Bauhaus Luftfahrt
Neue Wege.

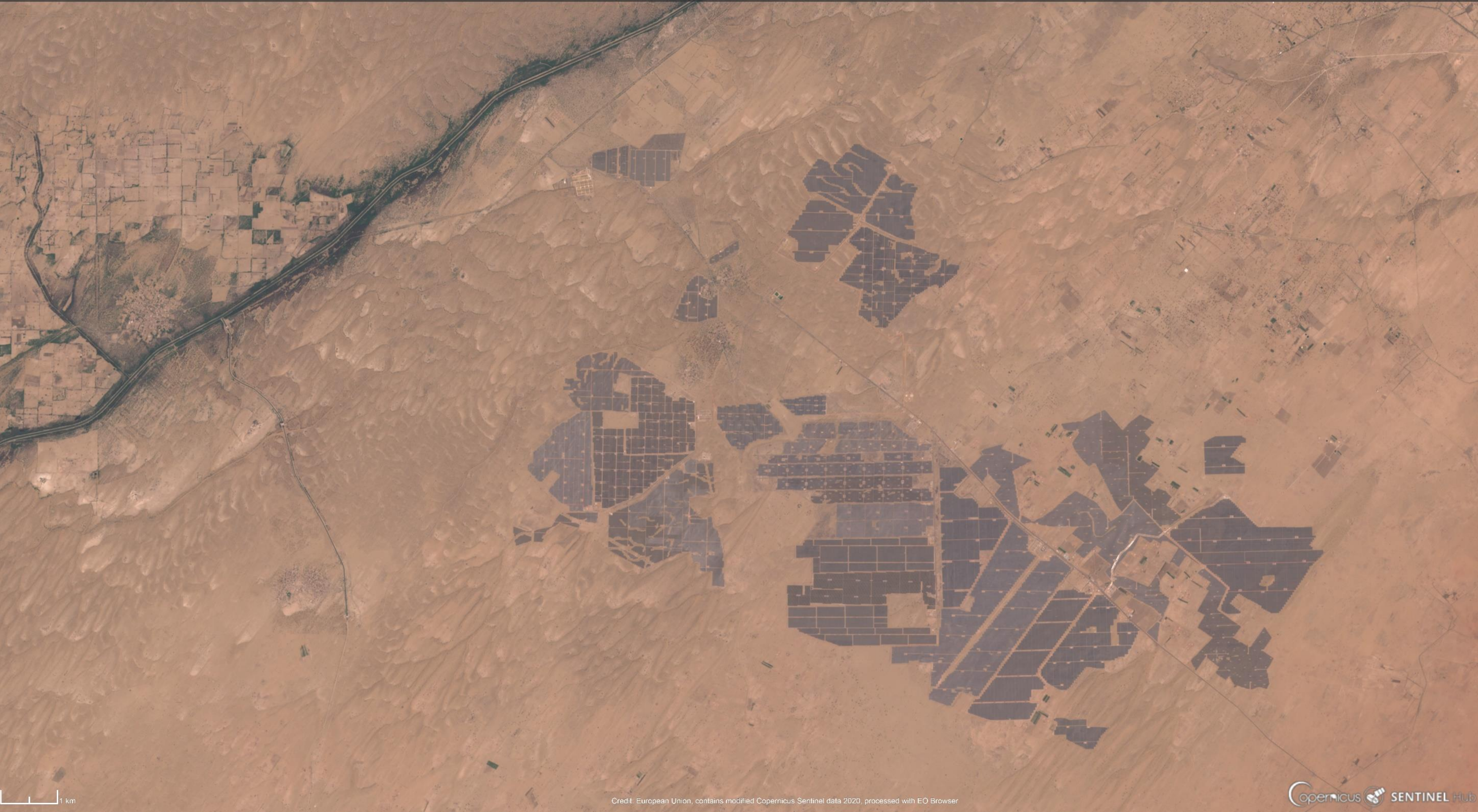
e-fuels as a key element to reduce the climate impact of aviation

Valentin Batteiger

Lunch Lecture e-Refinery
01.06.2021, TU Delft (virtual)

How will future e-refineries look like?

2020-05-20, Sentinel-2A L1C, True color



Credit: European Union, contains modified Copernicus Sentinel data 2020, processed with EO Browser

Conclusions from prologue

- **Mind the up-stream aspects of e-fuels, enormous electricity demand**
- **Renewable electricity generation is typically the dominating factor for key performance indicators:**
  - Area footprint
  - Visual impact
  - Material demand for construction
  - Water demand, fuel production cost & global warming potential
  - Performance w.r.t. further UN sustainable development goals

Climate impact of aviation, current status

GHG emissions related to 300 Mt/yr aviation fuel use:

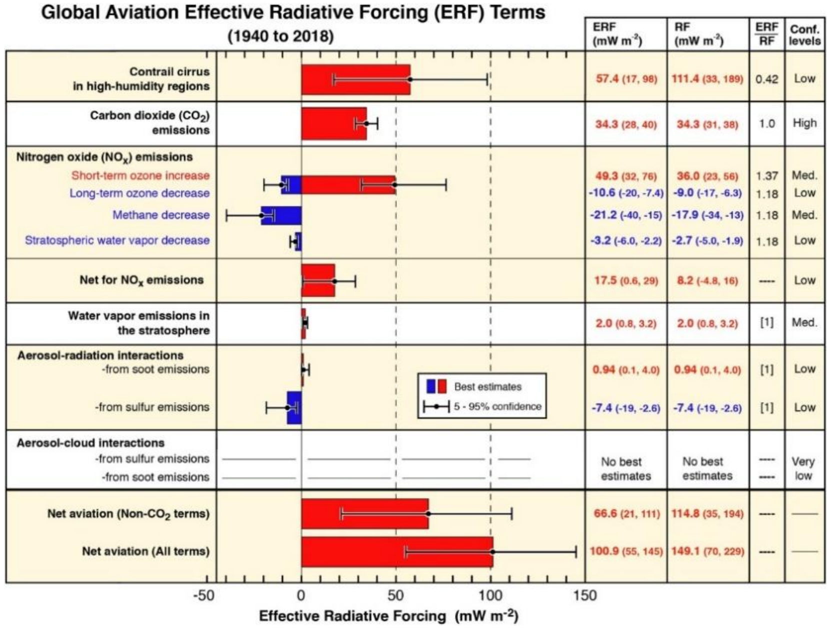
- 0.93 Gt_{CO2} from combustion (pre-Covid IATA 2019_{est})
- 1.1 $Gt_{CO2eq.}$ adjusting for upstream emissions

Climate impact of additional “non-CO_2 emissions”

- **Net effect: Additional warming**
- Mainly contrails, contrail cirrus and NOx effects
- Order of magnitude comparable to CO_2 effect

Aviation

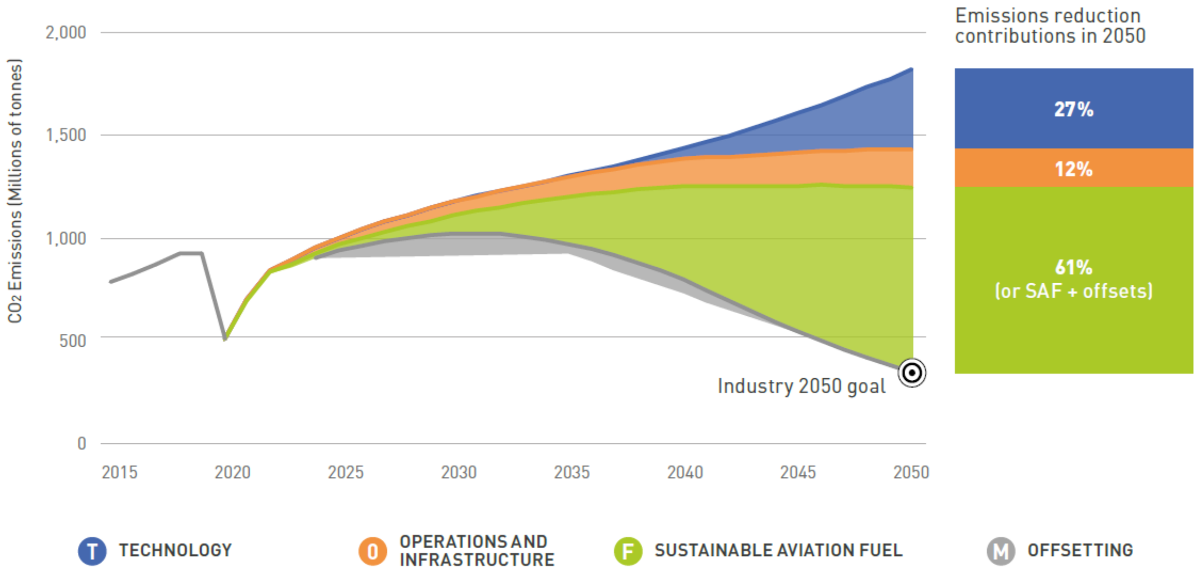
Total emissions	**0.93 Gt combustion**	**1.1 Gt well-to-wake**
33.4 Gt combustion	**2.7%**	**3.3%**
41.2 Gt total CO_2	2.3%	**2.7%**

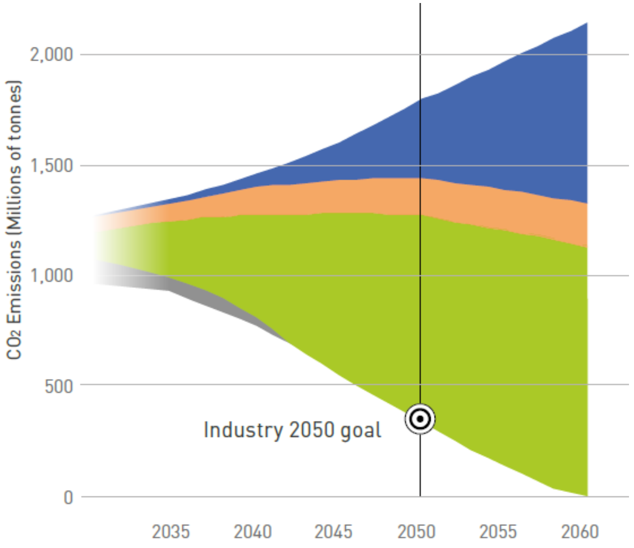


Data sources: IATA “*Economic performance of the airline industry*” 2018 End year report; Adjustment of CO_2 emission from combustion to well-to-wake emissions according to Stratton, “*Live cycle greenhouse gas emissions from alternative jet fuel*” 2010, MIT report PARTNER-COE-2010-001 (in line with: Masnadi, *Global carbon intensity of crude oil production*, Science 2018); Le Quéré, *Global Carbon Budget 2017*, Earth Syst. Sci. Data, 10, 405-448, 2018; BP “*Statistical Review of World Energy*”, June 2018; D.S. Lee et al, “*The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018*”, Atmospheric Environment in press https://doi.org/10.1016/j.atmosenv.2020.117834

Climate targets of the aviation industry

- **ATAG: 50% reduction by 2050 vs. 2005, pathway to net-zero by 2060 (global)**
- **Destination 2050 target: Net-zero by mid-century (EU)**



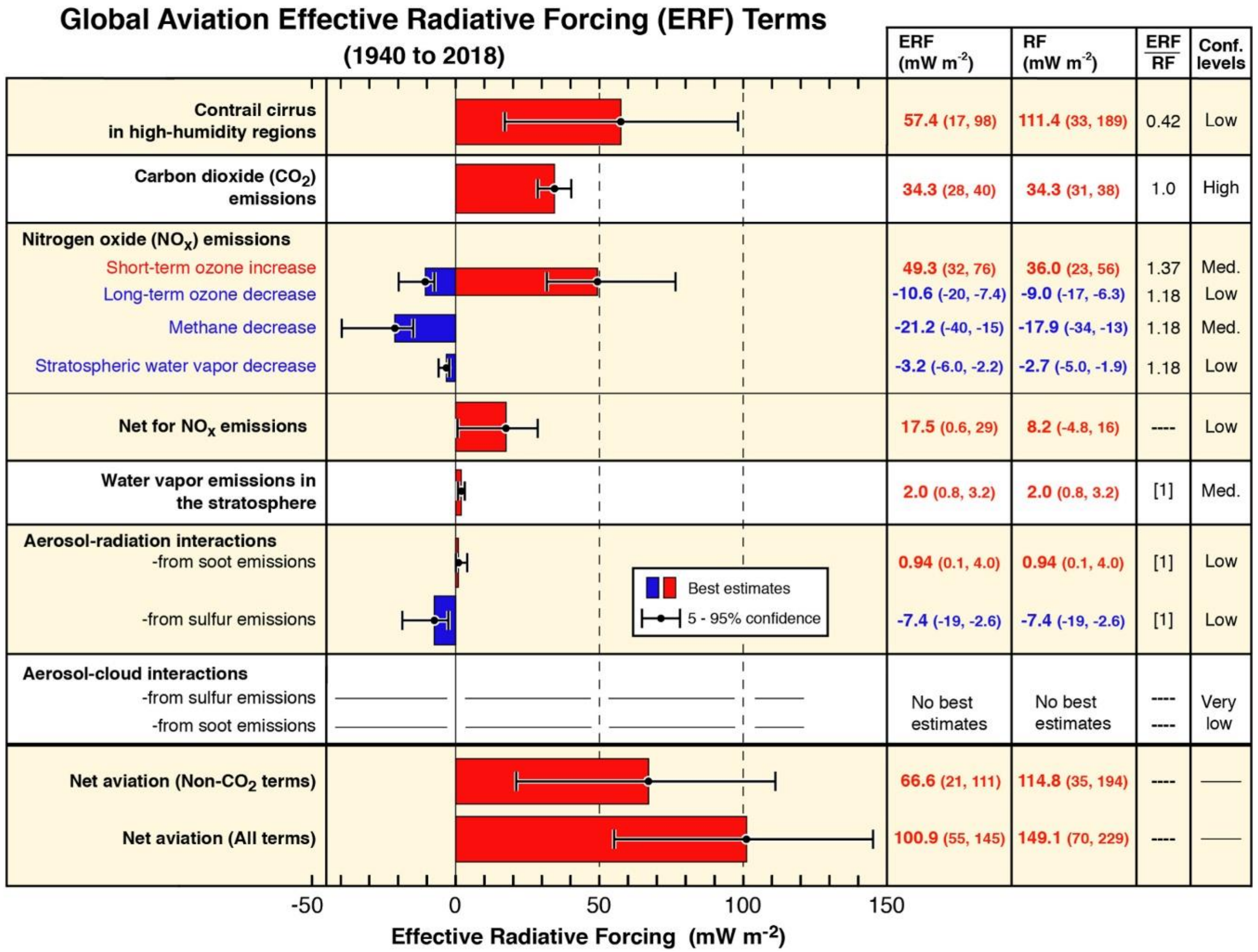


DESTINATION 2050

A ROUTE TO
NET ZERO EUROPEAN
AVIATION

Sources: ATAG, Waypoint 2050, First Edition September 2020 https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050
www.destination2050.eu

Full climate impact of aviation CO_2 and further emissions



	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions				
-from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
-from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

- Non-CO_2 contributions need to be to addressed to achieve climate neutrality
- Fuel properties are linked to non-CO_2 emissions
  - Mainly aromatics and sulphur
- Air-quality emissions need to be considered as well

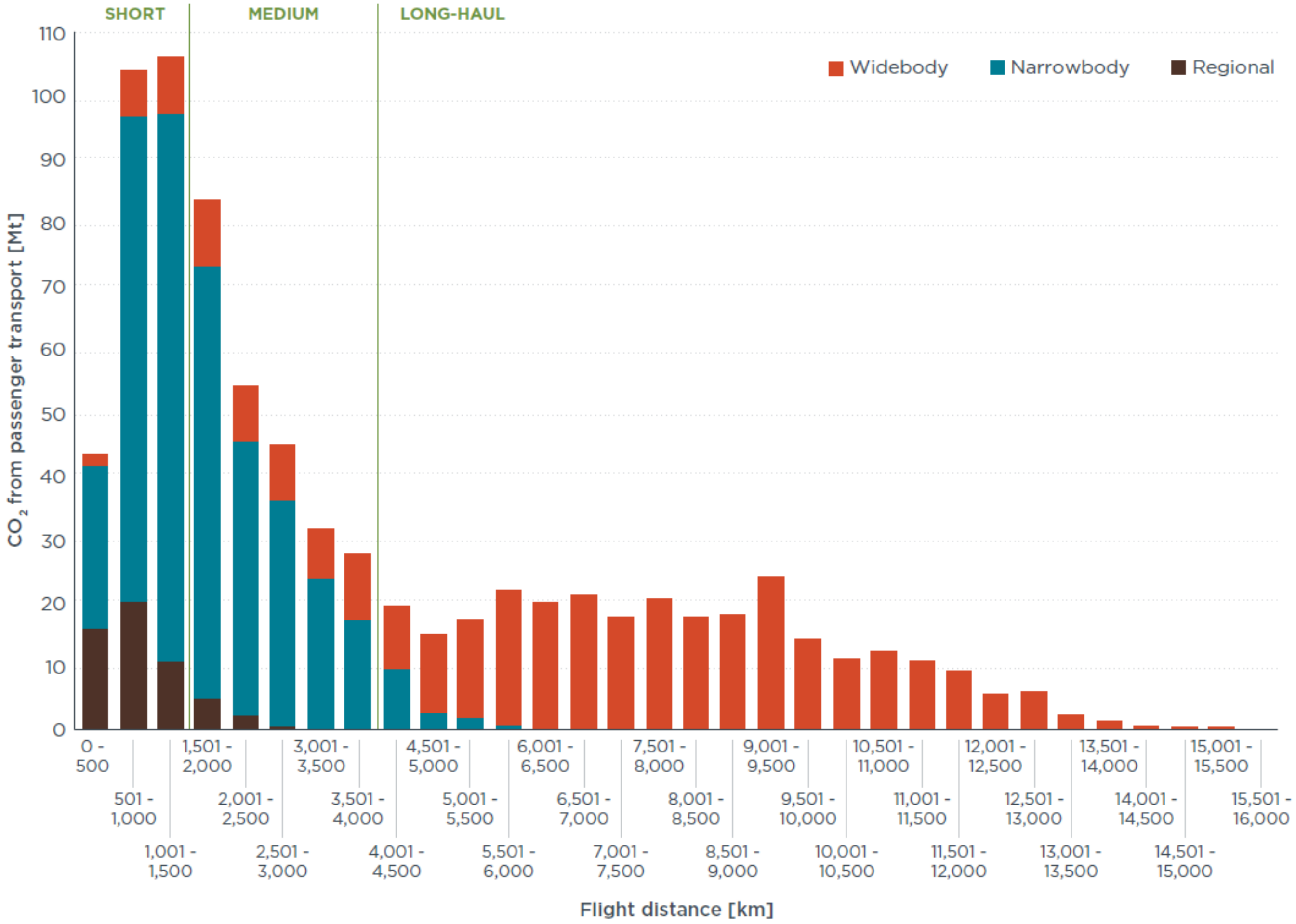
D.S. Lee et al, “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018”, Atmospheric Environment in press https://doi.org/10.1016/j.atmosenv.2020.117834
Grewe et al, Mitigating the Climate Impact from Aviation: Achievements and Results of the DLR WeCare Project, Aerospace 2017, 4, 34; doi:10.3390/aerospace4030034

