer: Started in June 2018, runs until March 2023

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Aims of BEniVer

- Comparison and evaluation of project results
- Development of road map for further research, production, and market launch of synthetic fuels
- Networking and communication within funding initiative
→ Status conference from 30 June to 01 July in Berlin
    - Presentation of project results
    - If interests write to beniver@dlr.de

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Synthetic Fuels in Road Transport

Synthetic diesel and gasoline

Synthetic Diesel

- Produced from FT process
- Paraffinic hydrocarbons, mainly linear and/or slightly branched
  - Standard EN 15940, but usage only in dedicated vehicles possible
  - Properties similar to fossil diesel (EN 590), besides density:

	Fossil diesel	FT diesel
CN	≥ 51	≥ 51
ρ (kg/m³)$_{15°C}$	820 to 845	765 to 810
CFPP (°C)	-20 to +5	-20 to +5
$T_{b,95\%}$ (°C)	360	360

  - Blends with FT diesel conform to EN 590 up to about 30 %(v/v)

Synthetic Gasoline

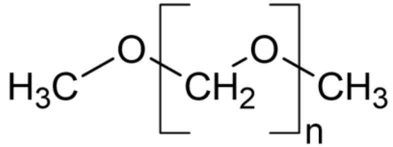
- Produced from FT process or as MtG (Methanol-to-Gasoline)
  → Paraffinic hydrocarbons (raw product)
- Isomerization and when needed aromatization necessary to meet standard EN 228
  → Easier to achieve within MtG process

- Compatibility with existing standards
- Full compatibility with current engine technology
- Use as neat fuel possible

Synthetic Fuels in Road Transport

Oxygenated fuels

Ether



- n = 0 → DME
- n ≥ 1 → OME (often n = 3-5)
- No C-C bonds
  → High potential to reduce soot emissions
- New emissions: Aldehydes and ketones

Alcohols

DMC / MeFo

Synthetic Fuels in Road Transport

Oxygenated fuels

Ether

	Diesel	DME	Oxymethylene ether (OME_n)				
			OME_1	OME_2	OME_3	OME_4	OME_5
T_b (°C)	360 (FBP)	-24.8	42	105	156	201	242
T_f (°C)	-40...6	≈ -140	-105	-70...-65	-43...-41	-10...-7	≈ 18.4
ρ (kg/m³)$_{15°C}$	820-845	Gas	850-867	961	1021	1059	1100
v (mm²/s)	2.0-4.5	Gas	0.32-0.33	0.64	1.05	1.75	2.63
FP (°C)	≥ 55	-42.2	-32	12	54	88	115
CN	≥ 51	> 55	29-37.6	63	70-78	90	100
H_u (MJ/l)	≈ 35	18.44	19.30	19.53	19.54	19.47	19.64
H_u (MJ/kg)	≈ 43	27.60	22.44	20.32	19.14	18.38	17.86

⇒ OME_n could improve ignition behavior (except OME_1)

Synthetic Fuels in Road Transport

Oxygenated fuels

Alcohols

Both blending component for gasoline or neat fuel possible

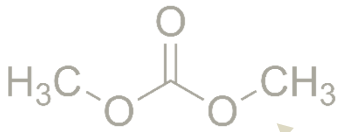
Well known as blending component for gasoline

Blending component for gasoline possible

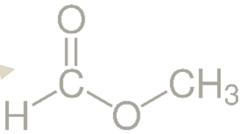
Considered as blending component for diesel

	Diesel	Gasoline	Alcohols						
			Methanol	**Ethanol**	**1-Butanol**	**2-Butanol**	**iso-Butanol**	**tert-Butanol**	**1-Octanol**
	$C_{14}H_{30}$	C_8H_{15}	CH_3OH	C_2H_5OH	nC_4H_9OH	sC_4H_9OH	iC_4H_9OH	tC_4H_9OH	$nC_8H_{17}OH$
T_b (°C)	360 (FBP)	210 (FBP)	65	78	117.7	99.5	108	83	195
T_f (°C)	-40...6	-90.5 ... -95.4	-98	-114	-89.5	-114.7	-108	26	-16
ρ (kg/m³)$_{15°C}$	820-845	720-775	792	785	810	806.3	801.8	$790_{(20\ °C)}$	$830_{(20\ °C)}$
v (mm²/s)	2.0-4.5		0.75	1.5	2.63-3.7				
FP (°C)	≥ 55	≤ -35	9	12	35	24	28	11	84
CN	≥ 51	--	5	8	17-25	--	--	--	--
RON	--	≥ 95	109	109	96-98	101-105	105-113	107	28
MON	--	≥ 85	89	90	78-85	82-93	90-94	94	27
H_u (MJ/l)	≈ 35	30-33	15.8	21.4	26.9	26.7	26.6	25.7	31.1

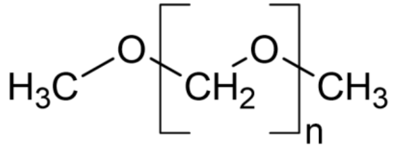
Synthetic Fuels in Road Transport



Oxygenated fuels



Ether



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Alcohols

- Methanol is considered as neat fuel in spark ignition engines
  → Used in China
  → In USA blends up to 85 %(v/v)
- Butanols as blending component for gasoline
- n-Octanol as blending component for diesel (not conform to EN 590)

DMC / MeFo

- DMC = Dimethyl carbonate
- MeFo = Methyl formate
- No C-C bonds
  → High potential to reduce soot emissions
- ON = 102-115
  → Better knock resistance than gasoline
- Considered as DMC+MeFo blend and blending components with gasoline and/or methanol

