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Energy for aviation:
How do we close the circle?

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BMK Endowed Professorship for Innovative Aviation Technologies

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Federal Ministry
Republic of Austria
Climate Action, Environment,
Energy, Mobility,
Innovation and Technology

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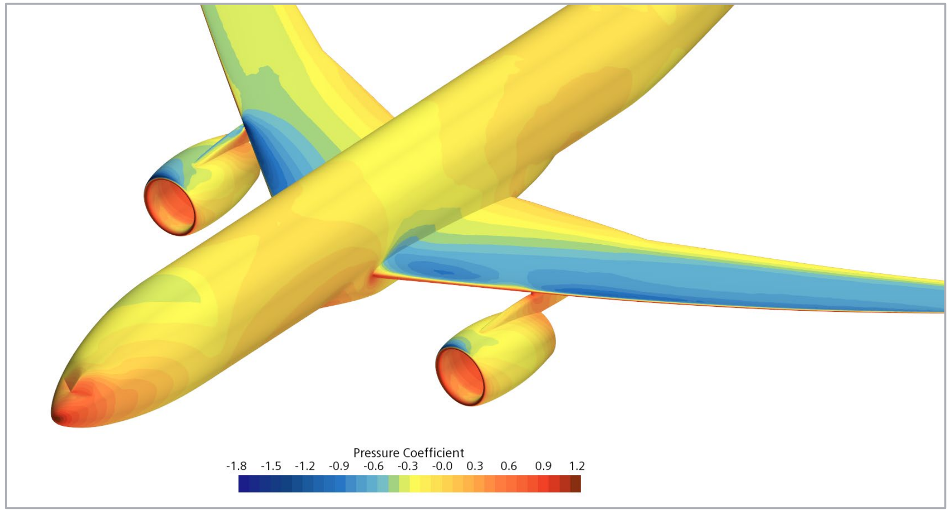


Citations

"The last drop of gasoline will flow through an aircraft engine." (Carsten Spohr 2019)

https://www.aero.de/news-32338/Lufthansa-Chef-Luftverkehr-muss-langsamer-wachsen.html

Hard-to-abate sectors

https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

"Tripling **renewable energy** capacity globally and doubling the global average annual rate of **energy efficiency improvements** by 2030"

https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

"Accelerating efforts globally towards **net zero emission** energy systems, utilizing zero- and low-carbon fuels well before or by around mid-century"

https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

"Accelerating and substantially **reducing non-carbon-dioxide emissions** globally, including in particular methane emissions by 2030"

https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

"Notes the importance of **transitioning to sustainable life-styles** ... in efforts to address climate change, including through **circular economy approaches**, ..."

https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

"Underlines the **fundamental role of technology** development ..."

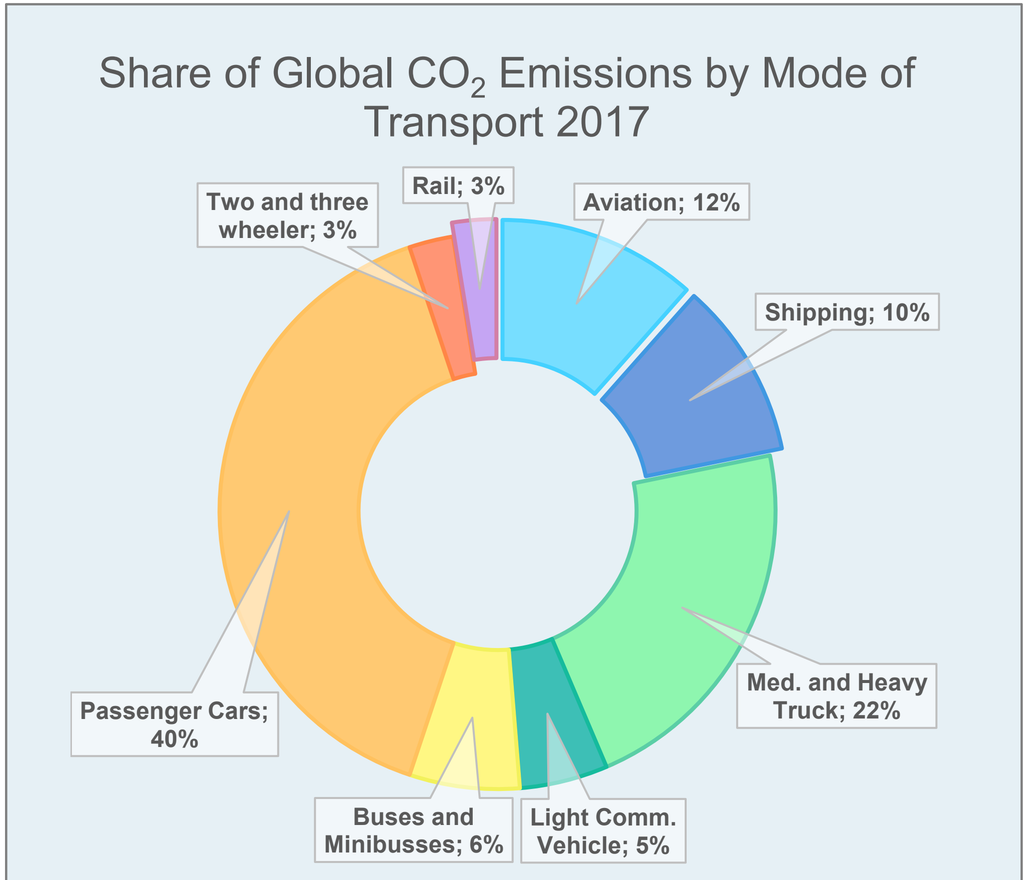
https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

"Underlines the **fundamental role of capacity building** ..."

