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

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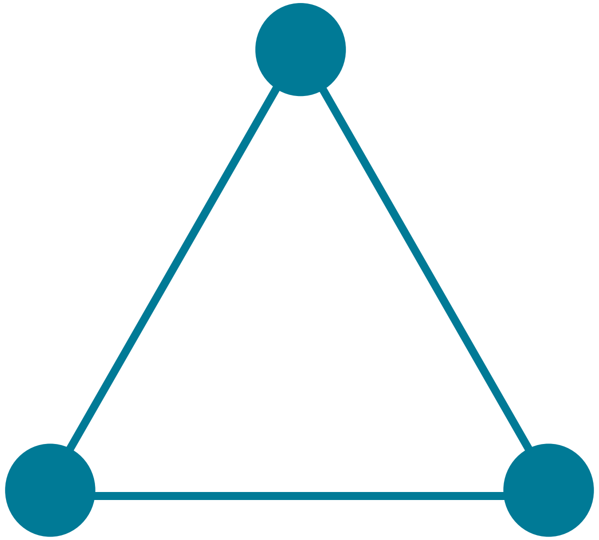
Relevant Questions

- Energy and Climate Challenges – the "Trilemma"
- «Decarbonization» of Transportation – CO_2-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 CO_2
(and minimization of other environmental impact)



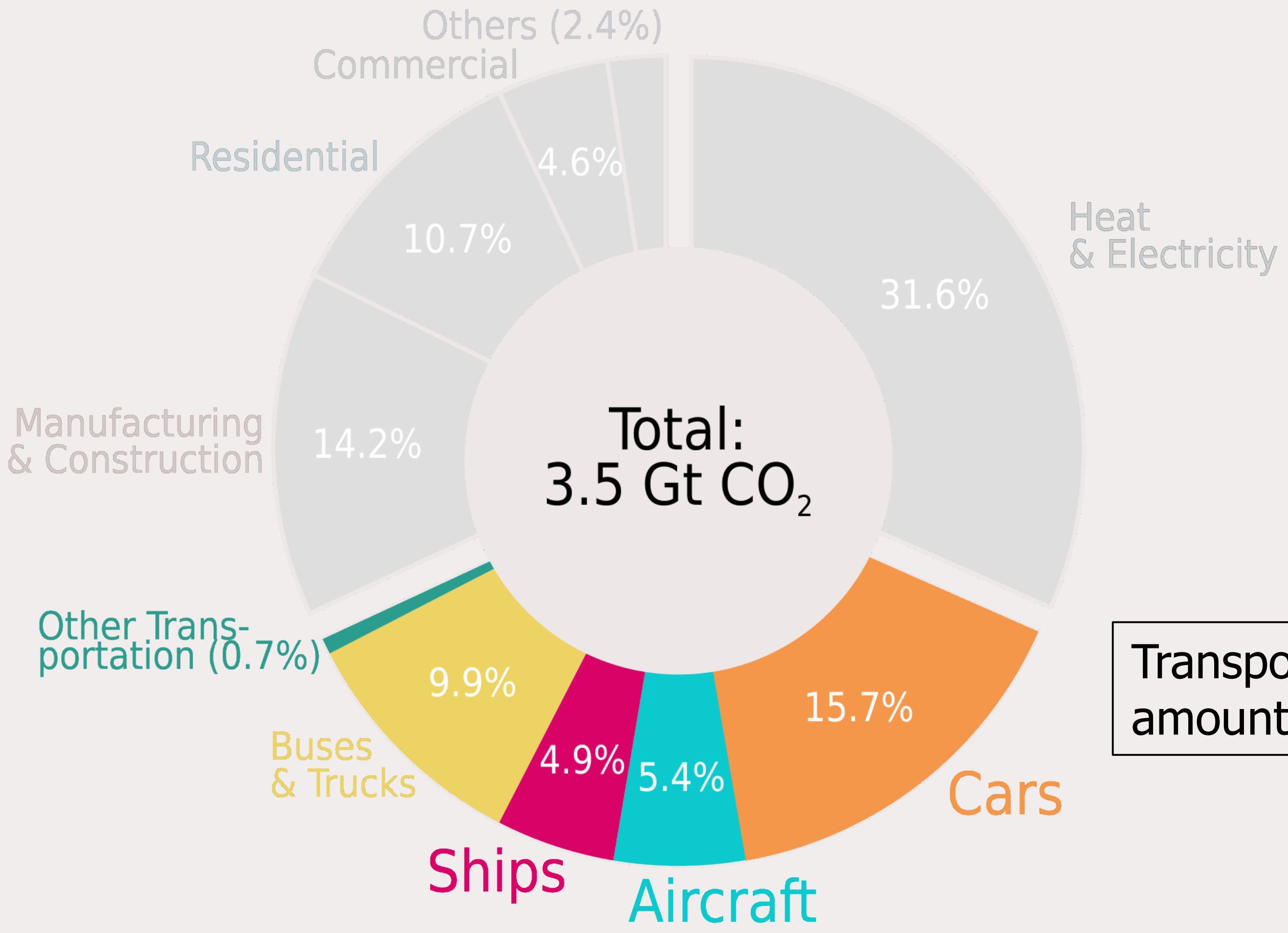
→ Partially conflincting goals
→ Optimisation required

