LBST
Ludwig Bölkow Systemtechnik

SUSTAINABLE AVIATION FUELS (SAF) – INTRO INTO POWER-TO-LIQUIDS (PTL)

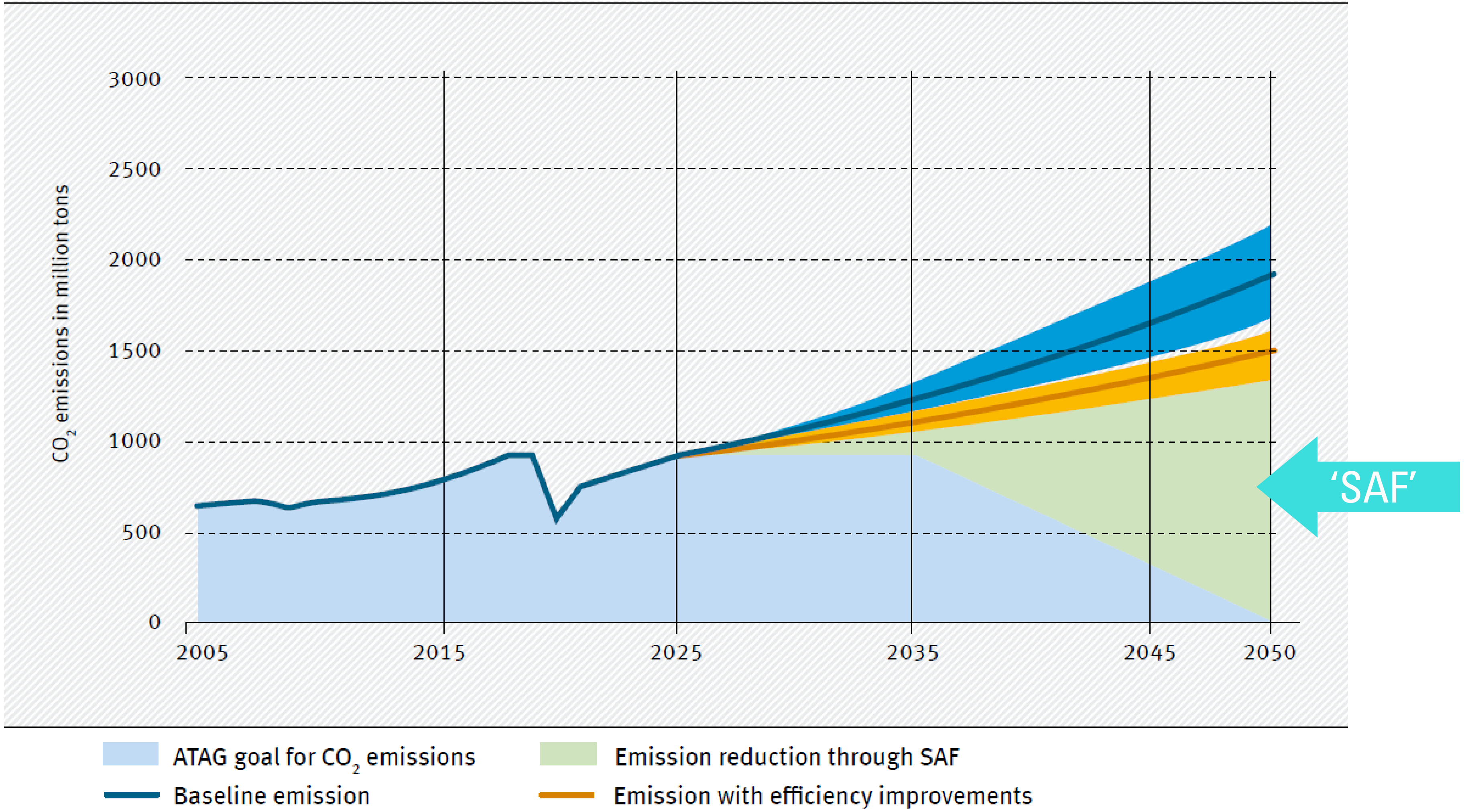
Patrick R Schmidt
SAF/PTL Lecture @ University of Surrey
6 February 2024

Contents

1 INTRO

Aviation decarbonisation

- Switch to a renewable fuel base is the key element ‘en route’ to achieve Paris Agreement



Source: BHL & LBST, Power-to-Liquids, 2022

LBST

Terms & definitions

There are different scopes of understanding of e.g. the class term ‘SAF‘.
→ To avoid misunderstandings and for precision, use explicit fuel terms!

SAF

[sæf] *Acronym*

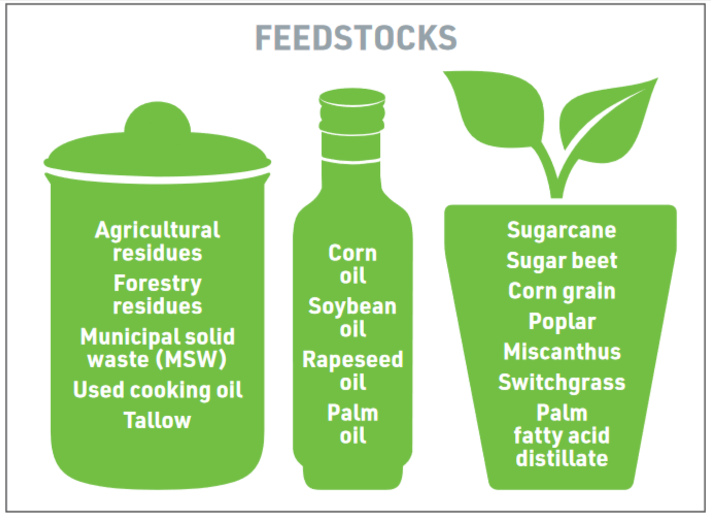
Sustainable Aviation Fuel –
Renewable or waste-derived aviation fuels that meet sustainability criteria [ICAO 2018]

E-SAF

[ʻi:sæf] *Acronym*

Electricity-derived Sustainable Aviation Fuel –
Fuels derived from renewable electricity,
e.g. power-to-hydrogen (PtH$_2$), power-to-liquids (PtL),
that meet sustainability criteria

To date, CORSIA lists only bio-derived SAF as default GHG values. Electricity-derived fuels are under development to become ‘CORSIA eligible fuel‘.