https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

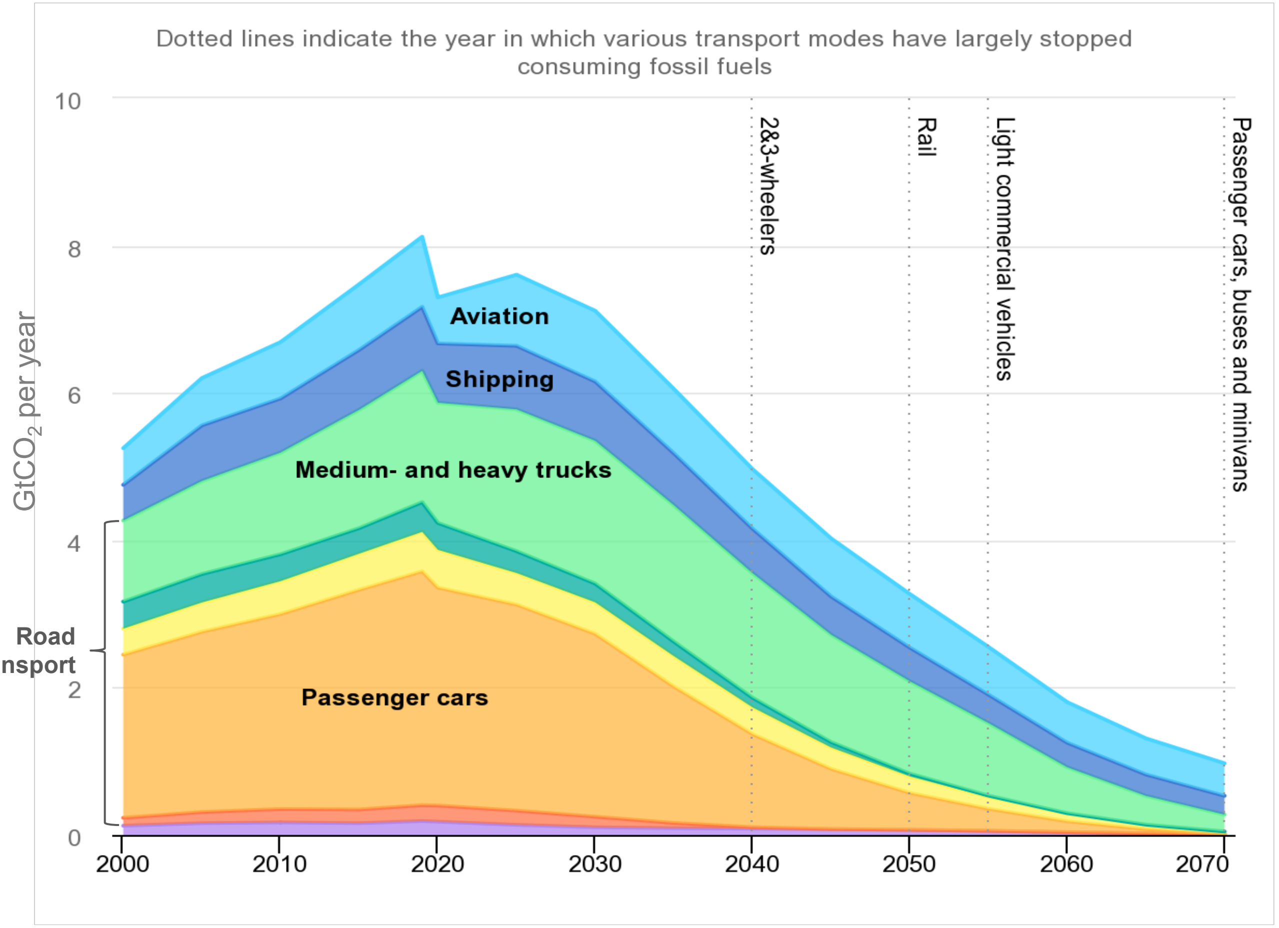
Aviation CO_2 Emissions

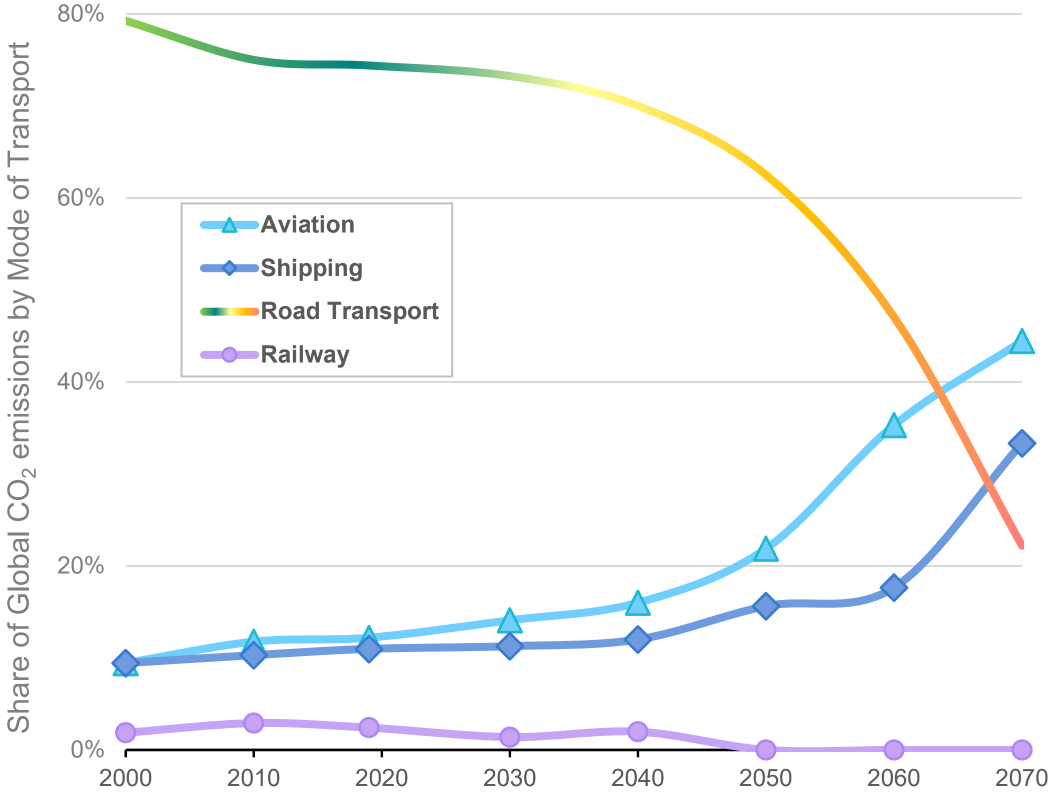
- CO_2 concentration in the atmosphere increases by about 3 ppm per year
  - Pre-industrial concentration: 280 ppm
  - Concentration in 2021: 420 ppm
- Aviation is responsible for approx. 2% of anthropogenic CO_2 emissions



IEA, Global CO2 emissions in transport by mode in the Sustainable Development Scenario, 2000-2070, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-co2-emissions-in-transport-by-mode-in-the-sustainable-development-scenario-2000-2070, IEA. Licence: CC BY 4.0

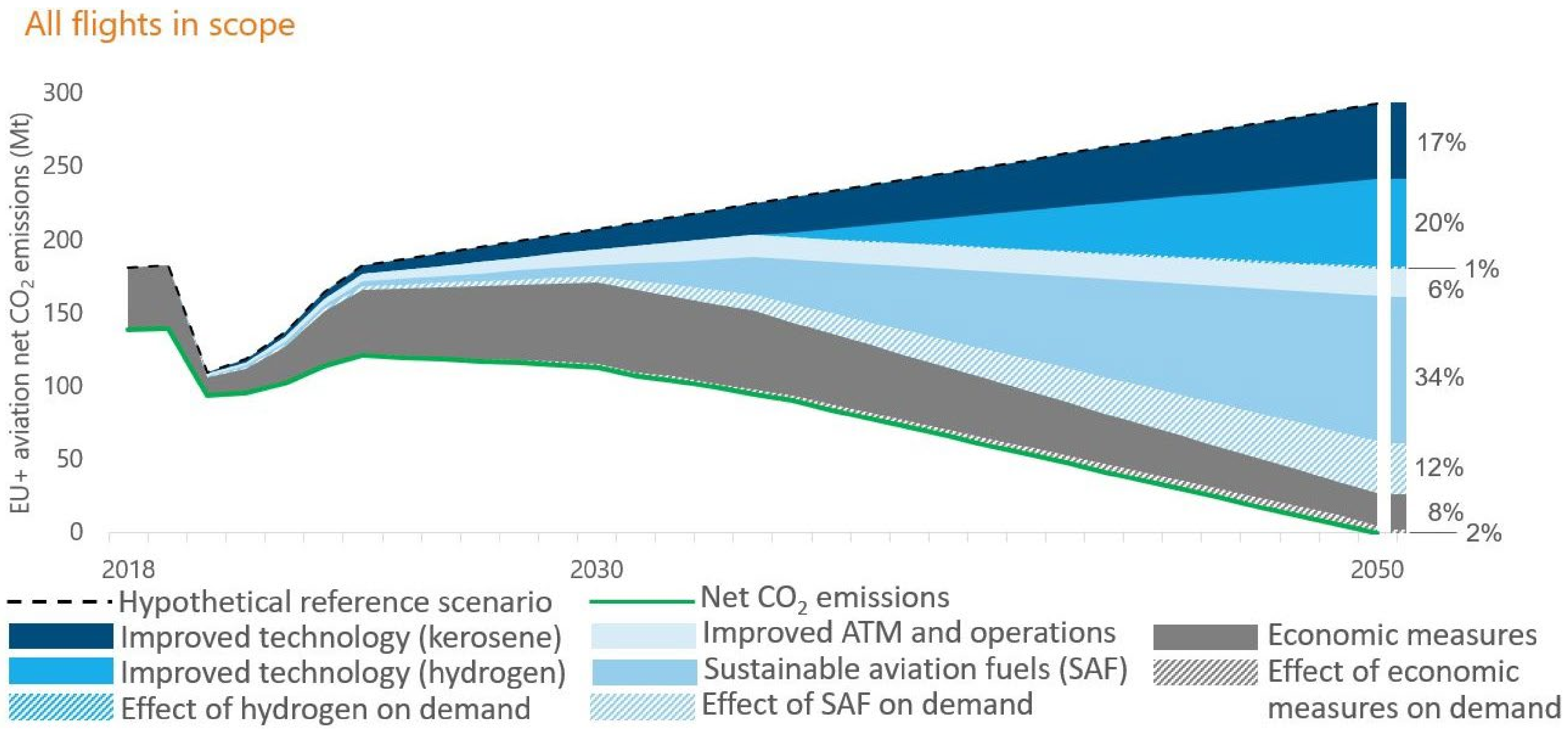
Aviation CO_2 Emissions in Transport by Mode 2020-2070





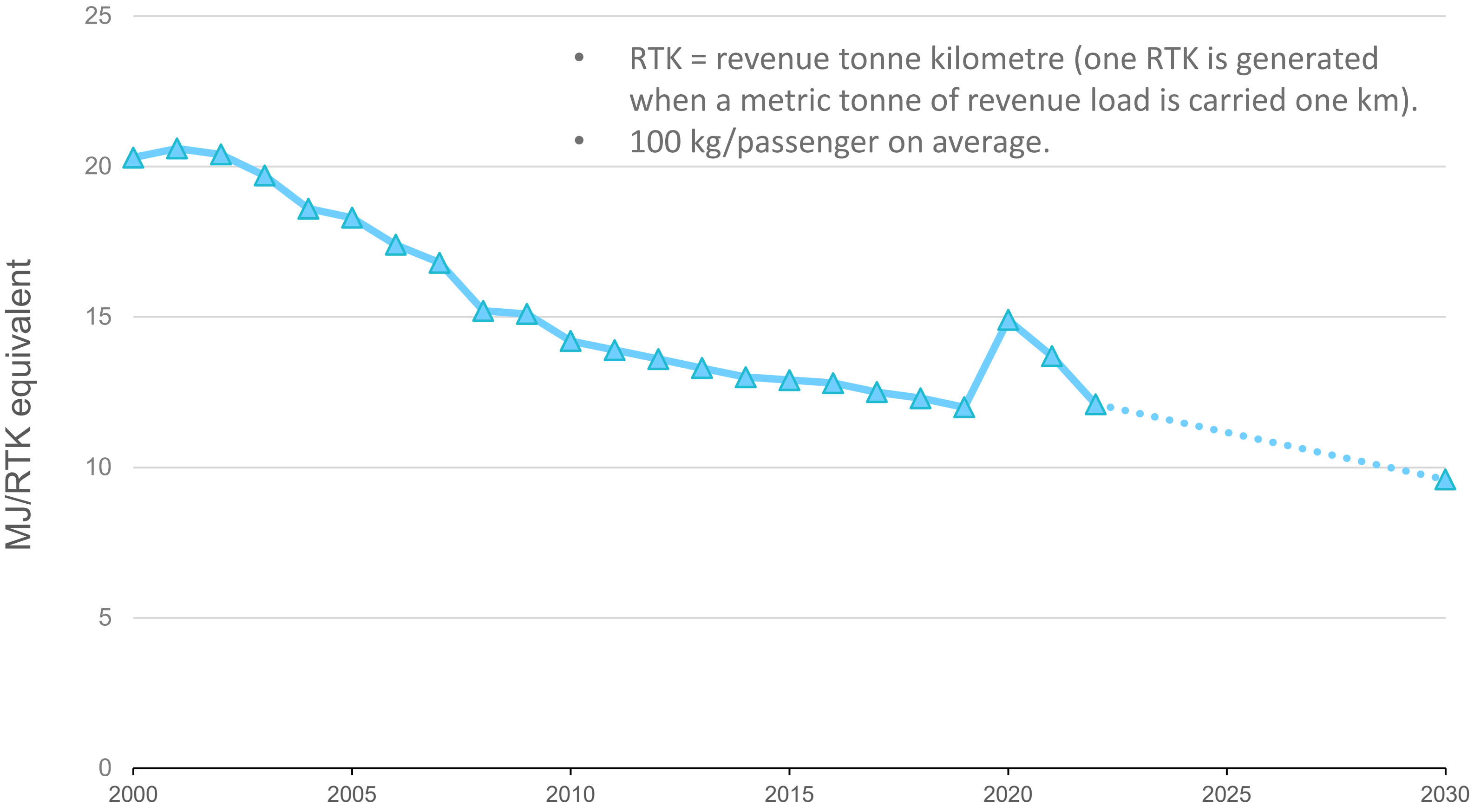
IEA, Global CO2 emissions in transport by mode in the Sustainable Development Scenario, 2000-2070, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-co2-emissions-in-transport-by-mode-in-the-sustainable-development-scenario-2000-2070, IEA. Licence: CC BY 4.0

Scenario to Aviation Net-Zero CO_2 Emissions in Europe



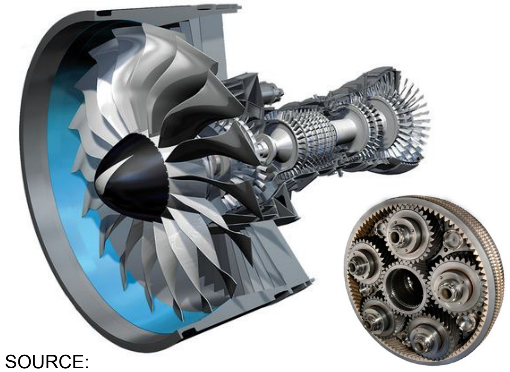
SOURCE: HTTPS://WWW.DESTINATION2050.EU/

Specific Energy Consumption Trend of Commercial Passenger Aviation 2020-2030



- RTK = revenue tonne kilometre (one RTK is generated when a metric tonne of revenue load is carried one km).
- 100 kg/passenger on average.