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

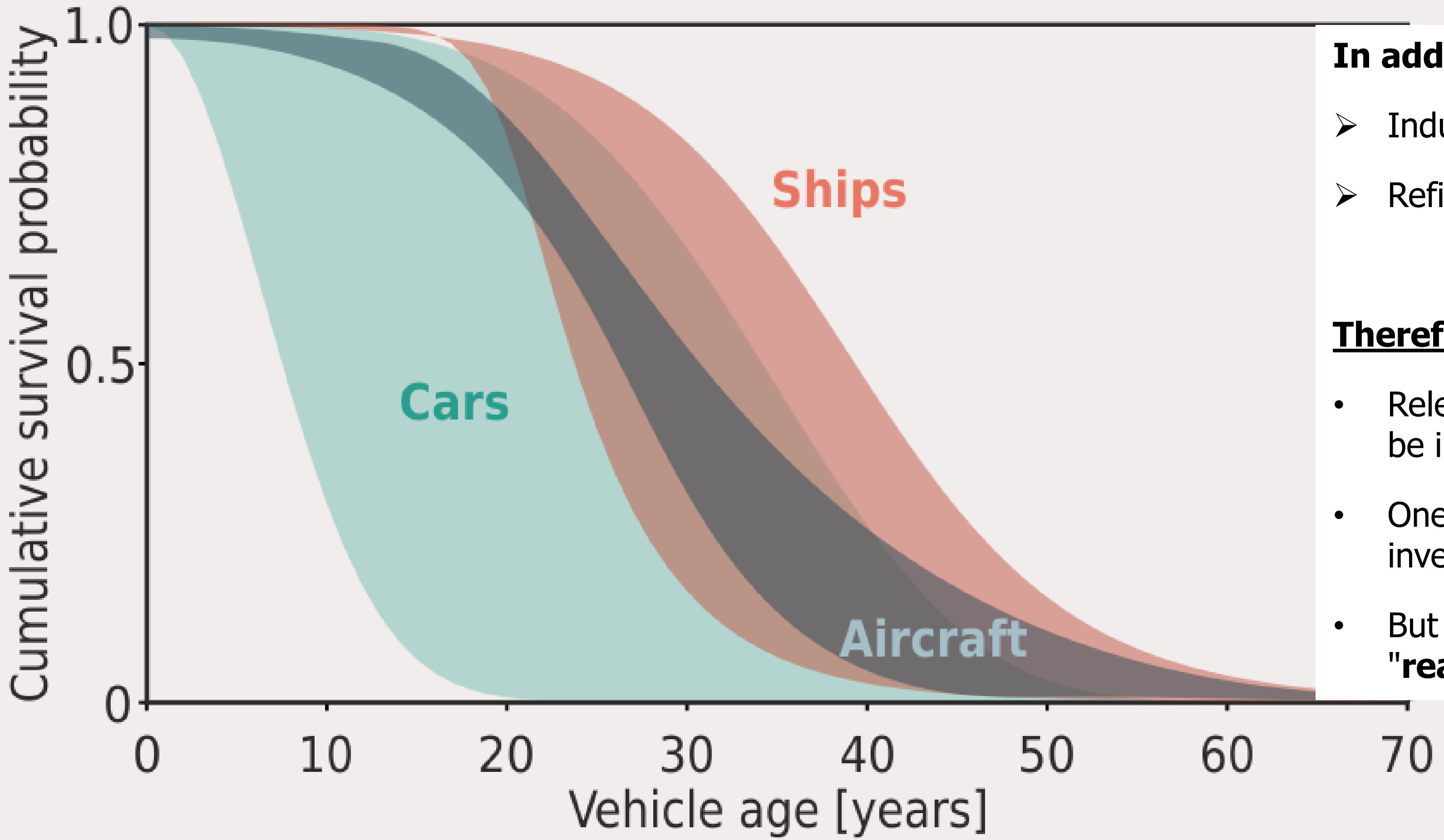
Sectoral shares of energy-related CO_2 emissions in "EU32".



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?



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**".

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*
Data for aircraft from Dray (2013): *Journal of Air Transport Management*, vol. 28, pp. 62-69

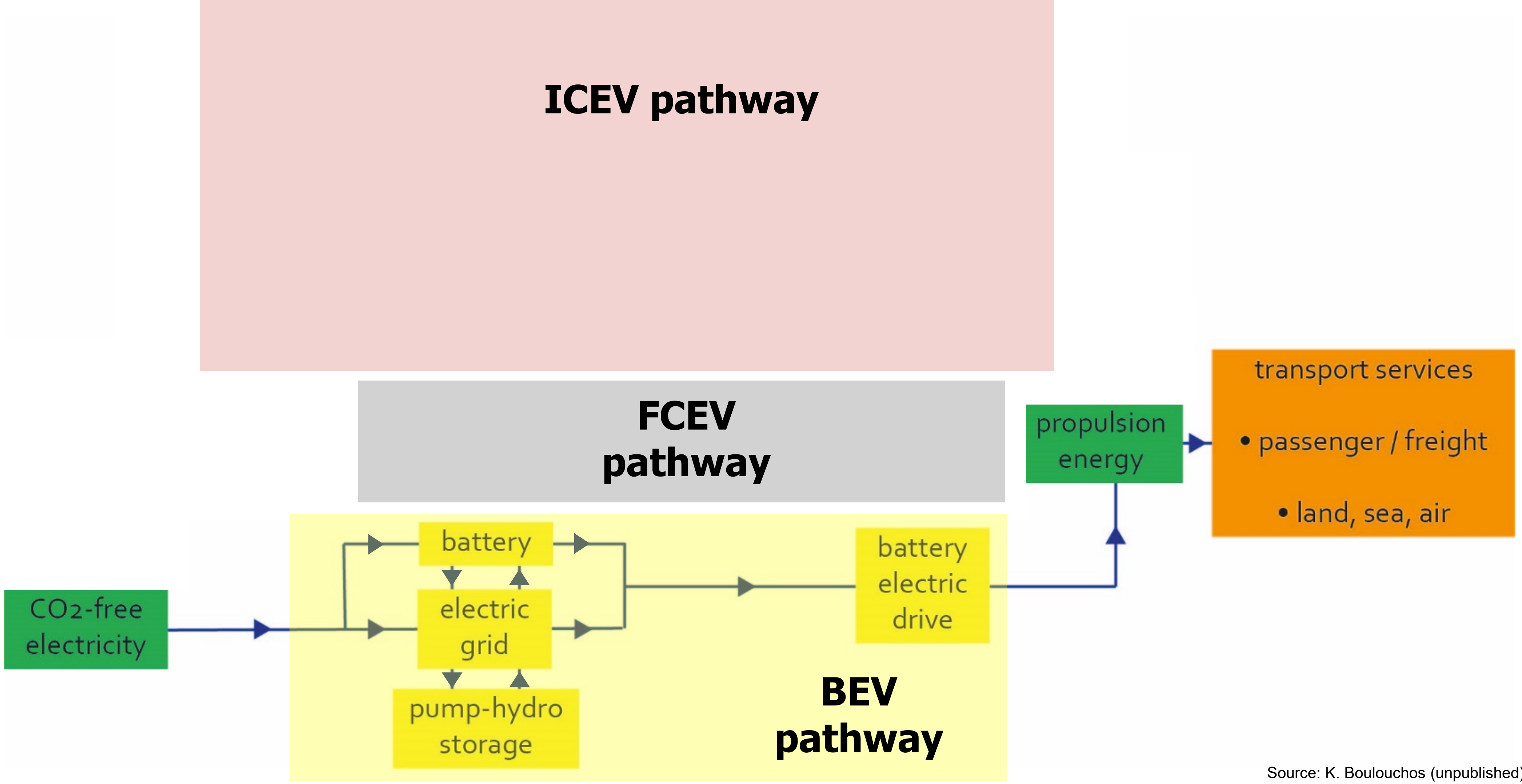
«Complete» Replacement of Fossil by Renewable Energy Carriers