Feedstocks with CORSIA Default Life Cycle Emission Values (February 2019)

Source: ICAO, An Overview of CORSIA Eligible Fuels, 2019

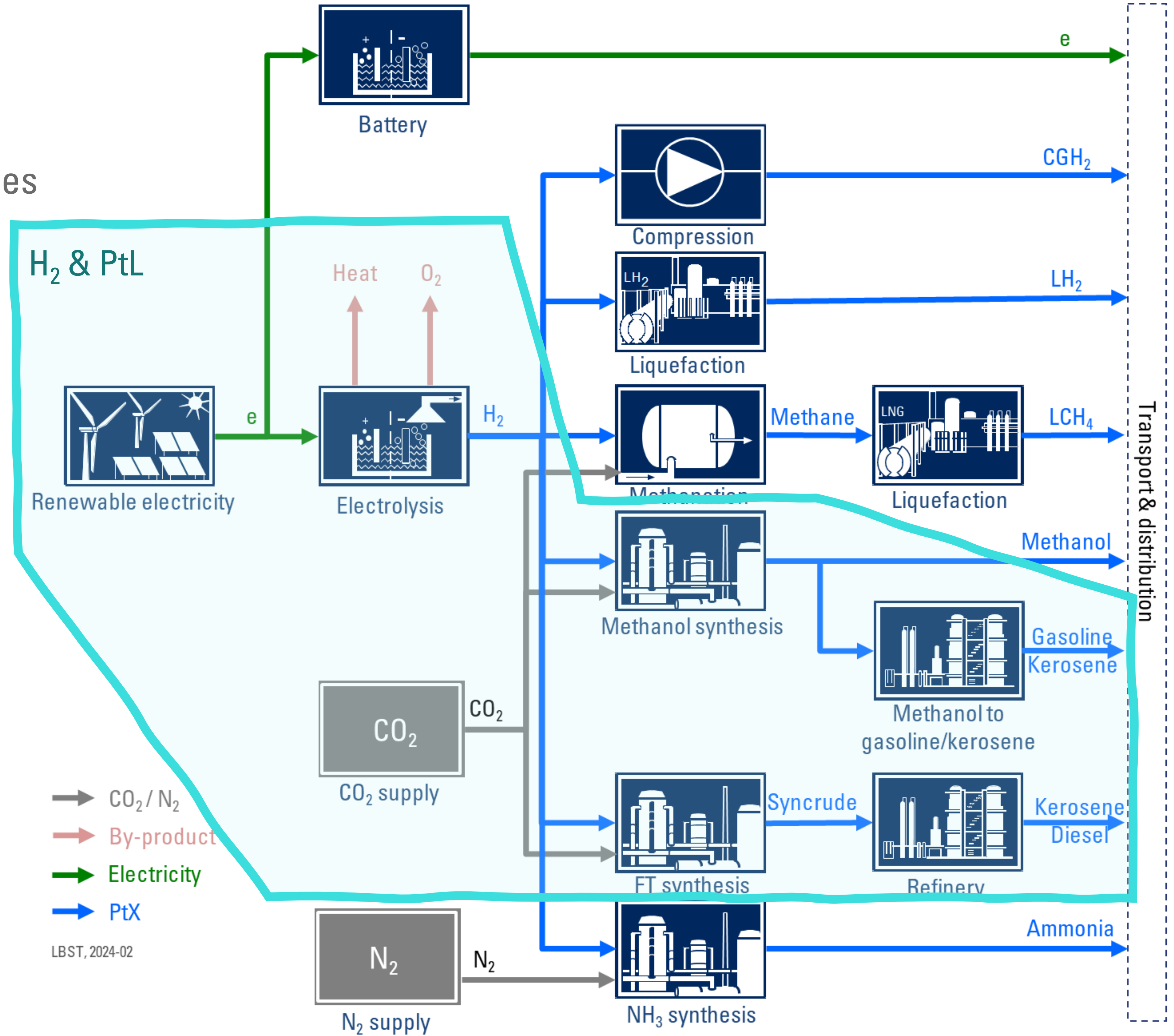
2 TECHNOLOGIES

PtX production routes

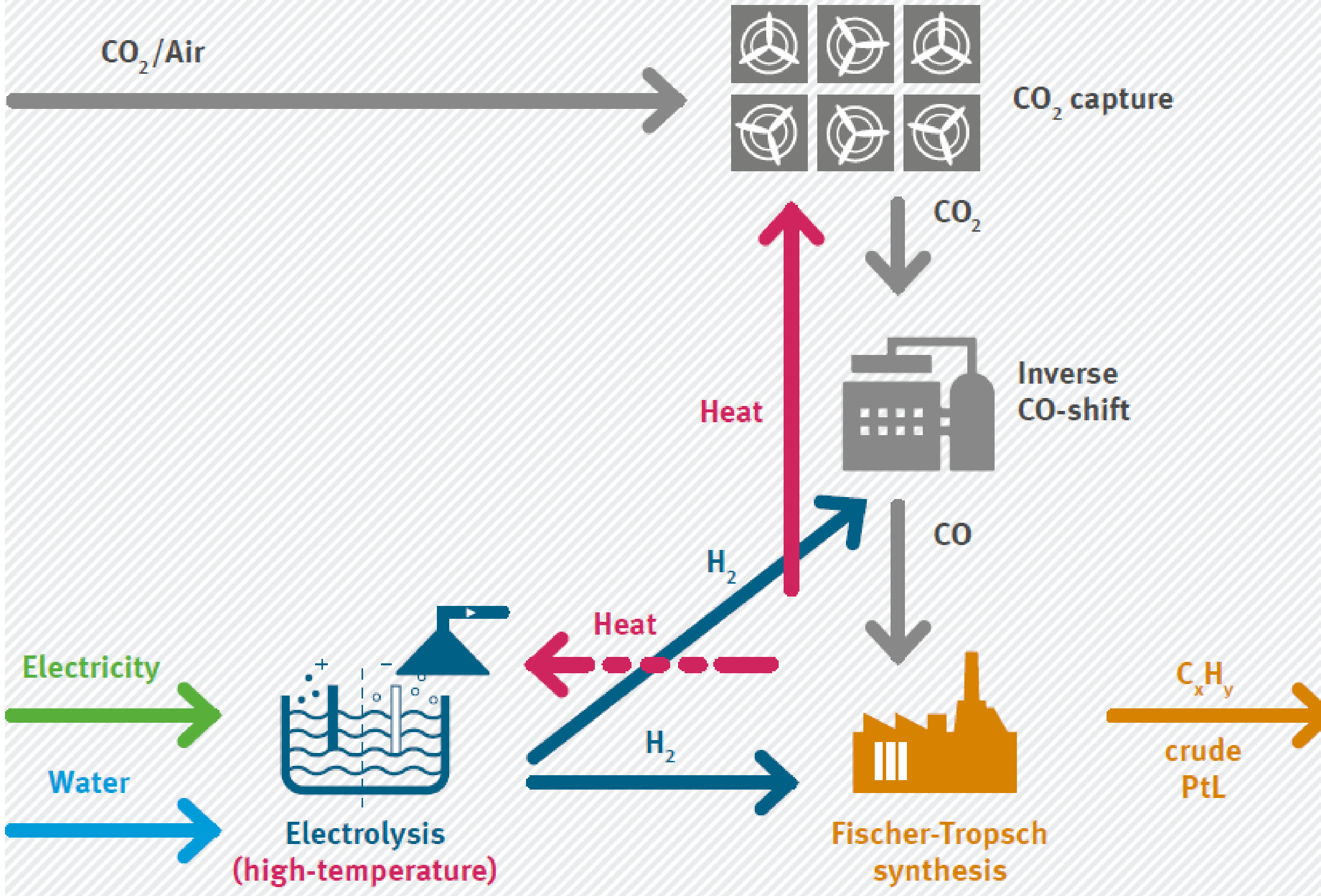
- with fuel products for all kinds of uses

Focus of this presentation: H_2 & PtL

- Where feasible, direct electrification is preferred for efficiency reasons → Likely only a niche option for aviation
- Hydrogen (H_2) is the chemical energy carrier most efficiently produced from electricity (via water electrolysis)
- H_2 is the starting point for all PtX fuels, thus no regret
- CO_2 may be sourced from concentrated sources (limited), alternatively from the air (DAC)