IEA, ENERGY INTENSITY OF COMMERCIAL PASSENGER AVIATION IN THE NET ZERO SCENARIO, 2000-2030, IEA, PARIS HTTPS://WWW.IEA.ORG/DATA-AND-STATISTICS/CHARTS/ENERGY-INTENSITY-OF-COMMERCIAL-PASSENGER-AVIATION-IN-THE-NET-ZERO-SCENARIO-2000-2030, IEA. LICENCE: CC BY 4.0



SOURCE: HTTPS://PRATTWHITNEY.COM/PRODUCTS-AND-SERVICES/PRODUCTS/COMMERCIAL-ENGINES/PRATT-AND-WHITNEY-GTF

<u>2010 – 2019:</u>

Average **fuel efficiency** per revenue tonne kilometre (RTK) equivalent travelled **improved by 1.8%** per year.

However, **demand growth was 5%** per year.

Non-CO$_2$ Emissions

Contrail cirrus formation
near Tropopause

SOURCE: HTTPS://WWW.YOUTUBE.COM/WATCH?V=EPA6WXEW1XK

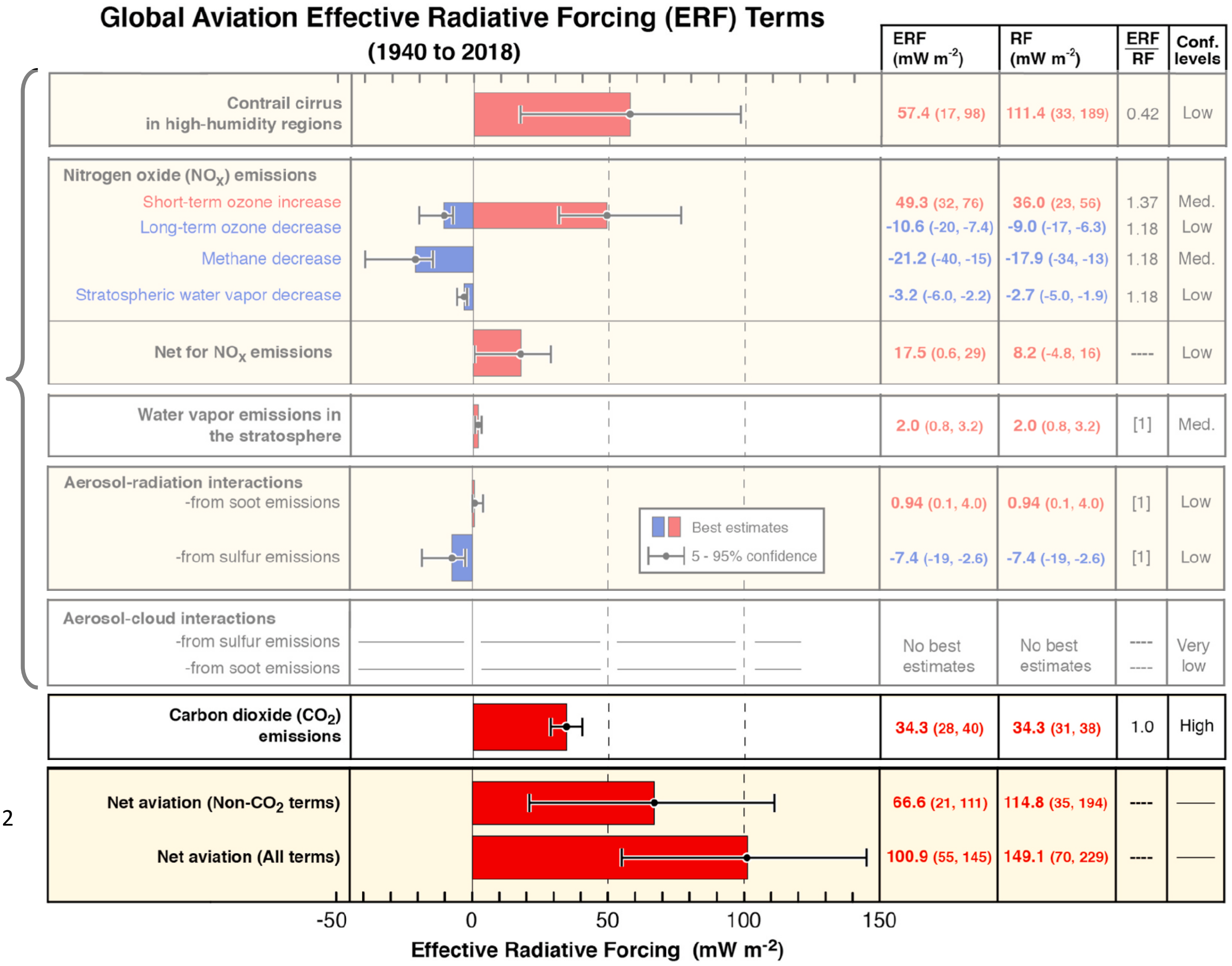
Aviation **non-CO$_2$** emissions have a **greater effect on global warming than CO$_2$**! Greatest contribution: **Aviation induced cloudiness**.

non-CO$_2$

CO$_2$

+ non-CO$_2$

= Total

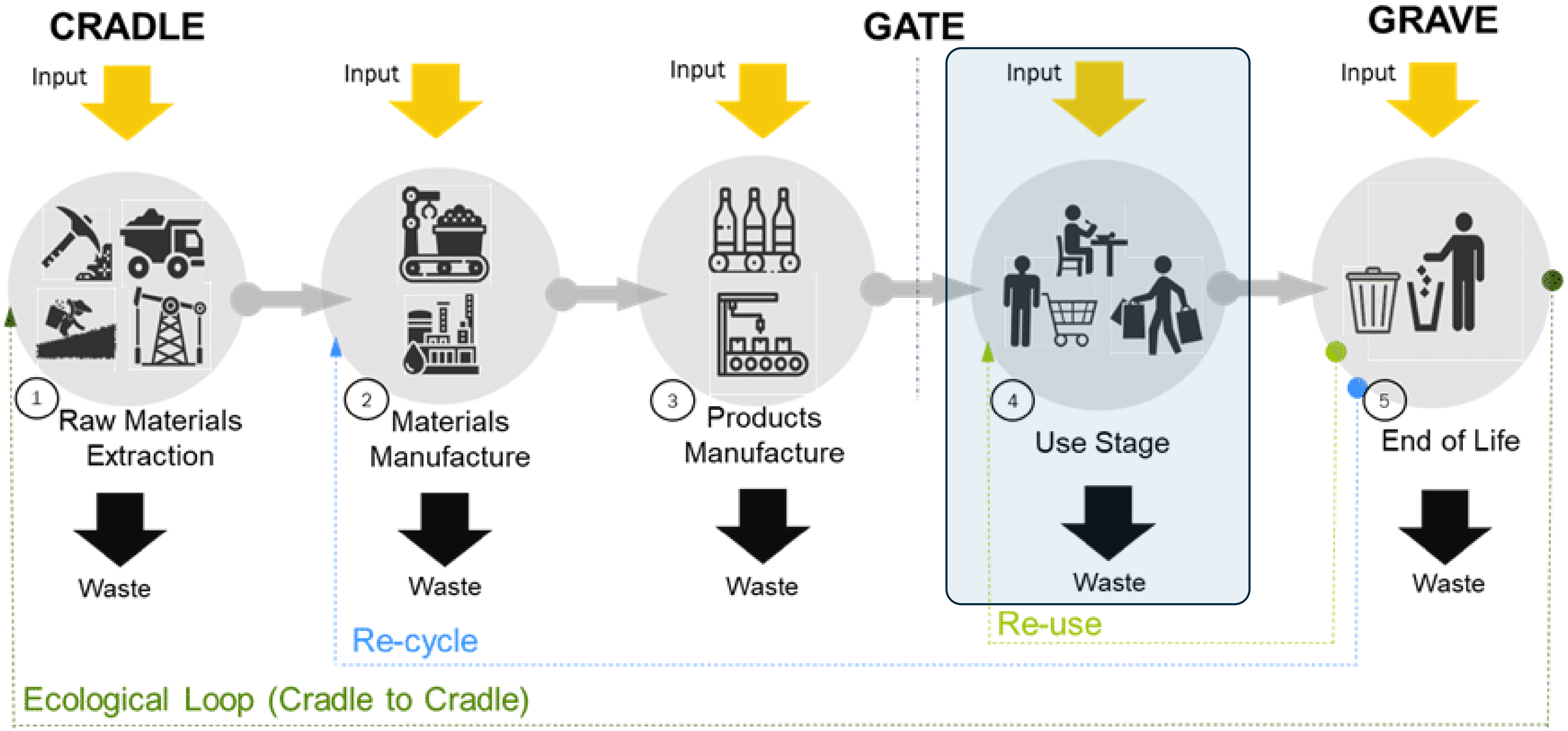


	ERF (mW m^{-2})	RF (mW m^{-2})	ERF / RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Nitrogen oxide (NO$_x$) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
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			----	
Carbon dioxide (CO$_2$) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
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)	----	——

SOURCE: LEE, D. S.; FAHEY, D. W.; SKOWRON, A.; ALLEN, M. R.; BURKHARDT, U.; CHEN, Q. ET AL. (2021): THE CONTRIBUTION OF GLOBAL AVIATION TO ANTHROPOGENIC CLIMATE FORCING FOR 2000 TO 2018 (244)**

Life Cycle Climate Impacts of Transport Aircraft

Aircraft operation is the most impactful stage in aviation regarding climate effects.