↓

SECTOR COUPLING

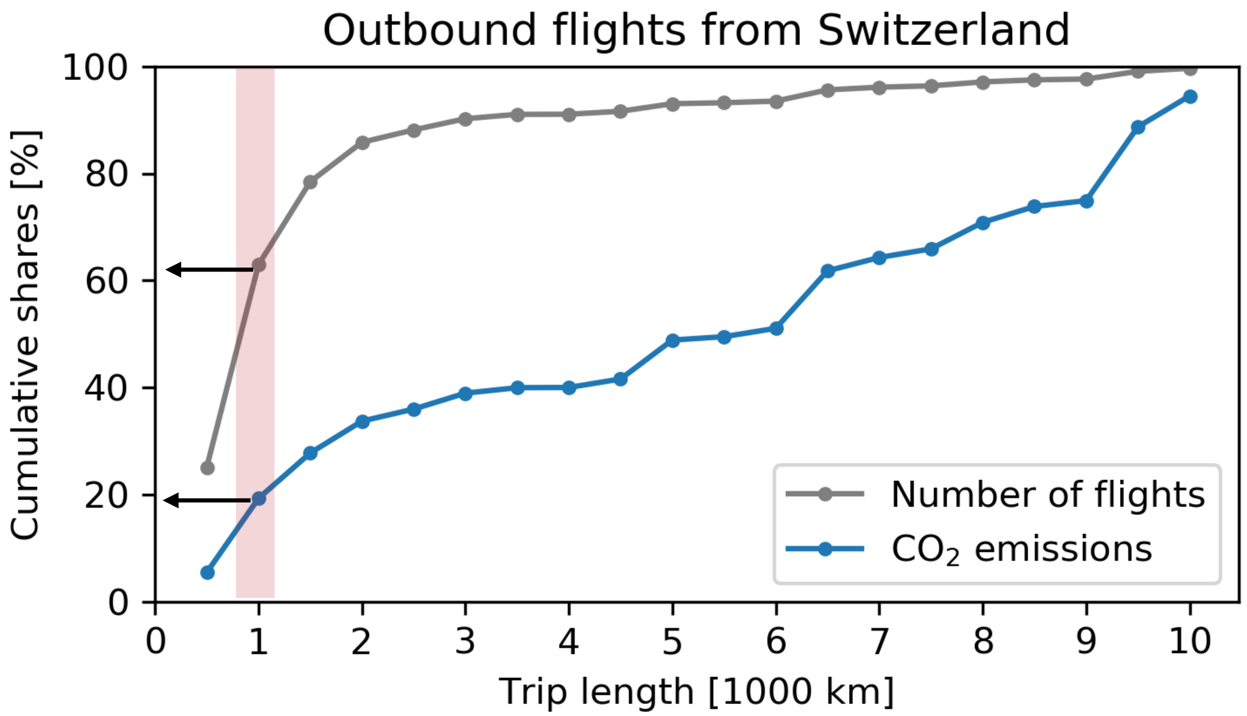
- Direct electrification of end-use sectors whenever feasible
- Indirect electrification in all other cases through renewable energy carriers (**e-, bio- and solar-chemical fuels**)
- Multiple interfaces between electricity and fuels along the conversion/storage/distribution chain from **primary** to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

Sector coupling - energy carrier portfolio for mobility (2050)



Source: K. Boulouchos (unpublished)

Aviation: Reducing CO_2 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 CO_2 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:
- Own calculation based on the methodology of: Seymour K., Held M., Georges G., Boulouchos K. (2020): "Fuel Estimation in Air Transportation: Modeling global fuel consumption for commercial aviation” in Transportation Research Part D: Transport and Environment, DOI: 10.1016/j.trd.2020.102528
- Schäfer A., et al. (2019): „Technological, economic and environmental prospects of all-electric aircraft” in Nature Energy, vol.4 (2), pp. 160-166

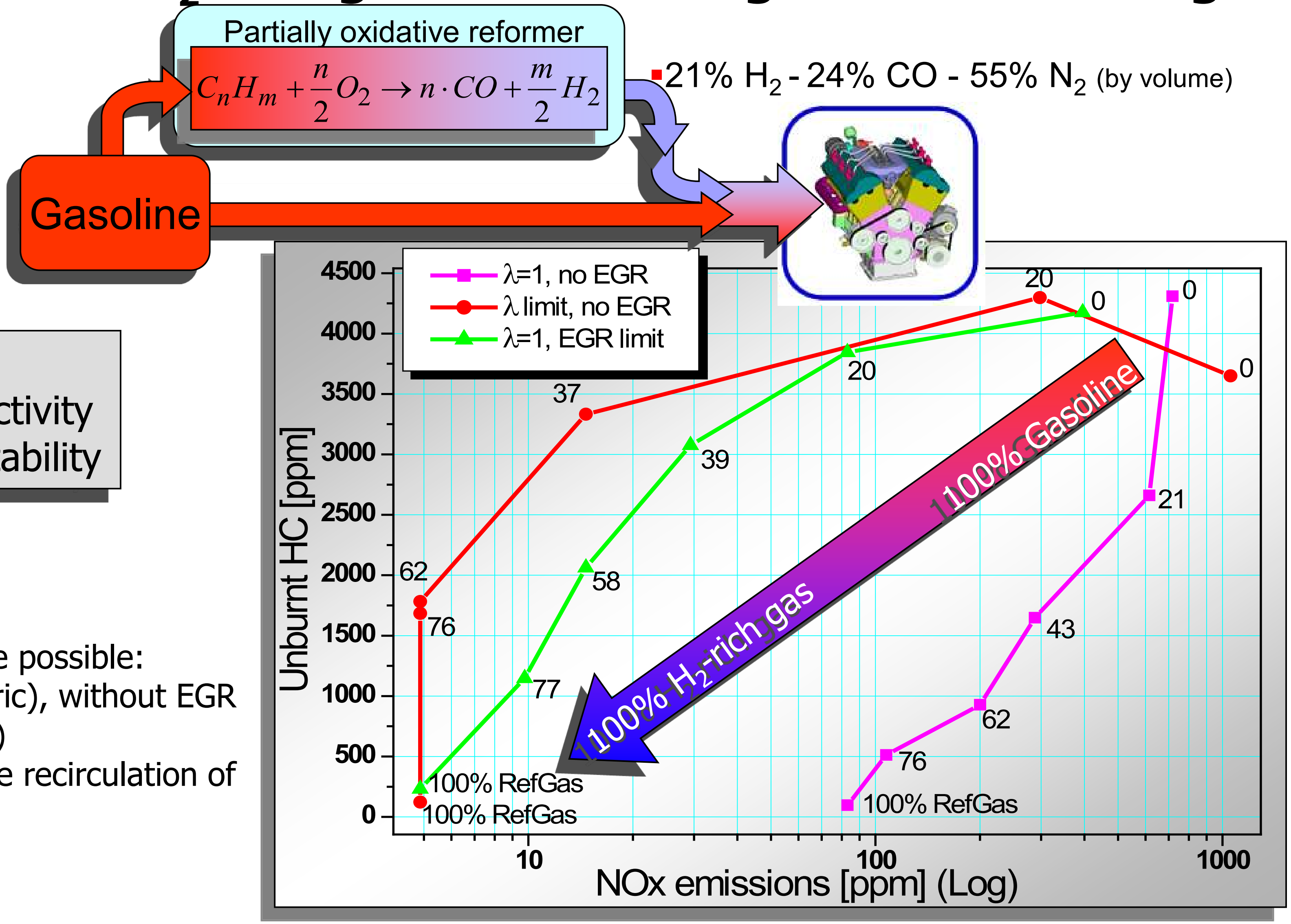
Different e-fuels depending on application