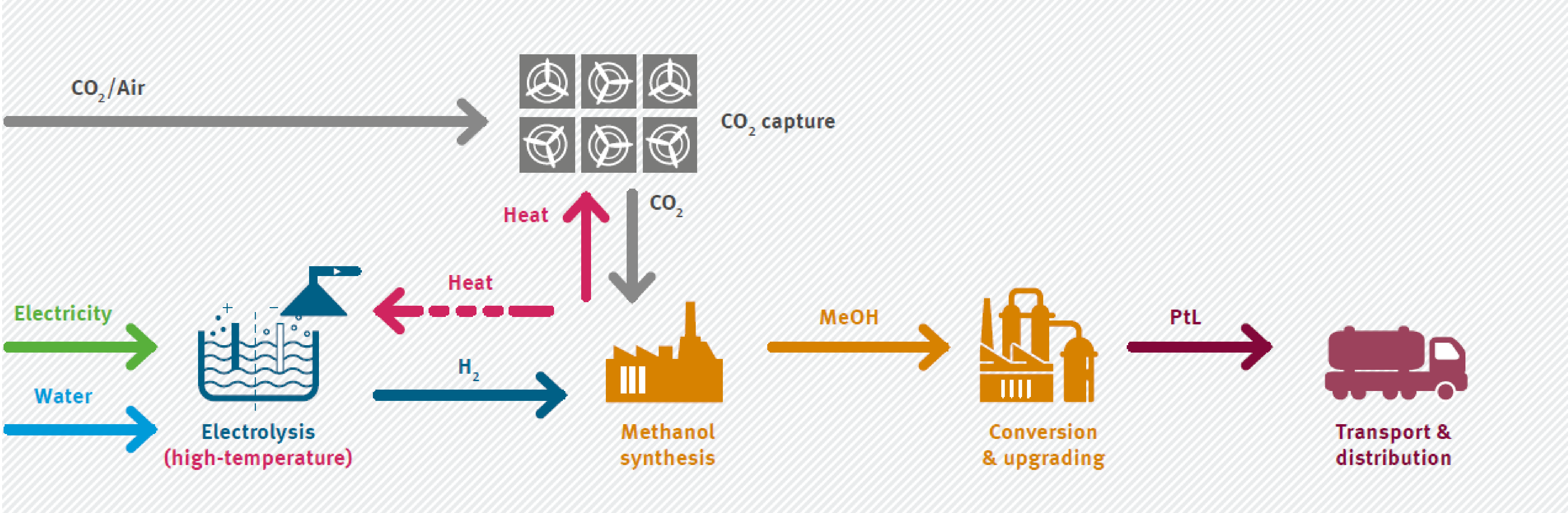
Deep dive:
PtL production via **Fischer-Tropsch** (FT) route



- Kerosene via Fischer-Tropsch route is ASTM certified up to 50% admixture (blend wall)
- Upscaling of inverse CO-shift is under development

Source: BHL & LBST, Power-to-Liquids, 2022

Deep dive:
PtL production via **methanol** (MtK) route



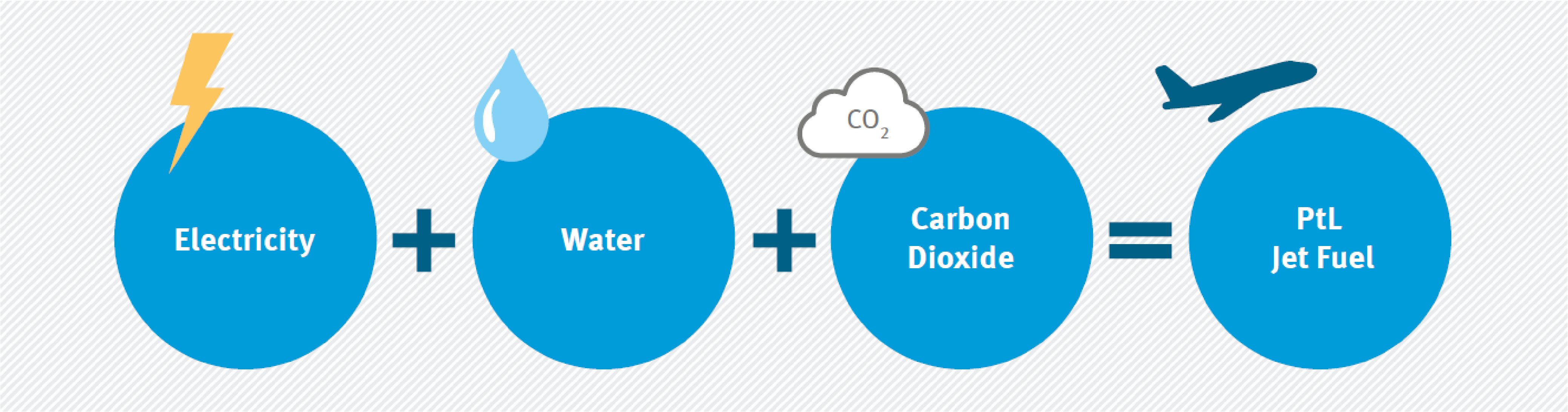
- Upscaling of direct air capture (DAC) and high-temperature electrolysis is under development
- Demonstration of commercial-scale methanol-to-kerosene process is pending
- Methanol route (MtK) not yet certified as ASTM jet fuel

Source: BHL & LBST, Power-to-Liquids, 2022

3 SUSTAINABILITY

The three main ingredients of PtL jet fuel

- Key environmental safeguards to secure multiple benefits from synthesised e-fuels like PtL



