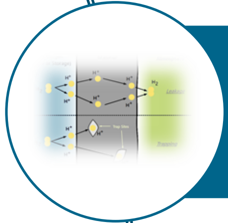
OVERVIEW OF SAFETY CHALLENGES ASSOCIATED WITH INTEGRATION OF HYDROGEN-BASED PROPULSION SYSTEMS FOR CLIMATE NEUTRAL AVIATION

Dimitrios Dimos, Stefanie de Graaf, Lars Enghardt

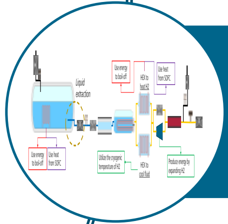
Institute of Electrified Aero Engines, Cottbus

Outline

- Motivation



- Challenges on Component and System Level

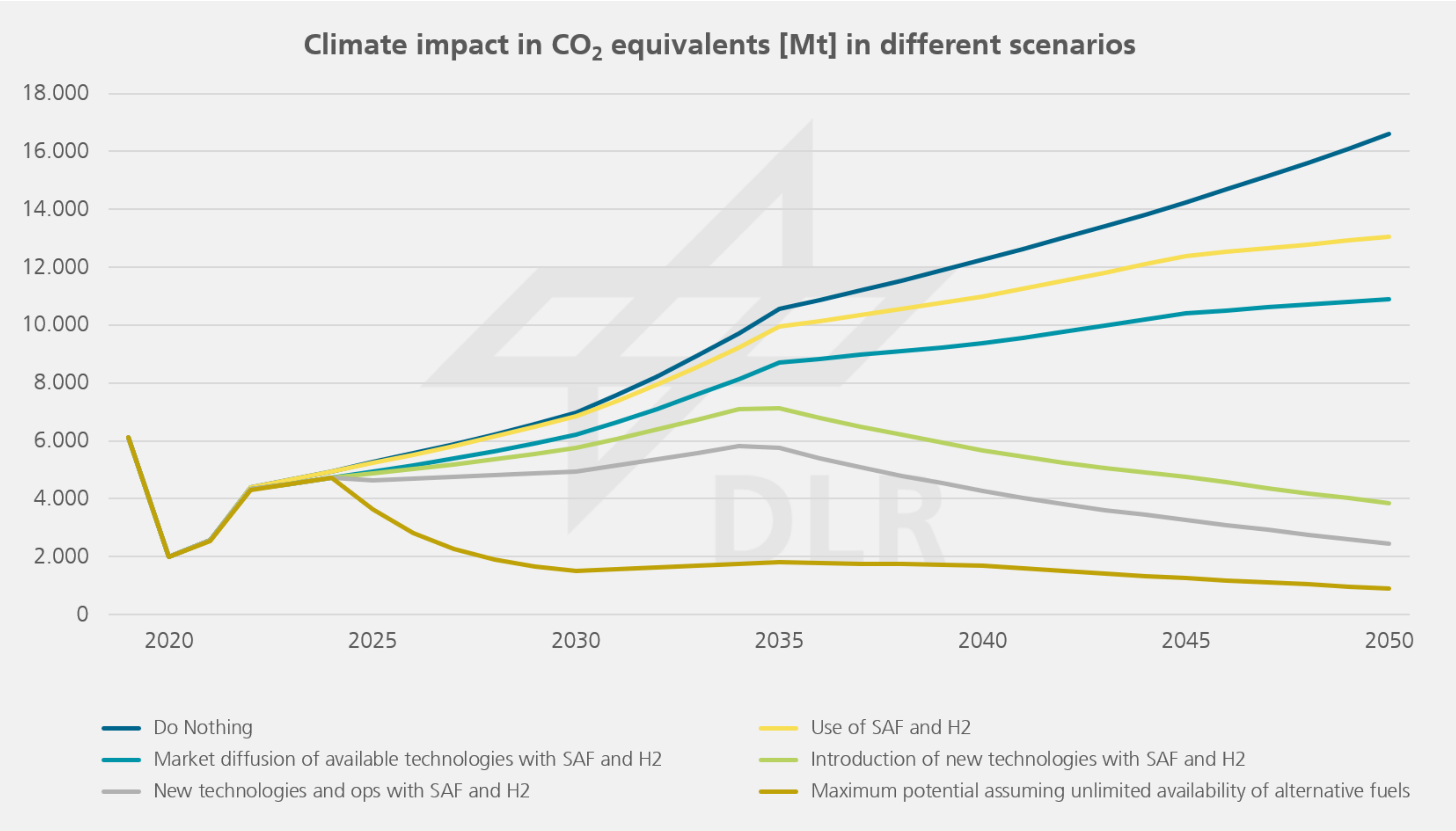


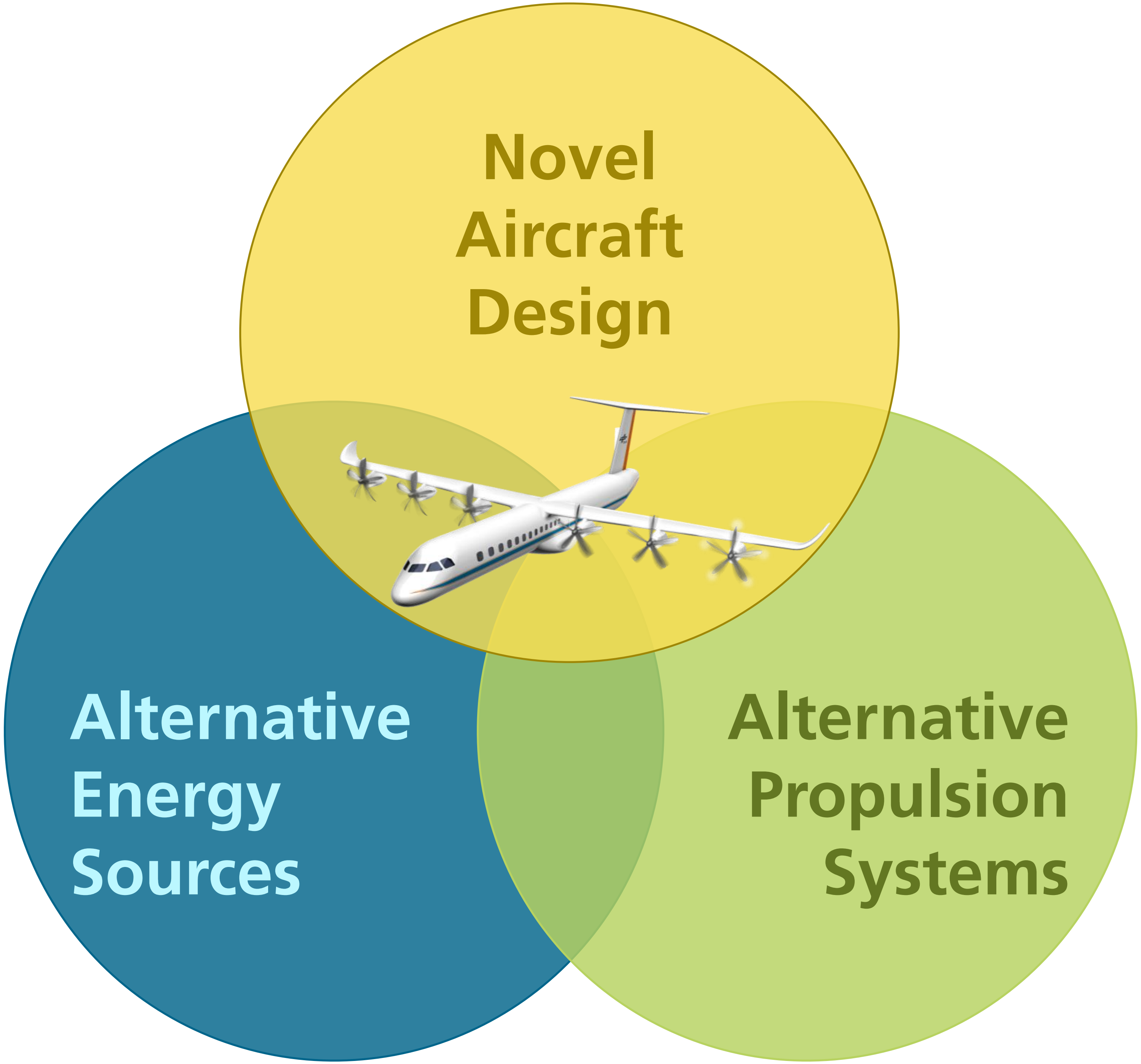
- Challenges on System and Aircraft Level