Pollutant emissions from aviation fuel combustion

- **Ground based and airborne measurements relate fuel composition to pollutant emissions**
  - **NOx and CO:** Mainly controlled by combustion process
  - **Particle emissions:** Clear link to sulphur and aromatic content, clean fuels can reduce, but not eliminate particle emissions from current engines
  - **SO_2** is (obviously) linked to sulphur content

Sources: T. Schripp et al, *Impact of Alternative Jet Fuels on Engine Exhaust Composition during the 2015 ECLIF Ground-Based Measurements Campaign*, Environ. Sci. Technol. 2018, 52, 4969−4978; Moore, *Biofuel blending reduces particle emissions from aircraft engines at cruise conditions,* Nature, Vol. 543, 411, 2017

Break-down of CO_2 emissions from civil aviation



Fuel capacity/MTOW
ca. 20-25%

Fuel capacity/MTOW
ca. 40-45%

Source: B. Graver et al., *CO_2 Emissions from commercial aviation 2013, 2018, and 2019*, International Council on Clean Transportation 2020, https://theicct.org/publications/co2-emissions-commercial-aviation-2020; Picture Sources: de.wikipedia.org/wiki/Embraer-E-Jet-Familie#/media/Datei:2010-07-08_ERJ190_Cityline_D-AECE_EDDF_01.jpg en.wikipedia.org/wiki/LATAM_Chile#/media/File:A320neo_LATAM_(30934637733).jpg; en.wikipedia.org/wiki/Azul_Brazilian_Airlines#/media/File:PR-ANY@PEK_(20200524171035).jpg;

Electric Flight

Potentials and limitations of battery-electric aviation

- **Power demand from equilibrium of forces in cruise**

$$P_{e,\,cruise} = \frac{m \cdot g \cdot v}{L/D \cdot \eta_v \cdot \eta_e}$$

ca. 110 W/kg

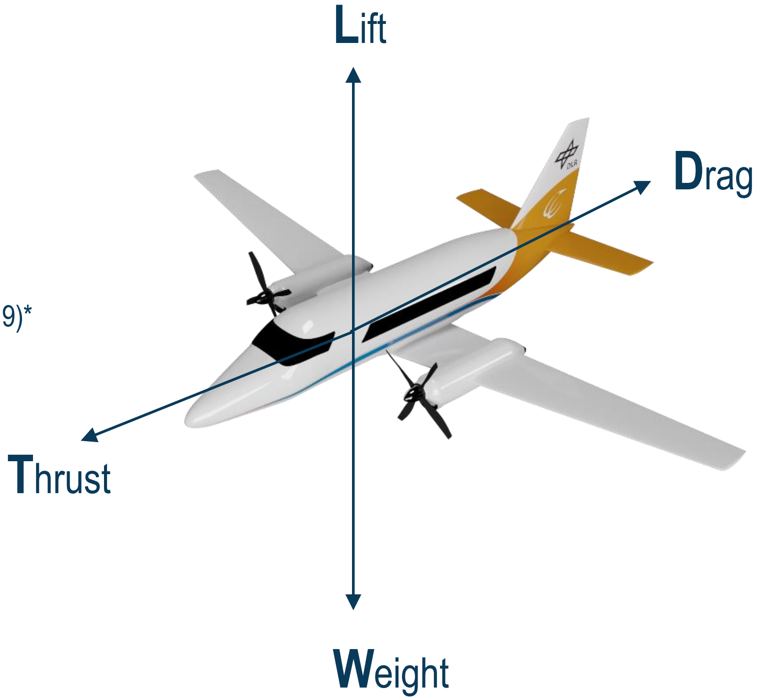
(with L/D = 17, v = 500 km/h, η_v = 0.8, η_e = 0.9)*

- **Range equation for battery-electric flight**

$$R = \frac{L/D \cdot \eta_v \cdot \eta_e \cdot \rho_e}{g} \cdot \frac{m_e}{m}$$

ca. 225 km

(with L/D = 17, η_v = 0.8, η_e = 0.9, **ρe=200 Wh/kg**, m_e/m=0.25)*



*Numbers are based on typical parameter, Choice not identical with CoCoRe Project (picture source)

Potentials and limitations of battery-electric aviation

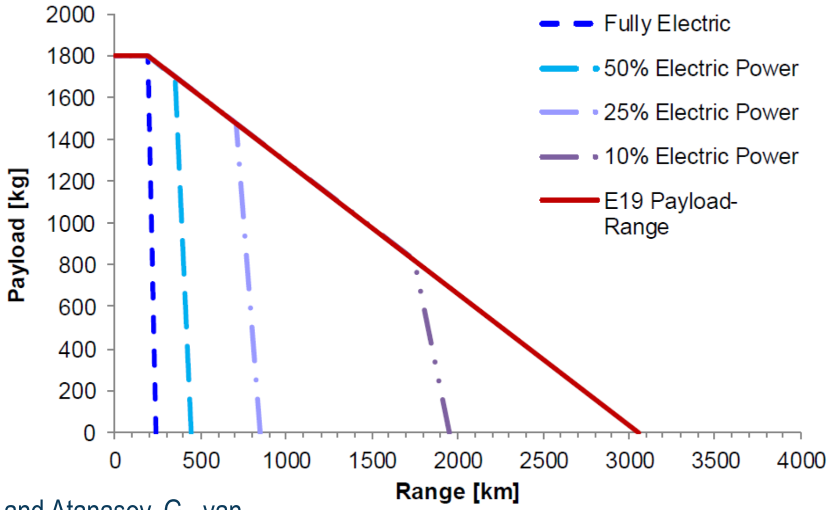
Δt cruise	12 Min	24 Min	36 Min	48 Min	1 h	2 h	3 h	5 h
Specific Energy Density	Addition energy demand (in Wh) to carry an additional 1 kWh battery at cruise conditions							
200 Wh/kg	111	223	334	445	557	1112	1670	2783
350 Wh/kg	64	127	191	254	318	636	954	1590
500 Wh/kg	45	89	134	178	223	445	668	1113
650 Wh/kg	34	69	103	137	171	343	514	856
800 Wh/kg	28	56	83	111	139	278	417	696

↳ EASA CS23: Reserve > 45 Minutes „maximum continuous power“

Assumptions: L/D = 17, v = 500 km/h, η_v = 80%, η_e = 90%

CoCoRe Concept Study (Bauhaus Luftfahrt/DLR)

- **19 Sitzer (Commuter-Class)**
  - 200 km purely electric range
  - Gas turbine range extender

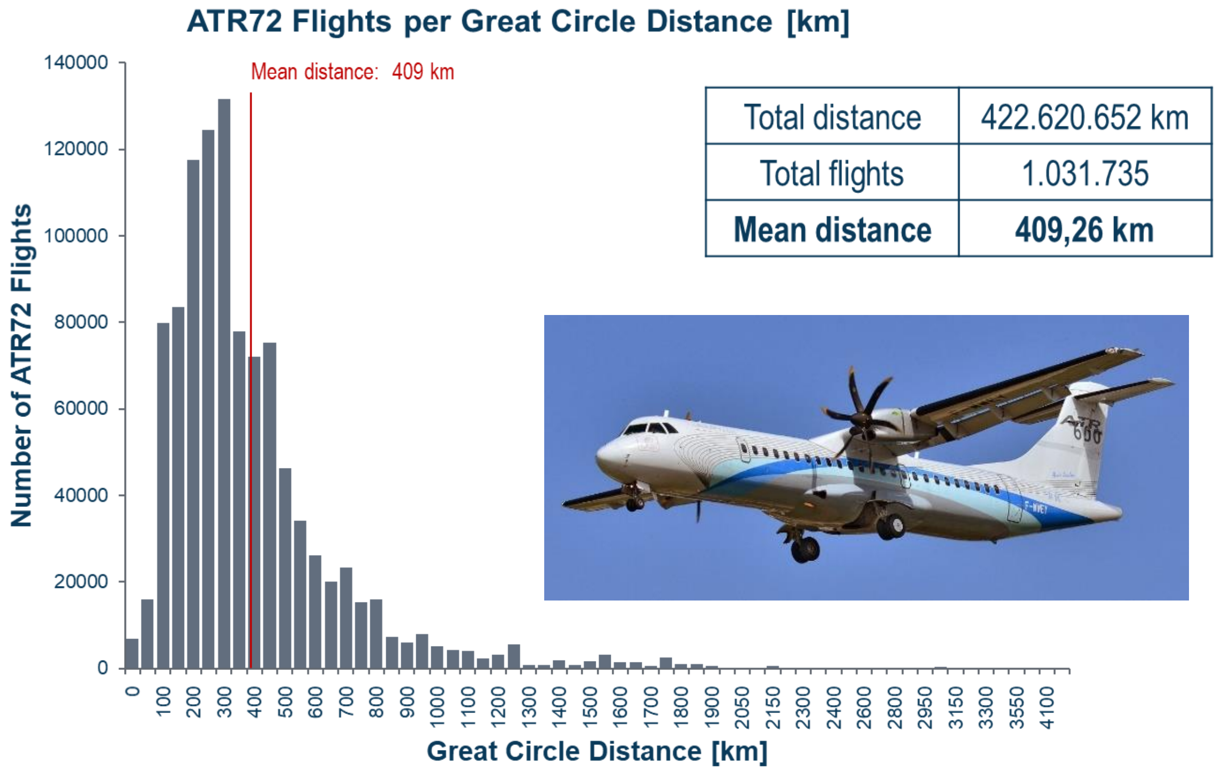


- **For comparison Commuter-Class in 2018**
  - 56% of all flights < 200 km
  - 83% of all flights < 350 km

Assumption battery pack: 230 Wh/kg (effective: 160 Wh/kg)
A. Paul, W. Grimme, G. Atanasov, J. van Wensveen, F. Peter, *Evaluation of the Market Potential and Technical Requirements for Thin-haul Air Transport* and Atanasov, G., van Wensveen, J., Peter, F. and T. Zill (2019), *Electric Commuter Transport Concept Enabled by Combustion Engine Range Extender*, Deutscher Luft- und Raumfahrtkongress 2019, Darmstadt, Germany, 2019. Siehe auch: www.dlr.de/content/de/artikel/news/2020/01/20200217_elektrisch-im-19-sitzer-von-mannheim-nach-berlin.html

Perspective: Electric regional aircraft

Regional turboprop mission spectrum



Total distance	422.620.652 km
Total flights	1.031.735
Mean distance	**409,26 km**

Target in Norway: First regular domestic flight by 2030

	Distance	Car	Train
Oslo-Bergen	305 km	6:50 h	6:50 h
Oslo-Trondheim	390 km	6:30 h	6:40 h
Bergen-Trondheim	430 km	10:30 h	15:40 h

https://kommunikasjon.ntb.no/pressemelding/norway-a-driving-force-and-arena-for-electrification-of-air-travel?publisherId=17507039&releaseId=17880988
https://de.wikipedia.org/wiki/ATR_72#/media/Datei:ATR_72-600_ATR_house_colors_F-WWEY_-_MSN_98_retusche.jpg

Liquid fuels needed for bulk part of aviation’s energy demand

Ce-Liner

Battery electric concept
Requires battery energy density > 1000 kWh/kg

Centreline:

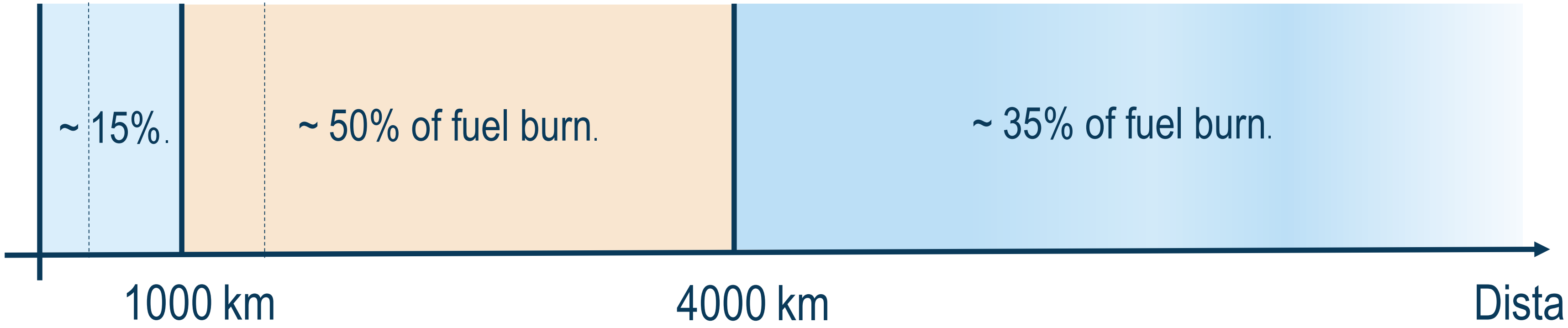
Turbo-electric concept
No change of energy carrier
Efficiency measure

CoCoRe

Hybrid-electric commuter
High battery utilization

HyLiner

Liquid hydrogen powered long-haul aircraft



~ 15%.

~ 50% of fuel burn.

~ 35% of fuel burn.

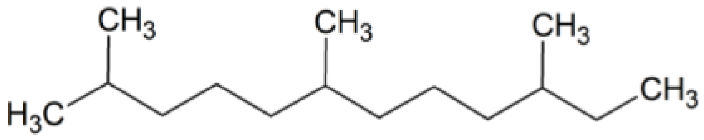
1000 km

4000 km

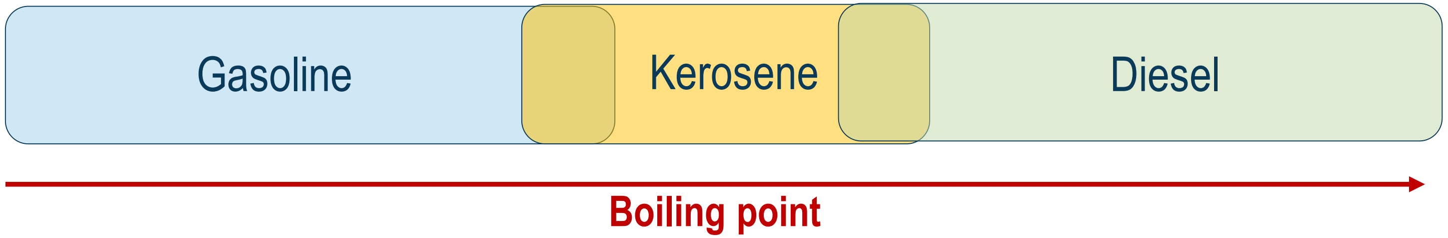
Distance

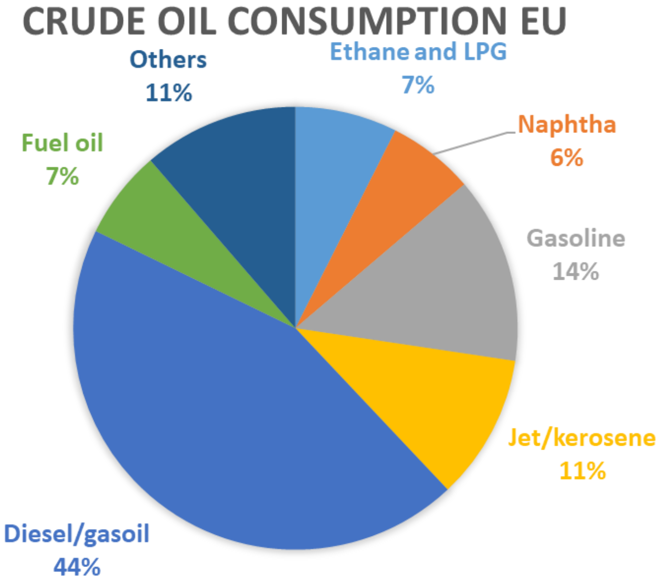
Sources: M. Hornung, *Ce-Liner – Case Study for eMobility in Air Transportation*, Aviation Technology, Integration and Operations Conference. Los Angeles. 12.8.2013
EU Project Centreline: www.centreline.eu ; F. Troeltsch - Concept for a hydrogen-powered long-haul aircraft, Bauhaus Luftfahrt Symposium, 8.5.2019
www.dlr.de/content/de/artikel/news/2020/01/20200217_elektrisch-im-19-sitzer-von-mannheim-nach-berlin.html

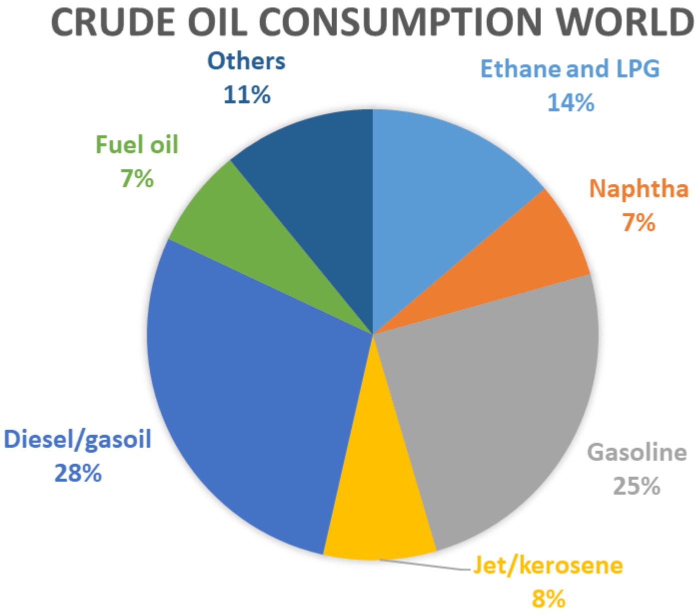
Synthetic Jet Fuels



Kerosene as turbine fuel for civil aviation (Jet-A, Jet-A1)

