TECHNOLOGIES ON THE RADAR – SIGNALS FOR INNOVATION POTENTIALS IN FUEL CELLS AND BATTERIES FOR ELECTRIC FLIGHT

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Abstract

Supported by the Bauhaus Luftfahrt Technology Radar, emerging fuel cell technologies with higher operating temperatures – enabling enhanced efficiency and system-specific power – together with key advances in battery technology are identified, benchmarked using relevant metrics and assessed against aviation-specific requirements. Scalability perspectives for (hybrid-)electric flight and development needs are discussed, providing key insights into the potential for climate-neutral aviation.

1. INTRODUCTION

Transitioning to climate-neutral aviation requires both shifting to 100% renewable energy carriers and mitigating non-CO_2 climate impacts such as from contrails and NO_x emissions. Enabling efficiency gains contributes to the reduction of emissions and costs, but alone cannot achieve complete elimination.

Fuel cells enable the direct use of Green Hydrogen (H_2) for propulsion in future aircraft, converting it electrochemically and emitting only water and heat. Like for H_2-combustion, no CO_2 emissions emerge, but with the added benefits of completely evading NOx emissions and offering potentials for contrail-free operation by water management as well as for improved efficiency [1]. However, system-specific power requirements severely limit scalability to larger aircraft propulsion (80+ PAX, cf. Fig 1a)): with increasing power output of conventional polymer electrolyte fuel cells operating at low temperatures (LT PEFCs), thermal management challenges grow, typically resulting in excessive weight and drag penalties. Advances in materials and designs supporting higher operating temperatures in PEFCs address durability challenges and facilitate thermal and water management, allowing for system-level advantages of so-called high temperature (HT) PEFCs (cf. Fig. 1b)) [1-2].

Moreover, solid oxide fuel cells (SOFCs) – operating at far higher temperatures – enable enhanced efficiency by utilizing their high-quality waste heat in gas turbines (GT) within SOFC–GT hybrid systems, thereby increasing overall power output. While limitations in SOFC gravimetric power density, thermo-mechanical stability and dynamic operability have historically confined such hybrid concepts to auxiliary power unit applications, advances in materials, design and manufacturing are shaping longer-term perspectives for short- to medium-range aircraft propulsion with significant potential for climate impact reduction (cf. Fig. 1b)) [3].

Battery electric flight is completely emission-free during operation and offers significantly higher propulsion chain efficiency than fuel-cell- or combustion-based systems. However, its range is severely limited by the specific energy of current lithium-ion technology (cf. Fig. 1a)). Peak power demands during takeoff and climb require sufficient specific power and high discharge rates for rapid energy delivery. As batteries must provide both energy storage and power output, a fundamental trade-off arises between energy density and discharge power capability, which is constrained by cell chemistry and strongly coupled to battery cycle life. The latter needs to reach competitiveness with current technology for economically viable business models. Given the interrelated performance metrics, future batteries require diverse optimization to meet aviation-specific requirements.

Lithium-metal battery technologies, including lithium-sulfur and lithium-air, intrinsically offer significantly higher specific energy potential than lithium-ion systems. Recent advancements in these still less mature technologies address key challenges in discharge power capability and cycle life, contributing to the reduction of maturity gaps and moving them closer to meeting aviation-specific requirements [4-5].

Supported by the proprietary institution-wide Technology Radar at Bauhaus Luftfahrt, key progress in fuel cell and battery technology from cutting-edge R&D is identified, benchmarked based on suitable metrics and evaluated in the context of aviation-specific performance requirements. Perspectives on scalability for (hybrid-)electric flight are discussed together with remaining limitations and development needs. These findings are seen as an essential basis for holistic considerations of the future role of electrochemical technologies on the path to climate-neutral aviation.

The following slides reproduce the presentation as delivered at the conference.