- Concluding Design Considerations

MOTIVATION

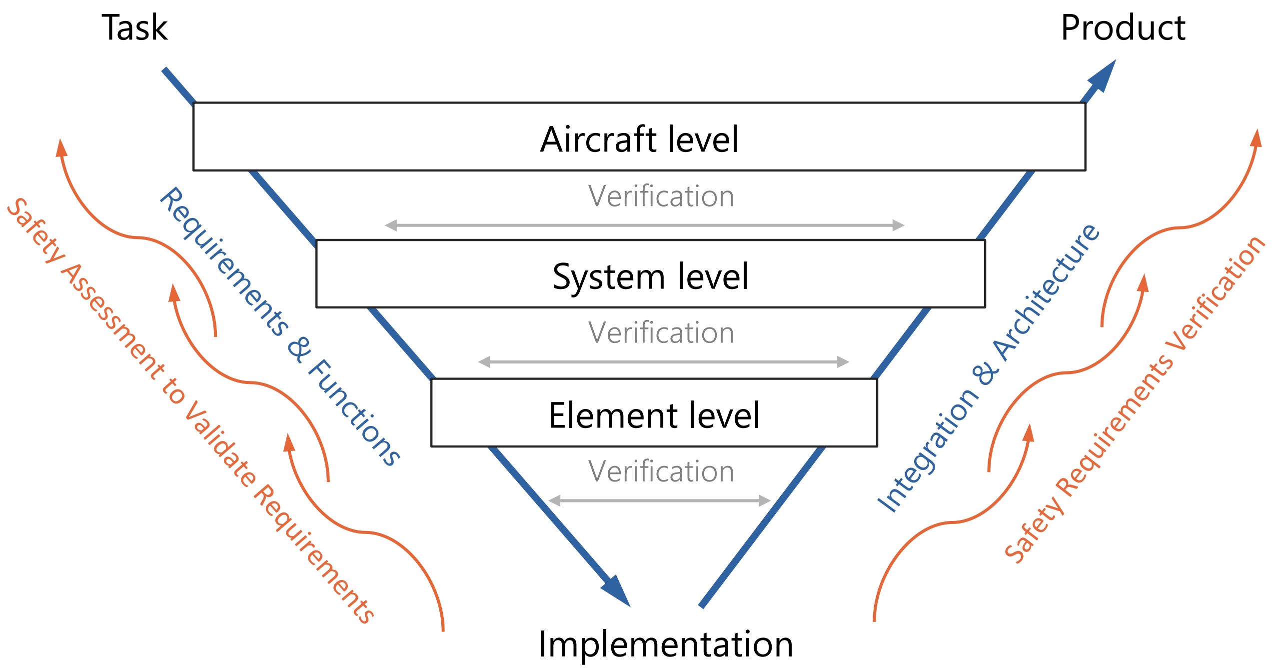
Why (hybrid-)electric propulsion? Why hydrogen as a fuel?

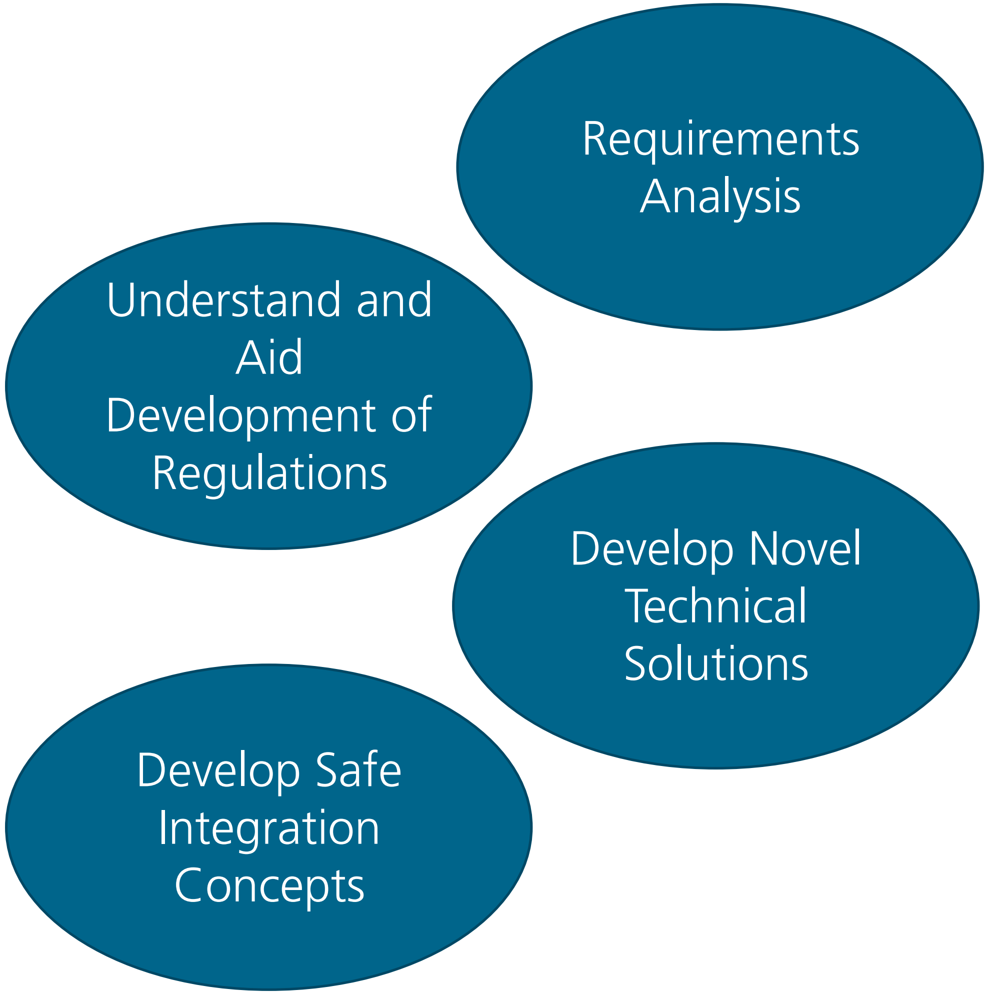



Novel Aircraft Design
Alternative Energy Sources
Alternative Propulsion Systems

Design Process in Aviation

- Systems engineering approach based on ARP4754A with a top-down design and validation process, followed by a bottom-up verification
- Safety analysis methods according to ARP4761 incorpurated into the overall design process