- 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)

H_2-rich gas addition to gasoline in IC-engines



H_2:
great reactivity
easy ignitability

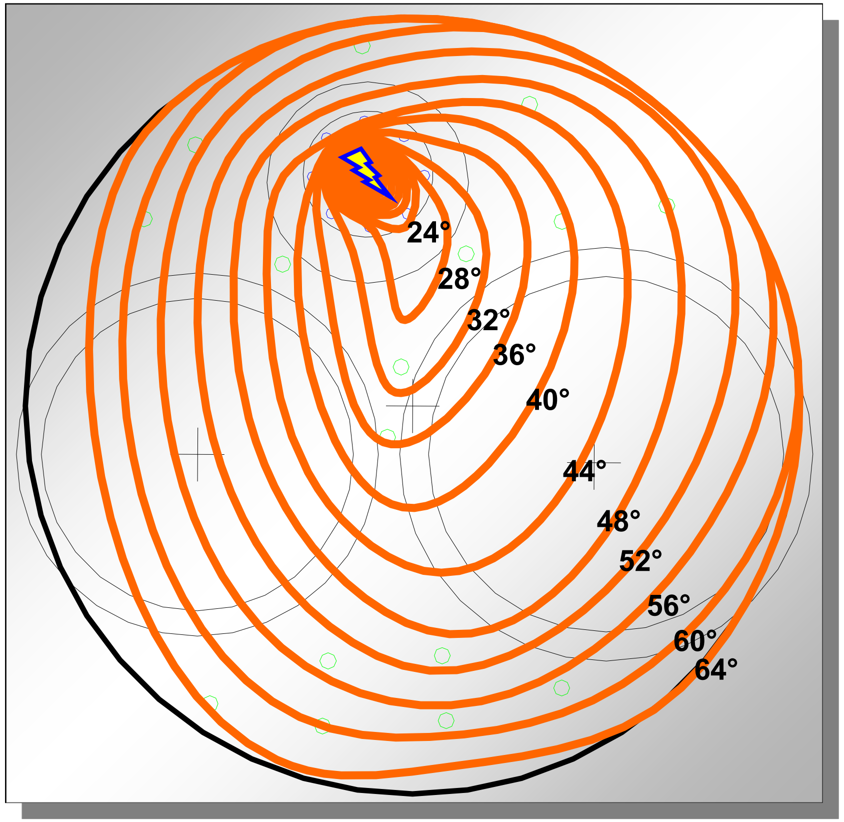
Three strategies are possible:
- λ=1 (stoichiometric), without EGR
- λ limit (ultra-lean)
- EGR limit (massive recirculation of exhaust gas)

Enrico Conte, PhD thesis,
ETH Zurich No. 16539, 2006

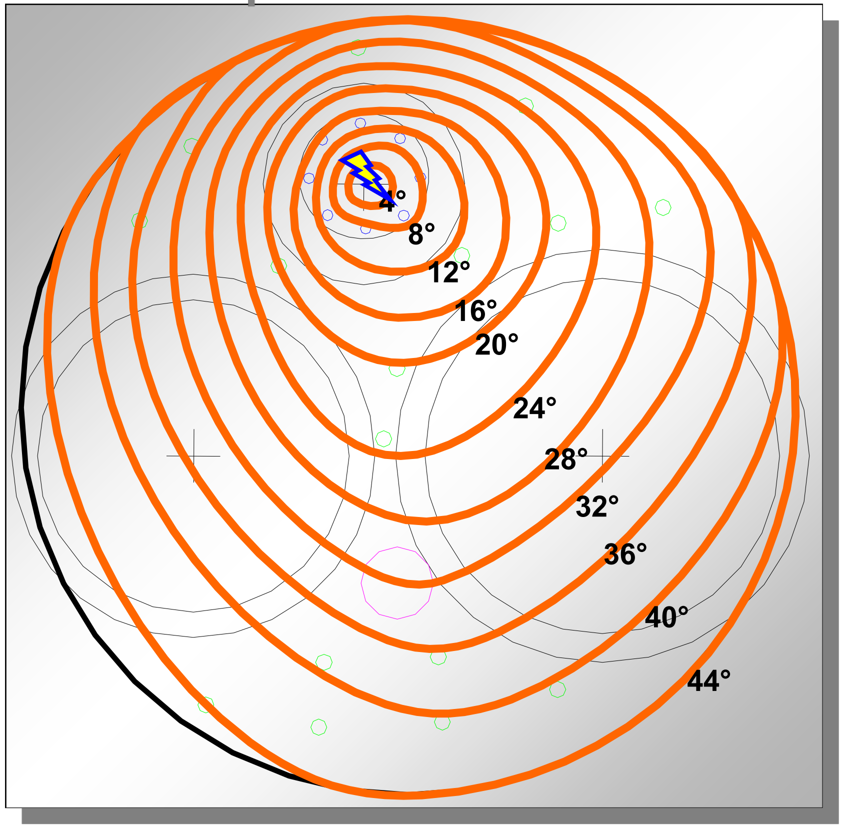
Combustion Characteristics of Alternative Fuels

λ=1 – no EGR

100% Gasoline
spark=-35°CA bTDC



100% RefGas
spark=-27°CA bTDC



Enrico Conte, PhD thesis,
ETH Zurich No. 16539, 2006

Combustion and Emission of OME Diesel Blends with Minimum Effect of LHV Compensation

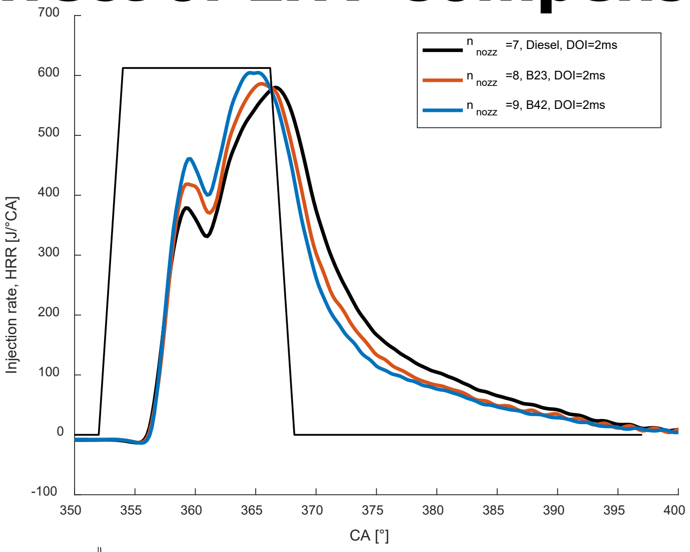
Investigated fuels

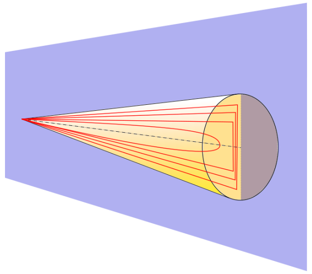
The composition of the fuel blends (OME* in Diesel) is chosen to compensate the reduction in lower heating value with one, respectively two additional nozzle holes; the injected energy per nozzle is constant among the all operating conditions