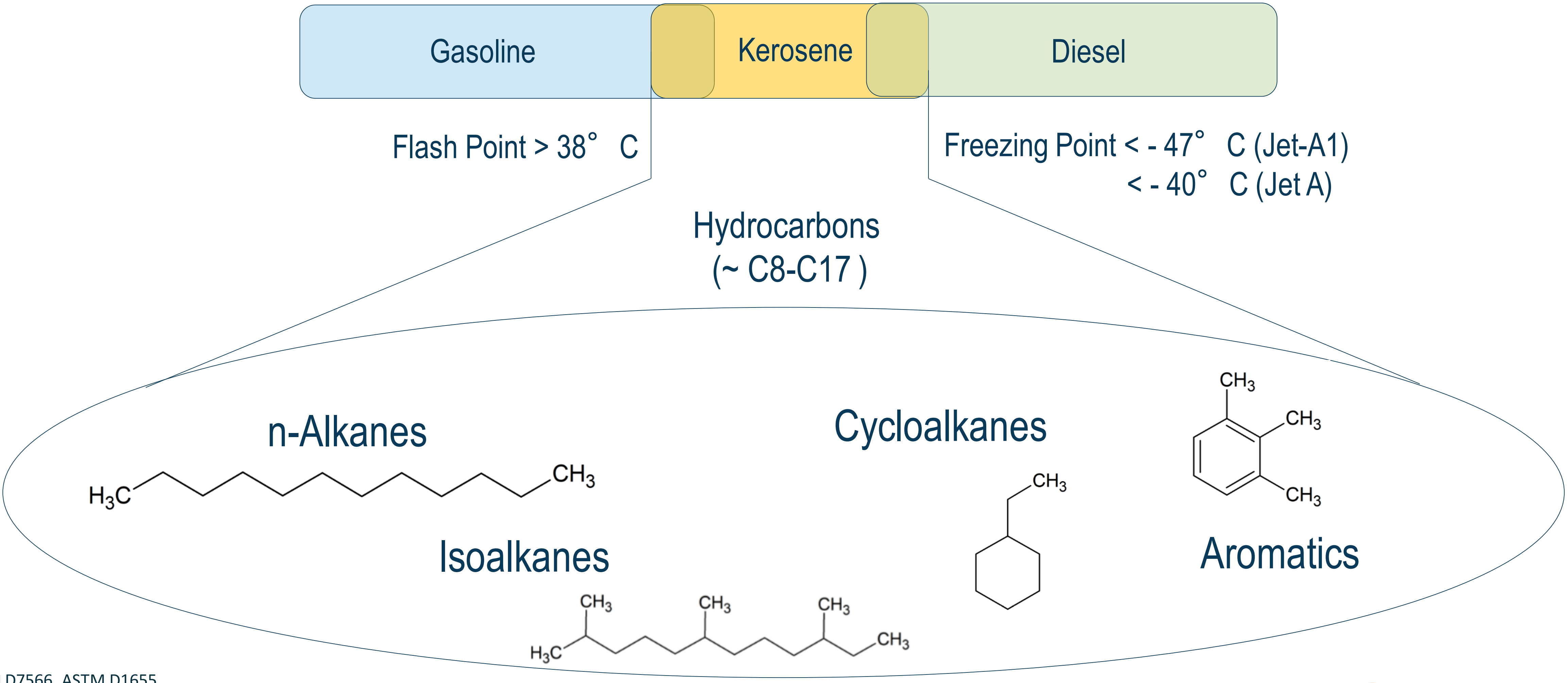






Daten: BP Statistical Review of World Energy 2020

Kerosene as turbine fuel for civil aviation (Jet-A, Jet-A1)



Gasoline

Kerosene

Diesel

Flash Point > 38° C

Freezing Point < - 47° C (Jet-A1)
< - 40° C (Jet A)

Hydrocarbons
(~ C8-C17)

n-Alkanes

Isoalkanes

Cycloalkanes

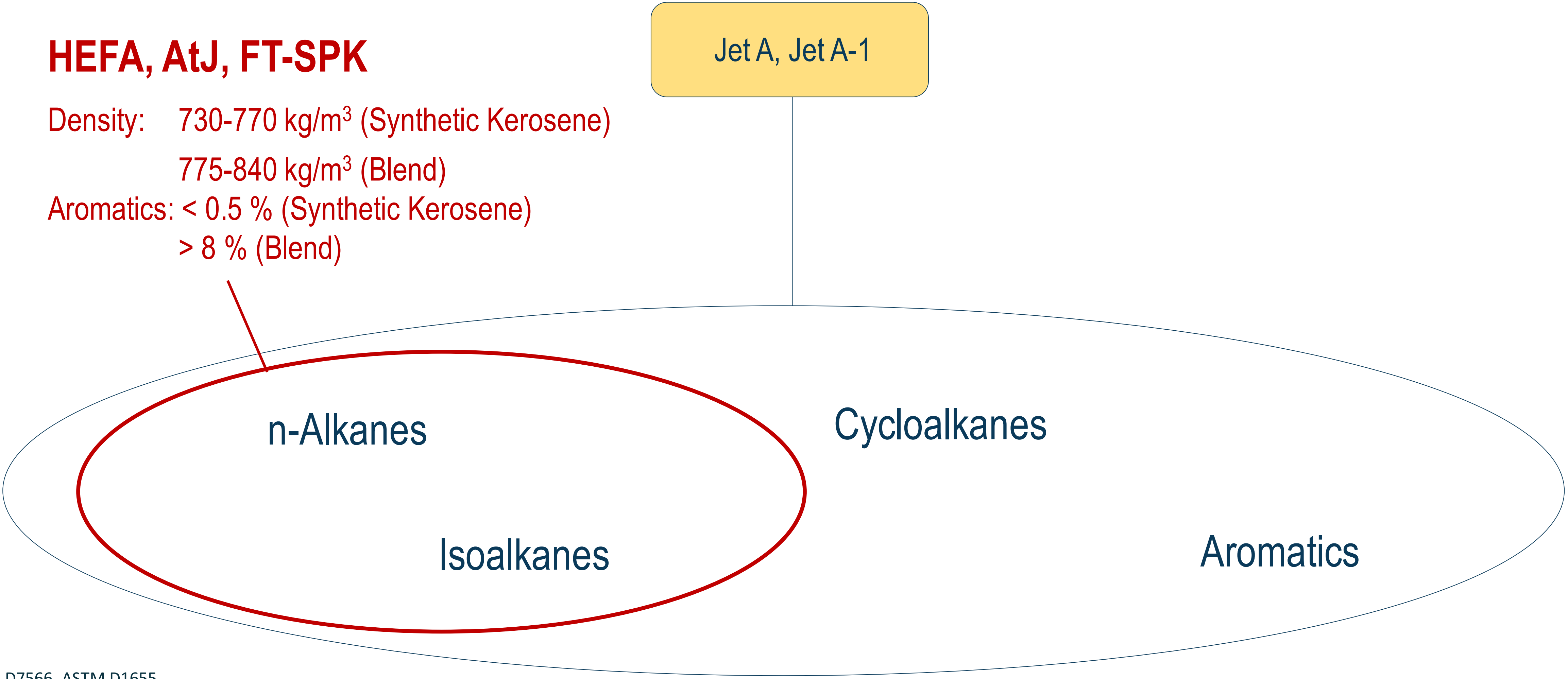
Aromatics

ASTM D7566, ASTM D1655
See www.caafi.org/focus_areas/fuel_qualification.html for description of all approved fuel pathways

Blending of synthetic kerosenes with Jet-A/Jet-A1

HEFA, AtJ, FT-SPK

Density: 730-770 kg/m^3 (Synthetic Kerosene)
775-840 kg/m^3 (Blend)
Aromatics: < 0.5 % (Synthetic Kerosene)
> 8 % (Blend)



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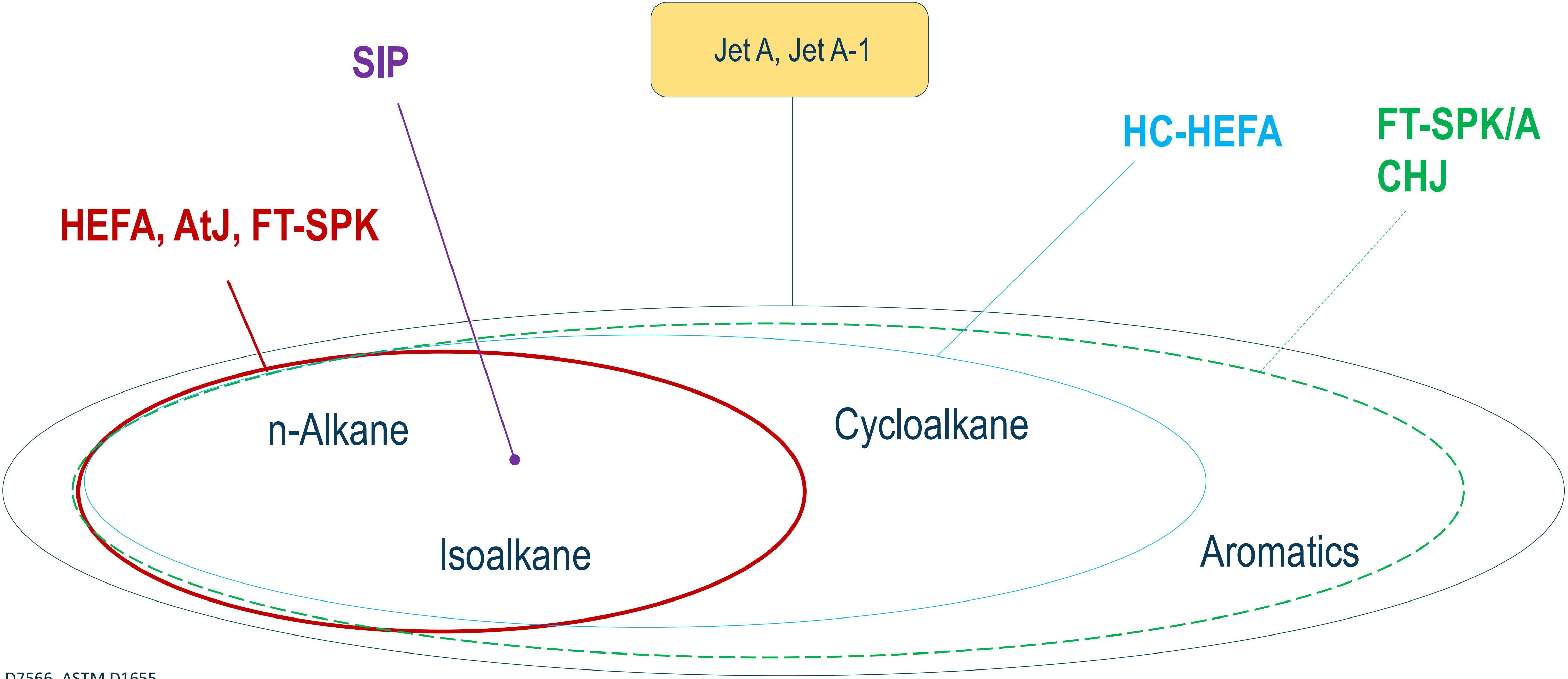


ASTM D7566, ASTM D1655
See www.caafi.org/focus_areas/fuel_qualification.html for description of all approved fuel pathways

Approval of alternative fuel pathways for civil aviation

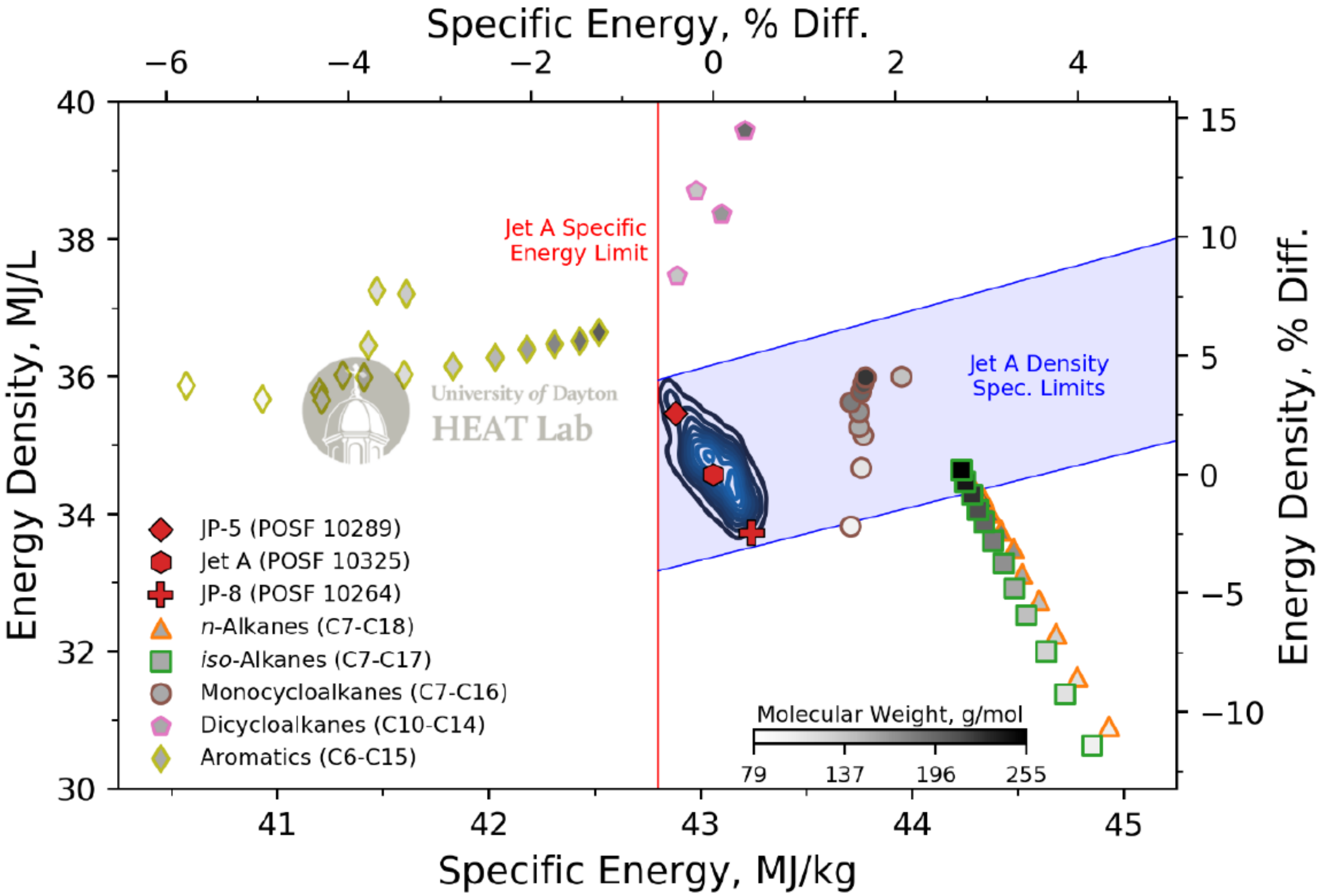
Most relevant
for e-refinery

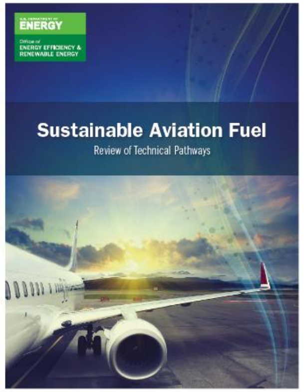
Seven alternative fuel pathways approved by ASTM D-7566:

Process	Blend ratio	Feedstock	Conversion process	Main limitation
HEFA-SPK	up to 50%	**Lipids** (e.g. plant oils, fats)	Hydroprocessing, including isomerization to adjust cold flow properties	Availability of sustainable feedstock
AtJ-SPK	up to 50%	**Sugars,** also from starch, or cellulosic feedstock	Fermentation > Dehydration of Alcohols > Oligomerisation of Alkenes	Competition for high-value intermediates
FT-SPK	up to 50%	Various organic feedstock, incl. wastes, H_2O, CO_2	Syngas production (H_2, CO, e.g. gasification), Fischer-Tropsch synthesis & refining	Cost, for some feedstock gasification & syngas clean-up
FT-SPK/A	up to 50%	See FT-SPK	FT and alkylation of light aromatics	Synthesis of soot precursors
HFS-SIP	up to 10%	See ATJ-SPK	Fermentation of sugars into farnesane (C15)	Competition with ATJ-SPK
CHJ	up to 50%	Lipids	Catalytic hydrothermolysis	Feedstock availability
HC-HEFA	up to 10%	HC, Lipids	Similar to HEFA specific to one algae species	Feedstock cost

ASTM D7566, ASTM D1655
See www.caafi.org/focus_areas/fuel_qualification.html for description of all approved fuel pathways

Typical characteristics of kerosene range hydrocarbons

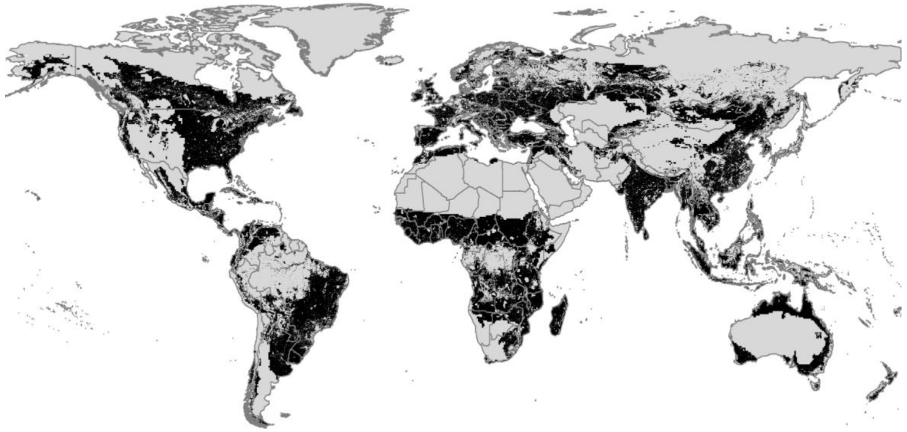




Sustainable Aviation Fuel
Review of Technical Pathways

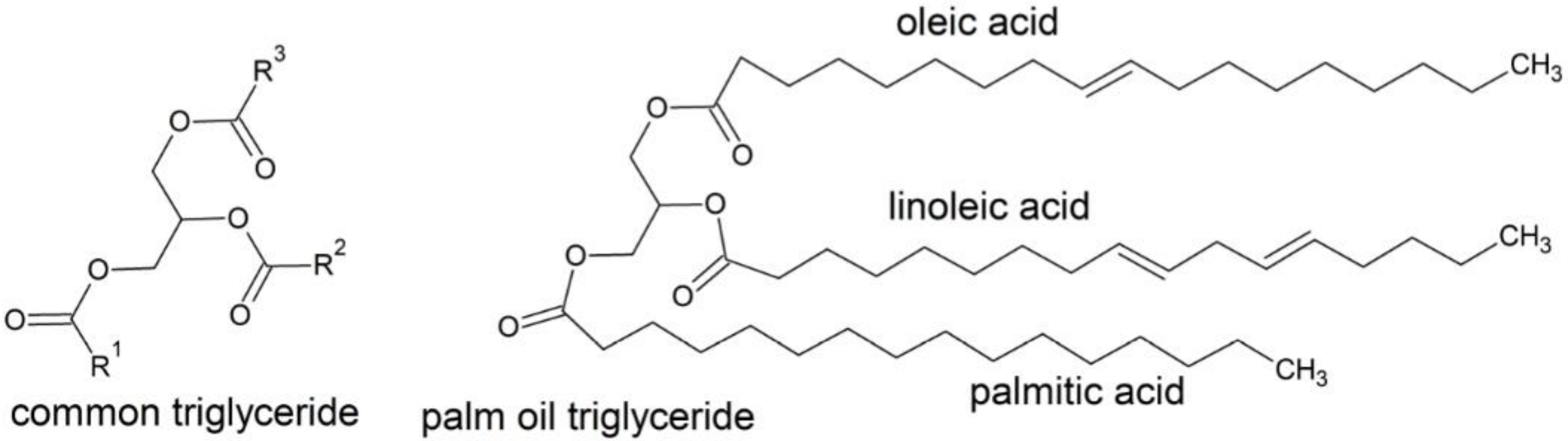
Source: Johnathan Holladay (PNNL), Zia Abdullah (NREL), and Joshua Heyne (U of Dayton), Sustainable Aviation Fuel - Review of Technical Pathways, DOE/EE–2041, Sep 2020
www.energy.gov/eere/bioenergy/downloads/sustainable-aviation-fuel-review-technical-pathways-report