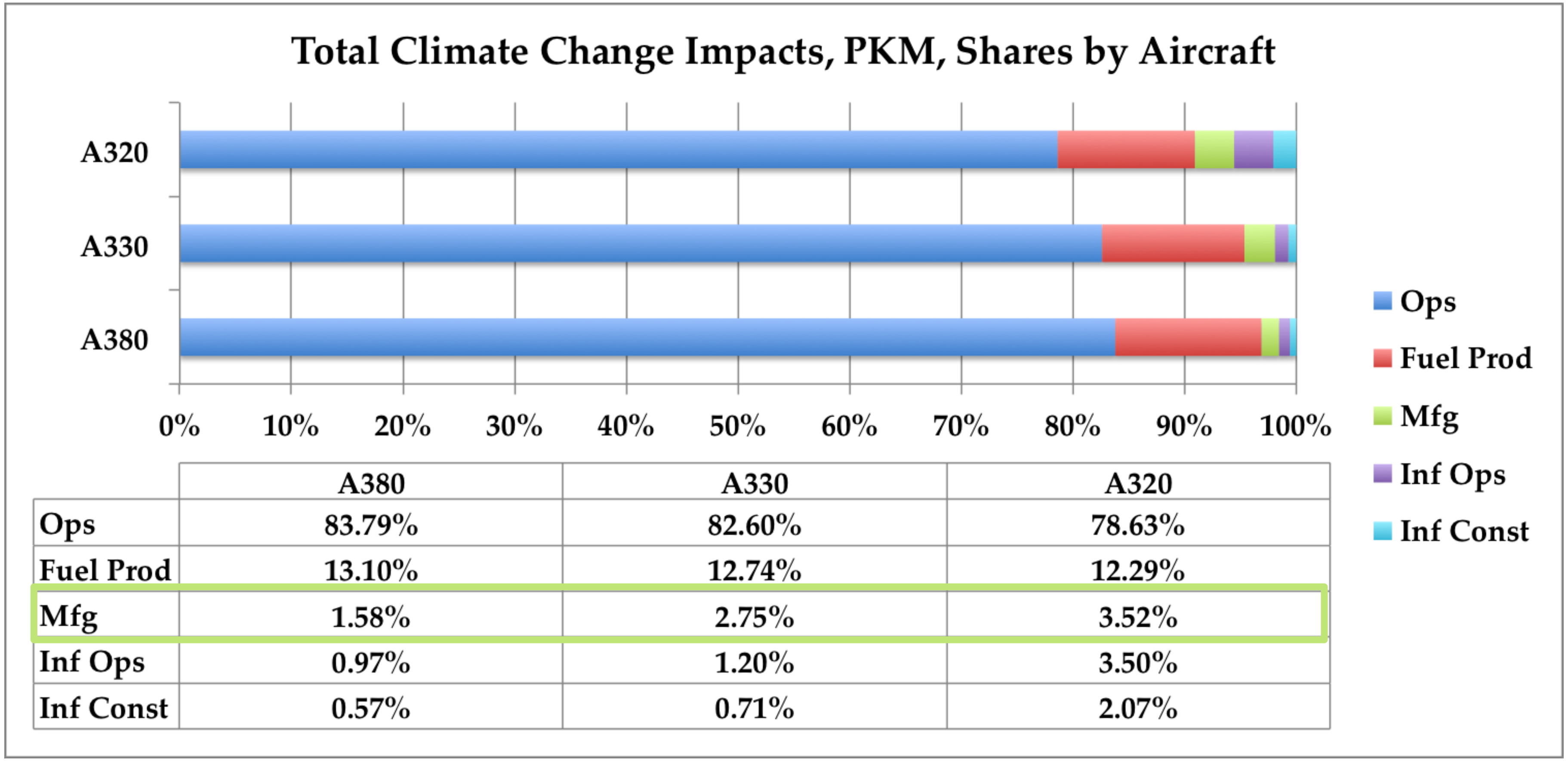
SOURCE: HTTPS://ECO-SOLUTISE.COM/LIFECYCLE-ASSESSMENT-LCA/

Life Cycle Climate Impacts of Transport Aircraft

PKM – Passenger Kilometre	Mfg - Manufacturing
Ops – Operations	Inf Ops - Infrastructure operation
Fuel Prod – Fuel Production	Inf Const - Infrastructure construction

Manufacturing and end of life processes only **contribute a minor fraction of life cycle climate impact** of aviation.

Aircraft operation dominates with **>95%** contributions.


Total Climate Change Impacts, PKM, Shares by Aircraft

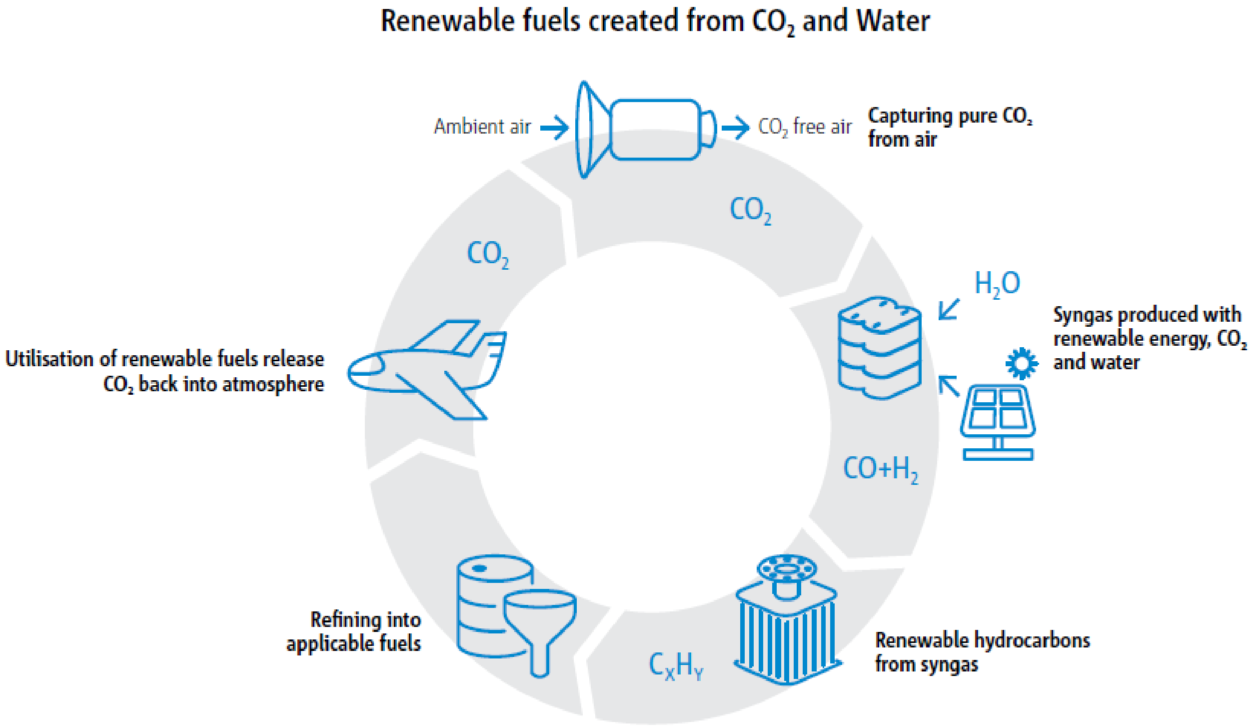
	A380	A330	A320
Ops	83.79%	82.60%	78.63%
Fuel Prod	13.10%	12.74%	12.29%
Mfg	1.58%	2.75%	3.52%
Inf Ops	0.97%	1.20%	3.50%
Inf Const	0.57%	0.71%	2.07%

„LEWIS - A LIFE CYCLE ASSESSMENT OF THE PASSENGER AIR TRANS.PDF“. ZUGEGRIFFEN: 14. DEZEMBER 2023. [ONLINE]. VERFÜGBAR UNTER: HTTPS://NTNUOPEN.NTNU.NO/NTNU-XMLUI/BITSTREAM/HANDLE/11250/235319/654869_FULLTEXT01.PDF

Sustainable Aviation Fuels

Drop-in SAF (Hydrocarbon Fuel)

- **Drop-in SAF** will play a key part in decarbonising the aviation sector as they **can be used within the existing global fleet and fuel** supply **infrastructure**.
- **Currently** certified **SAF maximum blending** ratio: **50%** (objective for 2030: 100%)
- The following four **production pathways** are expected to play a major role:
  - Hydroprocessed Esters and Fatty Acids (HEFA)
  - Alcohol-to-Jet (AtJ)
  - Biomass Gasification + Fischer-Tropsch (Gas+FT)
  - Power-to-Liquid (PtL)

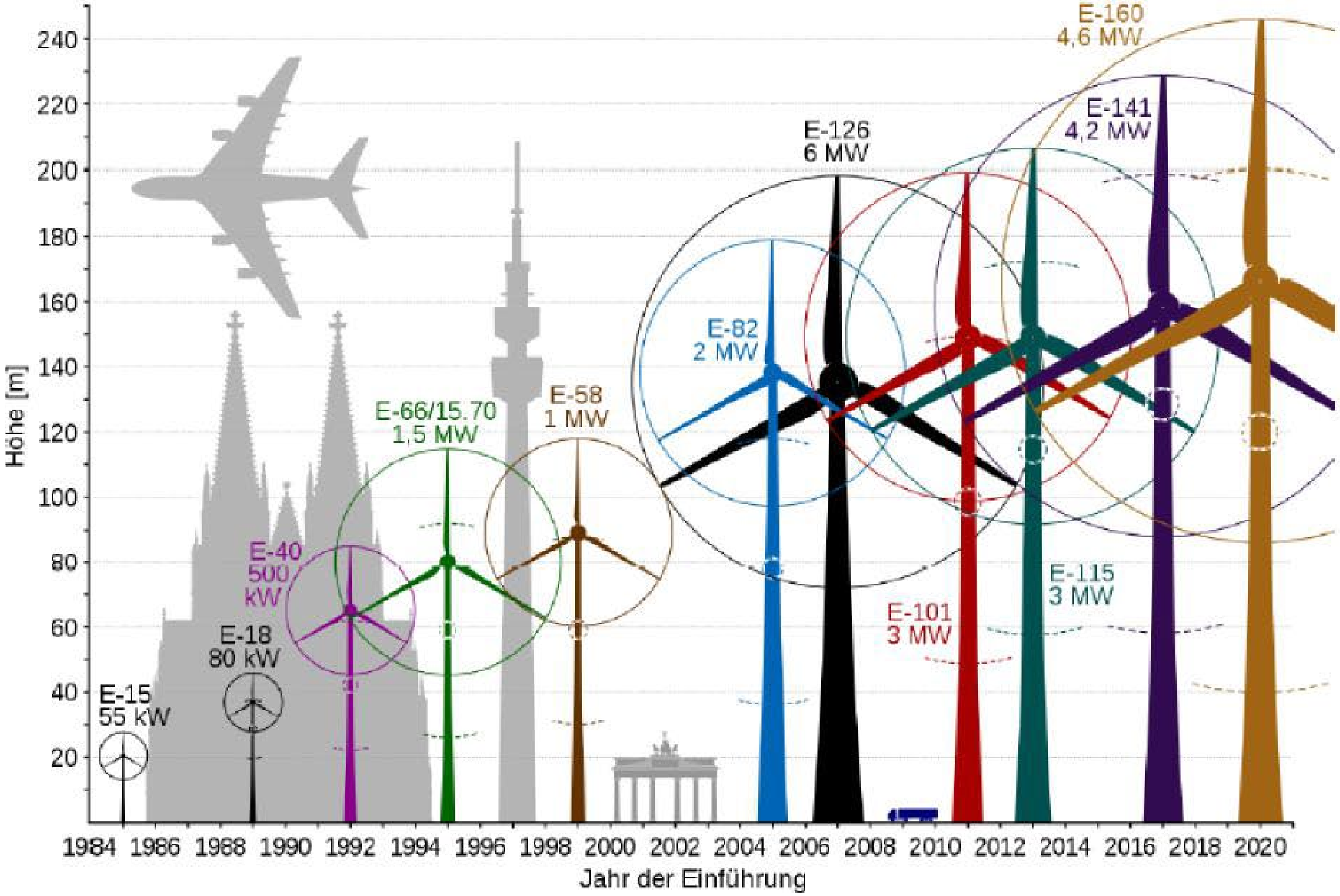


Carbon cycle in producing PtL SAF

SOURCE: EUROPEAN AVIATION ENVIRONMENTAL REPORT 2022, DOI: 10.2822/04357

Refueling an A350 Once per Day - Can Be Done with 52 Big Wind Power Plants (4.6 MW Each)

PtL!