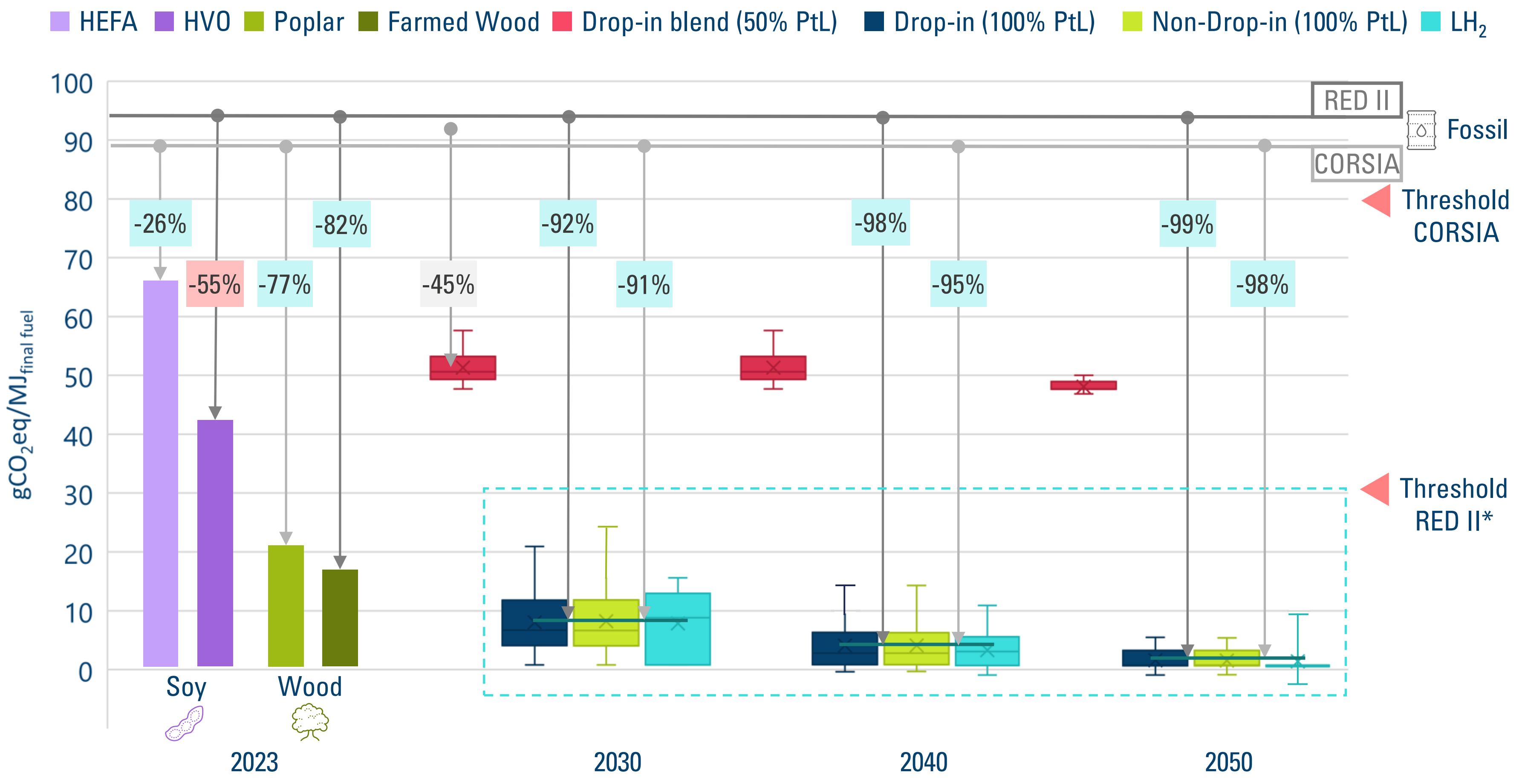
1) Additional renewable power plants (to avoid sector carbon leakage)
2) Renewable CO_2 sources (to avoid lock-in risk with fossils)
3) Use of treated waste or sea water (in regions prone to water supply stress)

Regulatory makes markets, and regulatory may allow for a range of options => Business case analysis

Graphic: BHL & LBST, Power-to-Liquids, 2022

100% e-SAF has significant greenhouse gas reduction potential

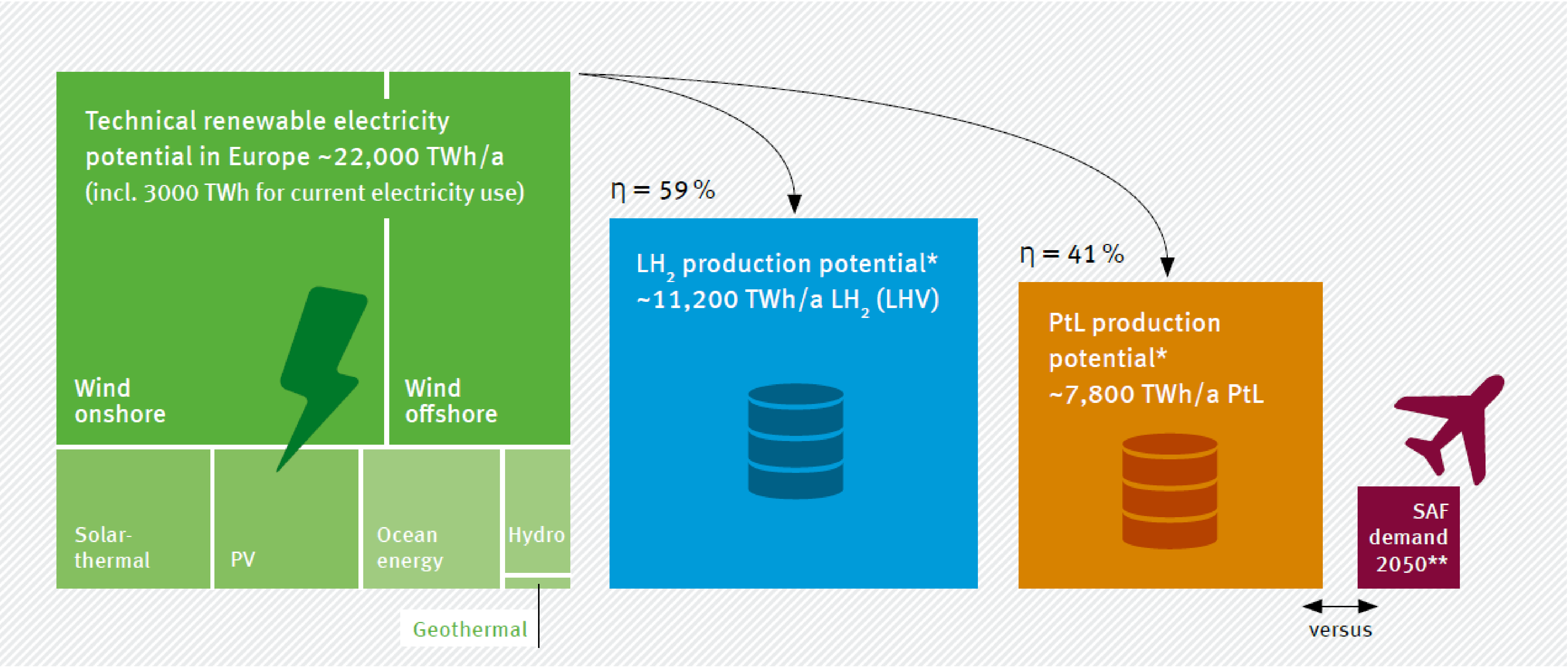
- Fuel GHG emissions by fuel type and year (in g_{CO2eq}/MJ)



* Average between -65% for biofuels and -70% for RFNBO (PtX fuels)
Routes (MeOH/, Fischer-Tropsch) and regions are within bandwidths
Well-to-wake according to RED II/CORSIA, without H_2 slip, no capex GHG, no high-altitude climate impacts

  Source: LBST, E-SAF Study, 2023

Renewable power potentials vs. potential SAF demand in 2050 (Europe)



* Excluding 3000 TWh/a current electricity use

** Best estimate of 2050 EU national and international flights (63 Mt/a) assumed as PtL (760 TWh_{fuel}/a) requiring some 1690 TWh_e/a

CO_2 sources have different levels of sustainability

Sustainability considerations of CO_2 sources for PtL jet fuel

	Science				Regulatory classification
CO_2 sources	**Renewability**	**Environmental sustainability**	**Alternative CO_2 uses**	**Towards carbon-neutrality; Risks**	**Eligible under EU RED II [RED II-DA 2023]**
! Extraction from air		Subject to renewable energy			
Biogas upgrading			Power-to-methane		
Solid biomass fired heat (& power) plants		Subject to feedstock & process	Bio-CCS (net negative)	Other land or sustainable biomass uses	Complies with sustainability and greenhouse gas savings criteria and CO_2 capture did not receive credits for emission savings
Fermentation to alcohols			e.g. beverage industry		
Geothermal sources		Subject to geo-physical CO_2 cycle	CO_2 re-injection (closed-loop)	Hot dry rock a potential no-go	CO_2 was previously released naturally
Cement, burnt lime or glass production		Subject to energy input; process-related emissions	Power-to-chemicals	Shift to alternative materials, recycling; Technology lock-in	
Steel production (coke-based)		Subject to feedstock & process	Top-gas for heating and reduction	Shift to direct reduction with H_2, recycling, alternative materials; Technology lock-in	CO_2 has been captured from an EU-ETS activity and has been taken into account upstream in an effective carbon pricing system and is incorporated in the chemical composition of the fuel before 2041 *
Fossil fuel firing			Fossil CCS	Phase-out; Technology lock-in	

* 2036 for combustion of fossil fuels for electricity generation. No fuel combustion for the specific purpose of producing CO_2.