COMPONENT AND SYSTEM LEVEL

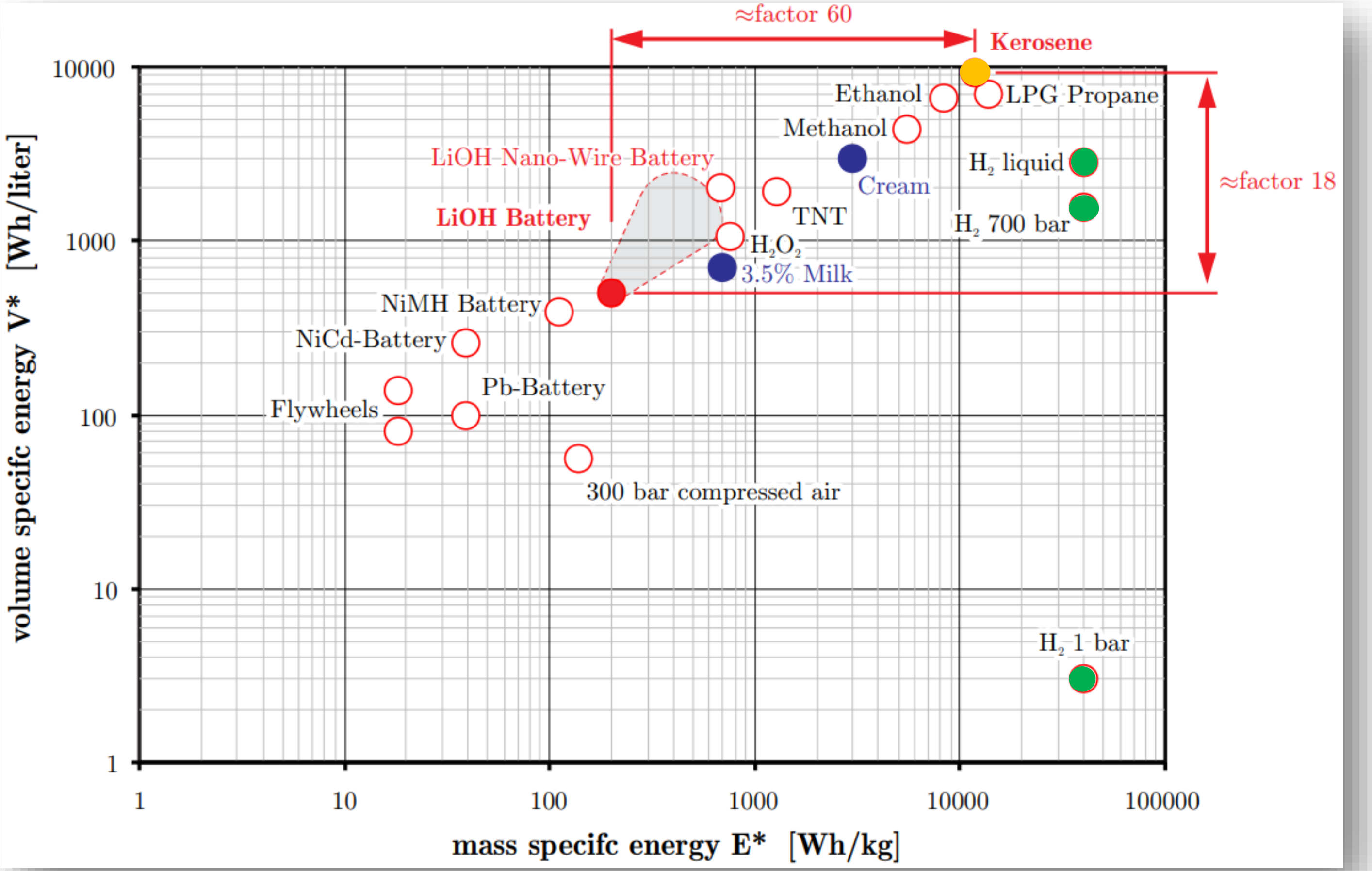
Challenges Associated with Hydrogen System Integration

Material and Component related Challenges

Hydrogen Material Properties

- Diatomic molecule H_2
- At STP it is gaseous
- Very low density at STP
- High volatility
- Odorless, colorless, non-toxic and non-metallic
- Low volumetric energy density

→ Source of many other challenges for handling of H_2 and component design

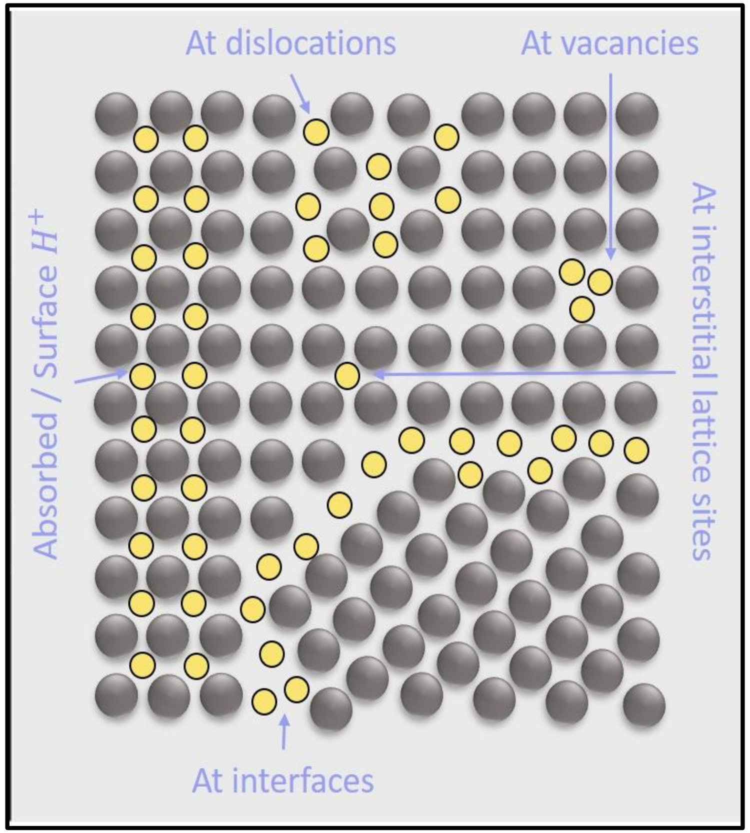


Source: Martin Hepperle (DLR), Electric Flight – Potential and Limitations.

Challenges Associated with Hydrogen System Integration

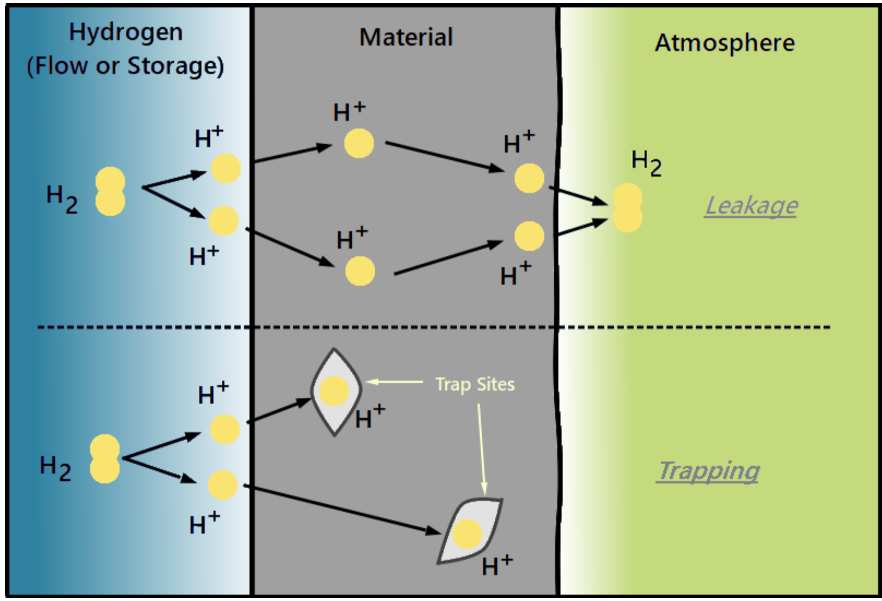
Material and Component related Challenges

Hydrogen Material Properties



Hydrogen Trapping

- Unavoidable when dealing with hydrogen
- Even when special treatment is applied to the material surface, trapping can occur
- Trap sites:
  - Grain and phase boundaries
  - Voids and cracks
  - Precipitates
  - …