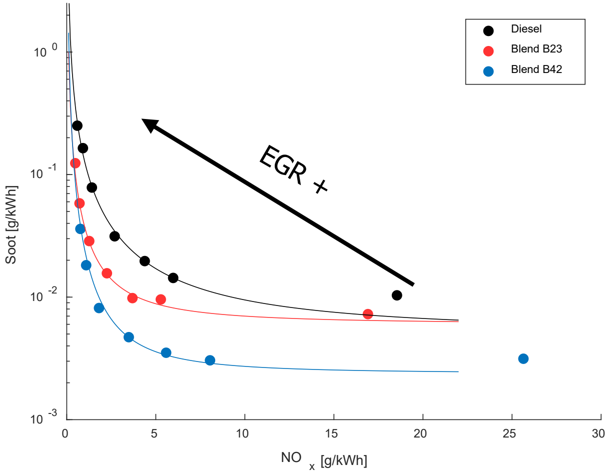
	7-holes	**8-holes**	**9-holes** nozzle
Fuel	Diesel	"B23"	"B42"
x_{OME} [*vol%*]	0	23	42
Den. [*kg/m³*]	827	876.8	918.1
LHV [*MJ/kg*]	43.51	36.96	32.08
x_O [wt%]	0	12.57	24.38

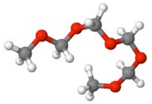
Operating conditions

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





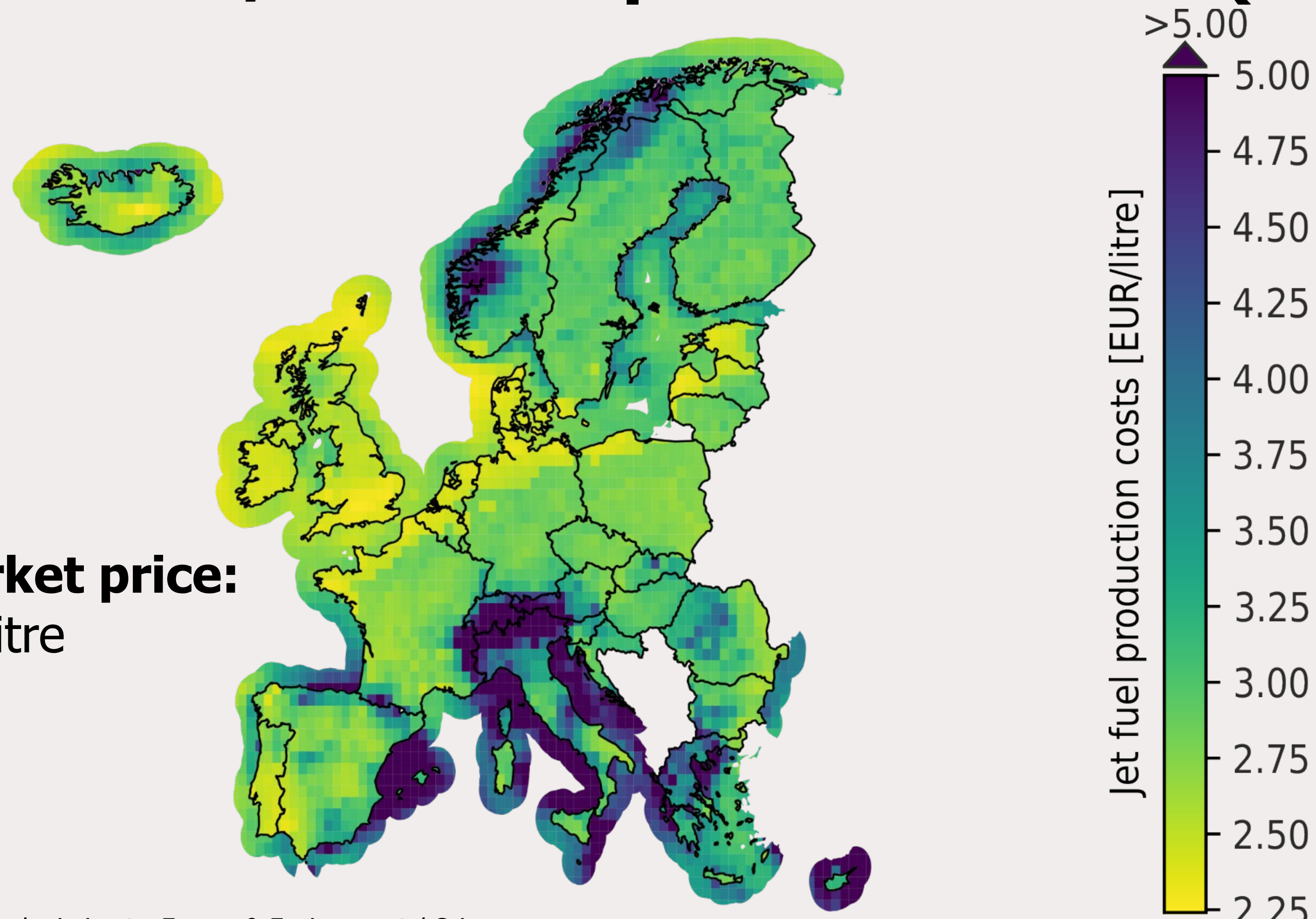




*OME/ POMDME : Polyoxymethylene dimethyl ether
** changes in nozzle number require a minor adjustment in electrical injection duration and rail fuel pressure