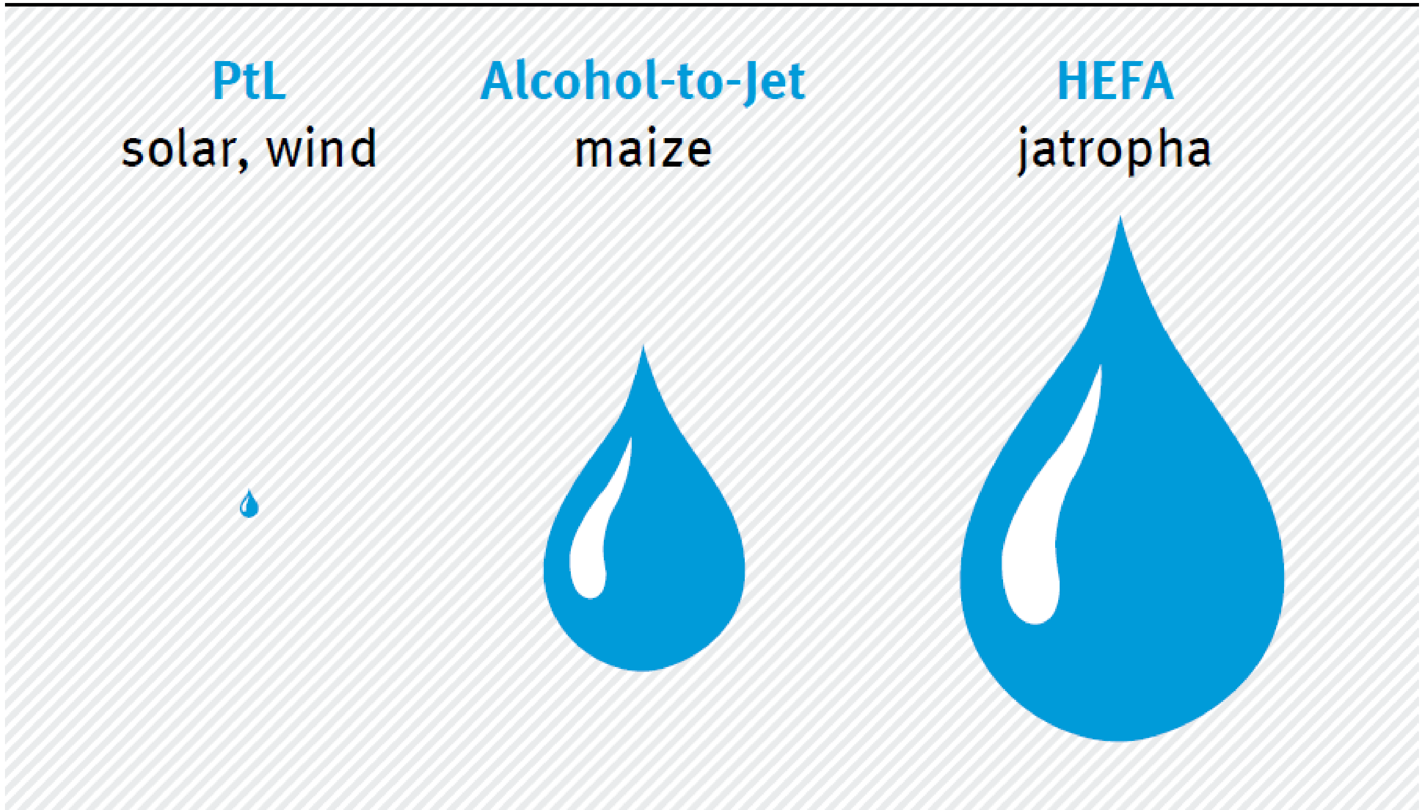
LBST, 2023-11-07

Source: LBST, E-SAF Study, 2023

PtL water demand compared to selected biofuels

- Energy crops in regions with sufficient water availability only
- PtL specific water demand is comparably negligible; point demand at PtL production plants requires check of local conditions
- PtL production may use sea and wastewater after treatment to process water quality

(Volume representation, PtL water demand 4 $L_{H_2O}/kg_{jet\ fuel}$)



Source: BHL & LBST, Power-to-Liquids, 2022

Deep dive:
Water footprint of various alternative fuel pathways (global average)

Feedstock (pathway)	Blue water (m^3 / GJ)	Green water (m^3 / GJ)	Grey water (m^3 / GJ)	Cumulative ($1000 L_{H_2O}/L_{jet\ fuel}$)	Reference
Jatropha oil (HEFA)	335	239	n.a.	**21.8**	Feedstock to product conversion efficiencies: (Mäki-Arvela et al. 2021) (Geleynse et al. 2018)
Rapeseed oil (HEFA)	20	145	29	**7.68**	
Soybean oil (HEFA)	11	326	6	**14.48**	
Palm oil (HEFA)	0	150	6	**6.05**	Jatropha oil water demand: (Gerbens-Leenes et al. 2009)
Bioethanol from sugar cane (AtJ)	25	60	6	**3.91**	
Bioethanol from sugar beet (AtJ)	10	31	10	**2.20**	All other feedstock water demand: (Mekonnen & Hoekstra 2010)
Bioethanol from maize (AtJ)	8	94	19	**5.21**	
PtL via FT	0.12	n.a.	n.a.	**0.0041**	LBST, this study
PtL via methanol	0.11	n.a.	n.a.	**0.0037**	LBST, this study

Pathway-specific feedstock to product conversion efficiencies and product fraction distributions have been taken from the references specified and considered in the calculations. Water footprints have been allocated to the respective products according to their energy content as proposed by Prussi et al. (2021).