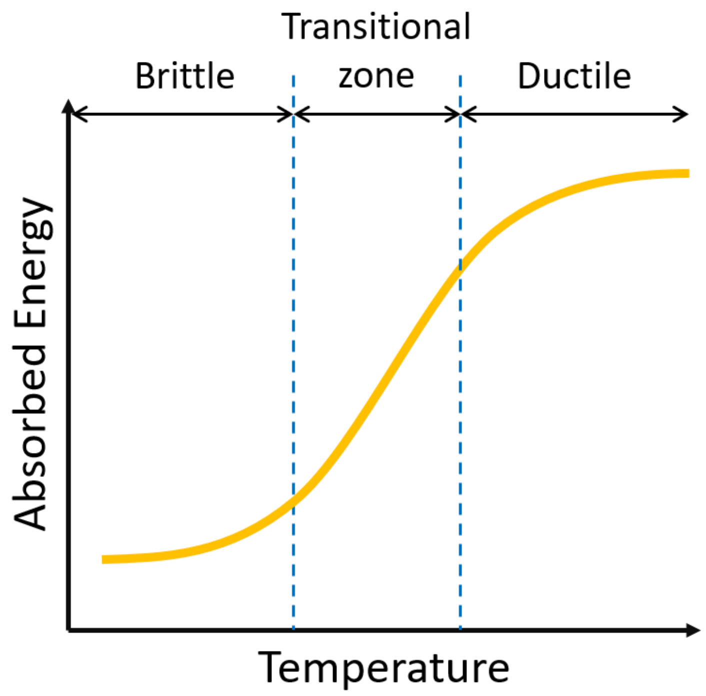


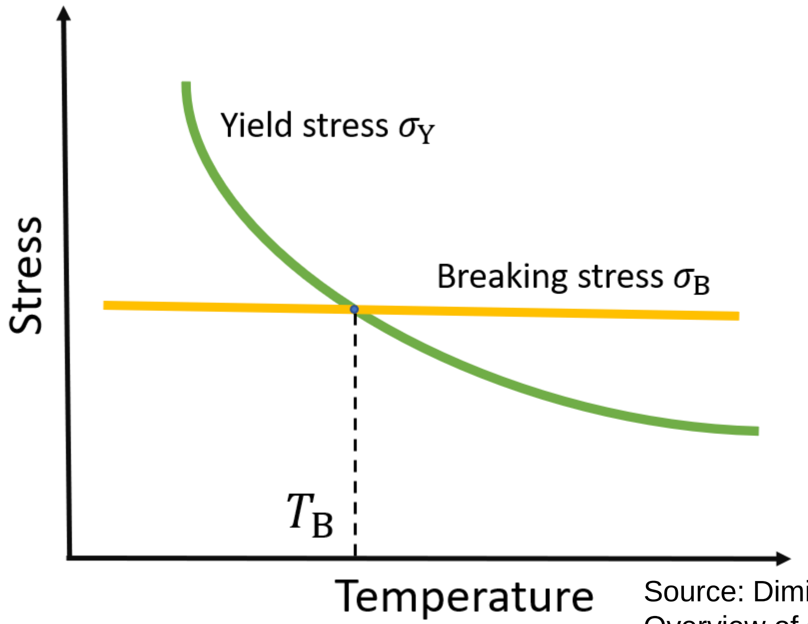
Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001 Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation
https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

Challenges Associated with Hydrogen System Integration

Material and Component related Challenges

Hydrogen Material Properties | **Hydrogen Trapping** | **Hydrogen Embrittlement**





- Degradation of the tensile strength and ductility of the material effected
- Leading to decrease in fracture resistance and sub-critical cracking

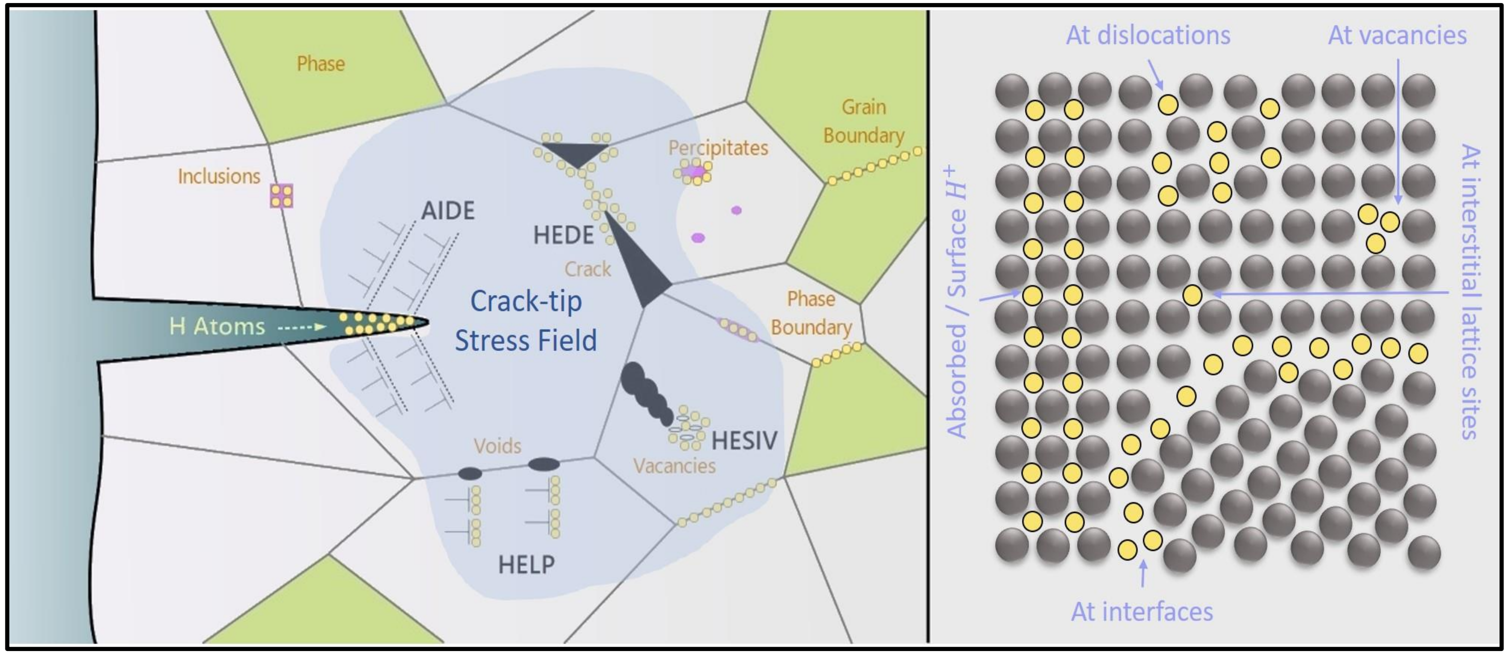
Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001 Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

Challenges Associated with Hydrogen System Integration

DLR

Material and Component related Challenges

Hydrogen Material Properties	Hydrogen Trapping	Hydrogen Embrittlement



Mechanisms of hydrogen embrittlement

- Degradation of the tensile strength and ductility of the material effected
- Leading to decrease in fracture resistance and sub-critical cracking
- Decohesion between grains of the material
- Shrinking the stress field inside the material core and consequent increase in hydrostatic pressure
- Creation of additional stresses inside the material

Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001 Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