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

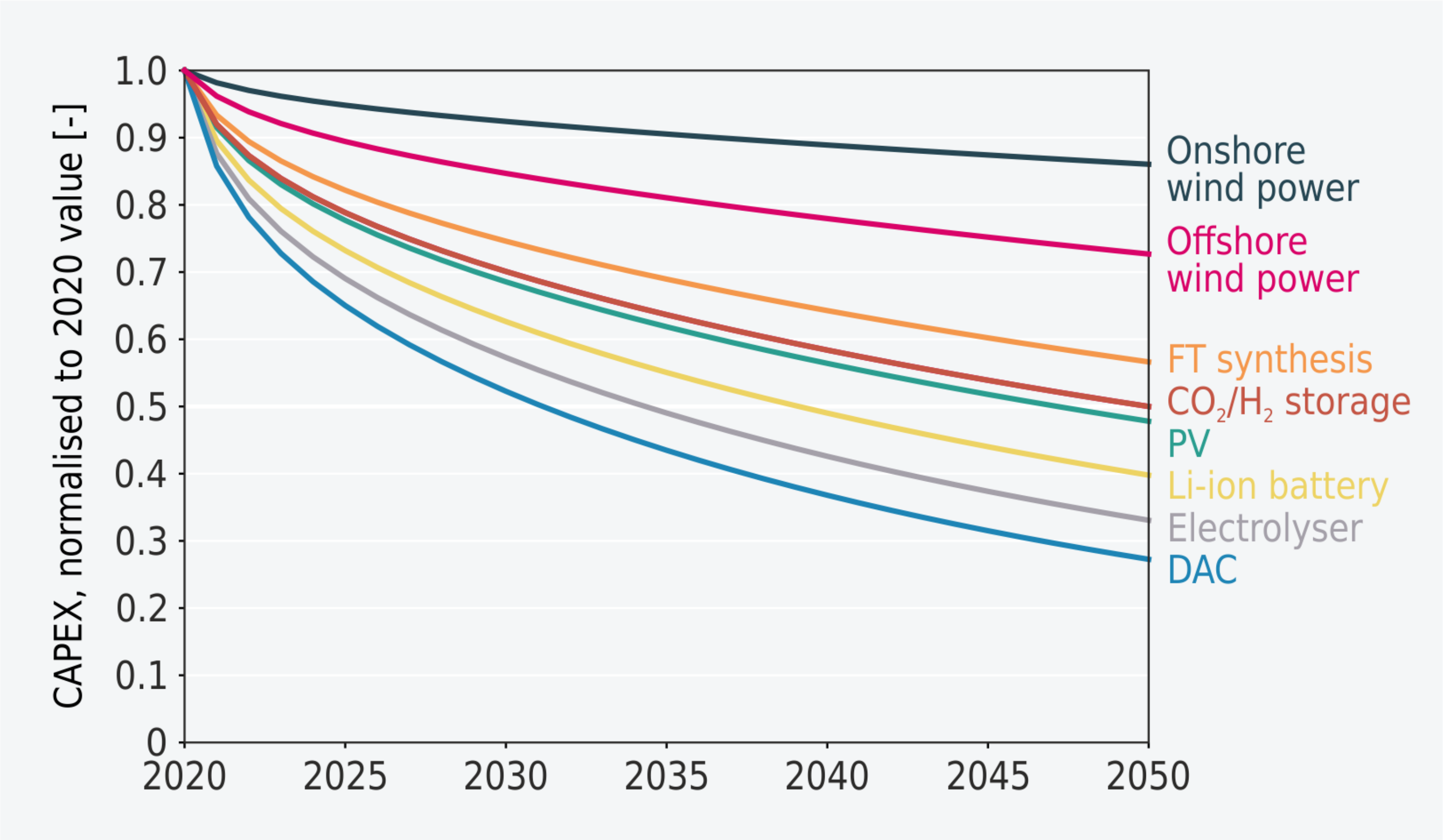
Estimated e-diesel/kerosene production costs (2020)



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

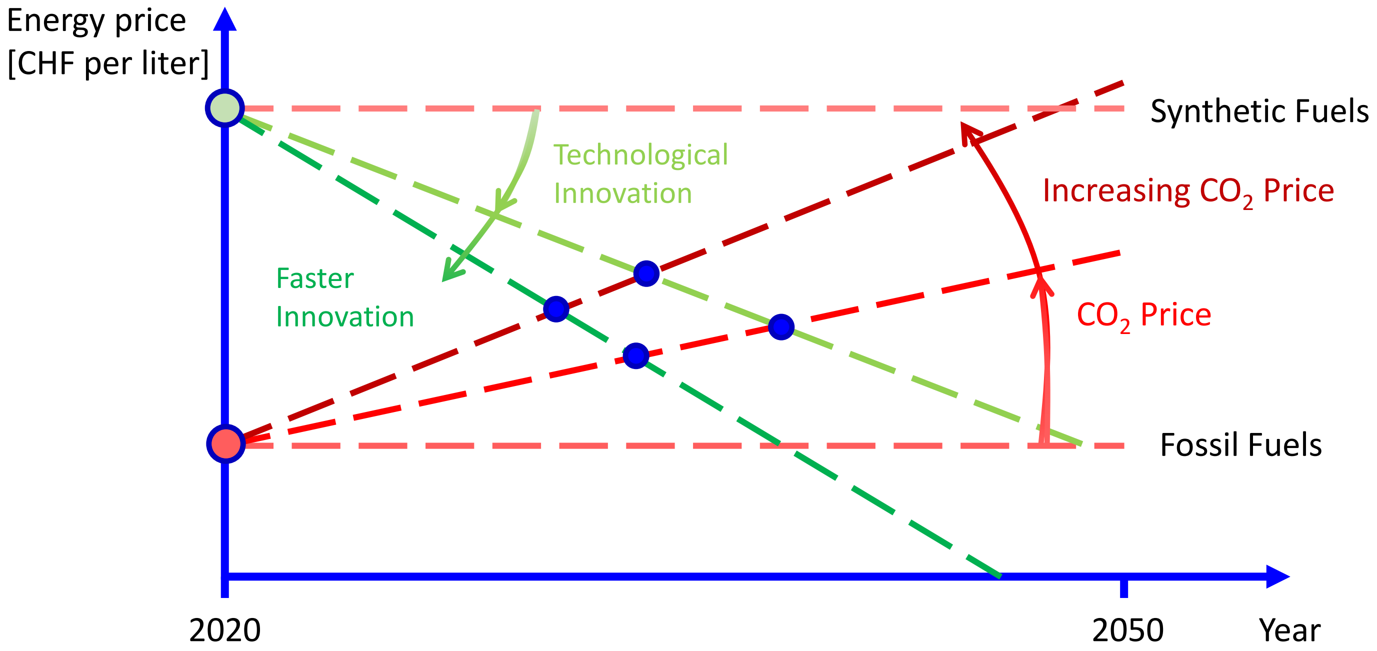
Reference: Seymour & Held et al., prepared for submission to *Energy & Environmental Science,*
Fossil jet fuel prices over the last decade from IATA Fuel Price Monitor (2021)

e-jet fuel production component costs projections, normalized to 2020



Source: M. Held (2021)

CO_2-Pricing & Technology innovation - We need both!