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- Methanol as neat fuel possible
- DMC/MeFo blends for special applications (e.g. range extender)
- No standard for direct use as fuel (for OME_n under progress)
- Compatibility with current engine technology limited, esp. regarding materials
- Use as drop-in or near-drop-in depends on amount of admixture (oxygen content)

Synthetic Fuels in Road Transport

Gaseous fuels

- Synthetic natural gas
- Three types of application:

Synthetic LNG

- For heavy duty vehicles

Synthetic CNG

- For passenger vehicles

(LNG and CNG:)

- Properties similar to fossil natural gas
- Less emissions compared to diesel or gasoline
- Shorter range due to lower volumetric energy density:

Diesel	Gasoline	LNG	CNG
36 MJ/l	31 MJ/l	23 MJ/l	7 MJ/l$_{200bar}$

- Compatibility with existing standard (EN 16723-2)
- Compatibility with current gas engine technology expected
- Use as neat fuel possible

Synthetic CNG + H_2

- For passenger vehicles
- H_2 content of about 30 %(v/v) considered
- Less CO_2 emissions than CNG
- Properties change with increasing amount of hydrogen (density, combustion temperature)
  → Material and technology being compatible with H_2 necessary

- 2 %(v/v) H_2 possible according to EN 16723-2
- Modifications necessary

Overview

Sustainable Aviation Fuels (SAF)

Some general facts

- Have to comply with ASTM D7566
  → Within the annex, seven SAF defined being certified for the use in mixture with fossil kerosene
- Currently only blends with max. 50 %(v/v) allowed since SAF mainly paraffinic
- Application of 100% SAFs possible → Stronger reduction of emission than with 50% blend
  - Have to meet current jet fuel specification (required)
  - Usability demonstrated in several test flights
- Oxygenated fuels not possible due to less stability than hydrocarbons
  → Less options than in road transport or shipping

SAF made from renewable energy

<u>FT kerosene</u>

- Already approved for usage and listed in annex of ASTM D7566

<u>Methanol-to-Jet (MtJ)</u>

- Not yet approved, but similarity to Alcohol-to-Jet (AtJ)
  → Shortened approval process expected

SAF made from biomass feedstock already available

- HEFA kerosene (Neste, Finland; World Energy, CA/USA)
- AtJ-SPK (Gevo, TX/USA; LanzaJet, GA/USA)
- Currently < 0.1% SAF share of worldwide fuel consumption (pre-Covid (2019) about 287 million t/a*)

*IATA

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Synthetic Maritime Fuels

Synthetic diesel and LNG

- Both fuels expected to be used without modification of current engine technology
- Help toward the reduction of emissions from maritime sector (besides CO_2 also soot and SO_x)
- Synthetic LNG as replacement fossil LNG (ISO 20519)
- FT diesel can replace marine gas oil (MGO; ISO 8217)
  → If applicable optimization of fuel control system
  → FT shipping diesel should have higher C-number than paraffinic diesel for automobiles (EN 15940)

Methanol

- In shipping currently fuel with highest potential as alternative fuel
- Distinct reduction of emissions → Possibility that no exhaust gas treatment is necessary
- Energy density close to LNG (MeOH: 16 MJ/l, LNG: 22 MJ/l)
- Already some single applications, expected to increase within next years
  → E.g. Maersk ordered 12 container vessels fuelled with methanol
- Existing global infrastructure since methanol is an important raw material in chemical industry
  → Need to be expanded to cover demand for ships
- No standard → Single permission needed

Synthetic Maritime Fuels

Oxymethylene ether (OME_n)

- Considered as blending component to marine diesel
  → Enables distinct reduction of soot emissions
- Compatibility with material limited, modification of sealing materials required when larger amounts used (up to 30 %(v/v))

Ammonia (NH_3)

- Non-carbon fuel → No CO_2 emissions
  → Increased emissions of NO_x and of N_2O in particular have to be avoided with appropriate exhaust gas treatment
- Only considered for bulk carriers due to toxicity
- Usage in direct combustion (only NH_3, dual or multi fuel) or in fuel cell under discussion
- Energy density of liquid ammonia (-33 °C): 15.6 MJ/l → Similar to methanol and LNG

Hydrogen (H_2)

- Non-carbon fuel → No CO_2 emissions
  → Exhaust gas consists only of water vapor
- Single applications in fuel cell powered ferries
- For use in bulk carriers also direct combustion possible, in dual or multi fuel engines
- Low energy density:
  - Liquid hydrogen 9.1 MJ/l (-253 °C)
  - Compressed hydrogen 5.6 MJ/l (700 bar)

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Summary and Conclusions

DLR

Summary and Conclusions

Emissions

- All synthetic fuels allow reduction of CO_2, CO, UHC, soot, SO_x
  → Reduction of NO_x depends on combustion behavior of fuel and conditions
- Use of ethers and methanol promises strongest reduction
- With NH_3 and H_2, no C related emissions

⇒ Avoiding of new / more emission!
(aldehydes/ketones / NO_x/N_2O / CH_4)

Compatibility

- Mostly given for paraffinic fuels from FT or methanol process as well as for synthetic CNG / LNG
- Use of oxygenated fuels depends on amount of admixture
  → Often modifications, at least of material, necessary
  → Not allowed in aviation due to less stability and higher risk of water contamination
- Use of pure NH_3 and H_2 in shipping requires new technology (material / storage / power unit / …)

Application

- Road transport: Synthetic fuels for existing vehicles → Transition towards electricity and fuel cells
  → Higher acceptance and focus of manufacturer (even in heavy transport)
- In aviation and shipping synthetic fuels needed
  → Use of electricity and H_2 only for short distances

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