Biofuels



Aviation biofuels - Current Status

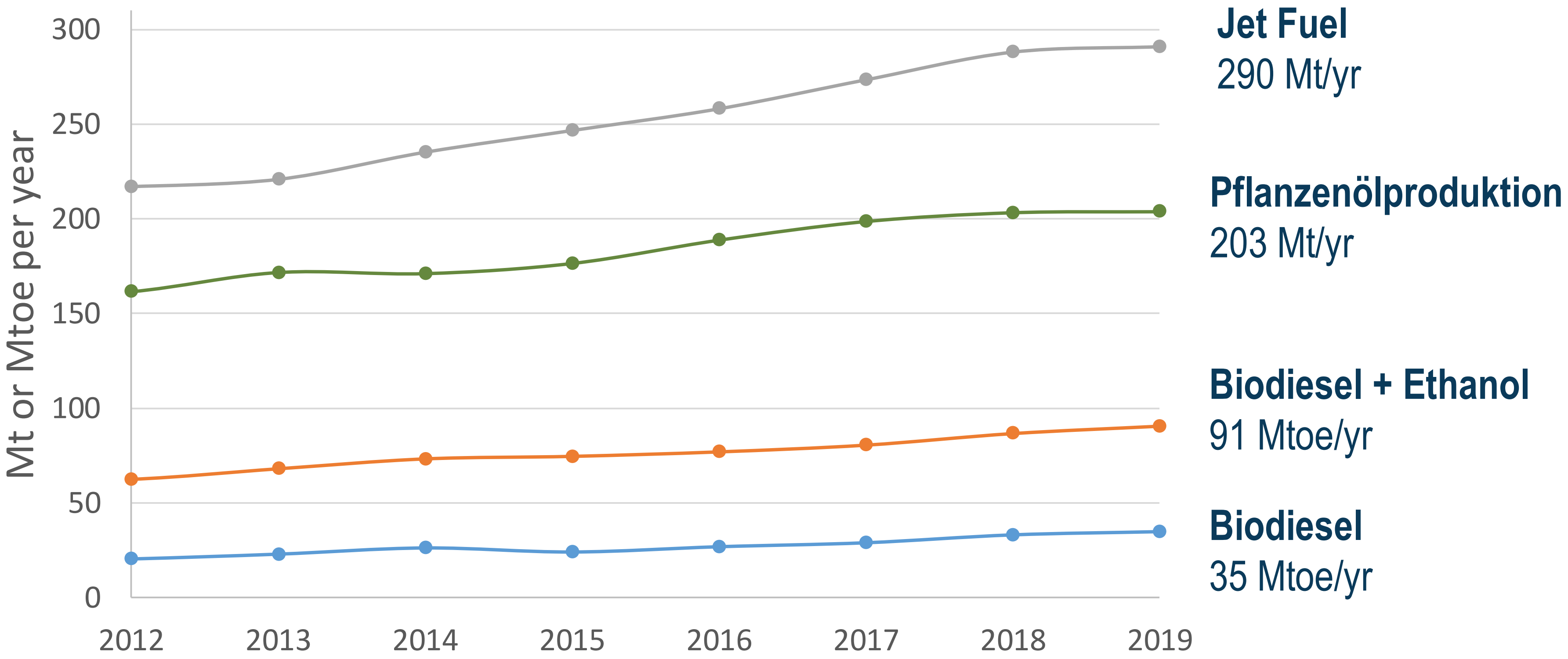
- **Growth from very low baseline (< 0.1%), almost exclusively HEFA fuels**
  - HEFA: Lipids (Plant oils, Fats) as feedstock for middle distillate production



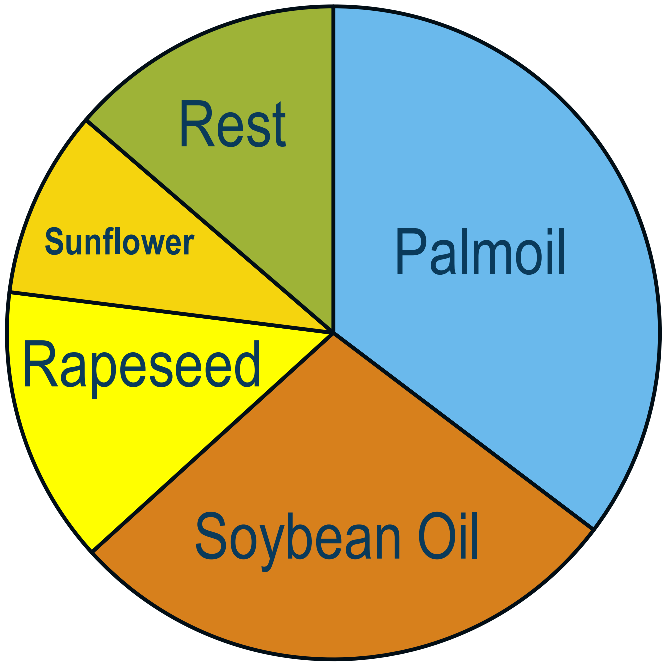
- **Relevant production capacity already exist for biodiesel production (HVO)**

Current Status: Biofuels for transportation (global)

Road transport: Ethanol and biodiesel

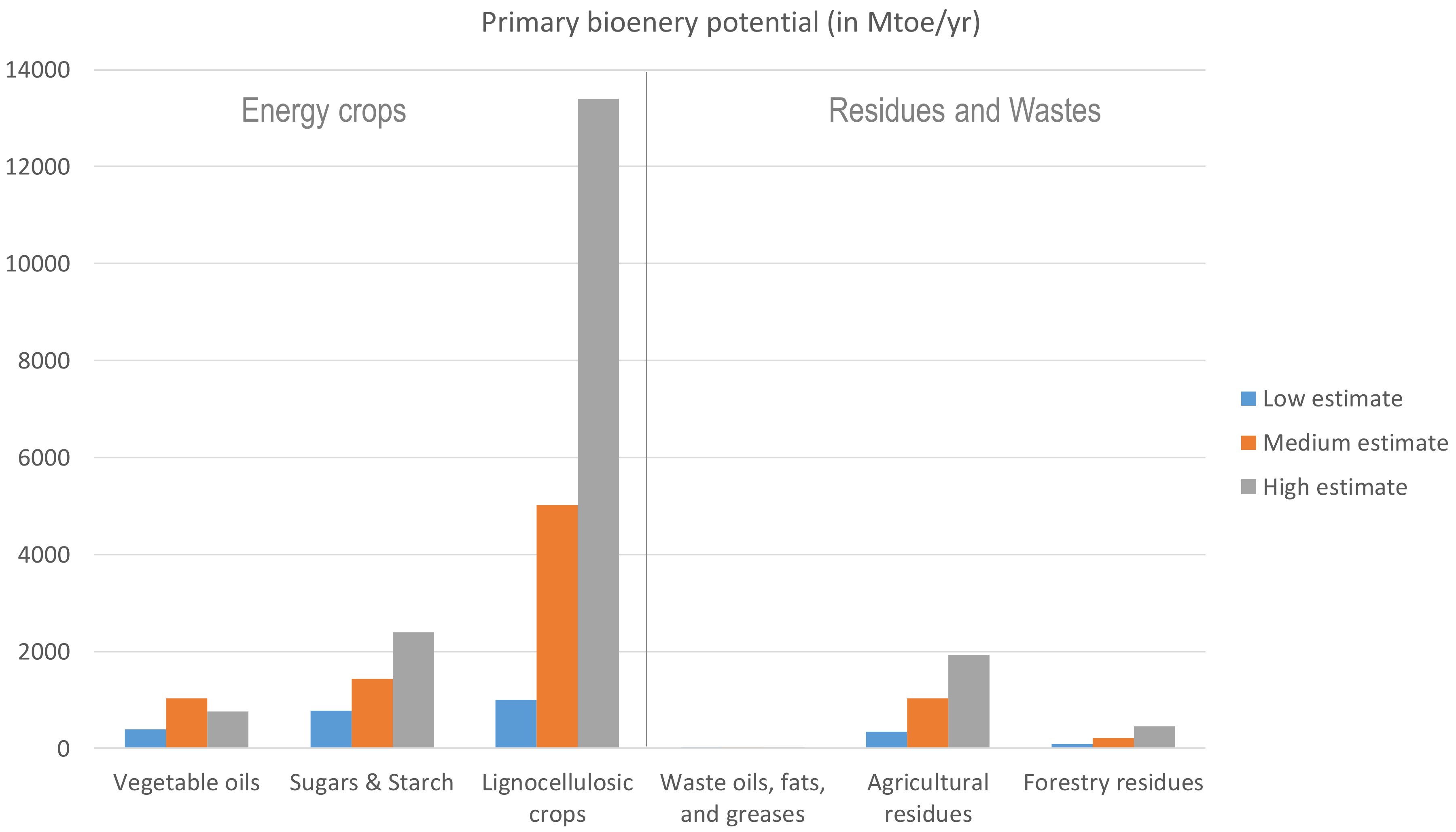


Plant oil production 2018/2019



Daten: Jet Fuel: IATA, Biodiesel und Ethanol: BP Statistical Review of World Energy 2020, Pflanzenöle: UFOP

Estimated primary bioenergy potential in 2050 (Staples 2017)



Data source: Mark D. Staples, Robert Malina, Steven R.H. Barrett, The limits of bioenergy for mitigating global life-cycle greenhouse gas emissions from fossil fuels, Nature Energy 2, 16202 (2017)

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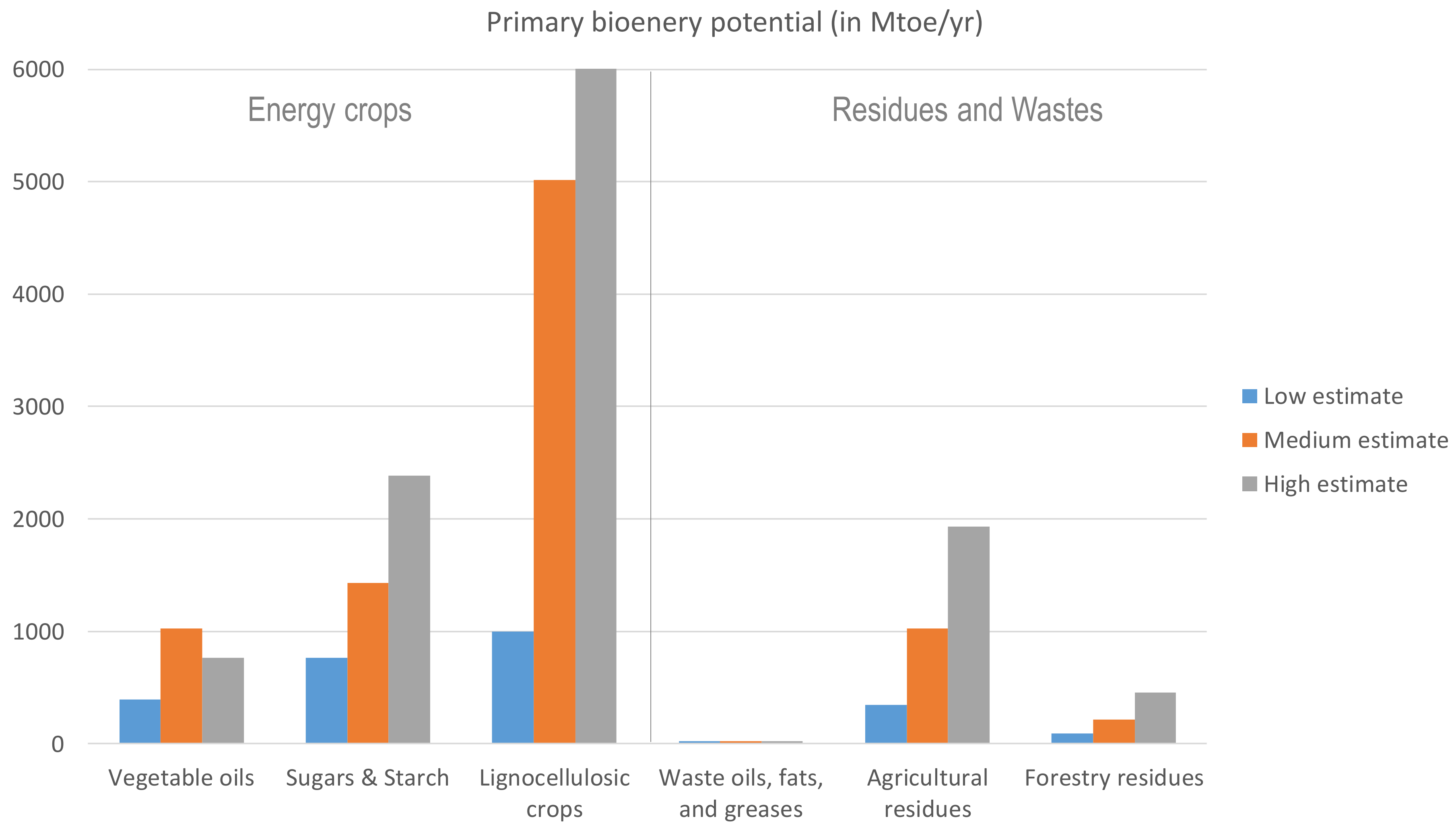
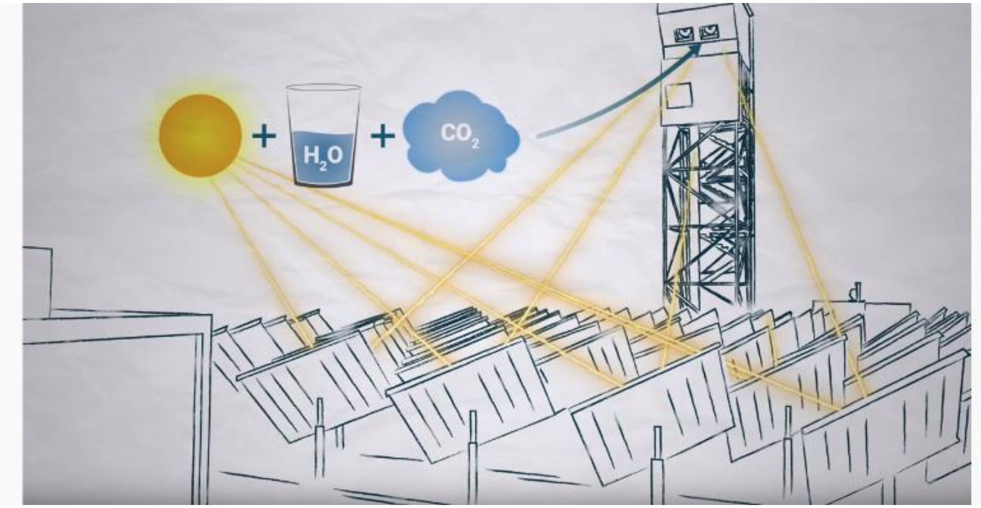


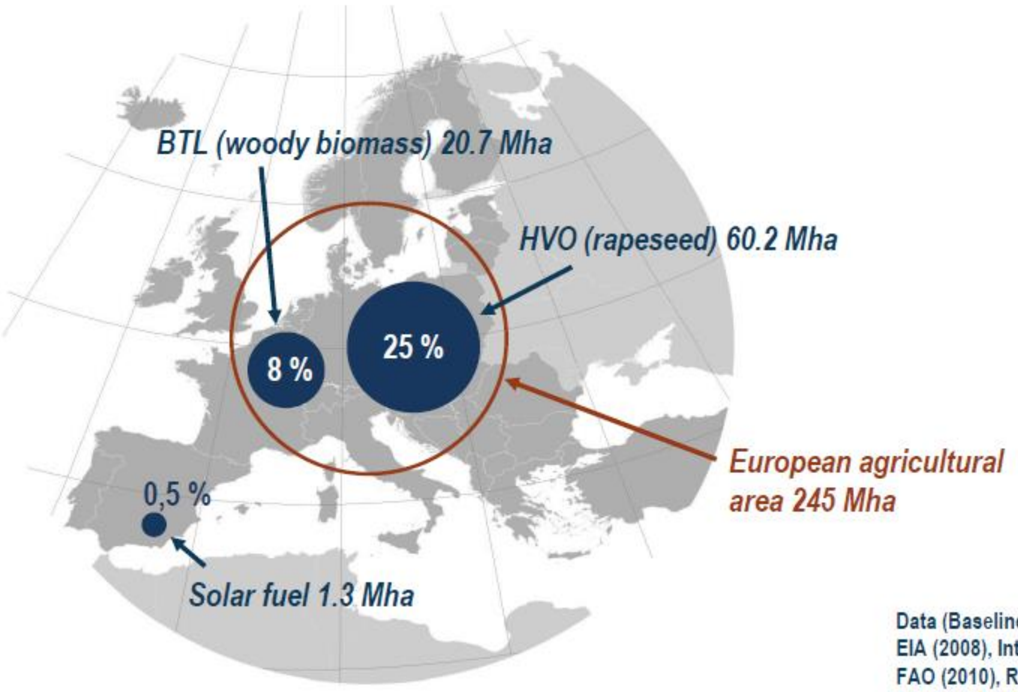
Data source: Mark D. Staples, Robert Malina, Steven R.H. Barrett, The limits of bioenergy for mitigating global life-cycle greenhouse gas emissions from fossil fuels, Nature Energy 2, 16202 (2017)

