Renewable fuels for combustion engines - candidates, supply sources and policy aspects

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Relevant Questions

- Energy and Climate Challenges – the “Trilemma”
- «Decarbonization» of Transportation – CO₂-budget and life-time of assets
- Sector Coupling – «free» or «chemically bound» electrons?
- Candidate fuels for different combustion modes
- E-fuels:
  - How much electricity is needed?
  - Where from?
  - At which costs?
  - Life-cylce CO₂-footprint?
- Innovation and policy – synergies along the transformation path
Energy and Climate Policy: The «trilemma»

- **Net-Zero CO₂**: (and minimization of other environmental impact)

- **Security** of Energy Supply: (Diversification, Share of imports)

- **Competitiveness** (of industry) / fair access to energy services

Alignment with international regulations / currently: CH-energy expenditures ~4% of GDP

→ Partially conflicting goals
→ Optimisation required
Sectoral shares of energy-related CO₂ emissions in “EU32”.

Total: 3.5 Gt CO₂

Transport related CO₂-emissions amount to 36.6% of the total.

Data from European Environment Agency (EEA). National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism, 2020
If we have 30 years, why is immediate action imperative?

Data for cars from Held et al. (2021): *European Transport Research Review*, vol. 13, art. 9
Data for ships from Held et al. (2021): 7th Internat. Symposium on Ship Operations, Management, & Economics

In addition:
- Industry processes: until/about 20 years
- Refinery, Grids, Roads, Rails: mehr als 50 years

Therefore:
- Relevant and cost-intensive "hardware" built today will be in operation by around 2050
- One must therefore avoid "lock-in" effects and stranded investments
- But until the perfect solutions are available, we must "reap the low-hanging fruits".
«Complete» Replacement of Fossil by Renewable Energy Carriers

- Direct electrification of end-use sectors whenever feasible
- Indirect electrification in all other cases through renewable energy carriers (e-, bio- and solar-chemical fuels)
- Multiple interfaces between electricity and fuels along the conversion/storage/distribution chain from primary to useful energy

SECTOR COUPLING
Sector coupling - energy carrier portfolio for mobility (2050)

ICEV pathway

FCEV pathway

BEV pathway

transport services
- passenger / freight
- land, sea, air

propulsion energy

CO₂-free electricity

battery

electric grid

pump-hydro storage

battery electric drive

Source: K. Boulouchos (unpublished)
Aviation: Reducing CO₂ emissions by short-haul electrification or shift to high-speed rail?

- 63% of all flights departing from Swiss airports are shorter than 1’000 km, corresponding to 19% of total Swiss CO₂ emissions from aviation.
- Estimates indicate that with a battery-pack energy density of 800 Wh/kg (expected around 2050), this could be covered by all-electric aircraft.
- However, assuming 7 flights a day, one year of continuous flight operation would already exceed 2’500 battery charging cycles.
- Therefore, shifting short-haul aviation to high-speed rail makes more sense and is in principal feasible in the near future.

Reference:
Different e-fuels depending on application

- Synthetic methane
- Higher liquid hydrocarbons (w/o aromatic components)
- Compressed / liquified hydrogen and/or ammonia
- Methanol, DME, OEM...
- etc.

Costs of production, transmission, distribution but also issues of safety, security of supply etc. will be highly relevant.

But also competition expected between thermo- and electrochemical converters (based on thermodynamic efficiency, durability and costs)
H₂-rich gas addition to gasoline in IC-engines

Partially oxidative reformer

\[ C_nH_m + \frac{n}{2}O_2 \rightarrow n \cdot CO + \frac{m}{2}H_2 \]

- 21% H₂ - 24% CO - 55% N₂ (by volume)

H₂: great reactivity
- easy ignitability

Three strategies are possible:
- \( \lambda = 1 \) (stoichiometric), without EGR
- \( \lambda \) limit (ultra-lean)
- EGR limit (massive recirculation of exhaust gas)

Enrico Conte, PhD thesis, ETH Zurich No. 16539, 2006
Combustion Characteristics of Alternative Fuels

$\lambda = 1$ – no EGR

100% Gasoline

$\text{spark} = -35^\circ \text{CA bTDC}$

100% RefGas

$\text{spark} = -27^\circ \text{CA bTDC}$

Enrico Conte, PhD thesis, ETH Zurich No. 16539, 2006
Combustion and Emission of OME Diesel Blends with Minimum Effect of LHV Compensation