Assuming an average cost for e-fuels around

2 EUR/litre vs. 0.5 EUR/litre for fossile fuels

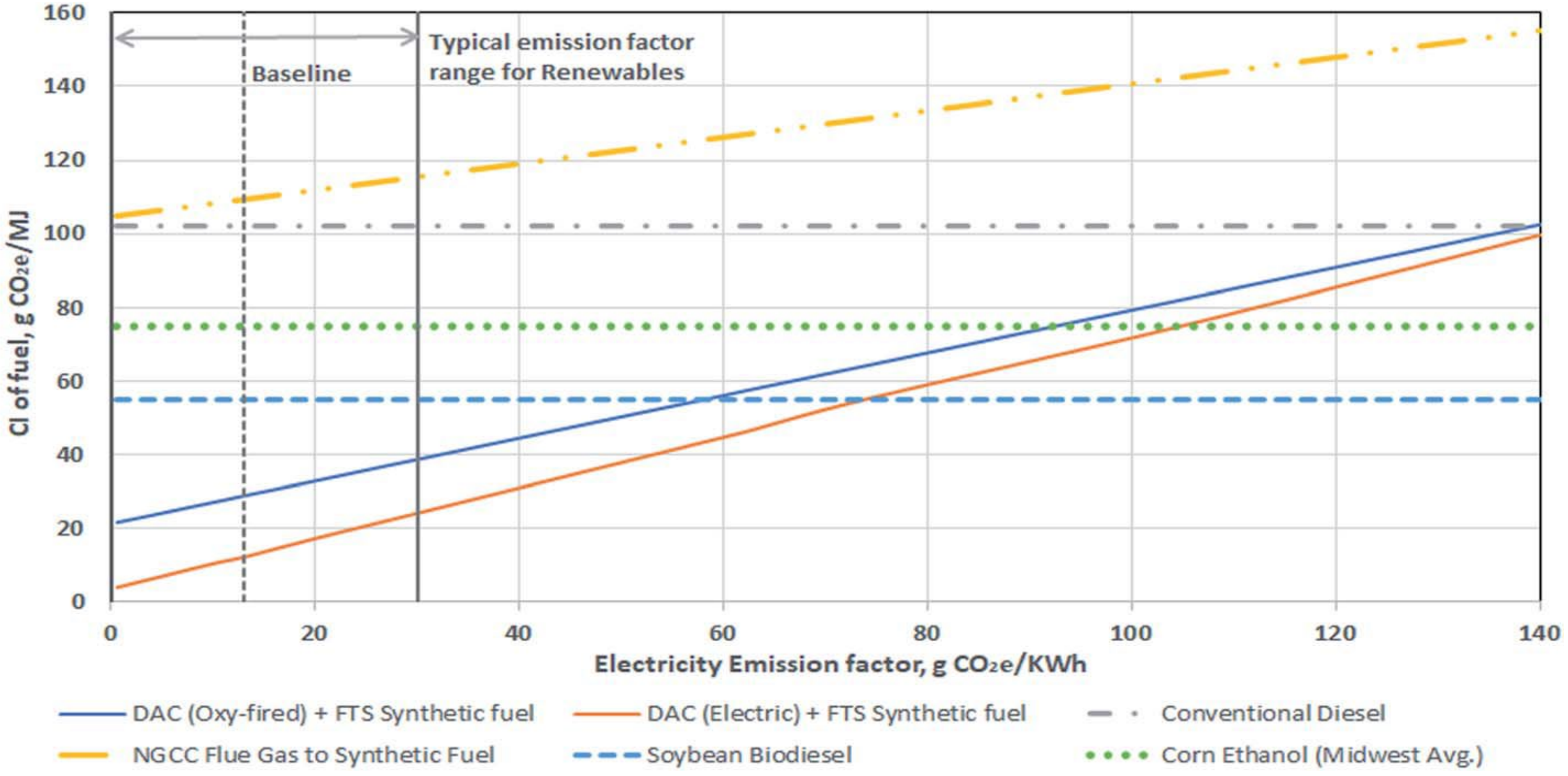
would lead to a CO2-Mitigation cost of

600 EUR/tCO2 (tank-to-wheel)

→ same order of magnitude for e-mobility

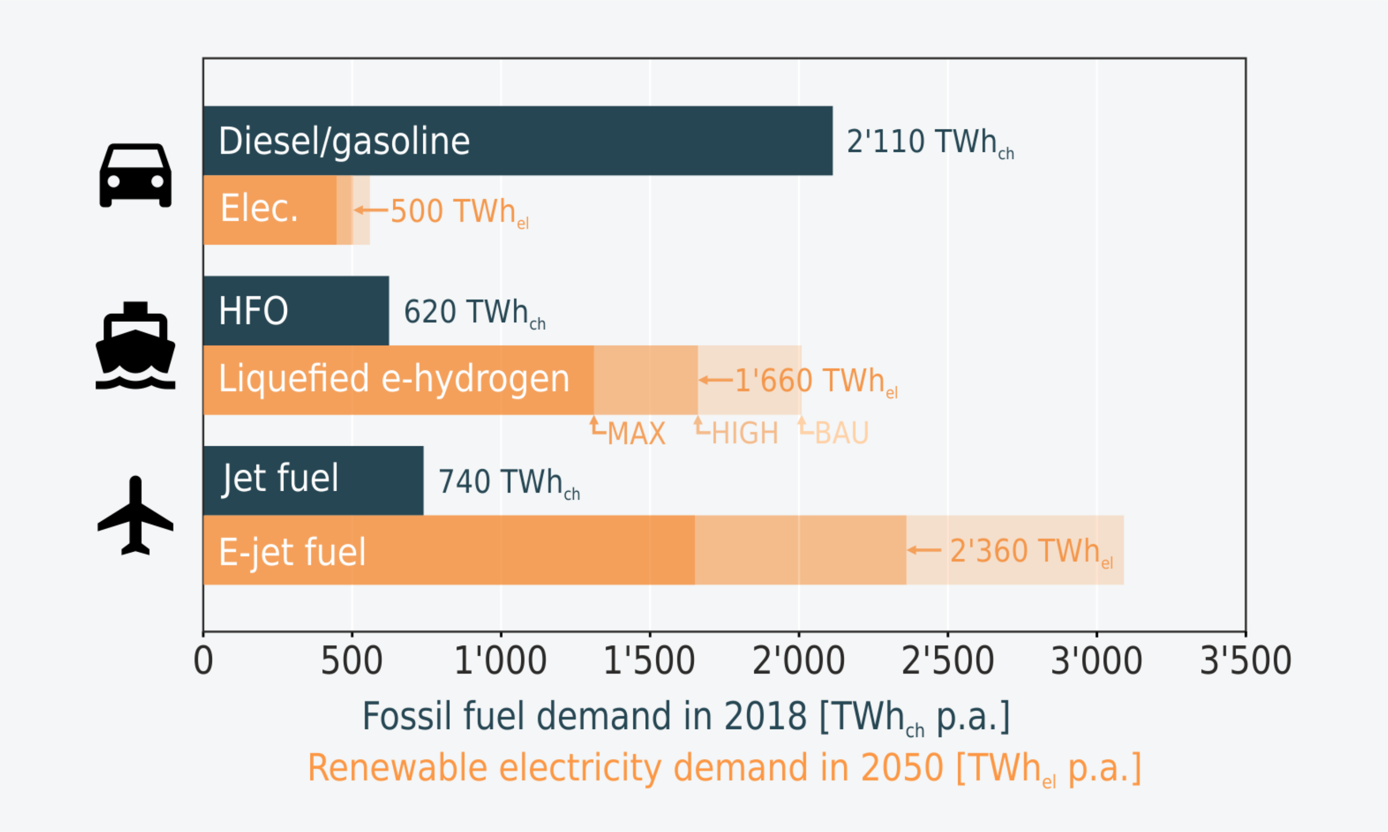
Source: K. Boulouchos (2020)

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?