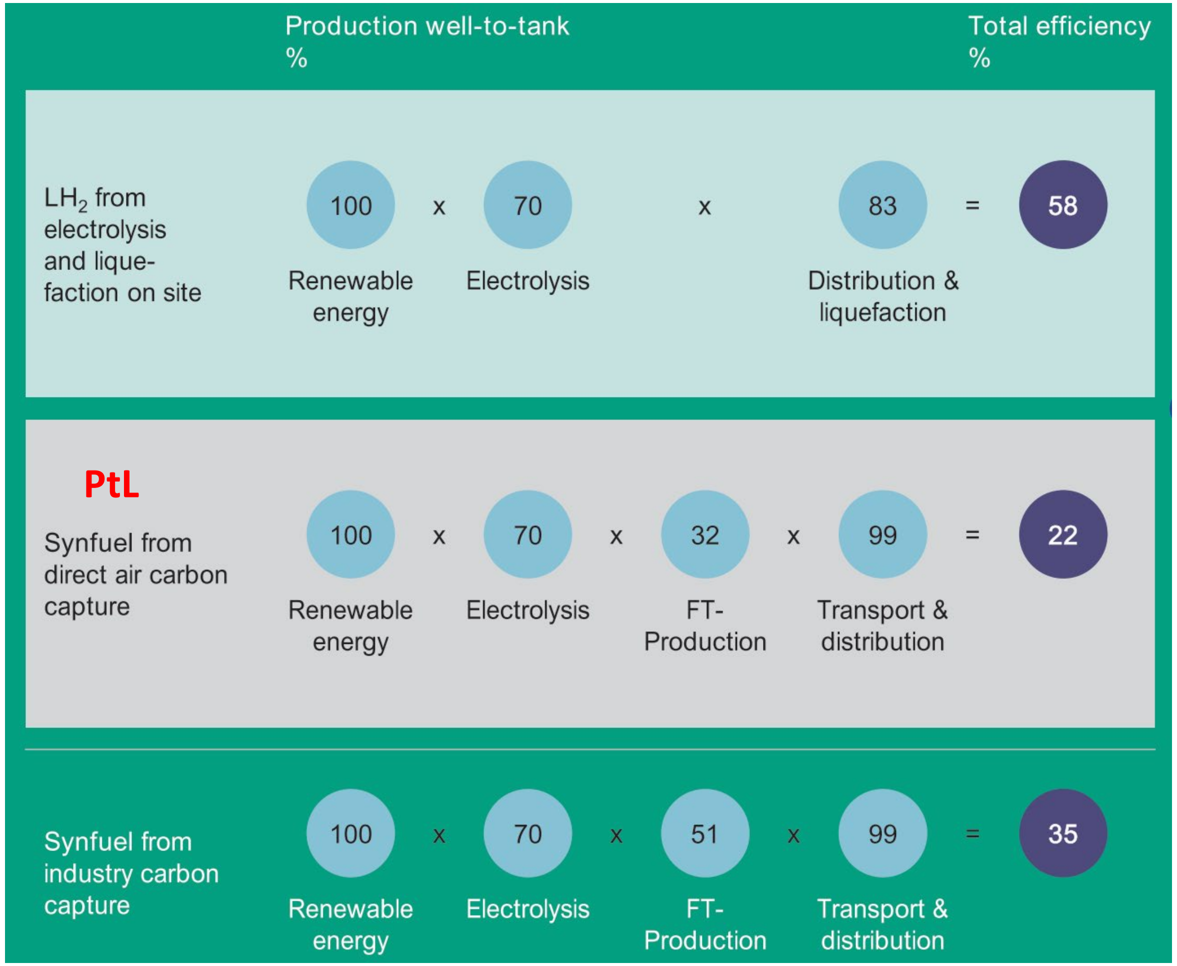


SOURCE: SCHOLZ, DIETER. DESIGN OF HYDROGEN PASSENGER AIRCRAFT. AERO LECTURES, HAW HAMBURG, 19.11.2020, HTTPS://DOI.ORG/10.5281/ZENODO.4301104

Airbus A350-900:
Fuel capacity: 138.000 L
1 x Refuel per day
is equivalent to
52 x E-160 4,6 MW
(total PtL efficiency = 22%)

Required **global renewable energy capacity** as compared to today for aviation sector **decarbonization via PtL Synfuel: 4x – 5x**

Energy Requirement and Efficiency of LH2 Compared to Synfuels



	Production well-to-tank %								Total efficiency %
LH_2 from electrolysis and lique-faction on site	100 Renewable energy	x	70 Electrolysis			x	83 Distribution & liquefaction	=	58
PtL Synfuel from direct air carbon capture	100 Renewable energy	x	70 Electrolysis	x	32 FT-Production	x	99 Transport & distribution	=	22
Synfuel from industry carbon capture	100 Renewable energy	x	70 Electrolysis	x	51 FT-Production	x	99 Transport & distribution	=	35

SOURCE: MCKINSEY & COMPANY; CLEAN SKY 2 JOINT UNDERTAKING; FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (2020): HYDROGEN-POWERED AVIATION. A FACT-BASED STUDY OF HYDROGEN TECHNOLOGY, ECONOMICS, AND CLIMATE IMPACT BY 2050. FIRST EDITION. LUXEMBOURG: PUBLICATIONS OFFICE OF THE EUROPEAN UNION. HTTPS://DOI.ORG/10.2843/471510

- Total efficiencies = “**well-to-tank**” efficiencies
- **CO_2 air capture (PtL)**: Energy to produce and distribute an LH_2 energy-equivalent amount of Synfuel: **3x**
- **CO_2 is captured from biomass or industrial processes**: Energy to produce and distribute an energy-equivalent amount of synfuel compared to LH_2: **2x**

Note: Hydrogen promotors (CS2JU+FCH2JU) point of view!

Some Alternative Numbers for Drop-In SAF: AVL Synfuel Process

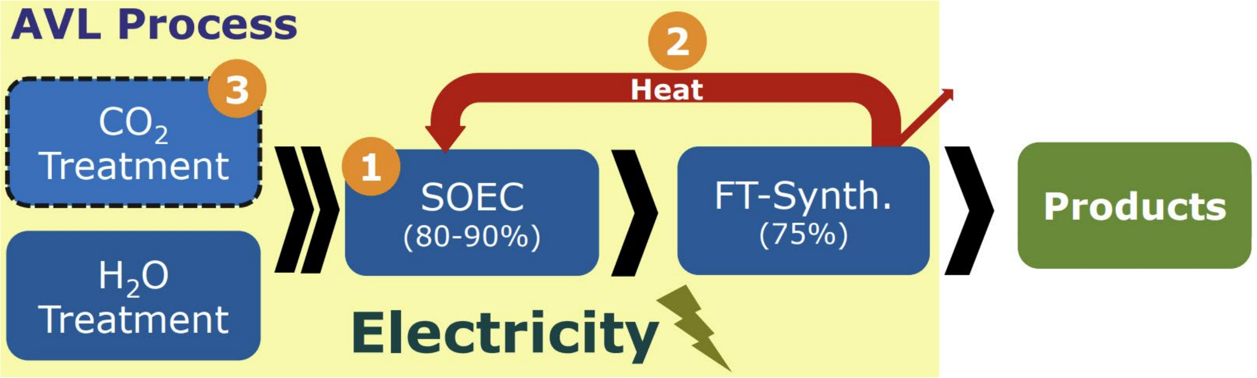
Assumption: CO_2 from biomass or industrial processes carbon capture

Conventional Approach

100	x	70	x	51	x	99	=	35
Renewable energy		Electrolysis		FT-Production		Transport & distribution		

AVL List Approach

100	x	85	x	75	x	99	=	63
Renewable energy		Electrolysis		FT-Production		Transport & distribution		