SYSTEM AND AIRCRAFT LEVEL

Challenges Associated with Hydrogen System Integration

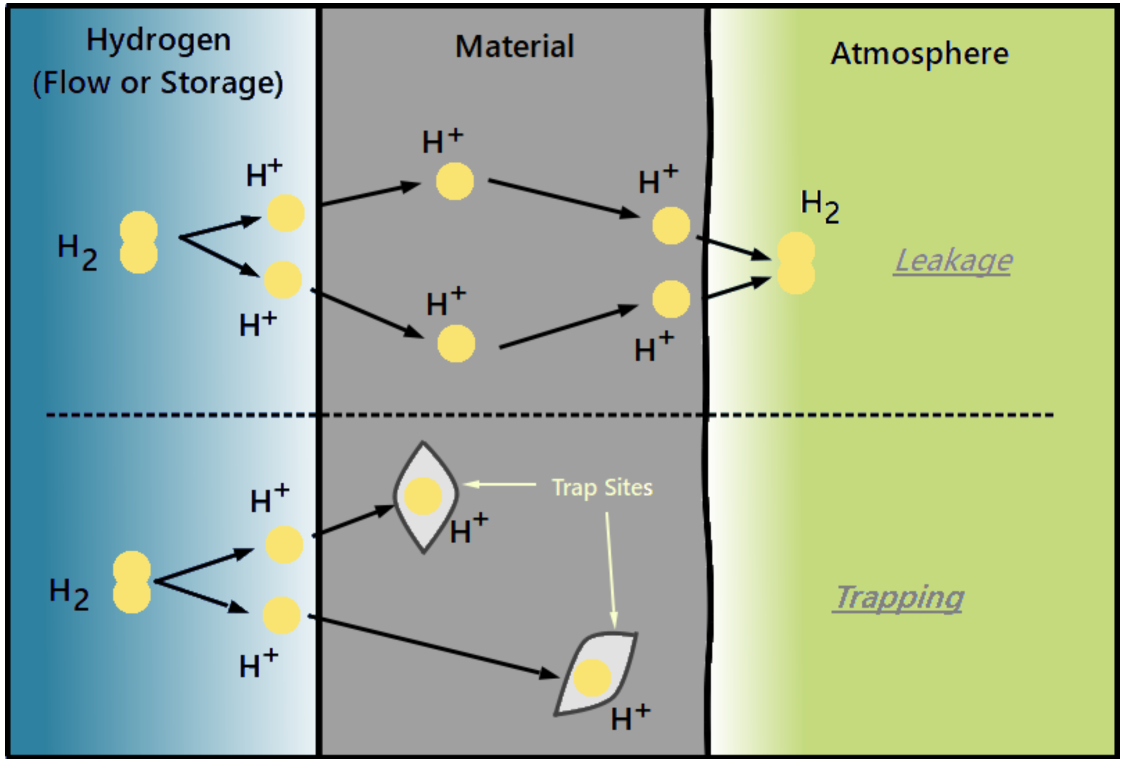
System and Aircraft Level

Hydrogen Leakage

- Leakage is unavoidable
- High diffusivity of hydrogen

→ High local concentrations possibly inside the flammability region

→ **Liquid and gaseous hydrogen behave differently**



Challenges Associated with Hydrogen System Integration

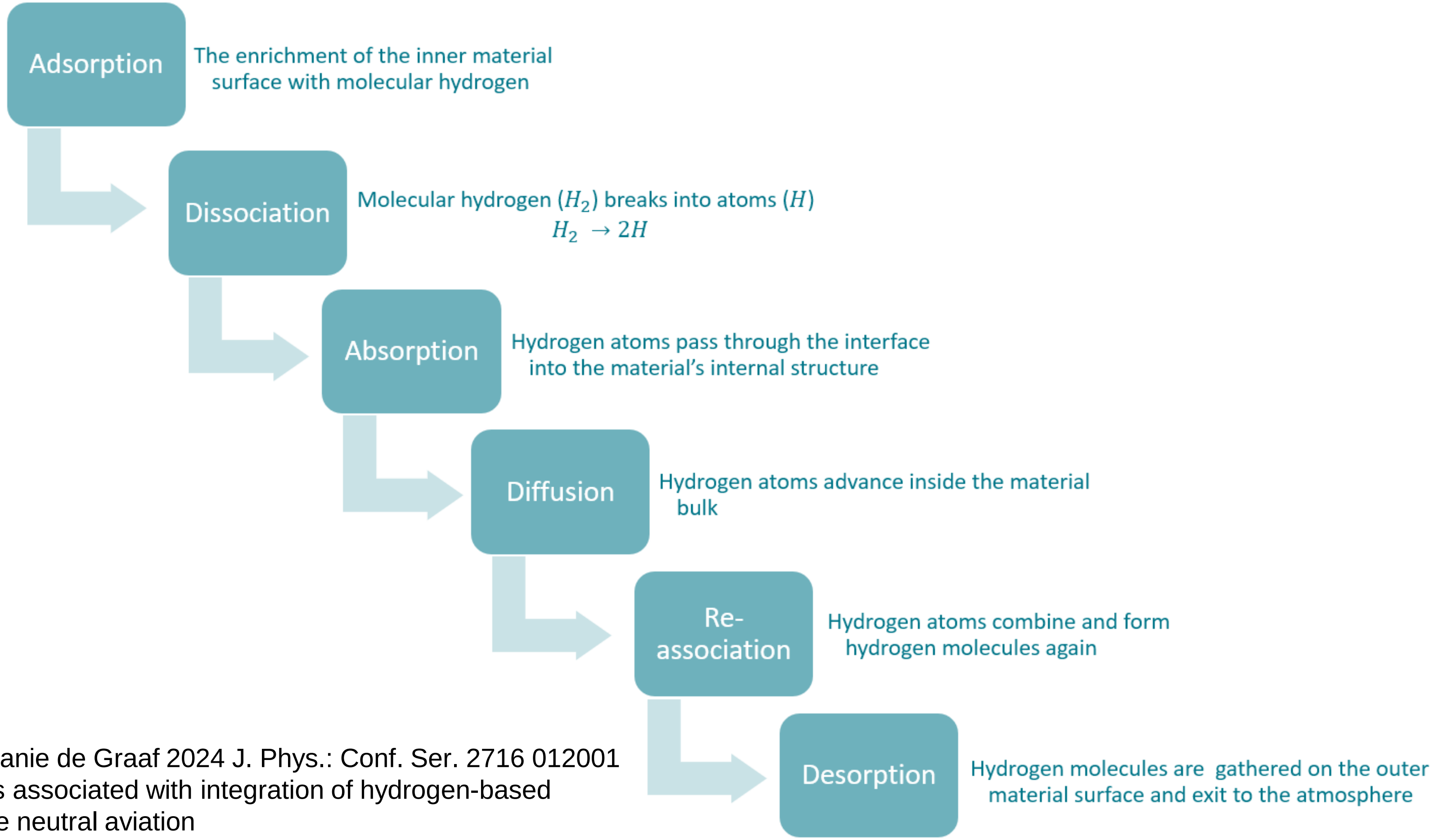
System and Aircraft Level

Hydrogen Leakage

- Leakage is unavoidable
- High diffusivity of hydrogen

→ High local concentrations possibly inside the flammability region

→ **Liquid and gaseous hydrogen behave differently**



Source. Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001 Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