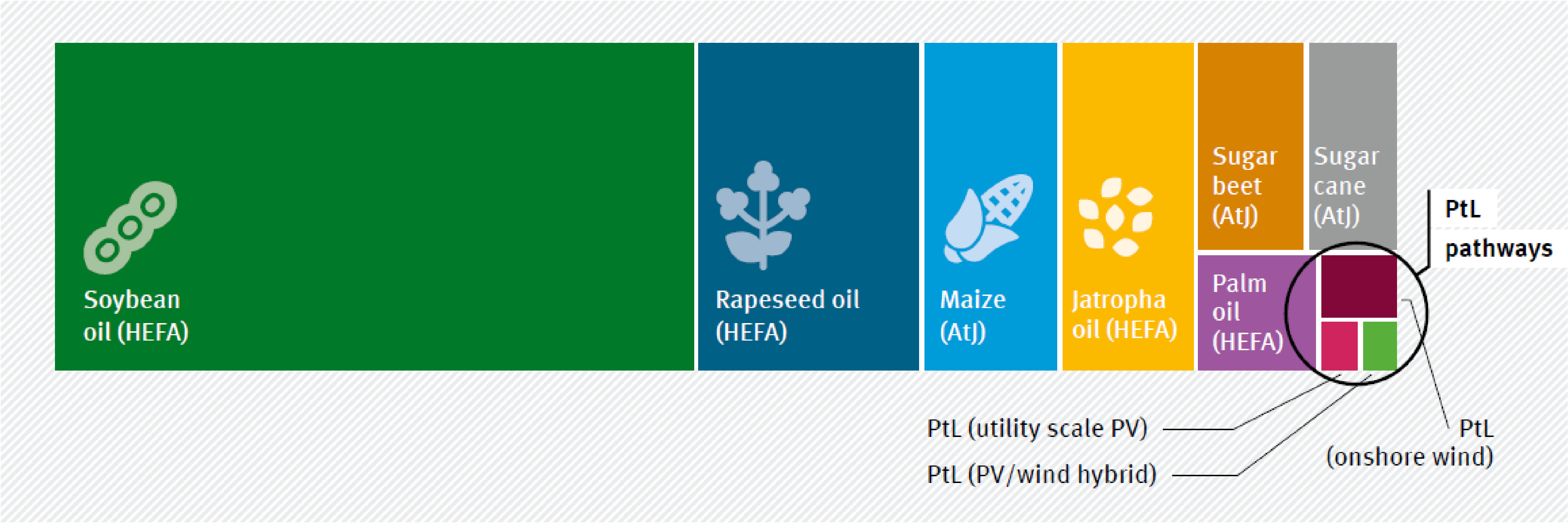
Definitions

Blue water footprint: ground/surface water consumed for production of feedstock
(evapotranspiration + water contained in product)

Green water footprint: precipitation water consumed for production of feedstock
(evapotranspiration + water contained in product)

Grey water footprint: freshwater required for pollution offset
(pollutant assimilation)

Gross area needed to yield one ton of jet fuel per year



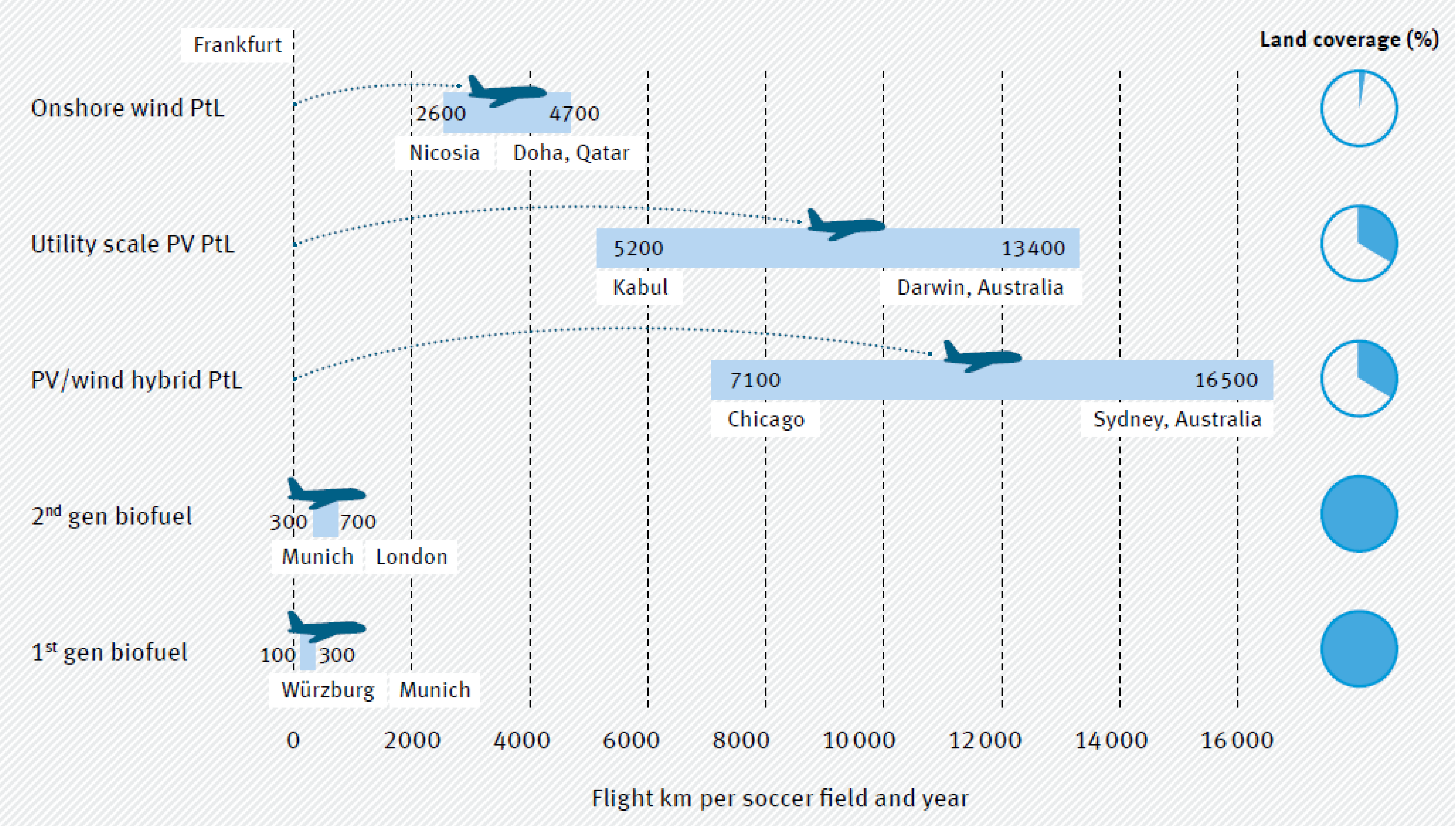
⇒ PtL **net** area demand* is furthermore much lower compared to energy crops (where gross ~ net)

* i.e. actual area occupation (e.g. for wind tower foundations, access ways, etc.)

Source: BHL & LBST, Power-to-Liquids, 2022

Achievable air mileage for an A320neo using the annual energy yield from an area the size of a soccer field