1. High-temperature electrolysis
2. Thermal Coupling
3. Co-electrolysis

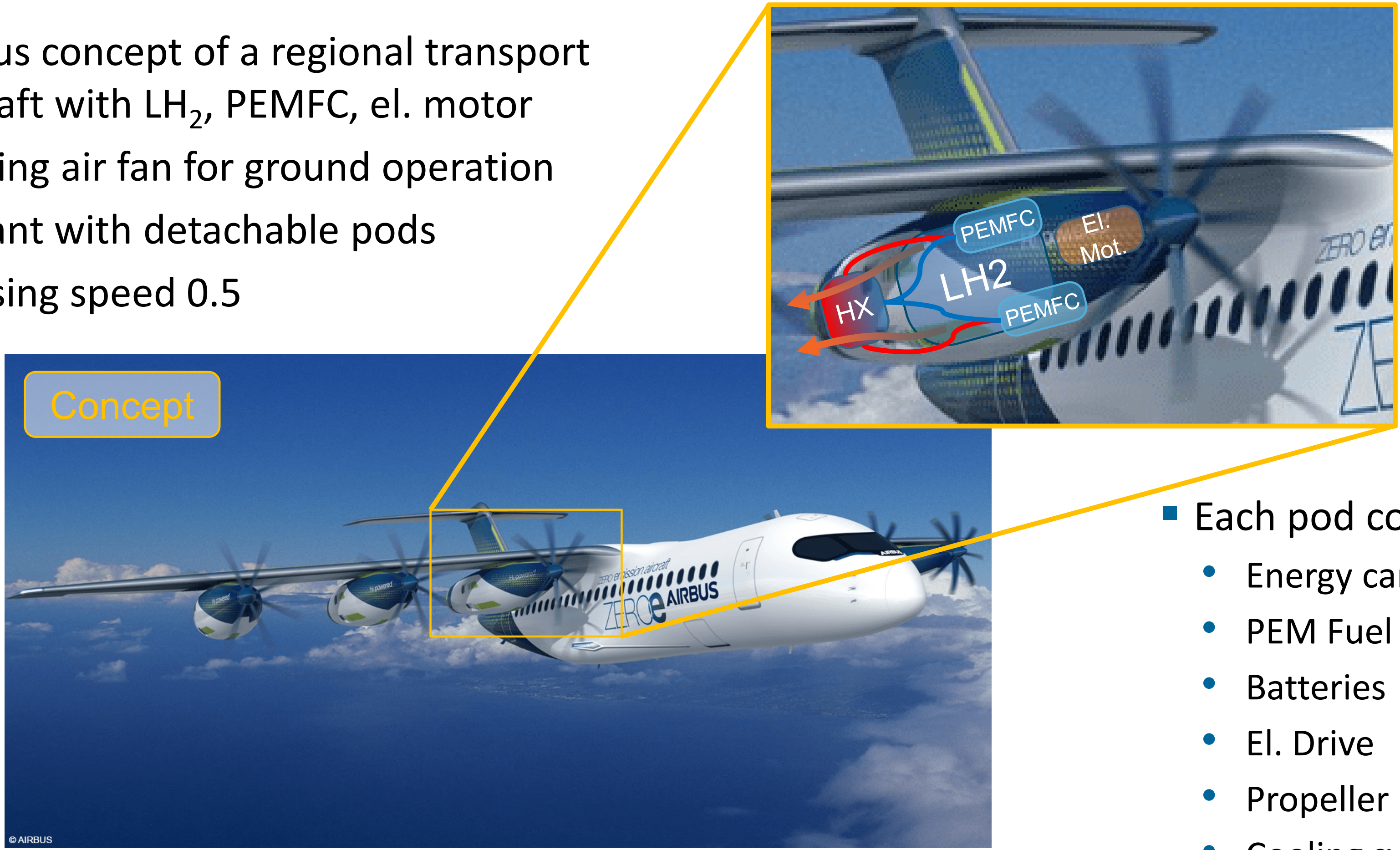
If industry decarbonisation progresses, the availability of concentrated CO_2 sources reduces. Hence, the amount of Synfuels to be made via the direct air CO_2 capture (PtL) pathway increases with time.

SOURCE: AVL LIST GMBH:
HTTPS://WWW.IEA-AMF.ORG/APP/WEBROOT/FILES/FILE/WORKSHOP_TASK63/10_SCHAUPERL_AVL%20LIST_EFFIZIENTERE%20HERSTELLUNG%20VON%20SAF%20UBER%20HOCHTEMPERATURELEKTROLYSE.PDF

PEM Fuel Cells - Heat Dissipation or Heat Utilisation?

Hydrogen Fuel Cell Electric Aircraft Propulsion

- Airbus concept of a regional transport aircraft with LH_2, PEMFC, el. motor
- Cooling air fan for ground operation
- Variant with detachable pods
- Cruising speed 0.5



Source: https://www.electrive.net/2021/01/04/zeroe-airbus-zeigt-studie-mit-bz-propellerantrieben/

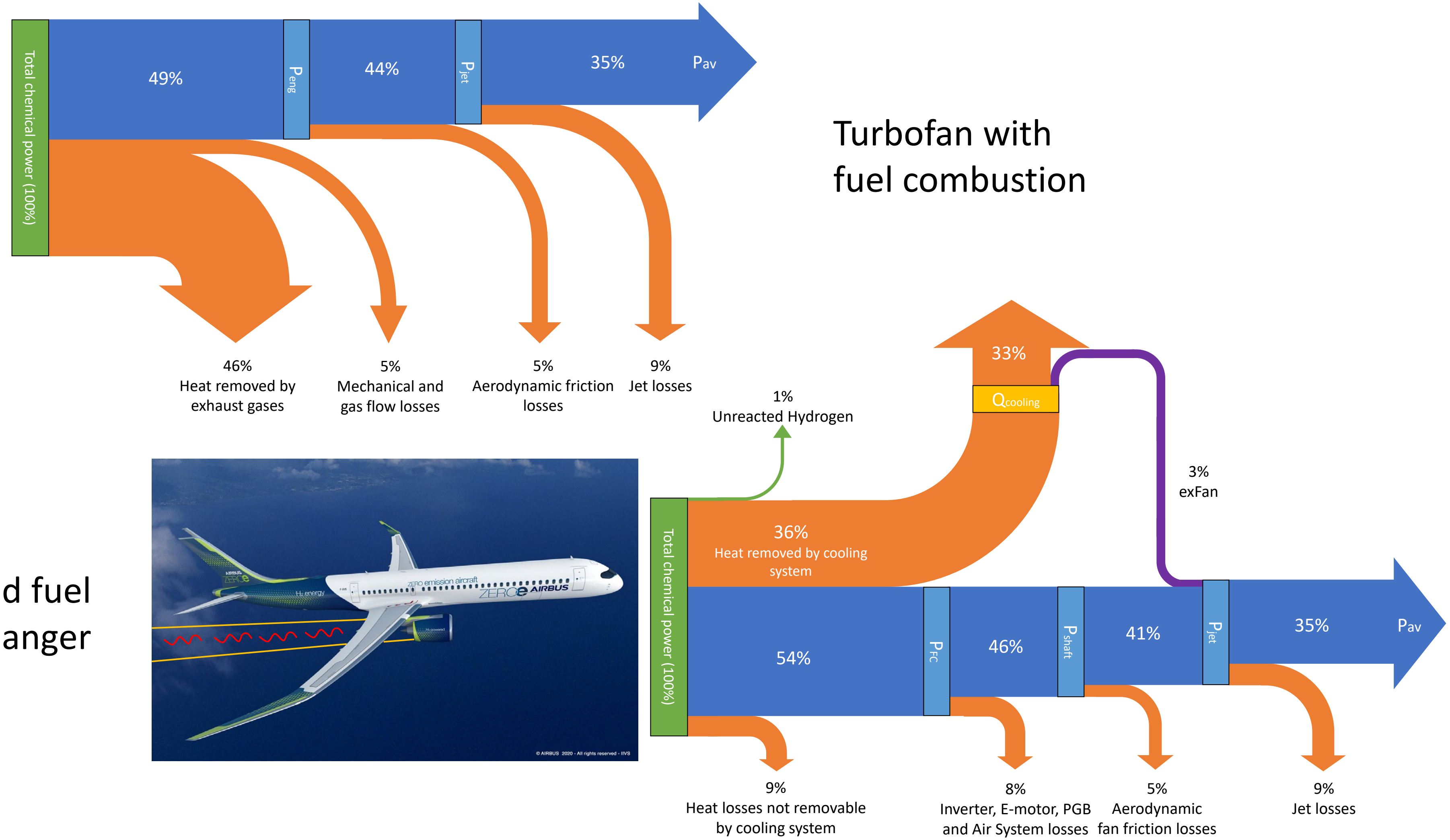
- Advantages:
  - Zero op. CO_2 emissions
  - Zero NO_x emissions
  - Low- Noise el. propeller drive (but potentially additional noise from thermal management system)

- Each pod comprises:
  - Energy carrier: LH_2
  - PEM Fuel Cells (PEMFC)
  - Batteries
  - El. Drive
  - Propeller
  - Cooling system

Exploration of the design space to identify optimal conditions for alternative propulsion system operation.

PEM Fuel Cells - Heat Dissipation or Heat Utilisation?


© GE Aviation

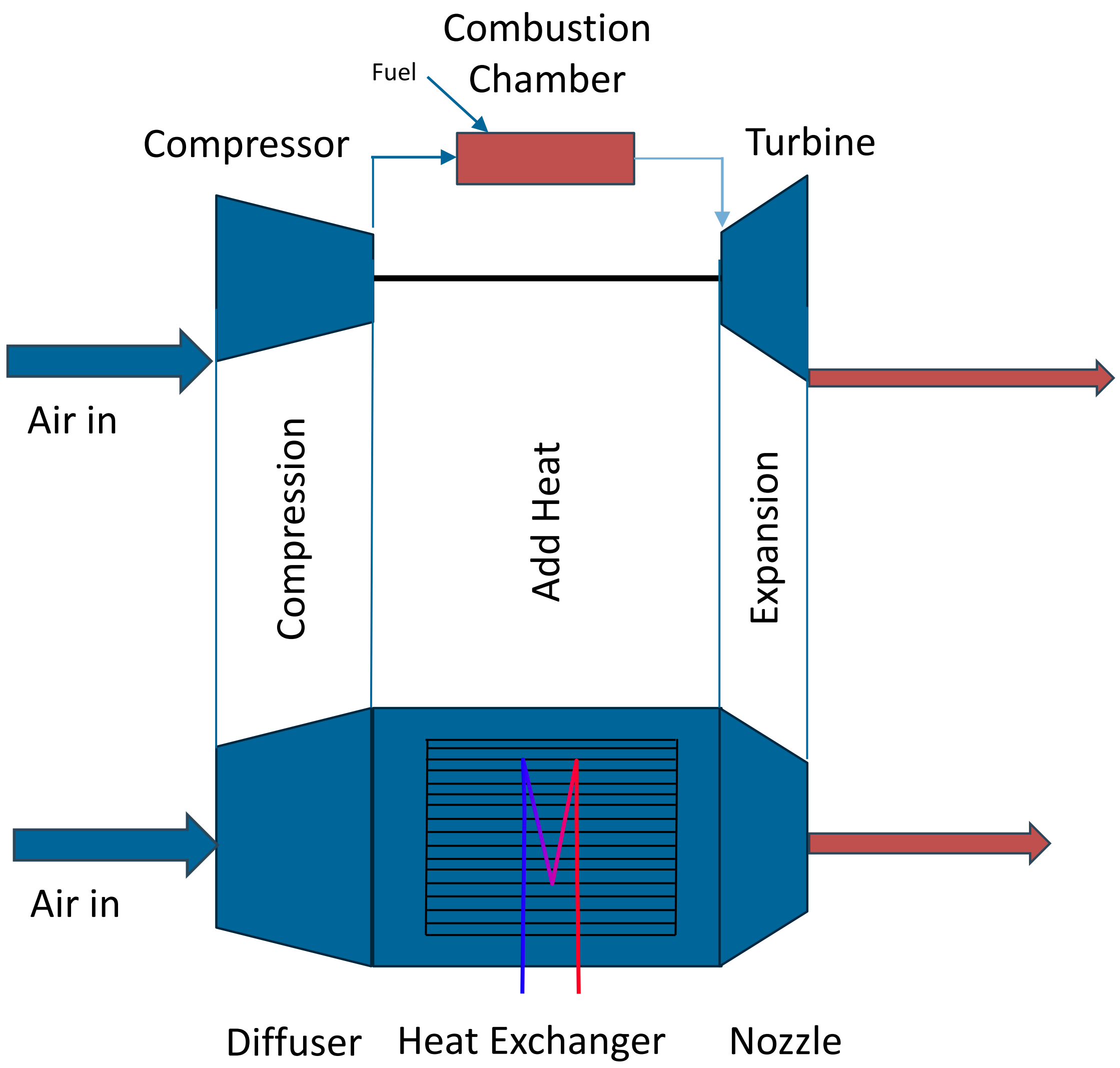


Turbofan with fuel combustion

El. impeller with integrated fuel cell cooling heat exchanger

PEM Fuel Cells - Heat Dissipation or Heat Utilisation?