Challenges Associated with Hydrogen System Integration

System and Aircraft Level

Hydrogen Leakage

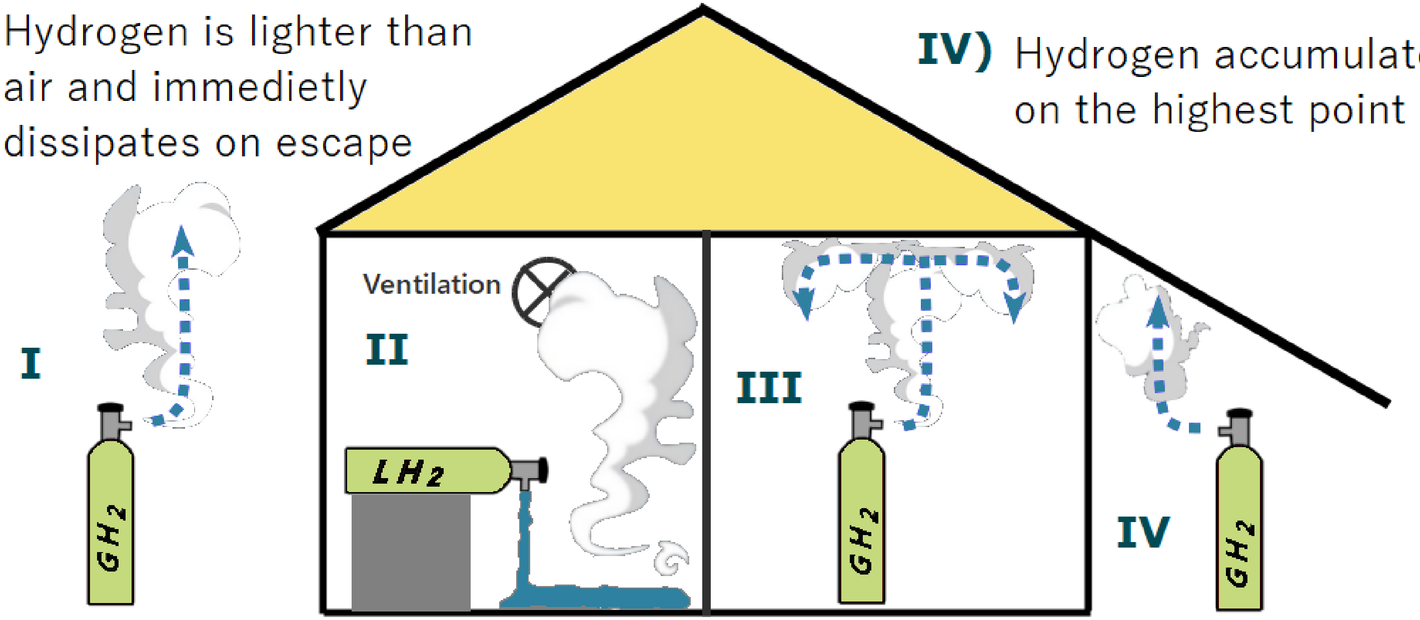
- Leakage is unavoidable
- High diffusivity of hydrogen

→ High local concentrations possibly inside the flammability region

→ **Liquid and gaseous hydrogen behave differently**

I) Hydrogen is lighter than air and immediietly dissipates on escape

IV) Hydrogen accumulates on the highest point



II) When liquid hydrogen leaks, it forms a cloud of hydrogen, condensed water and air which is heavier than air. Then it evaporates

III) If the upwards path is blocked, hydrogen moves to all other directions, including downwards

Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001
Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation
https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

Challenges Associated with Hydrogen System Integration

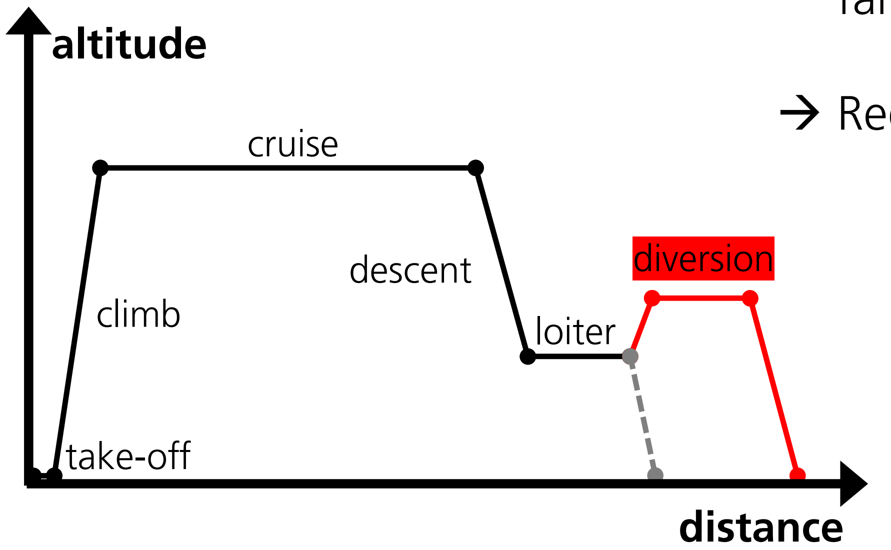
System and Aircraft Level

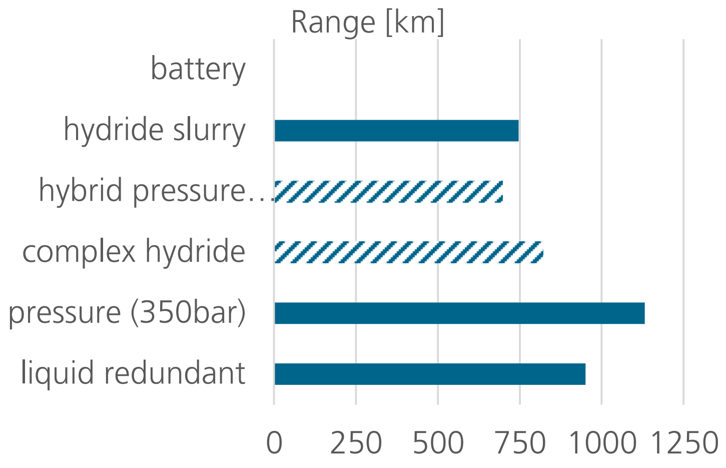
Hydrogen Leakage

H2 Storage Oversizing

- Diversion requirements
- Temperature-related cycling limitations
- Reliability and common-cause failure potential

→ Redundancy? Oversizing?





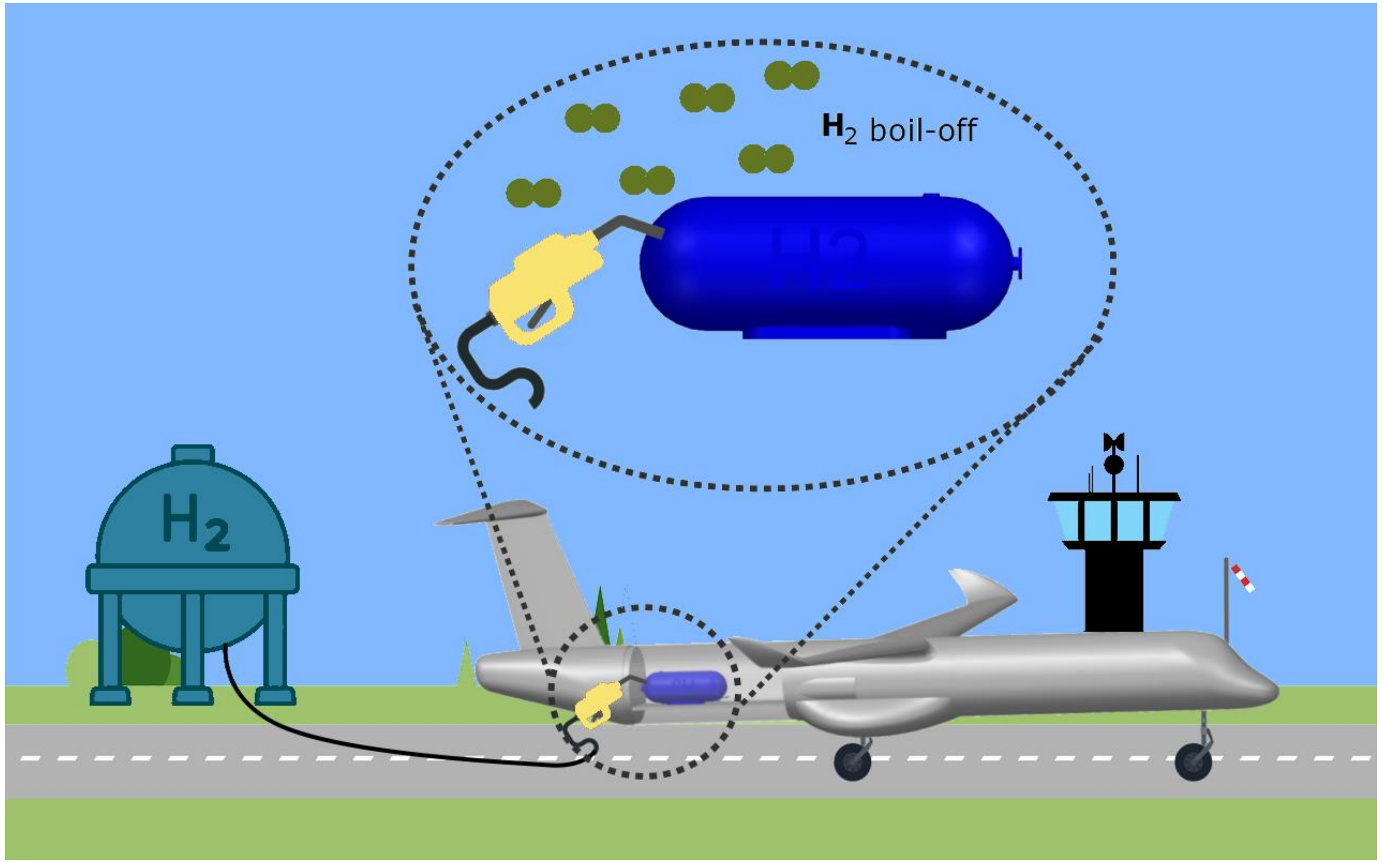
	CgH_2	Complex hydrides (CxH)	Hybrid (MH + CgH_2)	Hydride slurry	Battery	LH_2 redundant
Performance	+	-	+	o	++	o
Weight/Range	++	-	-	o	--	+
Integration	o	+	+	o	-	-
Safety	o	+	-	+	o	o
Cost	-	-	-	-	+	-
Rating	**0,71**	**0,45**	**0,38**	**0,58**	**0,43**	**0,56**