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

Source: PhD M. Held (ETH Zürich 2021)

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.

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 CO_2-pricing policy will be crucial

Aknowledgement

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- Forschungsvereinigung Verbrennungskraftmaschinen, FVV, Frankfurt am Main

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

- *"Pathways to a net zero CO_2 Swiss mobility system" - see homepage: www.sccer-mobility.ch*

RESERVE SLIDES

Life Cycle Analysis of Powertrains for cars (meta-study of 80 publications)

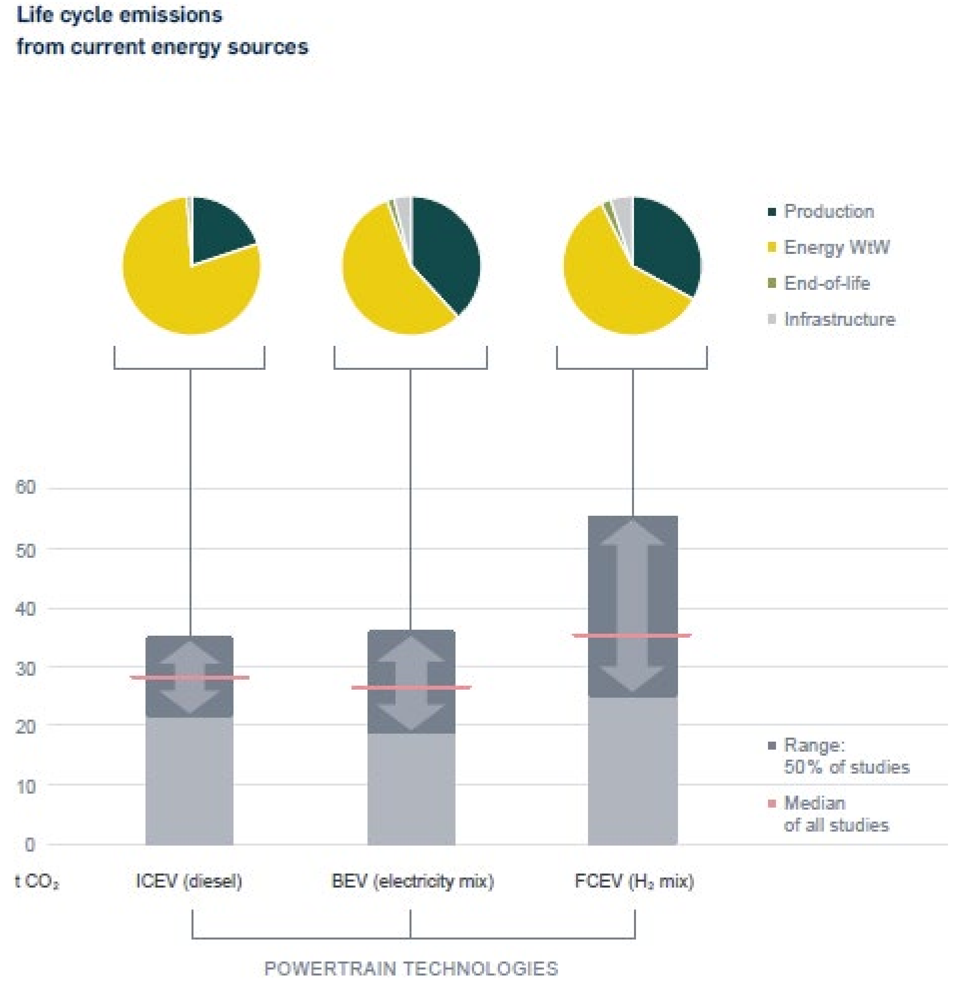

Figure 2-A: If cars are powered by fossil fuels, with electricity from the current energy mix or with conventionally generated hydrogen, battery electric vehicles and internal combustion engine vehicles have comparable life cycle emissions.

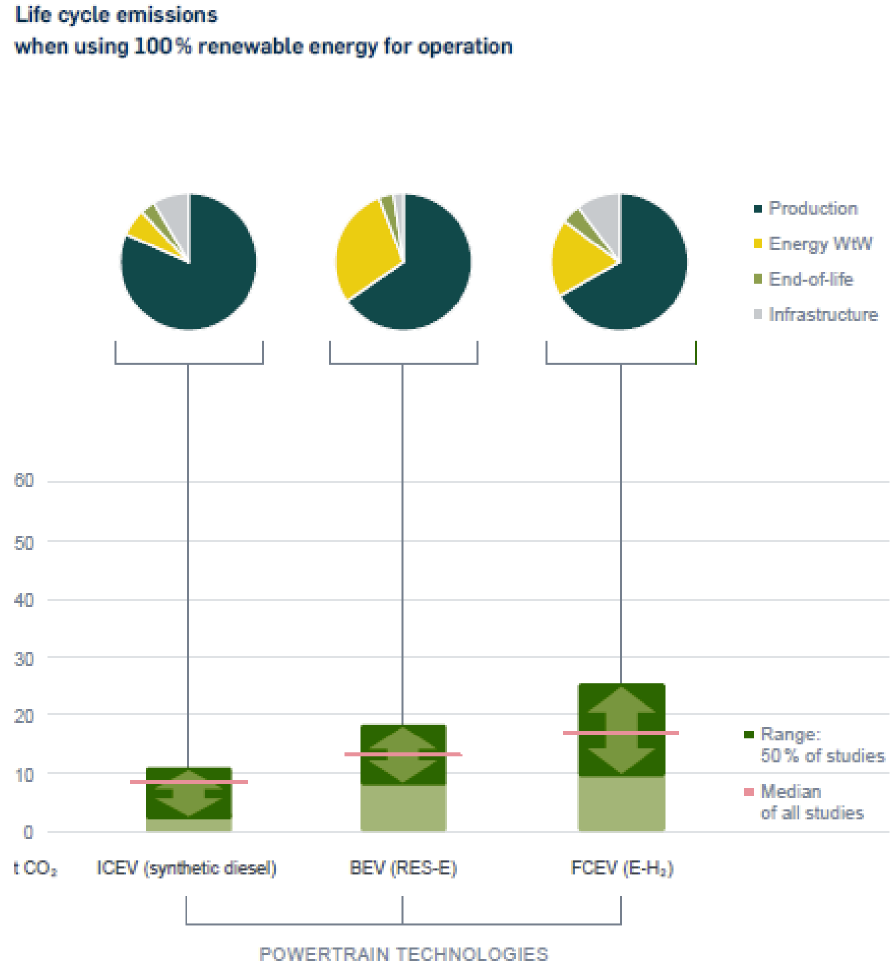

Figure 2-B: If only renewable energy carriers are used during operation, a vehicle powered by synthetic fuels may even have lower CO_2 emissions than a battery electric vehicle. There is still room for optimisation of the fuel cell.

Source: FVV Prime Movers, 2020