Investigated fuels

The composition of the fuel blends (OME* in Diesel) is chosen to compensate the reduction in lower heating value with one, respectively two additional nozzle holes; the injected energy per nozzle is constant among the all operating conditions.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>xOME (vol%)</th>
<th>DEN. (kg/m³)</th>
<th>LHV (MJ/kg)</th>
<th>xO (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>0</td>
<td>827</td>
<td>43.51</td>
<td>0</td>
</tr>
<tr>
<td>Blend B23</td>
<td>23</td>
<td>876.8</td>
<td>36.96</td>
<td>12.57</td>
</tr>
<tr>
<td>Blend B42</td>
<td>42</td>
<td>918.1</td>
<td>32.08</td>
<td>24.38</td>
</tr>
</tbody>
</table>

Operating conditions

EGR variation with all nozzles for constant engine speed, start of injection, hydraulic injection duration and nozzle exit fuel pressure**

*OME/ POMDME : Polyoxymethylene dimethyl ether  
** changes in nozzle number require a minor adjustment in electrical injection duration and rail fuel pressure

Parravicini, Barro & Boulouchos, Compensation for the differences in LHV of diesel-OME blends by using injector nozzles with different number of holes: Emissions and combustion Fuel 2019  
Parravicini, Barro. & Boulouchos, Experimental characterization of GTL, HVO, and OME based alternative fuels for diesel engines Fuel 2021
Estimated e-diesel/kerosene production costs (2020)

Fossil liquid fuel market price:
~0.5 (0.35-0.65) EUR/litre

Reference: Seymour & Held et al., prepared for submission to Energy & Environmental Science,
Fossil jet fuel prices over the last decade from IATA Fuel Price Monitor (2021)
e-jet fuel production component costs projections, normalized to 2020

Source: M. Held (2021)
CO₂-Pricing & Technology innovation - We need both!

Assuming an average cost for e-fuels around 2 EUR/litre vs. 0.5 EUR/litre for fossil fuels would lead to a CO₂-Mitigation cost of 600 EUR/tCO₂ (tank-to-wheel) → same order of magnitude for e-mobility.

Source: K. Boulouchos (2020)
Impact of electricity emissions intensity on the CO2-footprint for different transportation fuel production pathways (LCA)

Source: Caroline M. Liu et al. / Sustainable Energy Fuels, 2020, 4, 3129
Decarbonizing transport (cars, ships and airplanes) in EU27
How much electricity is needed @ current demand?

Current (2018) annual demand for fossil fuels vs. future (2050) annual demand for renewable electricity for the automotive, the shipping, and the aviation sector. Renewable electricity is either used directly in BEVs, or used to produce liquid e-hydrogen and e-jet fuel.

For comparison: Current electricity demand (EU 27) amounts to about 3’300 TWh!

Source: PhD M. Held (ETH Zürich 2021)
Decarbonizing transport (cars, ships and airplanes) in EU27

- Installed **power generation and electrolyzer capacity** for in total about 4’500 TWh
  - PV in Central Europe @ 1’000 FLH: 4’500 GW !
  - On-shore wind in Europe @ 2’000 FLH: 2’250 GW !
  - PV in Northern Africa @ 2’250 FLH: 2’000 GW !
  - Off-shore wind (North Sea, Patagonia) @ 4’500 FLH: 1’000 GW !

**Therefore:** A certain share of required e-fuels will be imported to Europe from optimal locations all over the world
Conclusions

- Paris Agreement Targets cannot be met w/o renewable synthetic chemical energy carriers (long-haul transport, power-on-demand, industrial processes)

- Different candidate fuels for combustion processes with no clear winner yet

- Very large investments in power generation necessary – Europe must probably source e-fuels from all over the world

- For achieving «break-even» of costs between e- and fossil fuels early enough, the combined role of technology innovation and CO₂-pricing policy will be crucial
Aknowledgement

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If interested, take a look at the White Paper of the SCCER Mobility (March 20, 2021)

- “Pathways to a net zero CO₂ Swiss mobility system” - see homepage: www.sccer-mobility.ch
RESERVE SLIDES
Life Cycle Analysis of Powertrains for cars
(meta-study of 80 publications)

Figure 3A: If cars are powered by fossil fuels, with electricity from the current energy mix or with conventionally generated hydrogen, battery electric vehicles and internal combustion engine vehicles have comparable life cycle emissions.

Figure 3B: If only renewable energy carriers are used during operation, a vehicle powered by synthetic fuels may even have lower CO₂ emissions than a battery electric vehicle. There is still room for optimization of the fuel cell.

Source: FVV Prime Movers, 2020