Source: V. Bahrs, F. Franke, S. Kazula and S. de Graaf; DLRK 2023; Stuttgart; *in press*

Challenges Associated with Hydrogen System Integration

System and Aircraft Level

Hydrogen Leakage | **H2 Storage** | **Boil-Off at Airport**



- Unavoidable side effect
- Reduction of efficiency of LH_2 pathway
- Significant environmental impact through H_2 emissions

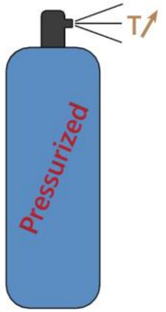
→ New technical solutions and considerations for airport infrastructure

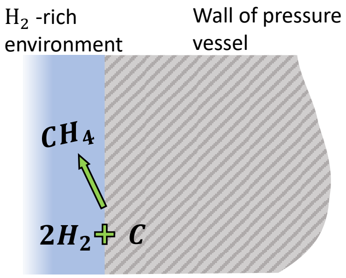
Challenges Associated with Hydrogen System Integration

System and Aircraft Level

Extraction Method

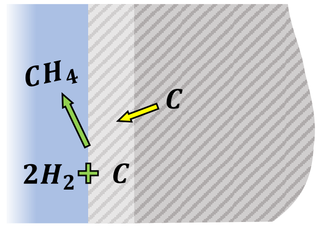
- Utilization of synergies in the system
- Consideration of high-temperature hydrogen attack
- Conditioning of hydrogen
  - Consideration of negative Joule-Thompson effect



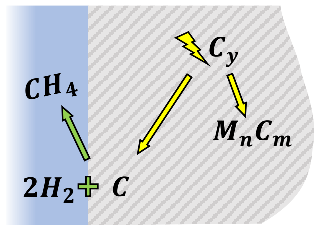


Stage I
- Production of methane out of the wall

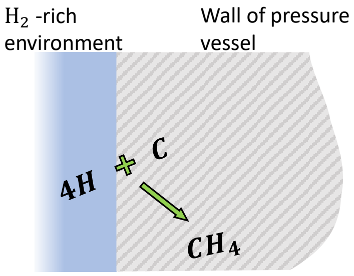
$[2H_2 + C \rightarrow CH_4]$



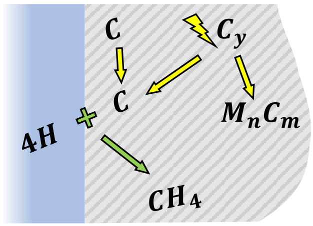
Stage II
- Decarburization of the surface
- Migration of carbon towards surface
- Production of methane out of the wall $[2H_2 + C \rightarrow CH_4]$



Stage III
- Decarburization of the wall
- Dissolution of less stable carbides
- Migration of carbon to the surface
- Production of methane out of the wall $[2H_2 + C \rightarrow CH_4]$



Stage IV
- Diffusion of hydrogen in the wall
- Production of methane inside the wall $[2H_2 + C \rightarrow CH_4]$
- Increase of pressure inside the wall



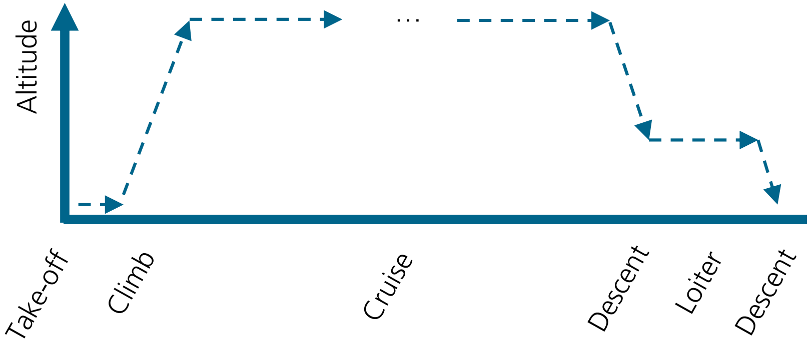
Stage V
- Diffusion of hydrogen in the wall
- Diffusion of carbon near the reaction site
- Dissolution of carbides
- Production of methane inside the wall $[2H_2 + C \rightarrow CH_4]$
- Increase of pressure inside the wall

Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001 Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

Challenges Associated with Hydrogen System Integration

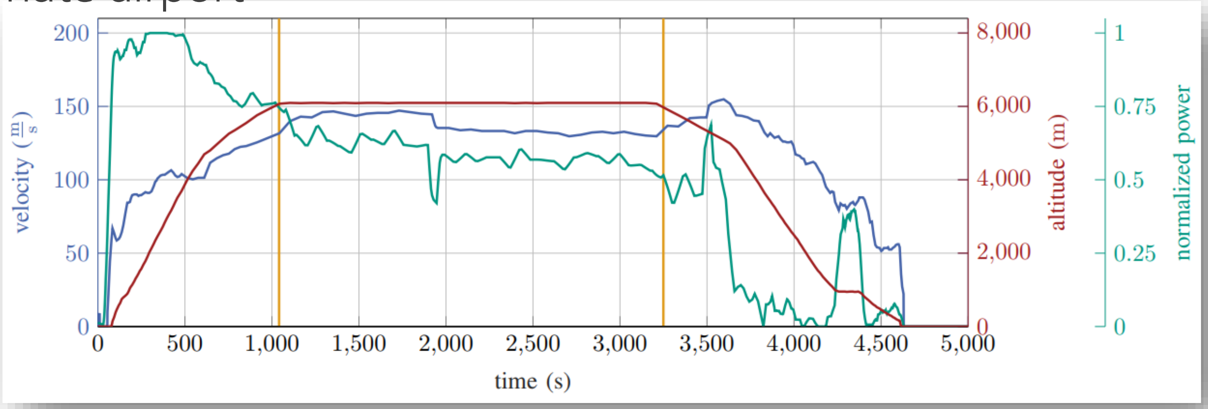
System and Aircraft Level

Extraction Method



Operational Considerations

- Start-up and restart procedure for fuel cell system
- Rejected take-off scenario
- High gradients in power demand
- Emergency landing scenario
- Diversion to alternate airport
- Redundancy
- …