Excursion to solar fuels



Motivation: Un-lock large additional feedstock potentials

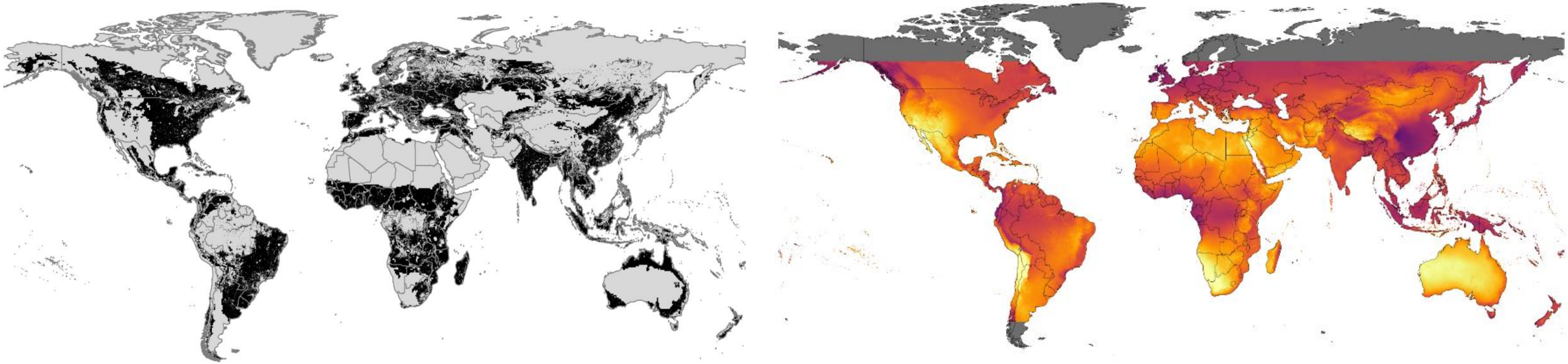
Area required for 100% substitution of European jet fuel demand



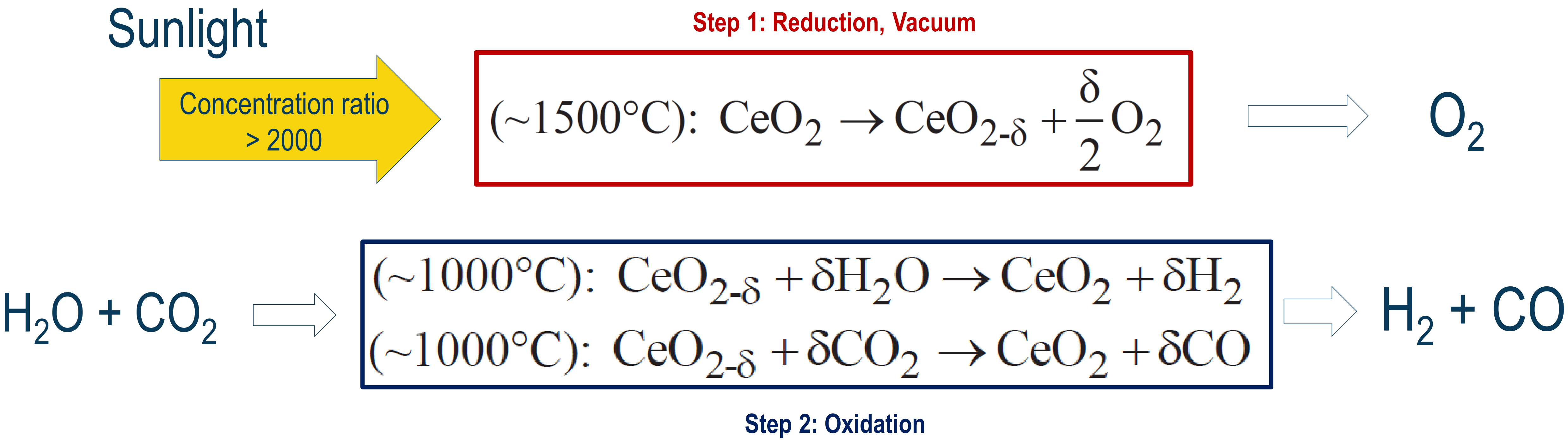
Data (Baseline 2005):
EIA (2008), International Energy Annual 2006
FAO (2010), ResourceSTAT-Land 2005
Bauhaus Luftfahrt Inventory of Energy Crops
Mha: Million Hectare

Motivation: Un-lock large additional feedstock potentials

- Solar fuels achieve high area-specific yields (compared to biofuels)
- Suitable areas are complementary to areas for agricultural production



Solar-thermochemical cycles



Sunlight

Concentration ratio > 2000

Step 1: Reduction, Vacuum

$$(\sim 1500°C):\ CeO_2 \rightarrow CeO_{2-\delta} + \frac{\delta}{2} O_2$$

O_2

$H_2O + CO_2$

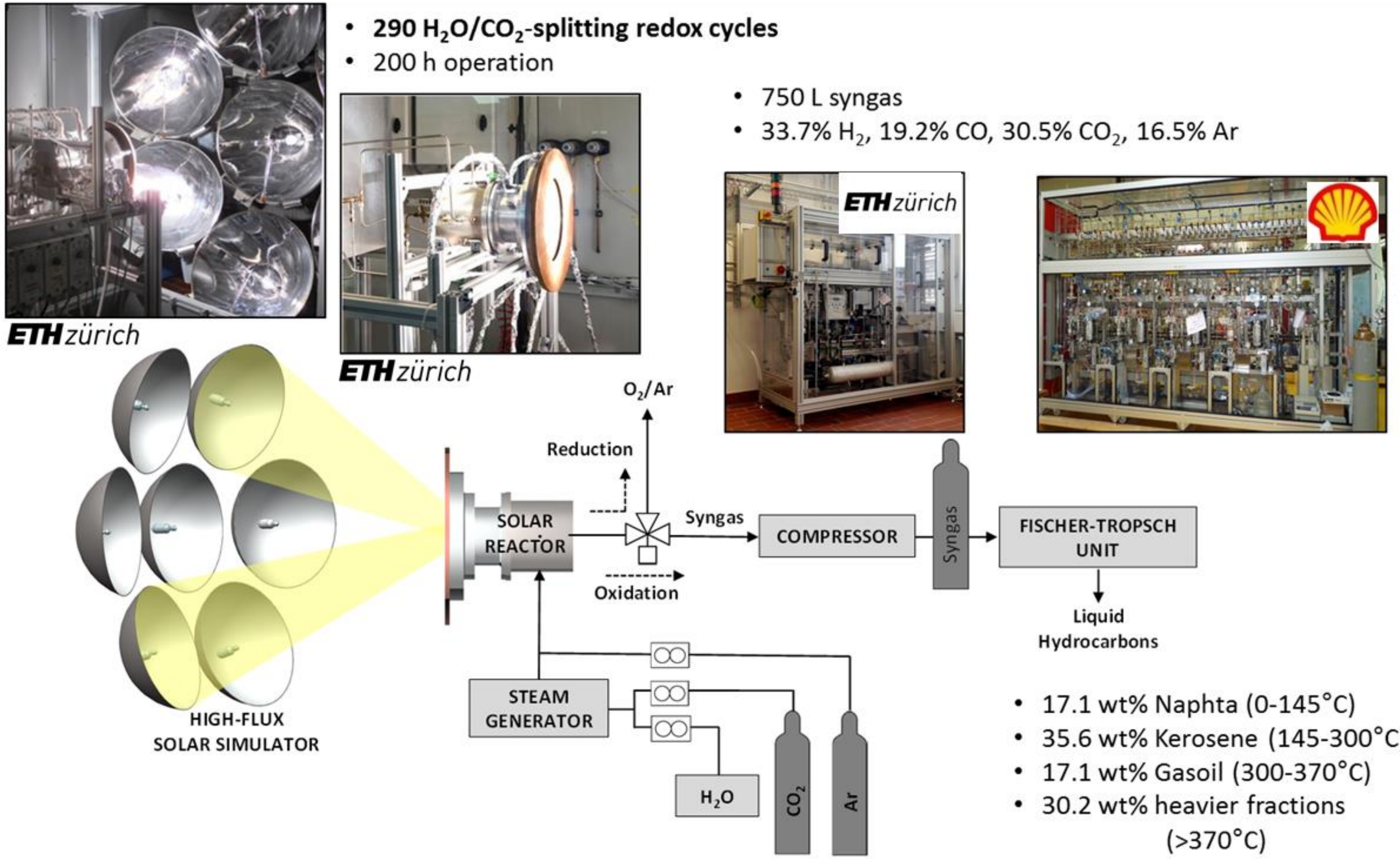
$$(\sim 1000°C):\ CeO_{2-\delta} + \delta H_2O \rightarrow CeO_2 + \delta H_2$$
$$(\sim 1000°C):\ CeO_{2-\delta} + \delta CO_2 \rightarrow CeO_2 + \delta CO$$

$H_2 + CO$

Step 2: Oxidation

Chueh, Falter, Abbott, Scipio, Furler, Haile, Steinfeld, *High-flux solar-driven thermochemical dissociation of CO_2 and H_2O using nonstoichiometric ceria*. Science, 330, 1797-1801, 2010

First solar-thermochemical kerosene, FP7 SOLAR-JET (2011-2015)



- **290 H_2O/CO_2-splitting redox cycles**
- 200 h operation

- 750 L syngas
- 33.7% H_2, 19.2% CO, 30.5% CO_2, 16.5% Ar

- 17.1 wt% Naphta (0-145°C)
- 35.6 wt% Kerosene (145-300°C)
- 17.1 wt% Gasoil (300-370°C)
- 30.2 wt% heavier fractions (>370°C)

SOLAR-JET

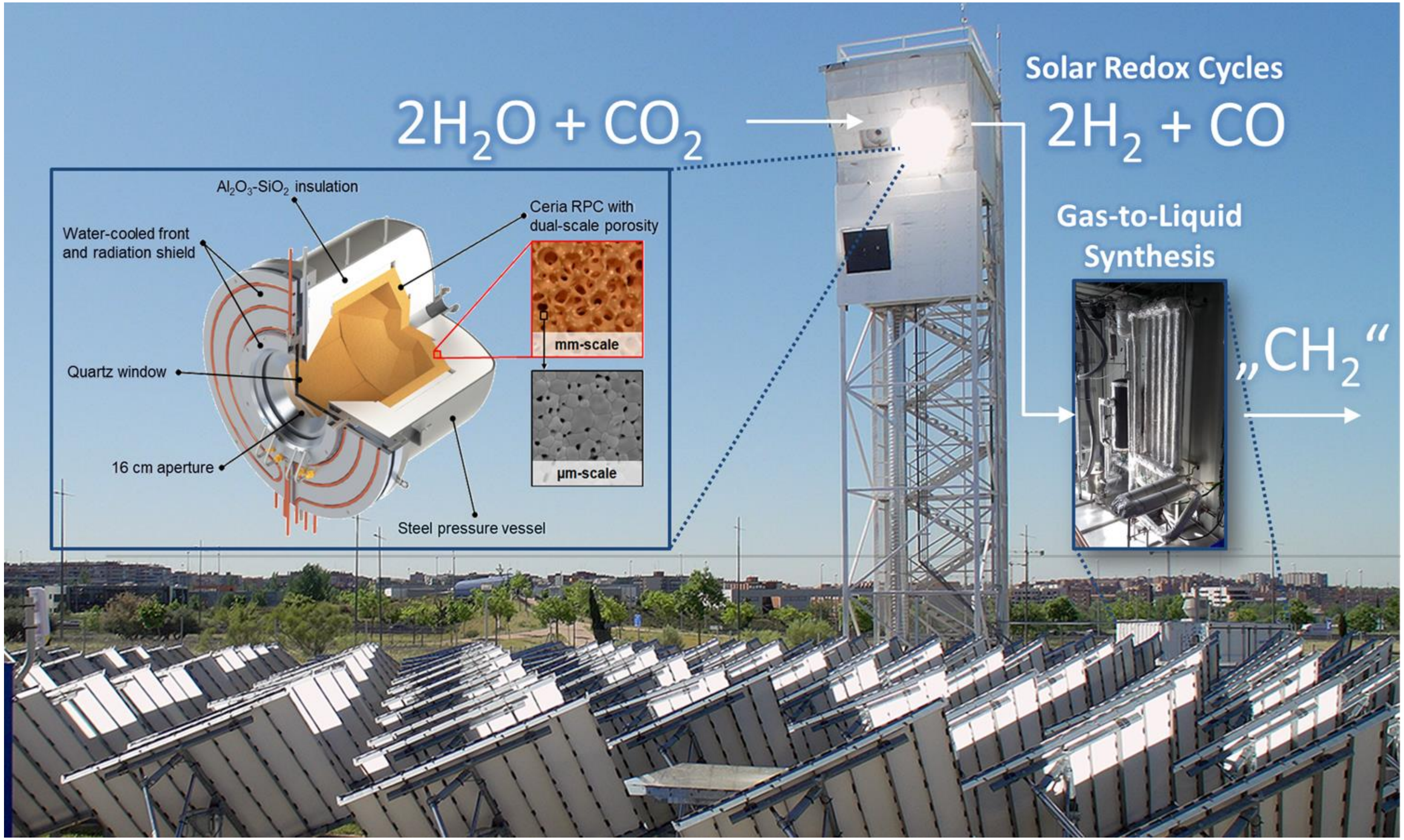
Heavy product (FT-waxes)

Light product (H_2O, hydro-carbons)

Liquids from hydrocracking (incl. kerosene)

Source: D. Marxer, *Demonstration of the entire production chain to renewable kerosene via solar-thermochemical splitting of H_2O and CO_2*, Energy & Fuels, 2015;
P. Furler, *Solar Kerosene from H_2O and CO_2*, AIP Conference Proceedings 1850, 100006 (2017)

SUN-to-LIQUID (2016-2019)



$2H_2O + CO_2$ →

Solar Redox Cycles

$2H_2 + CO$

Gas-to-Liquid Synthesis

„CH_2“ →

SUN to LIQUID
Fuels from concentrated sunlight

imdea energy institute

ETH zürich

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

HYGEAR COST-EFFECTIVE GAS SUPPLY

Bauhaus Luftfahrt Neue Wege.

ABENGOA

ARTTIC

www.sun-to-liquid.eu

SUN-to-LIQUID Projektvideo:

www.youtube.com/watch?v=laUe23OhHXg

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654408

Design & construction of demo plant

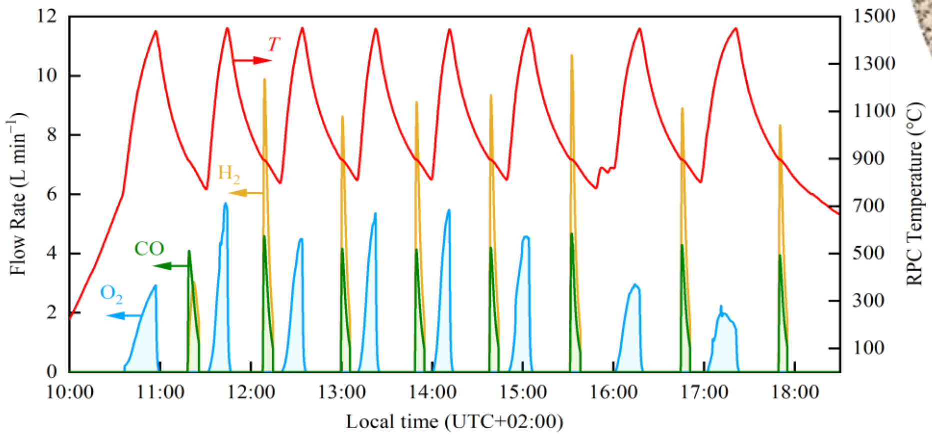
institute imdea energy

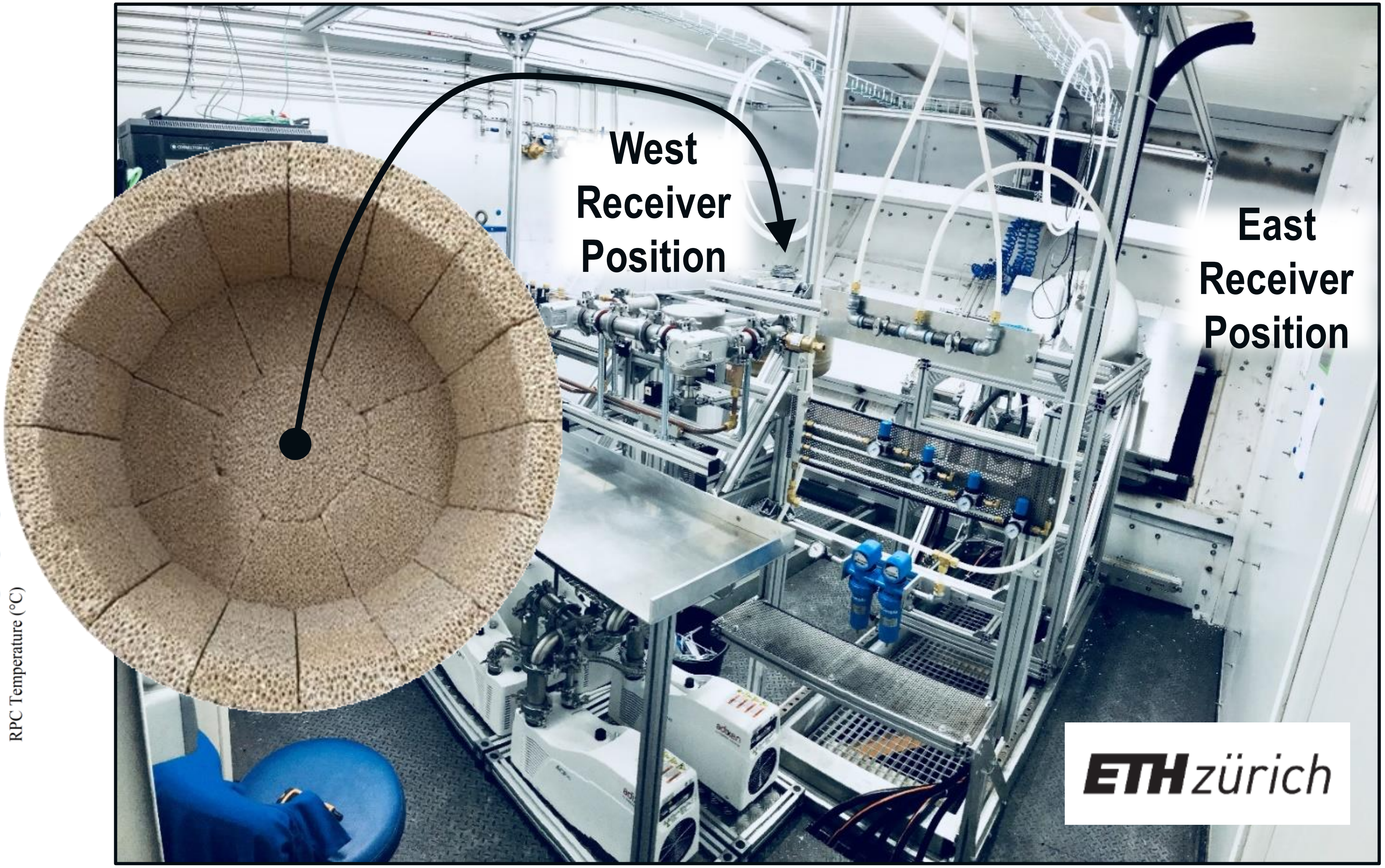
SUN to LIQUID
Fuels from concentrated sunlight

Picture source: SUN-to-LIQUID, IMDEA, Erik Koepf

Bauhaus Luftfahrt
Neue Wege.