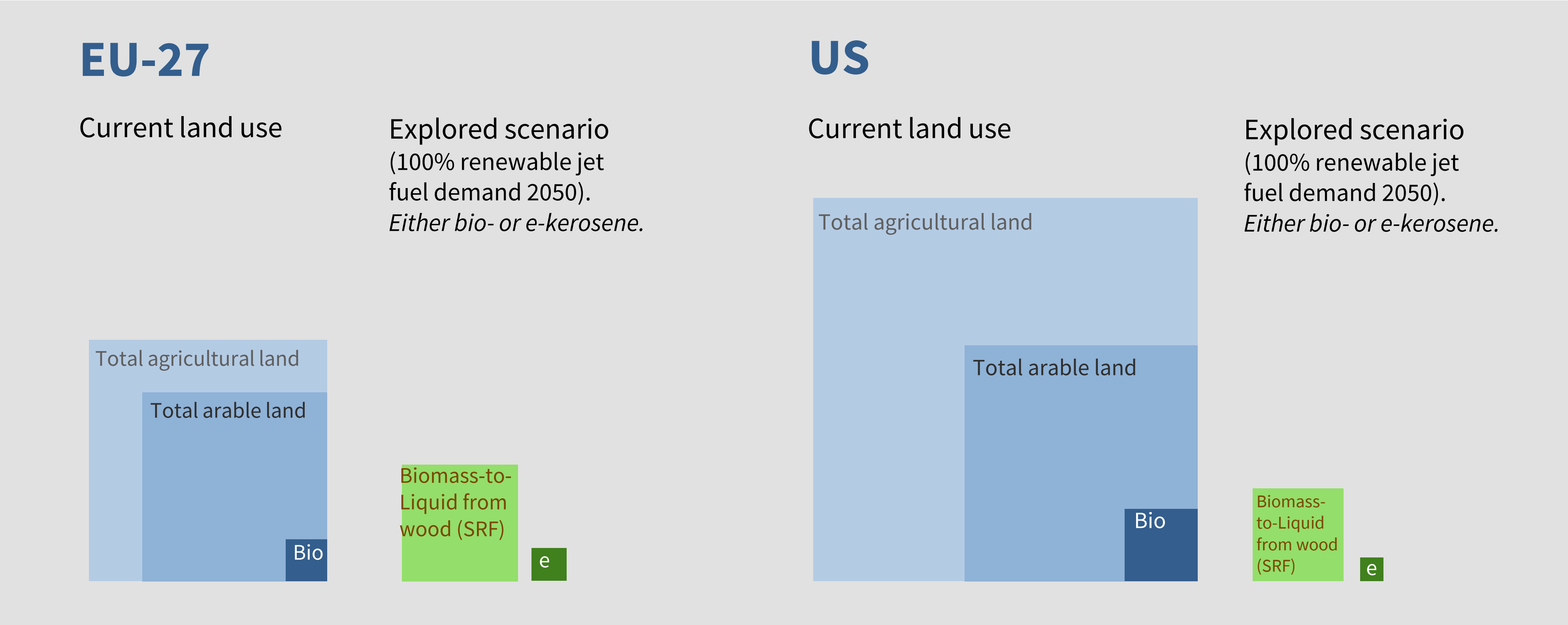
- Soccer field = 0.71 ha



Source: BHL & LBST, Power-to-Liquids, 2022

Counterfactual:
Comparison of current land uses vs. gross area requirement

- Approximately 80% and 20% of gross land area currently dedicated to bioenergy production in the EU-27 and the US respectively would be sufficient to supply the estimated kerosene jet fuel demand in 2050 with e-kerosene.

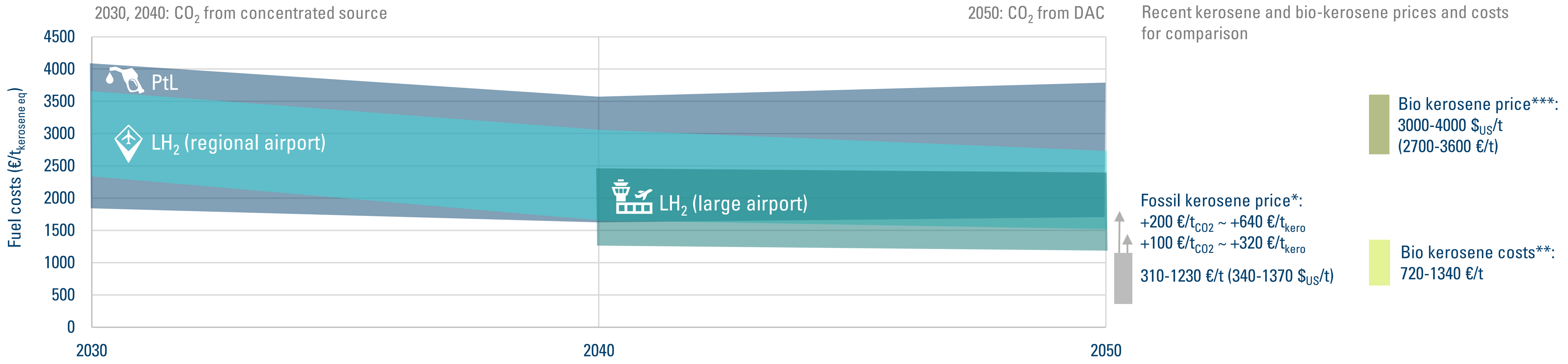


Source: dena / LUT / LBST, E-Kerosene for Commercial Aviation, 2022

4 ECONOMICS

E-SAFs show significant cost reduction potential in the next decades and main driver for LH_2 economics is liquefaction capacity

Fuel cost bandwidths (€/t kerosene-equivalent) by fuels, capacity, and time



* Min/max in the timeframe 01/2016-07/2023 based on market data by [IATA 07/2023] (COVID 19 effect excluded)
** BtL via Fischer-Tropsch synthesis of gasified woody biomass from short-rotation forestry, Data by [IEA 2020]
*** Data by [Argus 05/2023]

Source: LBST, E-SAF Study, 2023

5 DISCUSSION

Key take aways – up for discussion

- Aviation is too important to build its fuel future 'on waste'
- Two SAF avenues that need to be pushed in parallel for their sustainability & scalability: PtL and PtH_2
- European renewable power production potentials are (technically) sufficient to cater for all energy needs
- A minimum share of domestic SAF production is recommendable for energy supply security
- The slower the progress in switching aviation's energy basis, the more likely become demand measures to achieve Paris Agreement
- Climate impacts from aircraft non-CO_2 emissions in high altitudes are the elephant in the room

Thank you for your attention

- Feel free to reach out for any questions

Patrick R Schmidt
Senior Project Manager / Consultant
E: Patrick.Schmidt@LBST.de
LinkedIn

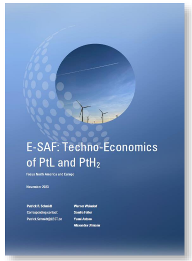
Yanni S Astono
Researcher
E: Yanni.Astono@LBST.de
LinkedIn

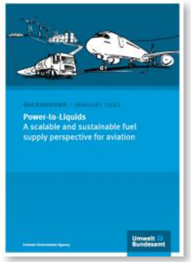
Ludwig-Bölkow-Systemtechnik GmbH
Daimlerstrasse 15
85521 Ottobrunn
Germany
T +49 89 608110-0
info@LBST.de
www.LBST.de

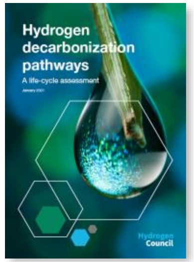
ANNEX

Ludwig-Bölkow-Systemtechnik

LBST







Profile

- Independent expert for sustainable energy and mobility with 4 decades of experience
- Bridging technology, markets, and policy
- Renewable energies, fuels, infrastructure
- Technology-based strategy consulting, System and technology studies, Sustainability assessment
- Global and long-term perspective
- Rigorous system approach – thinking outside the box
- Serving international clients in industry, finance, politics, NGOs

References

- Deutsche Aircraft – *E-SAF Study*
- ClimateWorks Foundation – *E-Kerosene for Commercial Aviation*
- UBA – *Power-to-Liquids for Aviation*
- World Energy Council (Germany) – *International H_2 Strategies*
- Hydrogen Council – *H_2 Decarbonization Pathways*
- Numerous PtX studies for industry, politics, and associations