The Brayton Cycle



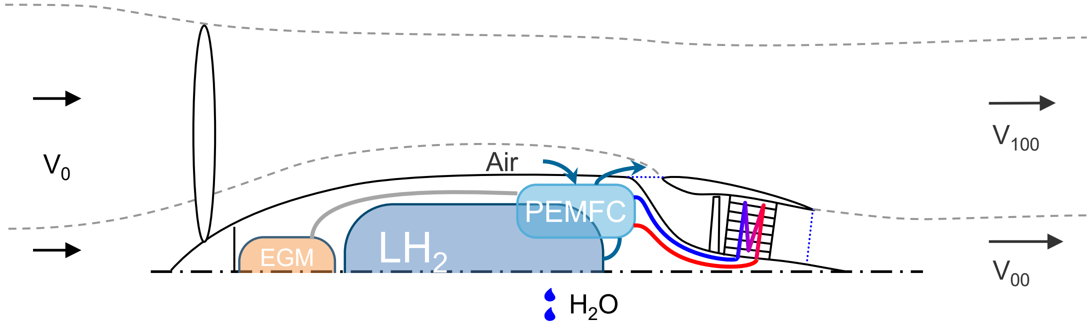
Functional principle is similar to a jet engine

- Compression ratio in jet engine is higher allowing higher cycle efficiencies
- This **ramjet** type uses no additional fuel but heat from various sources

PEM Fuel Cells - Heat Dissipation or Heat Utilisation?

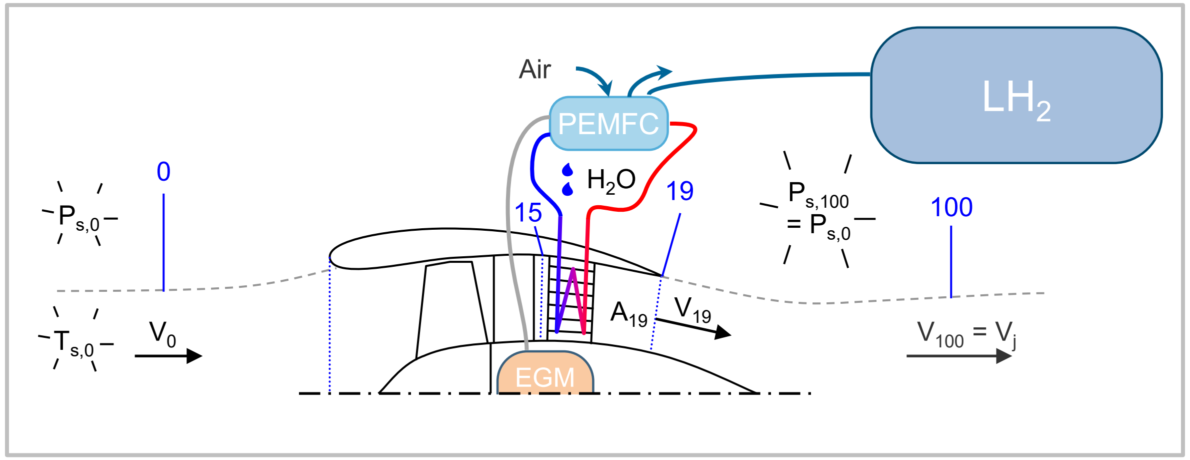
Propeller and Impeller Variants

AIRBUS Nacelle-integrated Propulsion System



Intermediate Variants

Fan-Stage with EGM and Heat Exchanger



EGM - Electric Geared Motor

PEMFC - Polymer Electrolyte Membrane Fuel Cell

LH_2 – Liquefied Hydrogen

Note: Depending on systems design assumptions, the relative size of components may differ from those indicated in the sketches!

PEM Fuel Cells - Heat Dissipation or Heat Utilisation?

Assumptions

$\eta_{f,p} = 0.9$	Polytropic Fan-Efficiency
$\eta_{EGM} = 0.95$	Efficiency of EGM*
$\eta_{FC} = 0.5$	PEMFC electric Efficiency
$\eta_{prop} = 0.8$	Propulsive Efficiency
⇨ $V_j/V_0 = 1.5$	Ratio of Jet-to-Freestream Velocity
m = 66 t	Aircraft Gross Mass
L/D = 18	Aircraft Lift-to-Drag ratio

$q_0 = 9639\ \mathrm{N/m^2}$	Freestream Dynamic Pressure
$T_{hx,w,max} = 60°\mathrm{C}$	Maximum Liquid Coolant Temperature
$\zeta_{hx,ref} = 0.5$	Pressure Loss Coefficient HX
$M_{hx} = 0.2$	Average HX Mach No

Scaling of Pressure Loss Coefficients HX

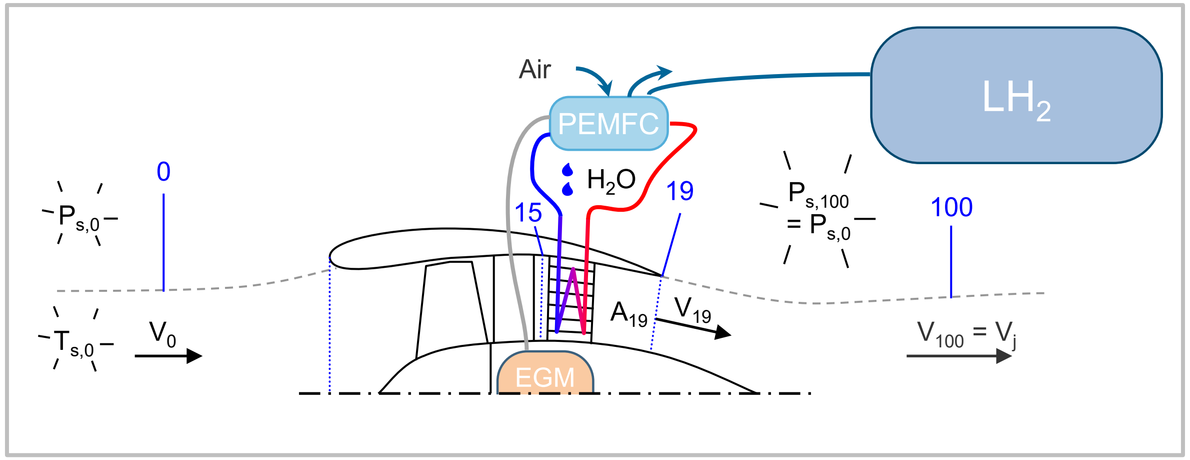
$$\frac{\zeta_{hx}}{\zeta_{hx,ref}} = \frac{P_{ref} \cdot T_{s,hx}}{P_{s,hx} \cdot T_{ref}}$$

$P_{ref} = 101325\ \mathrm{N/m^2}$

$T_{ref} = 288.15\ \mathrm{K}$

Index: hx – heat exchanger

El. Fan-Stage with Heat exchanger



* EGM = Power Gearbox + E-Motor + Drive Unit (Inverter)

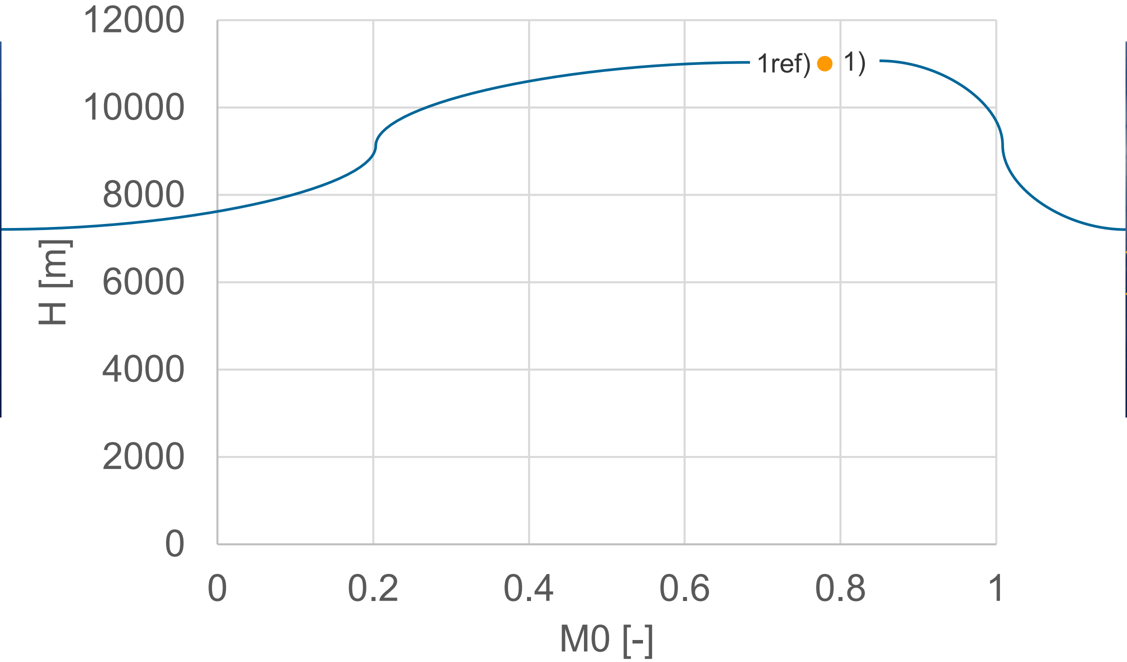
PEM Fuel Cells - Heat Dissipation or Heat Utilisation?