Experimental platform, solar reactor

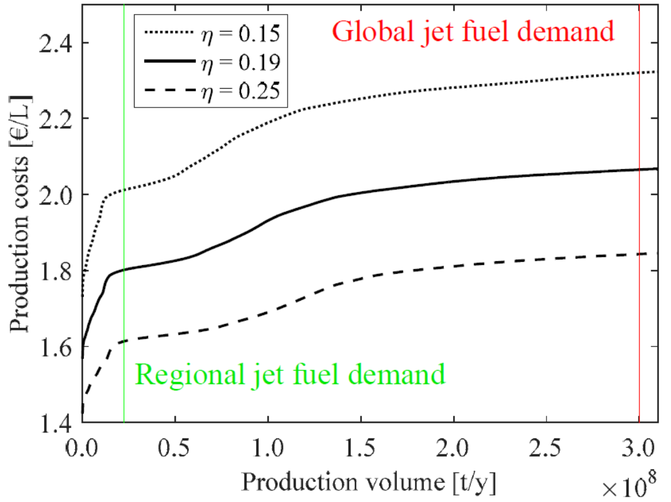


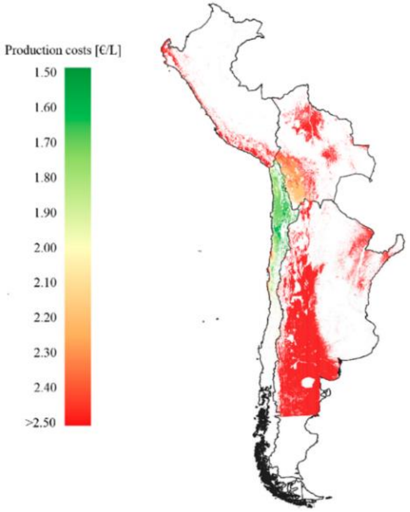


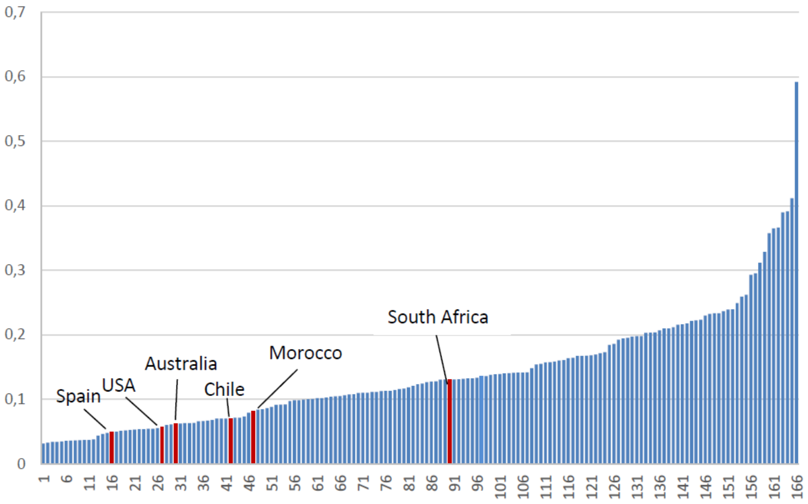
Source: E. Koepf et al, *Liquid Fuels from Concentrated Sunlight: Development and Integration of a 50 kW Solar Thermochemical Reactor and High Concentration Solar Field for the SUN-to-LIQUID Project*, SolarPACES2018, Stefan Zoller, Doctoral Thesis, ETH Zurich 2020

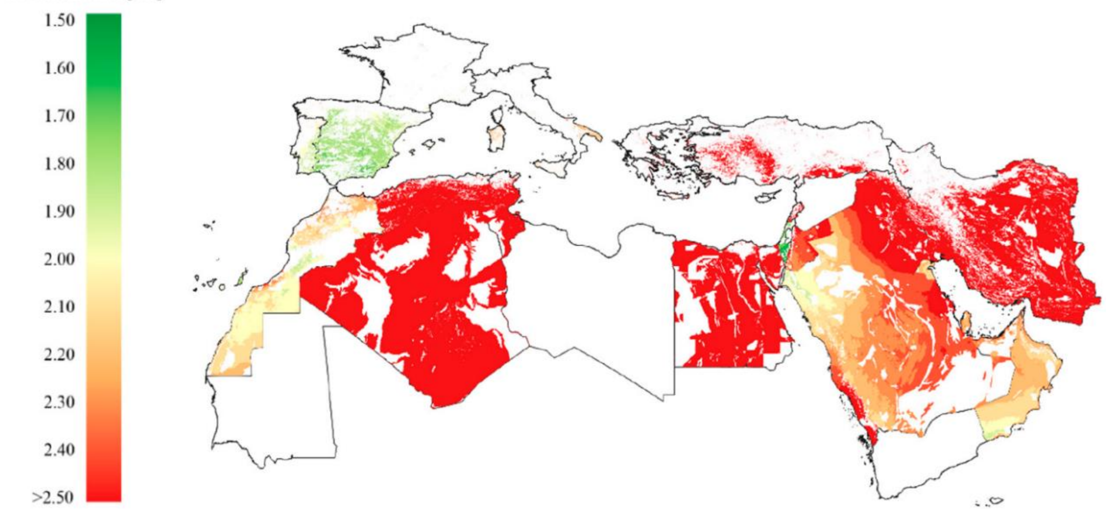
Geographical production potential

- **Production cost model highly sensitive to**
  - Solar resource, solar reactor efficiency, investment cost
  - Regional parameters: Capital cost assumptions, labour rates
- **Single countries have the potential to meet global jet fuel demand**



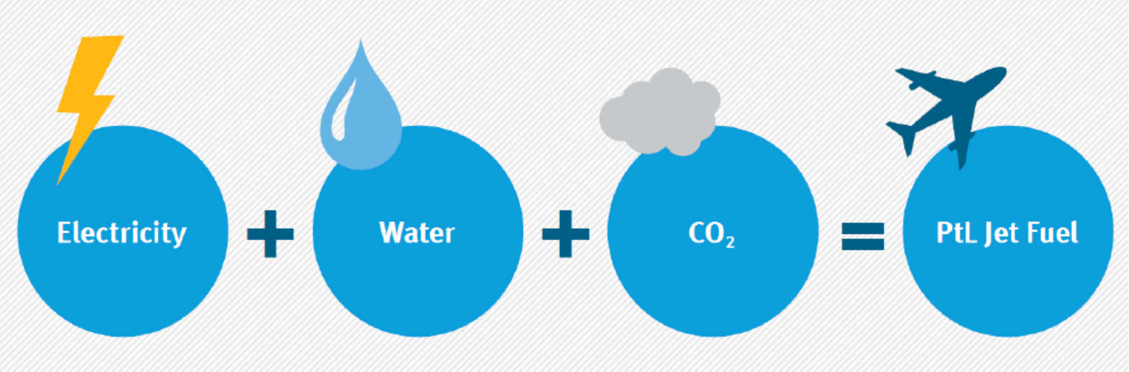




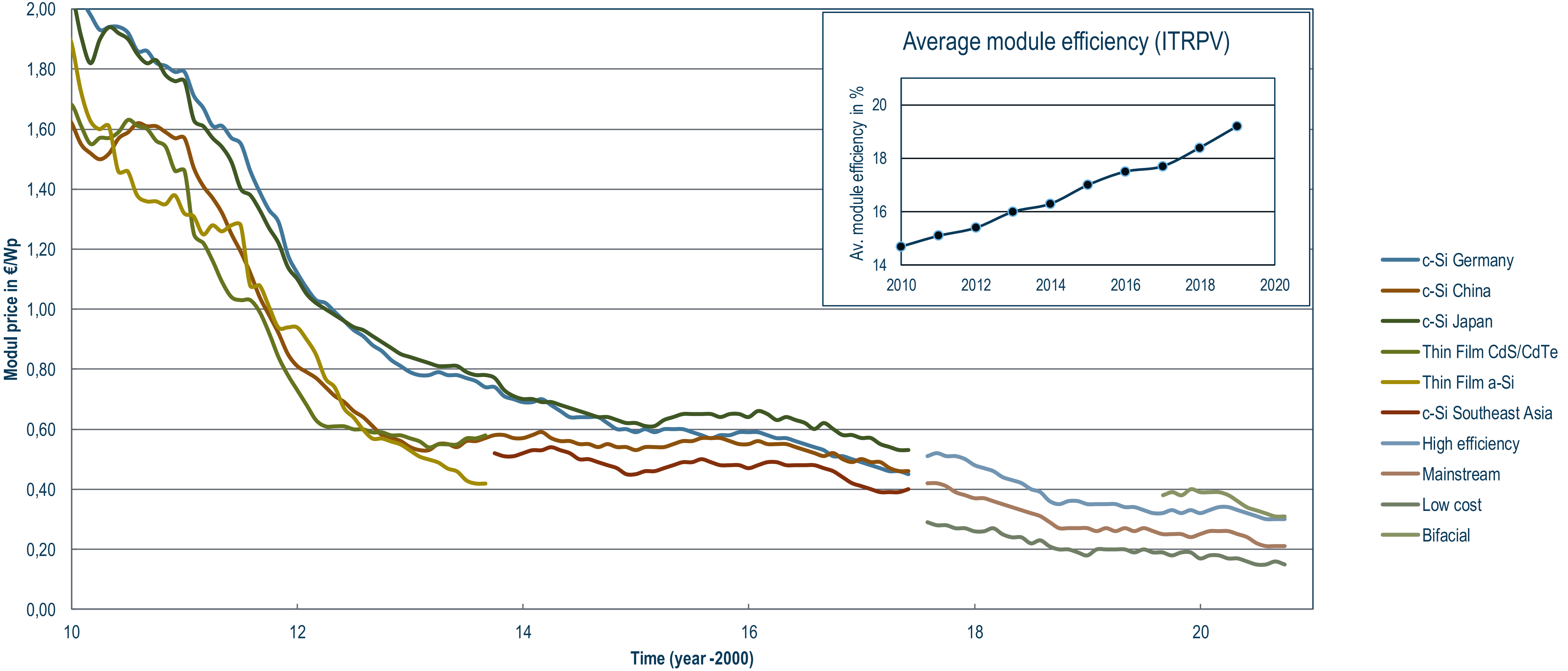


Falter, Scharfenberg, Habersetzer, *Geographical potential of solar thermochemical jet fuel production*, Energies, Vol 13(4), 2020 www.mdpi.com/1996-1073/13/4/802

Electricity based fuels

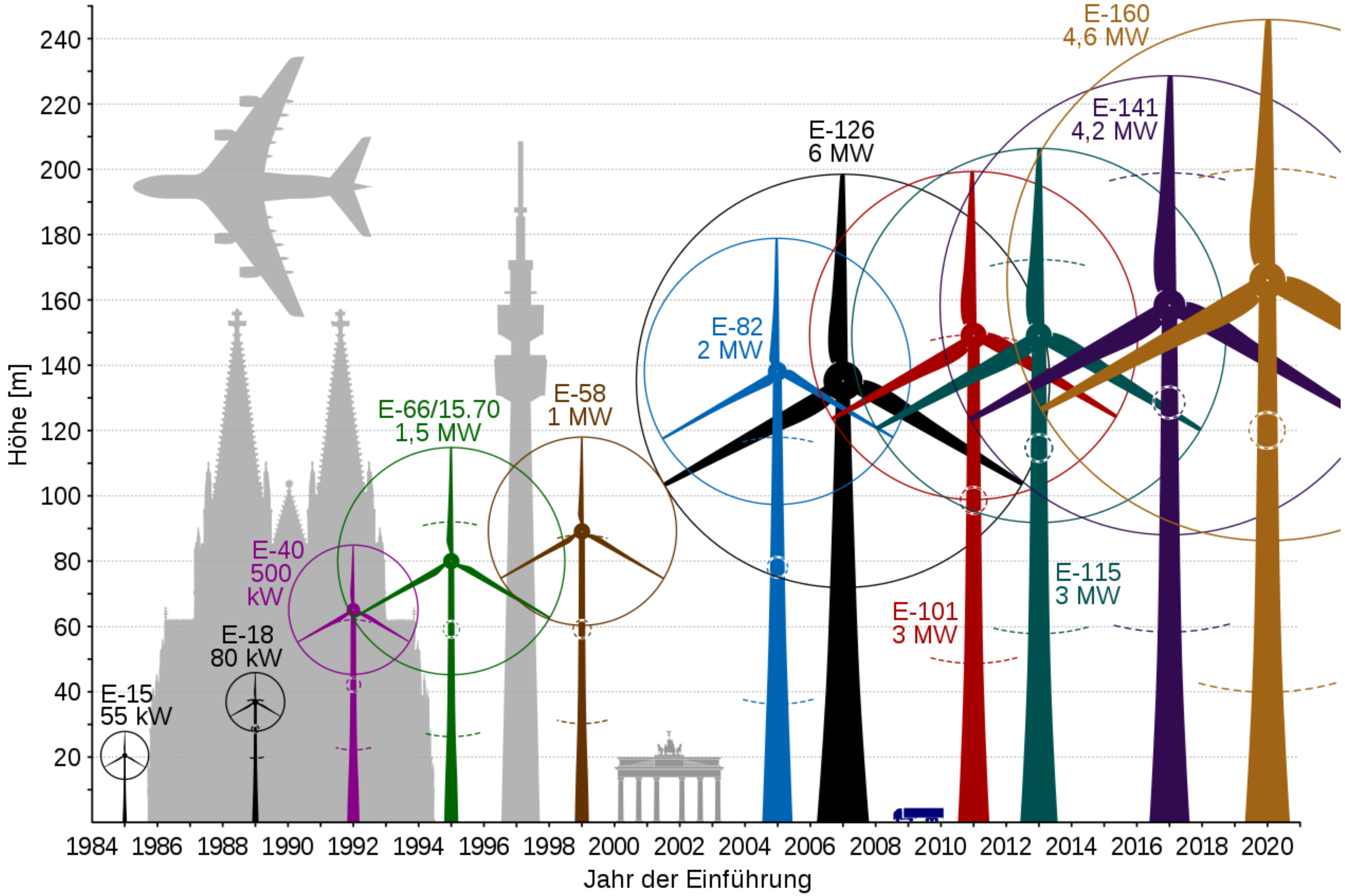


Falling cost for renewable electricity: PV Module prices



Data: www.solarserver.de/pv-modulpreise; International Technology Roadmap for Photovoltaiks (ITRPV), 2019 Results, April 2020

Technological progress (Onshore wind)



Airbus A350-900:

Fuel Capacity: 138.000 L

Fueling 1x per day

corresponds to

52 x E-160 4,6 MW

(Assumptions: CF=50%, η_{PtL}= 0.45%)

https://de.wikipedia.org/wiki/Enercon#/media/Datei:EnerconSizes_de.svg https://de.wikipedia.org/wiki/Airbus_A350#/media/Datei:A350_First_Flight_-_Low_pass_02.jpg

Electricity demand for substitution with PtL in Germany

Electricity demand for substitution with PtL in Germany (Jet Fuel: 11.8 Mt_{jet} in 2019)	
2 % PtL Jet Fuel (Jet Fuel optimized)	9 – 12 TWh
Renewable electricity generation (2019)	243 TWh (Wind: 126, PV: 47)
PtL Jet Fuel (Stochiometric)	283 – 354 TWh
PtL Jet Fuel (Jet Fuel optimized)	**472 – 590 TWh**
Total electricity generation (2019)	611 TWh
PtL Jet Fuel (Balanced product spectrum)	944 – 1180 TWh
Wind and PV Potential (FfE)	2074 TWh (Wind: 1500, PV: 574)
Consumption of crude oil products	3185 – 3981 TWh

Data basis for electricity generation potentials: http://opendata.ffe.de/eem2019

Comparably low resource demand for e-fuels

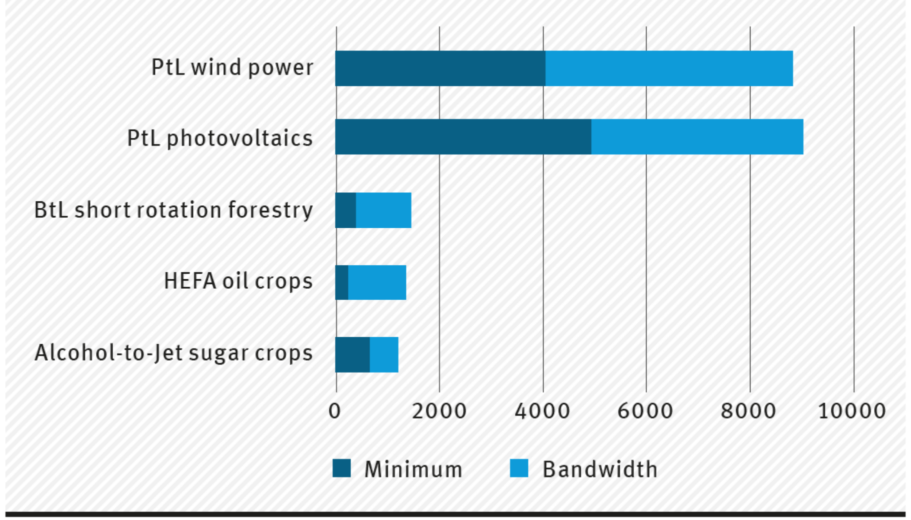
http://bit.ly/2cowOyf

ludwig bölkow
systemtechnik

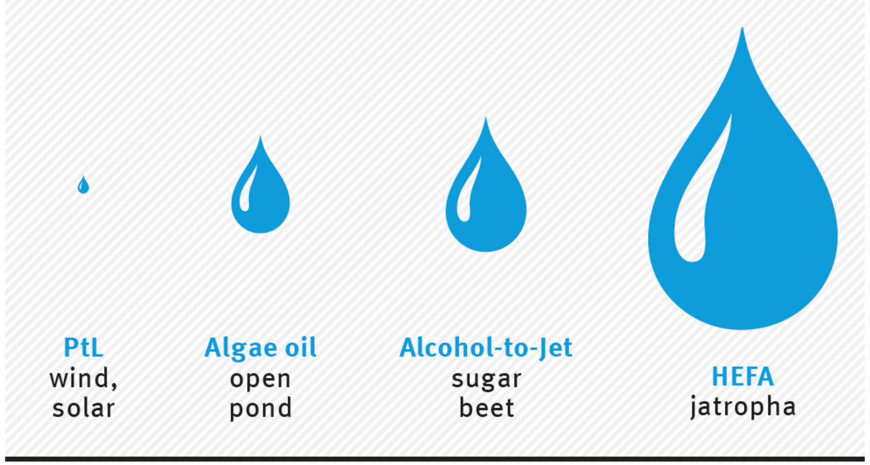
Despite enormous demand of renewable electricity:

- Much higher area specific yield than energy crops
- Very low water consumption

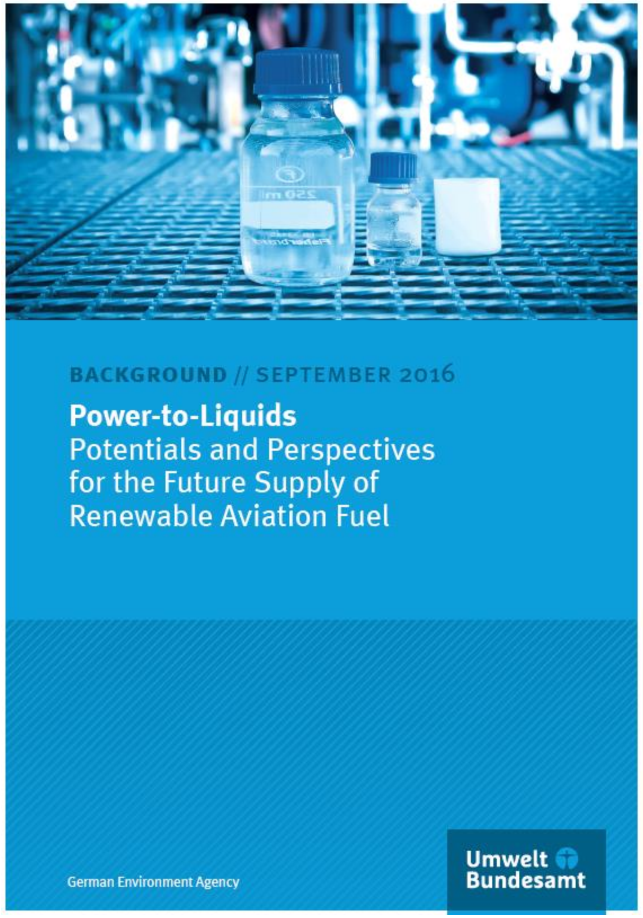
Achievable air mileage for an A320neo per ha of land (km/(ha·yr))



PtL water demand compared to selected biofuels
(volume representation, PtL water demand ~ 1.4 $L_{H_2O}/L_{jet fuel}$)



Source: LBST / BHL, 2016



BACKGROUND // SEPTEMBER 2016

Power-to-Liquids
Potentials and Perspectives
for the Future Supply of
Renewable Aviation Fuel

German Environment Agency

Umwelt Bundesamt

Sources: LBST and BHL: *Power-to-Liquids – Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*, Background Paper 2016 http://bit.ly/2cowOyf, P. Schmidt, V. Batteiger, A. Roth, W. Weindorf, T. Raksha, *Power-to-Liquids as Renewable Fuel Option for Aviation: A Review*, Chem. Ing. Tech. 2018, 90, No. 1–2, 127

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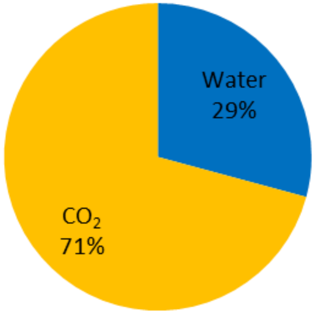
Neue Wege.

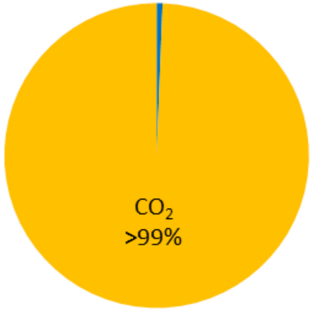
Impact of feedstock provision H_2O and CO_2

Relative impact of providing 1 mol H_2O and 1 mol CO_2

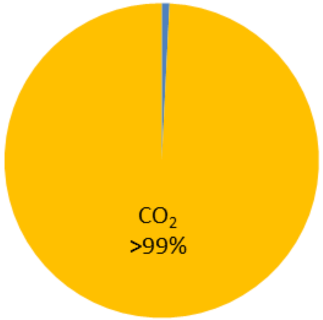
- Based on net reaction: $H_2O + CO_2 \rightarrow$ “CH_2” + 3/2 O_2 (“CH_2”: liquid hydrocarbons)



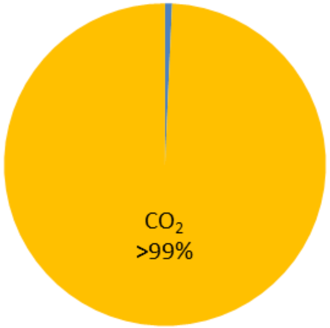
Weight
(stoichiometric)



Electricity demand
Seawater desalination vs.
CO_2 capture



Feedstock cost
Seawater desalination vs.
CO_2 capture



GHG emissions
Seawater desalination vs.
CO_2 capture

- Main challenge: CO_2 provision, impact of water provision small

Sources and main assumptions:
Seawater desalination: Elimelech, The Future of Seawater Desalination: Energy, Technology, and the Environment, Science 2011, 333, 712
Industrial CO_2 provision: Cost \$40/tCO_2, Supekar, Market-Driven Emissions from Recovery of Carbon Dioxide Gas, Environ. Sci. Technol., 2014, 48, 14615

Sustainability of PtL Fuels: The role of electricity feed

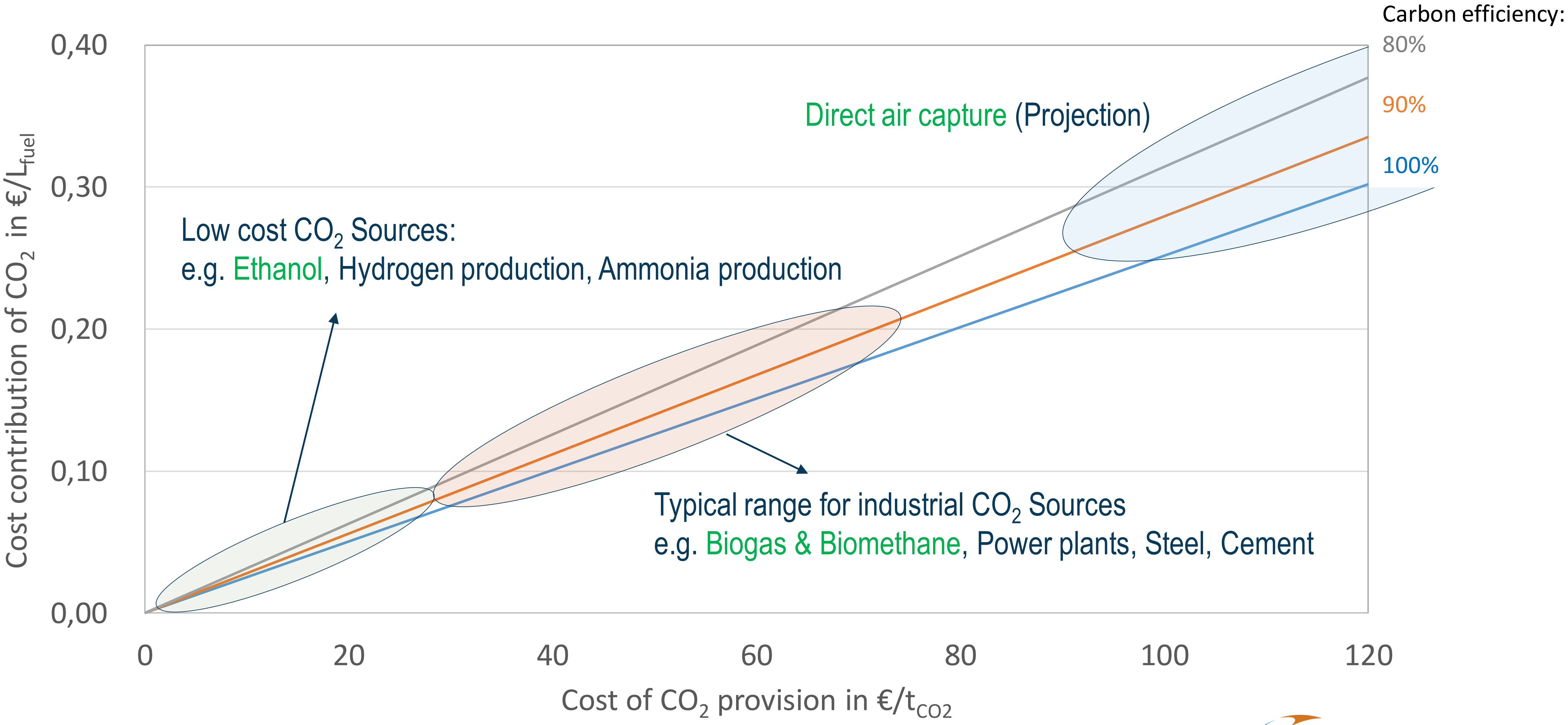
- **PtL fuels from grid electricity not yet sustainable in most EU member states**
- **Use of additional renewable electricity necessary**
  - Table accounts for electricity feed only (excludes further LC emission, CO_2 source etc.)

GHG emissions from EU electricity generation in 2020 and minimum requirements for PtL production (in g_{CO2}/kWh_{el})

Coal	Poland	Natural gas	Netherlands	Germany	Spain	PtL Break even	Denmark	Austria	Finland	France	PtL RED II	Sweden
> 800	**724**	**> 400**	**318**	**301**	**192**	**~125**	**116**	**86**	**67**	**55**	**38**	**13**
Higher GHG emissions than conventional jet fuel ←							**Potential GHG reduction** →					

Sources: LBST and BHL: *Power-to-Liquids – Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*, Background Paper 2016 http://bit.ly/2cowOyf,
P. Schmidt, V. Batteiger, A. Roth, W. Weindorf, T. Raksha, *Power-to-Liquids as Renewable Fuel Option for Aviation: A Review*, Chem. Ing. Tech. 2018, 90, No. 1–2, 127
Agora Energiewende: The European Power Sector in 2020 www.agora-energiewende.de/en/publications/the-european-power-sector-in-2020/

Further requirement for PtL: Sustainable CO_2 Source



Direct air capture (Projection)

Low cost CO_2 Sources:
e.g. Ethanol, Hydrogen production, Ammonia production

Typical range for industrial CO_2 Sources
e.g. Biogas & Biomethane, Power plants, Steel, Cement

Typical cost structure of PtL fuels

- **PtL production cost are much higher than conventional jet fuel prizes**
  - Dominant cost items: Electricity and Electrolysis
  - Further contributions: Fuel synthesis and CO_2 provision

Cost item	Cost
Electricity generation 3 ct/kWh, 50% energy conversion efficiency, 10 kWh/L	0.6 €/L
Electrolysis capex 600 €/kW, CF = 0.6, 5% acc, 5% O&M	0.3 €/L
FT 50000 €/bpd, CF = 0.9, 5% acc,	< 0.1 €/L
CO_2 provision 40 $/tCO2, 90% carbon efficiency	0.1 €/L
Sum of selected cost items	**1.1 €/L**

Cost item	Cost
Electricity generation 5 ct/kWh, 50% energy conversion efficiency, 10 kWh/L	1 €/L
Electrolysis capex 1000 €/kW, CF = 0.3, 5% acc, 5% O&M	1 €/L
FT 100000 €/bpd, CF = 0.5, 5% acc,	0.3 €/L
CO_2 provision 100 $/tCO2, 90% carbon efficiency	0.3 €/L
Sum of selected cost items	**2.60 €/L**

PtL Project: PowerFuel (2018-2021)

Bundesministerium
für Wirtschaft
und Energie

Demonstration of a complete PtL process chain at KIT, Karlsruhe

- From CO_2 air capture to FT-SPK blend component to Jet A-1
- Load-flexible operation (micro-structured Fischer-Tropsch reactor)

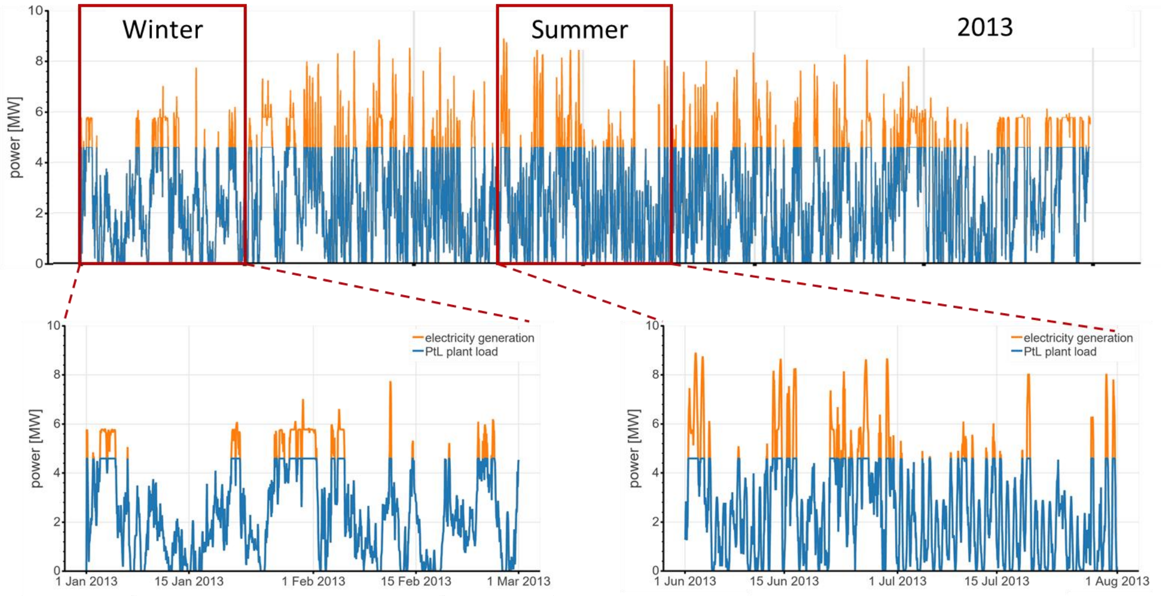
Quelle: R. Dittmeyer KIT/IMVT

Energy Lab 2.0 am Standort des KIT, Quelle: INERATEC

Insights of system analyses work package

Optimization of PtL plant with respect to renewable power profiles

- Favourable locations in Germany (and EU) are wind dominated
- Still, there is a benefit of adding PV but the cost advantage tends to be small
- No significant gas storage (H_2) for wind
- Day-night storage for PV
- Peaks of the power profile capped to increase capacity factor of the downstream systems