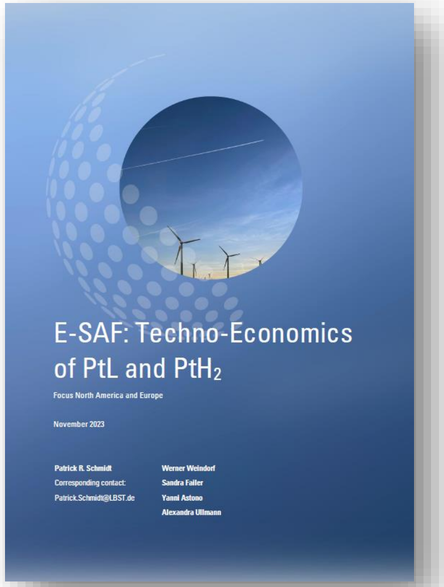
Study: E-SAF (2023)

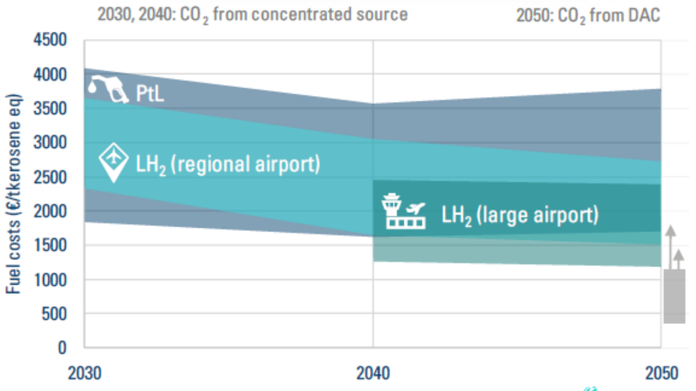
- Study commissioned by the Deutsche Aircraft
- Topics:
  - comparing the economic and environmental performance
  - of PtH_2 and PtL
  - for North America, Europe
  - including North Africa and the Middle East into account as export regions
- Link: https://en.lbst.de/publikationen/techno-economics-of-ptl-and-pth2-2023/

Authors & full title:

Schmidt, P.R., Weindorf, W., Failer, S., Astono, Y., Ullmann, A.:
E-SAF: Techno-Economics of PtL and PtH_2 – Focus North America and Europe; Ludwig-Bölkow-Systemtechnik GmbH – LBST, Ottobrunn/Munich, November 2023

DEUTSCHE AIRCRAFT



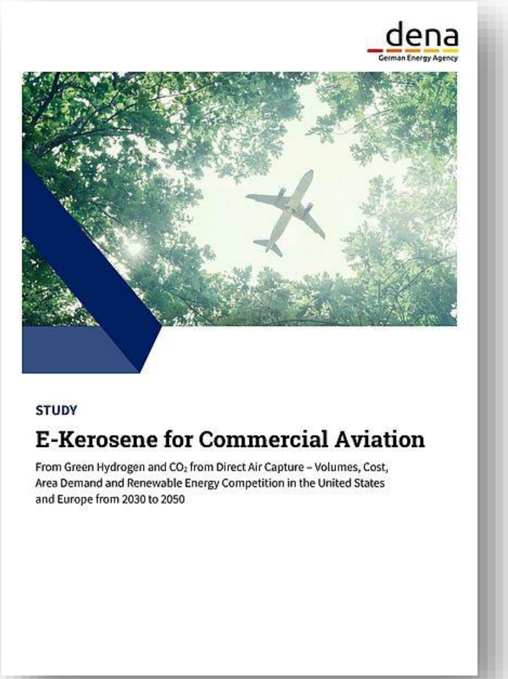


  6 February 2024

LBST

Study: E-Kerosene for Commercial Aviation (2022)

- Study funded by the ClimateWorks Foundation
- Joint expertise of dena, LUT and LBST
- Topics:
  PtL sustainable aviation fuel (SAF) volumes, cost,
  area demand and renewable energy competition
  in the US and Europe from 2030 to 2050
- Link: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2022/STUDY_E-Kerosene_for_Commercial_Aviation.pdf


dena
German Energy Agency

STUDY

E-Kerosene for Commercial Aviation

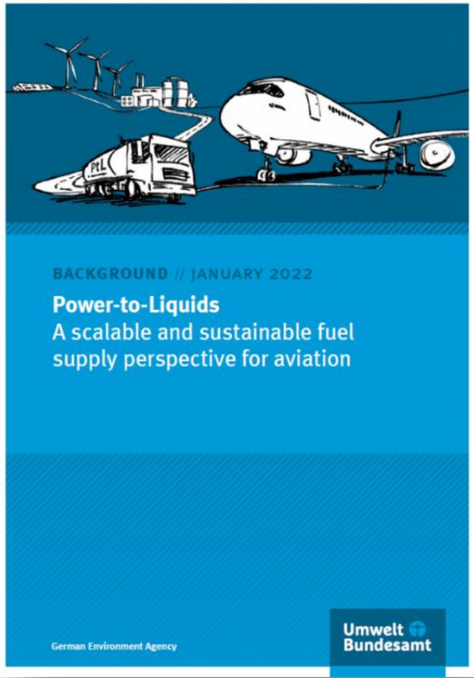
From Green Hydrogen and CO_2 from Direct Air Capture – Volumes, Cost, Area Demand and Renewable Energy Competition in the United States and Europe from 2030 to 2050

Authors & full title:

Matteo Micheli (dena), Christian Breyer (LUT), Mahdi Fasihi (LUT), Ayobami Solomon Oyewo (LUT), Werner Weindorf (LBST), Patrick R. Schmidt (LBST):
E-Kerosene for Commercial Aviation From Green Hydrogen and CO_2 from Direct Air Capture; September 2022

Study: PtL for Aviation 2.0 (2022)

- Commissioned by German Environment Agency (UBA)
- Joint expertise of LBST and Bauhaus Luftfahrt e.V.
- Topics:
  - Technology readiness and development potentials
  - Techno-economics
  - Environmental performance (efficiency, greenhouse gases, land and water demand)
- Link: https://www.umweltbundesamt.de/publikationen/power-to-liquids



Authors & full title:

Valentin Batteiger (BHL), Patrick Schmidt (LBST), Kathrin Ebner, Antoine Habersetzer, Leonard Moser, Werner Weindorf, Tetyana Raksha: Power-to-Liquids – A scalable and sustainable fuel supply perspective for aviation; German Environment Agency (ed.), Background // January 2022, ISSN: 2363-829X

Study: E-Fuels (2022, update planned 2024)

- Commissioned by Concawe and Aramco
- Expertise by LBST with support from E4tech
- Topics:
  - Techno-environmental (Part 1) and economic (Part 2) analysis of different e-fuels pathways produced in different regions of the world (North, Centre & South of Europe, as well as Middle East & North Africa) in 2020, 2030 & 2050, with assessments of sensitivities to multiple key techno-economic parameters
  - An assessment of stand-alone units versus e-plants integrated with oil refineries
  - A comparison of e-fuels production costs versus fossil fuels, biofuels & e-fuels from nuclear electricity
  - An analysis of the context of e-fuels in the future in Europe (potential demand, CAPEX, renewable electricity potential, land requirement, feedstocks requirements)
  - A deep dive into the safety and environmental considerations, societal acceptance, barriers to deployment and regulation
- Link: https://www.concawe.eu/publication/e-fuels-a-techno-economic-assessment-of-european-domestic-production-and-imports-towards-2050/

Authors & full title:

Alba Soler (Concawe), Victor Gordillo (Aramco), William Lilley (Aramco), Patrick Schmidt (LBST), Weindorf Werner (LBST), Tom Houghton (E4tech), Stefano Dell'Orco (E4tech): E-Fuels: A techno-economic assessment of European domestic production and imports towards 2050; November 2022