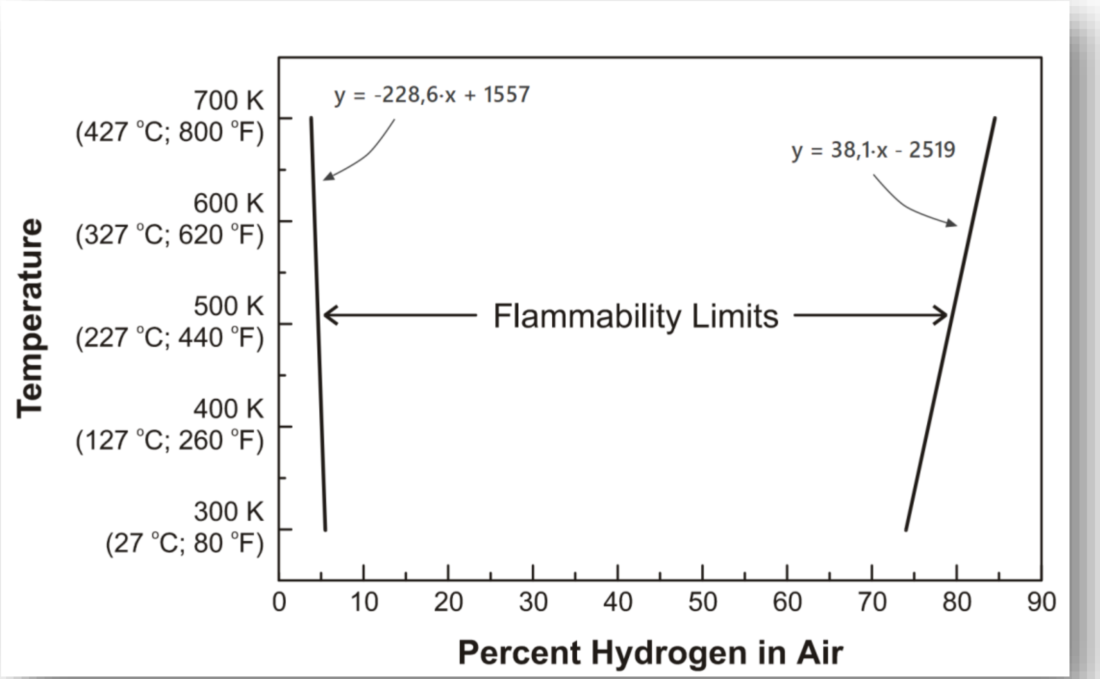


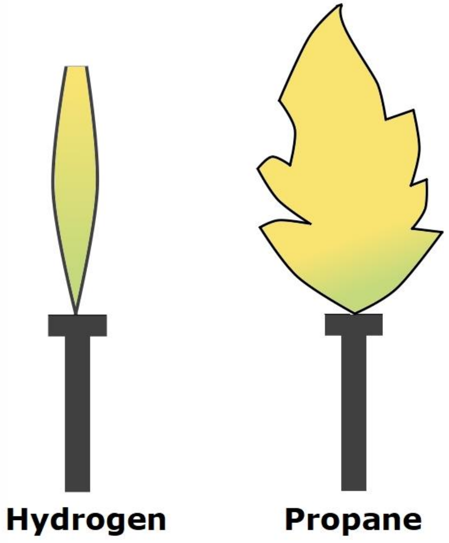
Source: Jux *et al.*; A Standard Mission Profile for Hybrid-Electric Regional Aircraft based on Web Flight Data

Challenges Associated with Hydrogen System Integration

System and Aircraft Level

Extraction Method | **Operational Considerations** | **Increased Flammability**





- Increased flammability range compared to conventional fuels (10 x)
- Auto-ignition at 585°C
- Very high laminar flame speed

→ Zonal Safety Analysis (ZSA)

Source: W. Lanz. Hydrogen properties. 2001.

Challenges Associated with Hydrogen System Integration

DLR

System and Aircraft Level

Extraction method	Operational Considerations	**Increased Flammability**

- Increased flammability range compared to conventional fuels (10 x)
- Auto-ignition at 585°C
- Very high laminar flame speed due to differential diffusion (5 x)

→ Zonal Safety Analysis (ZSA)

Source: Video - https://www.youtube.com/watch?v=IknzEAs34r0

DESIGN CONSIDERATIONS

Design Considerations

Component Level

- **Material choice** must meet requirements regarding all hydrogen-related challenges and its properties (embrittlement, temperature, pressure)
- **Novel material development** may be required
- Material **treatment against hydrogen embrittlement** may be required
- Modelling and experimental data on **lifing of novel components** necessary
- Consideration of potential **common mode failures**
- Potentially **necessary test procedures** have to be **anticipated in advance** as no certification regulations exist

Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001
Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation
https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

Design Considerations

DLR

Propulsion System Level

- **Zoning** in the entire aircraft during early stage of propulsion system design – particularly with regards to potential sources of ignition
- Integration of **shut-off valves** and **check valves**
- Adequate **concentration monitoring** and **leakage detection** required
- **Ventilation** in hydrogen exposed zones needed
- **Component placement** under consideration of hydrogen dissipation and dilution behaviour
- Consideration of all **operational scenarios** during design process of the hydrogen system
- Careful evaluation of **potential means of utilizing synergies** in the system to avoid common cause failure

Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001
Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation
https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

Handling Considerations

Potential Safety Guidelines

- Appropriate training of personnel to know the hazards of hydrogen
- Recognize human capabilities and limitations
- Isolate, vent, and purge H_2 lines before conducting maintenance
- Do not overload a vessel
- Avoid thermal cycling of relief system
- Oxygen content in a vessel should be < 2%
- Cool down storage vessels slowly
- Examine systems for corrosion or blistering
- …

Source: Dimitrios Dimos, Stefanie de Graaf 2024 J. Phys.: Conf. Ser. 2716 012001
Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation
https://iopscience.iop.org/article/10.1088/1742-6596/2716/1/012001

DLR Institute of Electrified Aero Engines

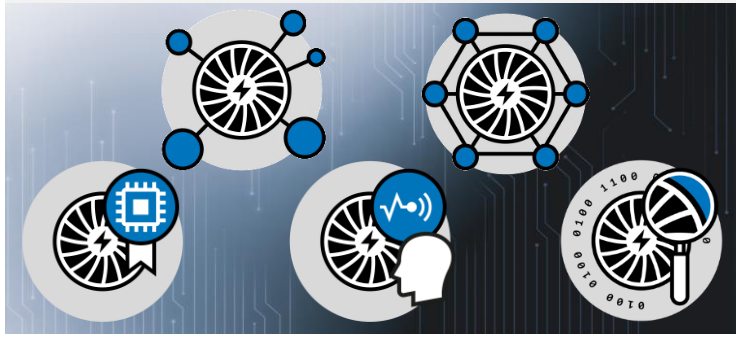
Climate-friendly and quiet air traffic of the future

Mission

- Research on lower-emission, more climate-friendly and quieter aero engines
- Closes gaps in the portfolio of German aviation propulsion research

Holistic Systems Approach

- Component Technologies
- Architecture and Integration of Propulsion System
- Aeronautical Requirements and Control of Propulsion System
- Environmental Impact and Sensor Technology
- Test facilities and infrastructure



Location and Network

- Cooperation within a broad competence and research network
- Contribution to structural change in the Lusatia region towards future aviation technology
- Hybrid Electric Propulsion Cottbus (HepCo) - test facilities as part of an cooperative test bench landscape in Cottbus

- Research on novel, low-emission aircraft engines for civil aviation

Contact:

https://www.dlr.de/el/en

lars.enghardt@dlr.de

Thank you!