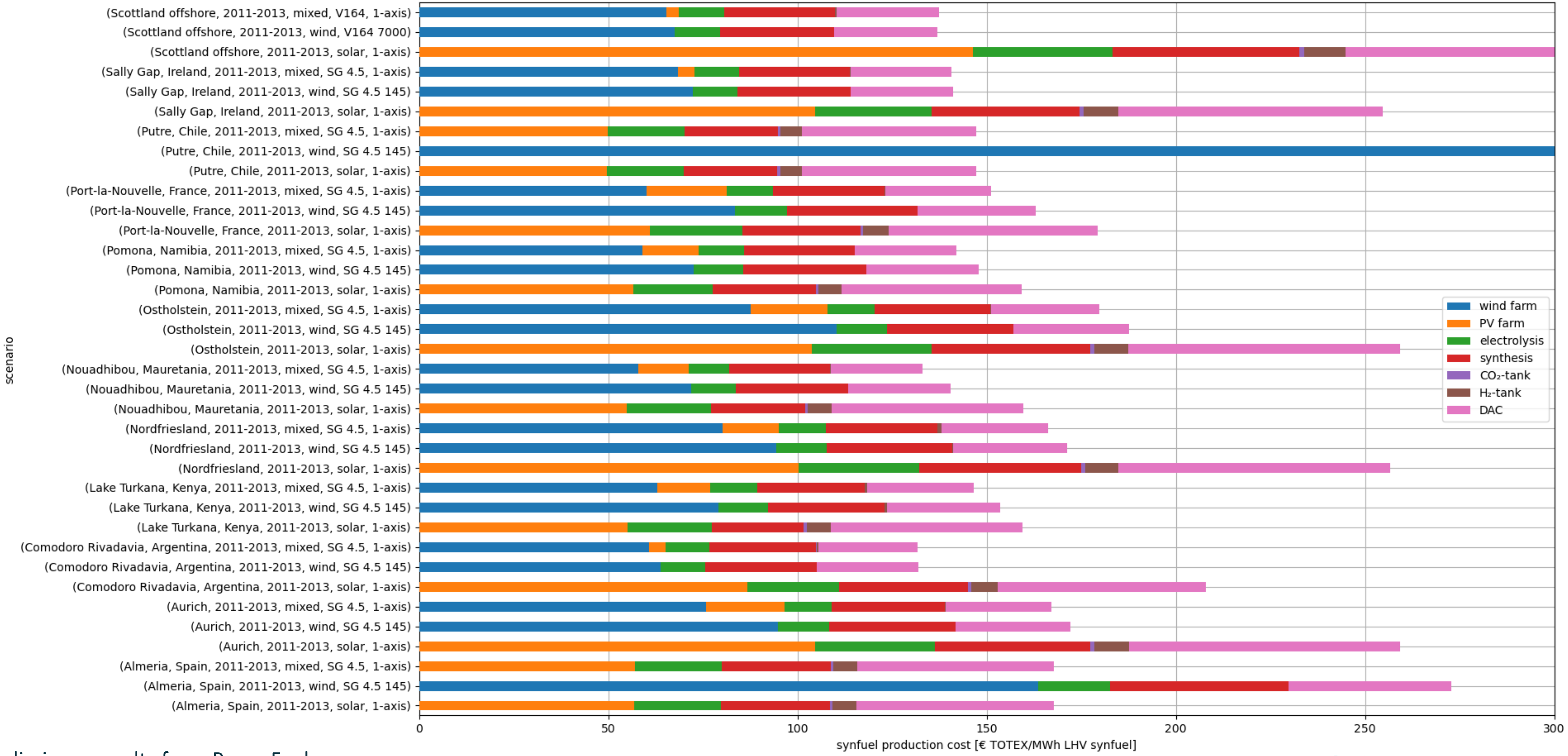


Winter, wind dominated

Summer, solar & wind

B. Portner, optimized PV/Wind hybrid for PtL production in northern Germany

Analyses for selected international sites

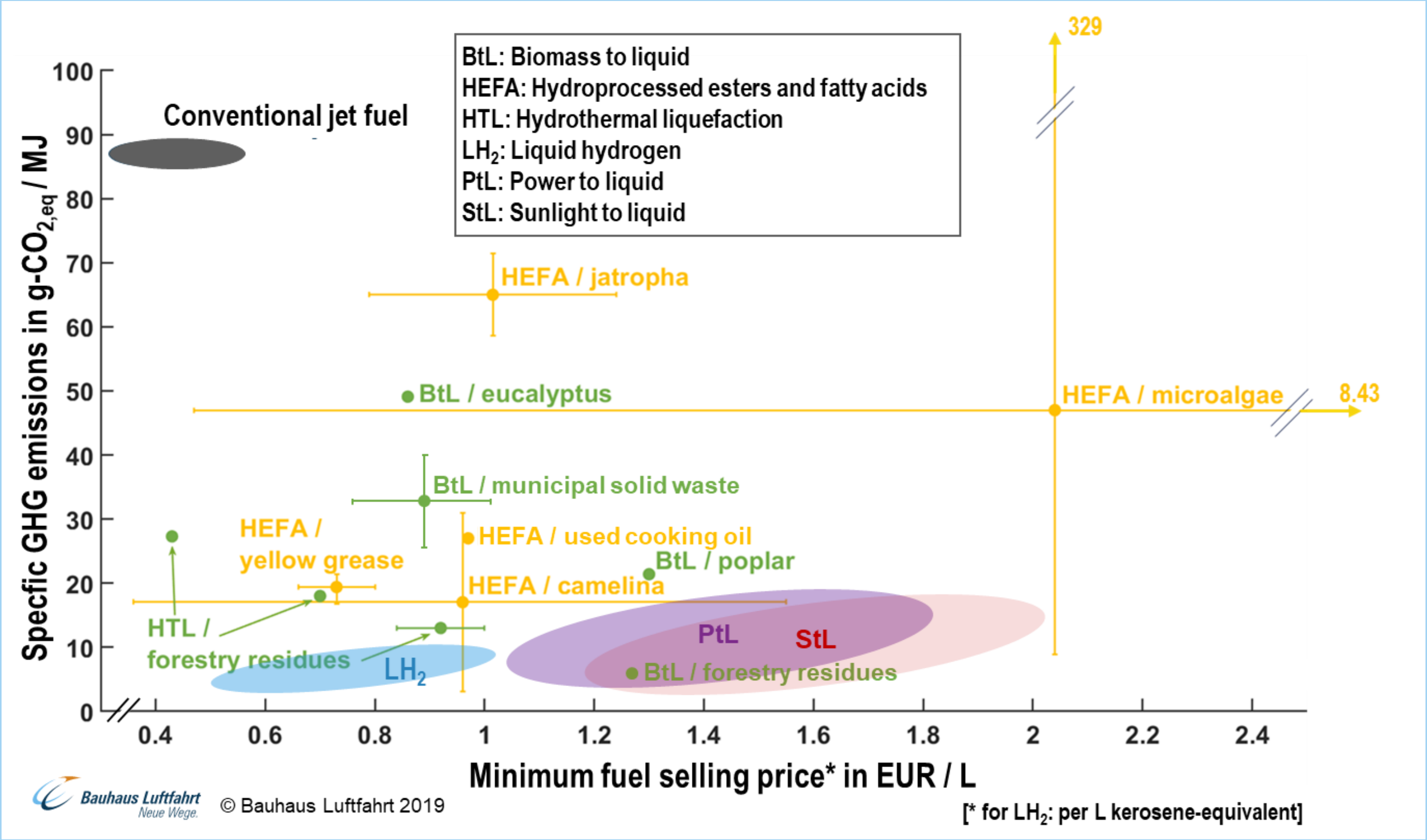


B. Portner, preliminary results from PowerFuel

Map of future renewable fuel options

HyFlexFuel

THE Hy-ShAir CONCEPT



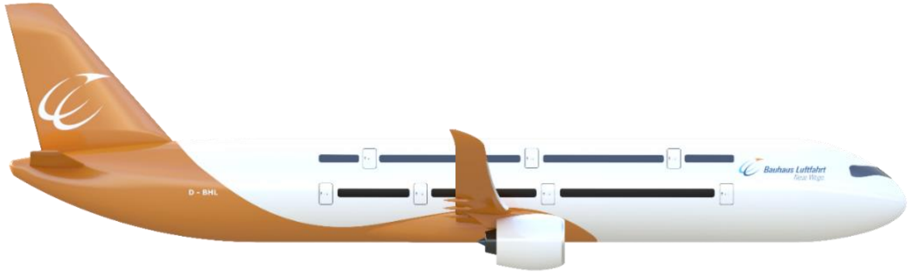
POWER FUEL

SUN to LIQUID
Fuels from concentrated sunlight

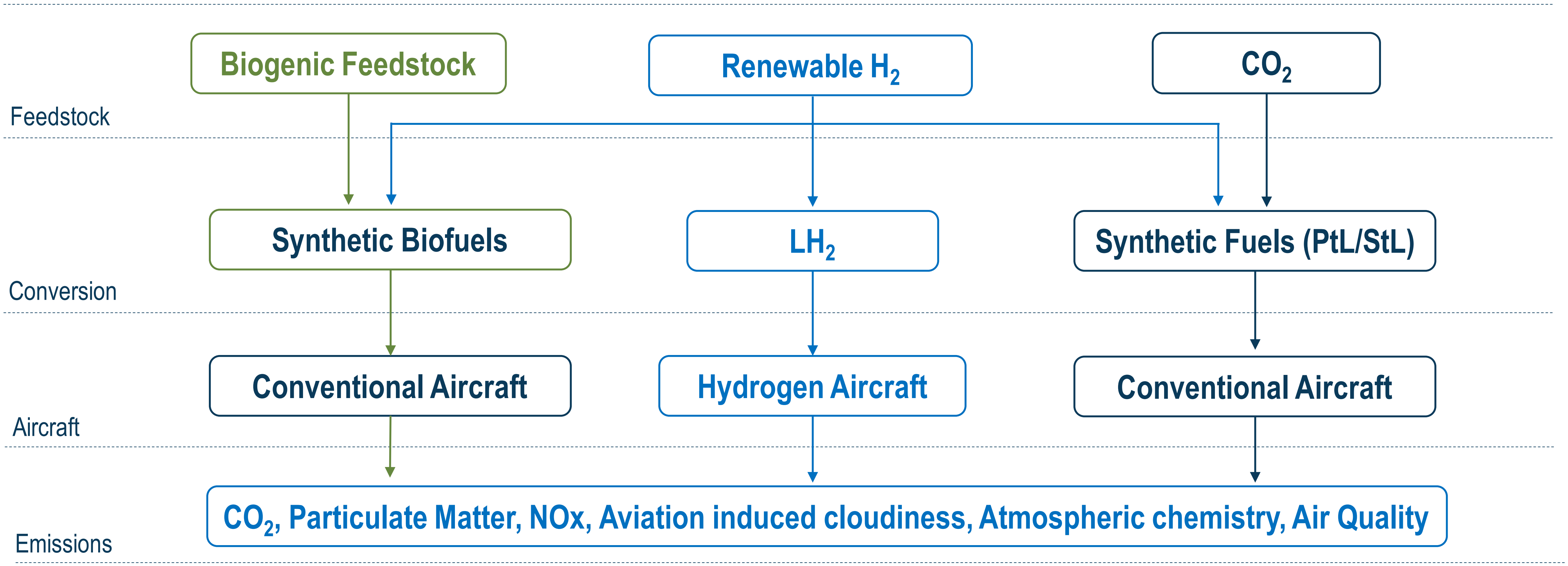
Adapted from: A. Sizmann, *Renewable jet fuel: Upcoming technology options*, 4th International Symposium of Bauhaus Luftfahrt, Taufkirchen, 2019

Bauhaus Luftfahrt
Neue Wege.

Hydrogen



Options to introduce renewable H_2 in long-haul aviation



Feedstock

Biogenic Feedstock

Renewable H_2

CO_2

Conversion

Synthetic Biofuels

LH_2

Synthetic Fuels (PtL/StL)

Aircraft

Conventional Aircraft

Hydrogen Aircraft

Conventional Aircraft

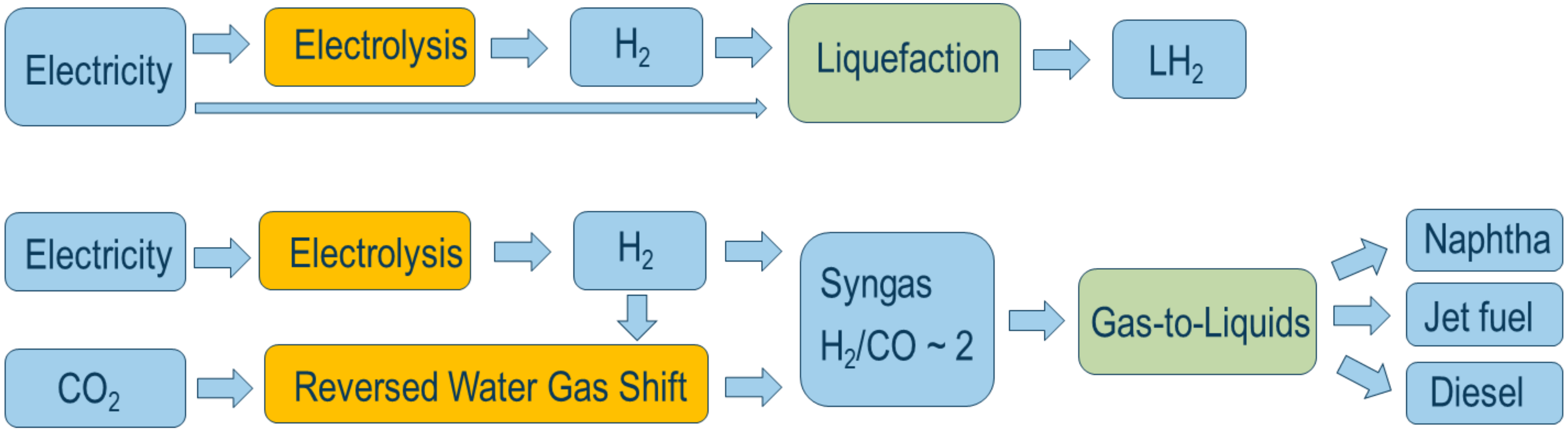
Emissions

CO_2, Particulate Matter, NOx, Aviation induced cloudiness, Atmospheric chemistry, Air Quality

Source: Penke, *Pathways and environmental assessment for the introduction of renewable hydrogen into the aviation sector,* Ökobilanzwerkstatt 2019

Cost Advantage of LH_2 Compared to PtL at Production Site

- **Robust and significant cost advantage of LH_2 production compared to PtL**
  - Higher energy conversion efficiency (relative efficiency advantage 20-30%)
  - No CO_2 source required, high selectivity towards LH_2 product

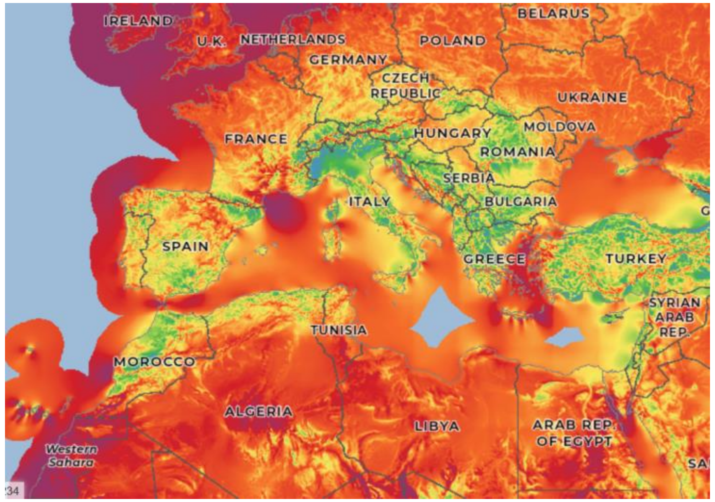

Electricity
Electrolysis
H_2
Liquefaction
LH_2

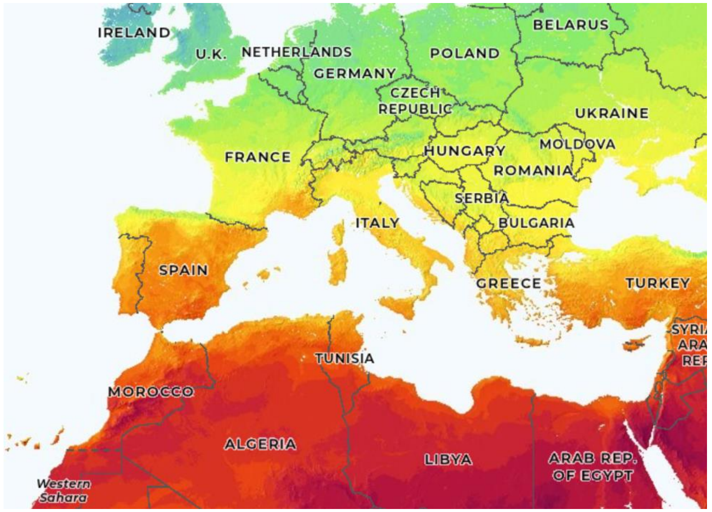
Electricity
Electrolysis
H_2
CO_2
Reversed Water Gas Shift
Syngas
$H_2/CO \sim 2$
Gas-to-Liquids
Naphtha
Jet fuel
Diesel

Bauhaus Luftfahrt
Neue Wege.

Regional Cost-sensitivity of Power-derived Fuels

- **E-fuel production cost strongly location dependent**
  - Significant differences between most excellent locations and conditions at various airport sites
  - Low transportation costs for liquid fuels
- **LH_2 costs at airports need to be competitive with imported synthetic fuels from excellent locations**
  - Local LH_2 production at selected airports
  - LH_2 import perspective for less favorable sites



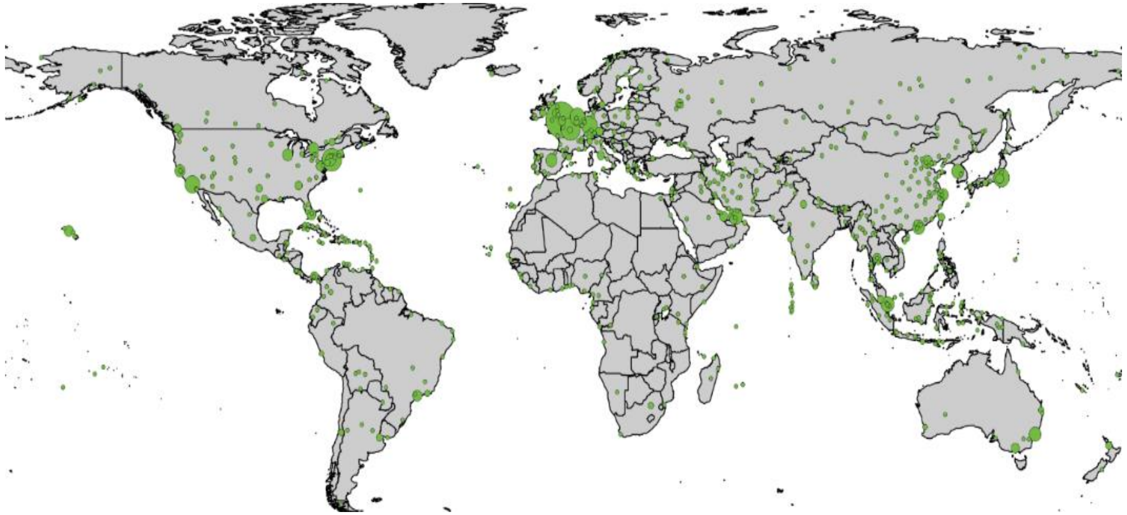


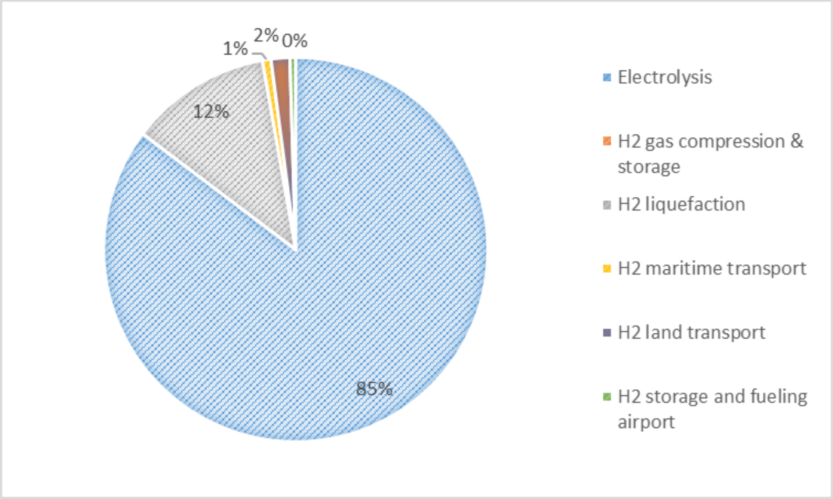
Wind resource: https://globalwindatlas.info, Solar resource: https://globalsolaratlas.info

Logistics of LH_2 in Large Quantities

Benefits of LH_2 production can overweigh logistic penalties of LH_2 supply

- H_2 is required in liquid phase and large quantities at a limited number of locations
- Airports with significant share of long-haul traffic tend to be close to coasts
- Energy demand of logistics much smaller than energy demand for LH_2 production





Source: Penke, Pathways and environmental assessment for the introduction of renewable hydrogen into the aviation sector, Ökobilanzwerkstatt 2019

Aircraft Design HyLiner 2.0

- Design-range 6400 nm (11 850 km)
- Cruise Speed Mach ~ 0.7
- 400 Passengers + cargo (46 t payload)
- MTOW: 196 t
- Wing span: 81 m
- Tank capacity: 371 m³ (ca. 20 t)

Troeltsch, F., Engelmann, M., Scholz, A., Peter, F., Kaiser, J. & Hornung, M. (2020).
Hydrogen-Powered Long-Haul Aircraft with Minimised Climate Impact. Proceedings of the 2020 AIAA AVIATION Forum. doi:10.2514/6.2020-2660

Conclusions

- **Battery electric aviation is only an option for very short distances**
- **Bulk part of the energy demand of aviation needs to be met by liquid fuels**
  - Plant oil based biofuels cannot be scaled to aviation fuel demand in a sustainable way
  - Biofuels from advanced feedstock are an option (expensive, still in development phase)
  - E-fuels from solar & wind can be produced in large quantities, but come at a cost as well
  - CO_2 provision is an important consideration for large-scale e-fuel production
  - Regional aspects play an important role (renewable resources, socio-economic indicators)
  - 100% synthetic fuels: Opportunity to minimize emission from combustion (soot, sulphur)
- **Liquefied hydrogen might be an option in the long-term**
  - Significant technological challenges remain (development of LH_2 aircraft)

HyFlexFuel

This project has received funding from the European Union`s Horizon 2020 research and innovation programme under grant agreement No 764734

www.hyflexfuel.eu Projektvideo: www.youtube.com/watch?v=yDBlxPf06go

SOLAR-JET

The research leading to these results has received funding from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement no. 285098 – Project SOLAR-JET.

SUN to LIQUID
Fuels from concentrated sunlight

This project has received funding from the European Union`s Horizon 2020 research and innovation programme under grant agreement No 654408

www.sun-to-liquid.eu Projektvideo: www.youtube.com/watch?v=IaUe23OhHXg

POWER FUEL

Gefördert durch:

Bundesministerium
für Wirtschaft
und Energie

aufgrund eines Beschlusses
des Deutschen Bundestages

www.energiesystem-forschung.de/forschen/projekte/powerfuel

Bauhaus Luftfahrt
Neue Wege.

Thank you for your attention

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