Assumptions (contn‘d)

Reference

1ref) - Notional surface Heat Exchanger

⇨ Assumption of no heat rejection effects on thrust & drag



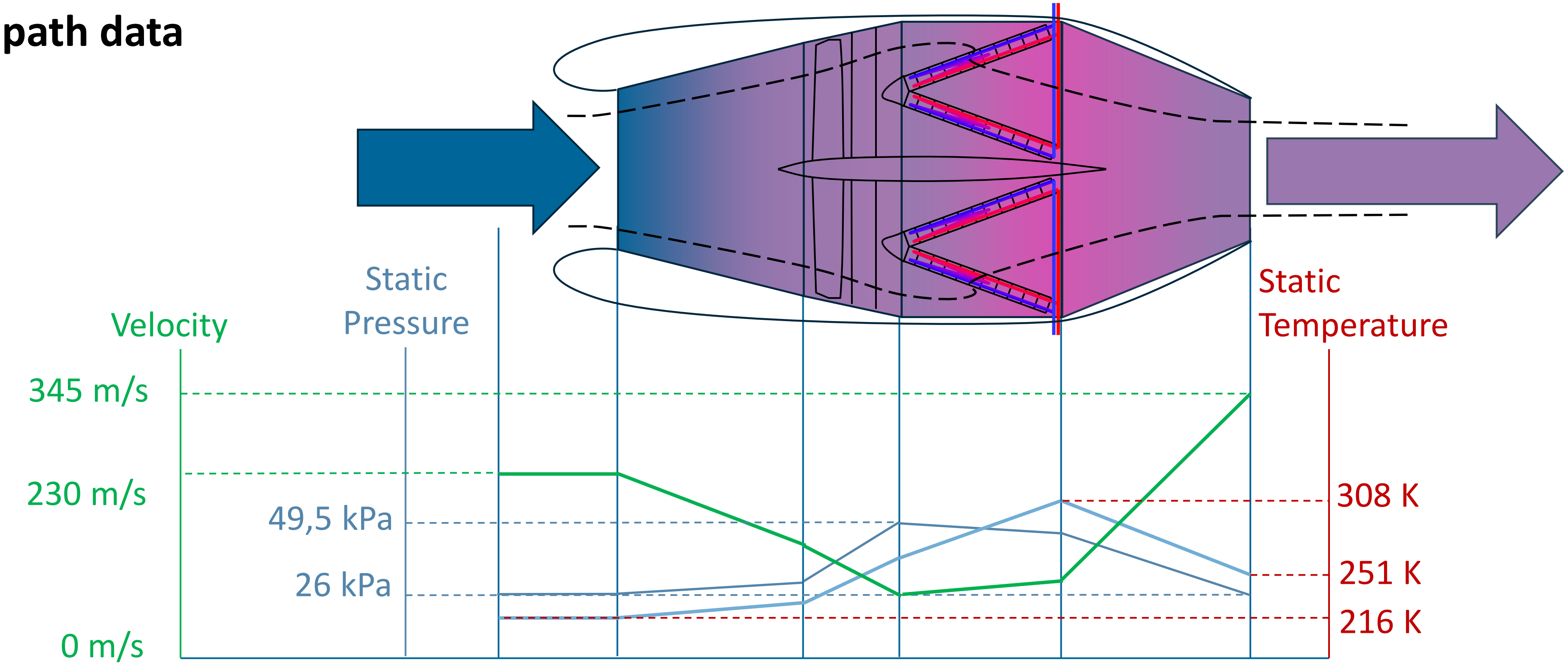
exFan

1) Heat Exchanger integrated in the Fan Duct

⇨ Heat rejection effects on thrust & drag w.r.t. reference

PEM Fuel Cells - Heat Dissipation or Heat Utilisation?

Results: exFan sketch and flow path data



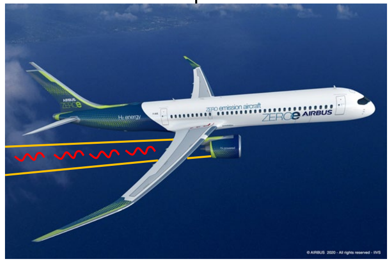
Data curves show development of average annular duct properties.

PEM Fuel Cells - Heat Dissipation or Heat Utilisation?

Results (contn‘d)

Thermal Efficiency Increment

$\Delta\eta_{th} = \eta_{th} - \eta_{th,ref}$



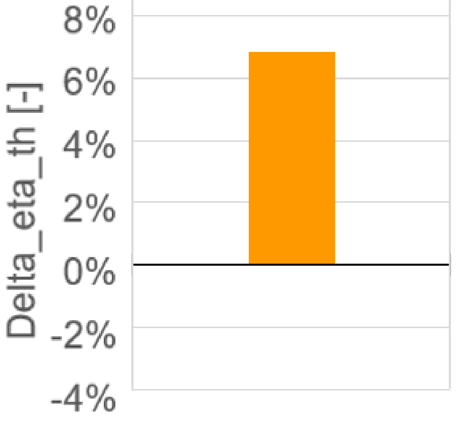
$$\eta_{th} = \frac{P_{j,add}}{P_{H2}}$$

$$\eta_{th,ref} = \left(\frac{P_{j,add}}{P_{H2}}\right)_{ref}$$

$$P_{j,add} = \frac{1}{2}\dot{m}\left(V_j^2 - V_0^2\right)$$

$P_{j,add}$ – Increment of kinetic jet power

Config.:	1
FPR:	1.46
$FNPR$:	2.10
ζ_{HX}:	1.06
H:	11000 m
M_0:	0.78



FPR	Fan total pressure ratio
FNPR	Fan nozzle pressure ratio
ζ_{HX}	Heat exchanger airside loss coefficient w.r.t. upstream HX dynamic pressure

⇦ Note: Percentage points with respect to H_2 chemical power!

- The **efficiency of conversion of heat into useful propulsive power depends on** overall compression ratio (**FNPR**) due to ram effect and the fan!*
- The **efficiency of the propulsion system depends on** an **advantageous tradeoff between heat added** to the fan flow (+ve) **and HX pressure losses** (-ve).

* J. V. BECKER und D. D. BAALS, „The Aerodynamic Effects of Heat and Compressibility in Internal Flow Systems, and High-Speed Tests of a Ram-jet System.“, NACA Rept. 773, 1943.

How to close the circle?

The **technology** for an aviation energy carrier (AEC) circular economy **is available**.

Drop-In SAF production is **currently** largely based on **biomass as feedstock**. This kind of feedstock will **not** be **sufficient** to decarbonize aviation at today's scale of operations.

Research in energy efficient production pathways, particularly for the **PtL** approach is ongoing.

Europe will further depend on **energy imports**. Transition from import of fossil to renewable energy.

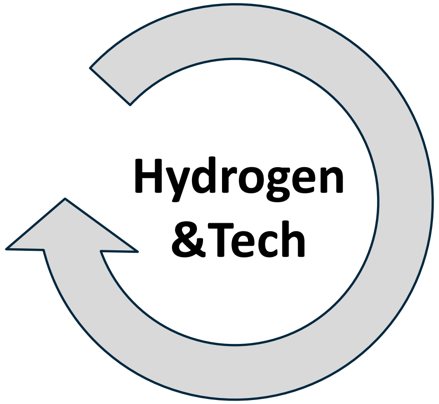
The **blending mandate** in Europe - ReFuelEU Initiative - sets ambitious targets to airlines, airports and fuel suppliers to ramp up SAF production capacities including PtL.

Implementation: **Ramp-up of production** capacities needed.

How to close the circle?

Green hydrogen may be **produced with lesser energy effort** compared to hydrocarbons. Combined with scaled up utilization of hydrogen as energy carrier in other sectors, it may become a viable AEC.

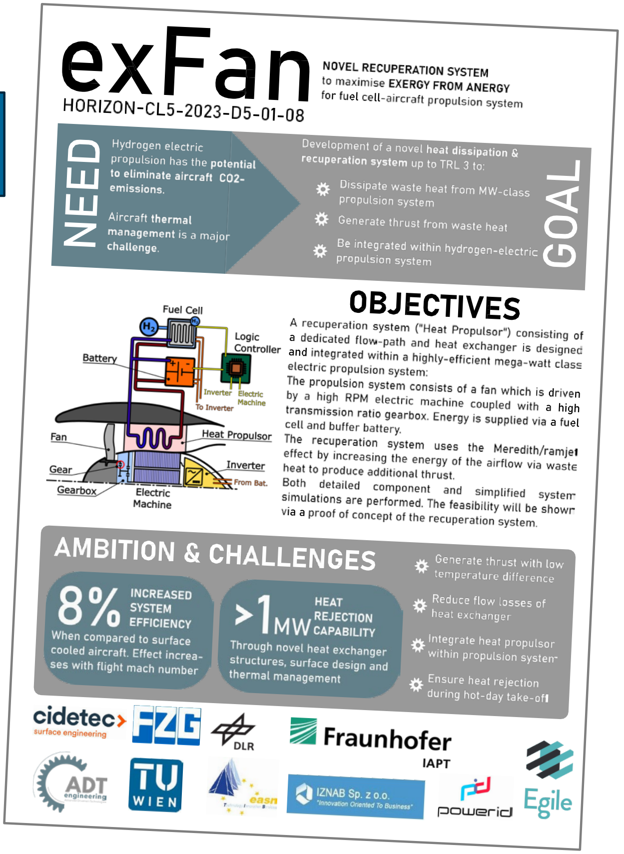
Research, simulation, **technology** development, testing and demonstration will provide **evidence** about risks, drawbacks but also opportunities and synergies of hydrogen technologies in aviation.



As of today, **little practical experience has been gained with hydrogen operation** apart from small aircraft demonstrators, drones and a few large-scale tests in the 1980’s.

Knowledge about hydrogen technologies in aviation **is not yet sufficient** to draw conclusions!

Funded by
the European Union



exFan

NOVEL RECUPERATION SYSTEM
to maximise **EXERGY FROM ANERGY**
for fuel cell-aircraft propulsion system

HORIZON-CL5-2023-D5-01-08

NEED

Hydrogen electric propulsion has the **potential to eliminate aircraft CO2-emissions.**

Aircraft **thermal management** is a major **challenge.**

GOAL

Development of a novel **heat dissipation & recuperation system** up to TRL 3 to:

- Dissipate waste heat from MW-class propulsion system
- Generate thrust from waste heat
- Be integrated within hydrogen-electric propulsion system

OBJECTIVES

A recuperation system ("Heat Propulsor") consisting of a dedicated flow-path and heat exchanger is designed and integrated within a highly-efficient mega-watt class electric propulsion system:
The propulsion system consists of a fan which is driven by a high RPM electric machine coupled with a high transmission ratio gearbox. Energy is supplied via a fuel cell and buffer battery.
The recuperation system uses the Meredith/ramjet effect by increasing the energy of the airflow via waste heat to produce additional thrust.
Both detailed component and simplified system simulations are performed. The feasibility will be shown via a proof of concept of the recuperation system.

AMBITION & CHALLENGES

8% INCREASED SYSTEM EFFICIENCY
When compared to surface cooled aircraft. Effect increases with flight mach number

>1MW HEAT REJECTION CAPABILITY
Through novel heat exchanger structures, surface design and thermal management

- Generate thrust with low temperature difference
- Reduce flow losses of heat exchanger
- Integrate heat propulsor within propulsion system
- Ensure heat rejection during hot-day take-off

„The challenges of the industry are huge, but so are the opportunities.“

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