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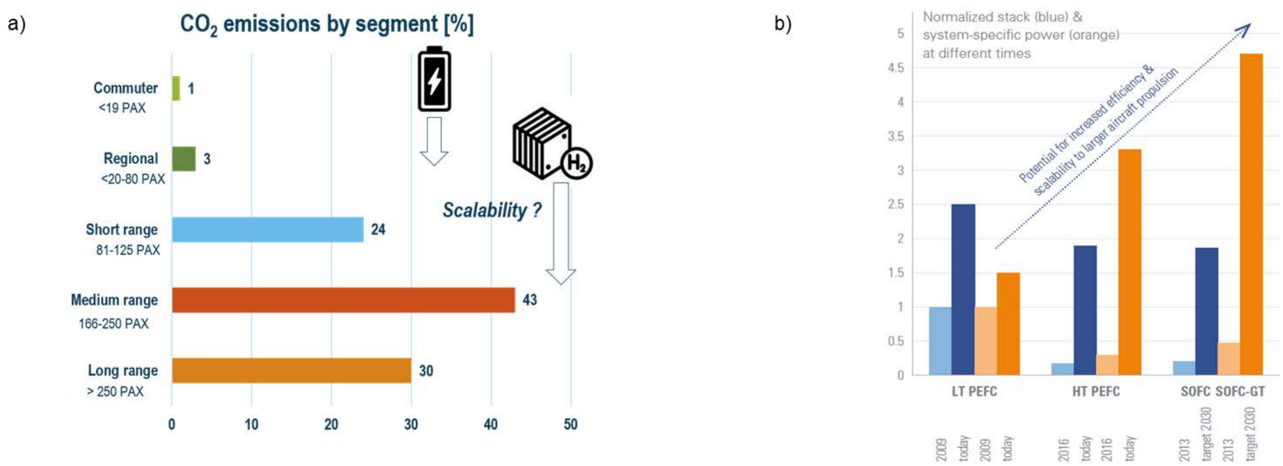

Figure 1 a) Share of CO_2 emission by segment [7] together with achievable typical ranges of battery- and fuel-cell-electric aircraft according to current technology demonstrating that scalability to larger aircraft is critical for maximized leverage of climate benefits at the overall system level; b) Normalized stack and system specific power of different fuel cell technologies over time showing a trajectory toward higher system-level performance and scalability to larger aircraft propulsion with increased operating temperature, especially for SOFC-GT hybrids with waste heat integration; Note: specific power metrics are normalized to fixed baseline, traditional LT-PEFCs in 2009 at 150 kW, to highlight technological progress, accounting for higher power outputs over time. Based on data from Refs. [2-3].

References

[1] Adler, E. J., Martins, J. R. R. A., Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts. Prog. Aerosp. Sci. 2023; 141(1).

[2] ZeroAvia, White paper, Scaling Hydrogen Electric Propulsion for Large Aircraft, 2024.

[3] Kierbel, D. et al. (2024). Aircraft Electrical Propulsion System Powered by Solid Oxide Fuel Cell and Combined With Gas Turbine. *26th International Society for Air Breathing Engines (ISABE).* Toulouse, France.

[4] Pai, R., Singh, A., Tang, M. H. – M., Kalra, V.. Stabilization of gamma sulfur at room temperature to enable the use of carbonate electrolyte in Li-S batteries. Communications Chemistry. 2022;5(17).

[5] Kondori, A. et al., A room temperature Li2O-based lithium-air battery enabled by a solid electrolyte. Science. 2023:379(6631)

[6] IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

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Technologies on the Radar – Signals for Innovation Potentials in Fuel Cells & Batteries for Electric Flight

Dr. Lily Koops

DLRK
Augsburg, 24.09.2025

Agenda

- Bauhaus Luftfahrt Technology Radar
- Technology Pull versus Push
- Future Technology Analysis
- Signals for Innovation Potentials
  - Batteries
  - Fuel Cells
- Summary & Conclusions
- Outlook

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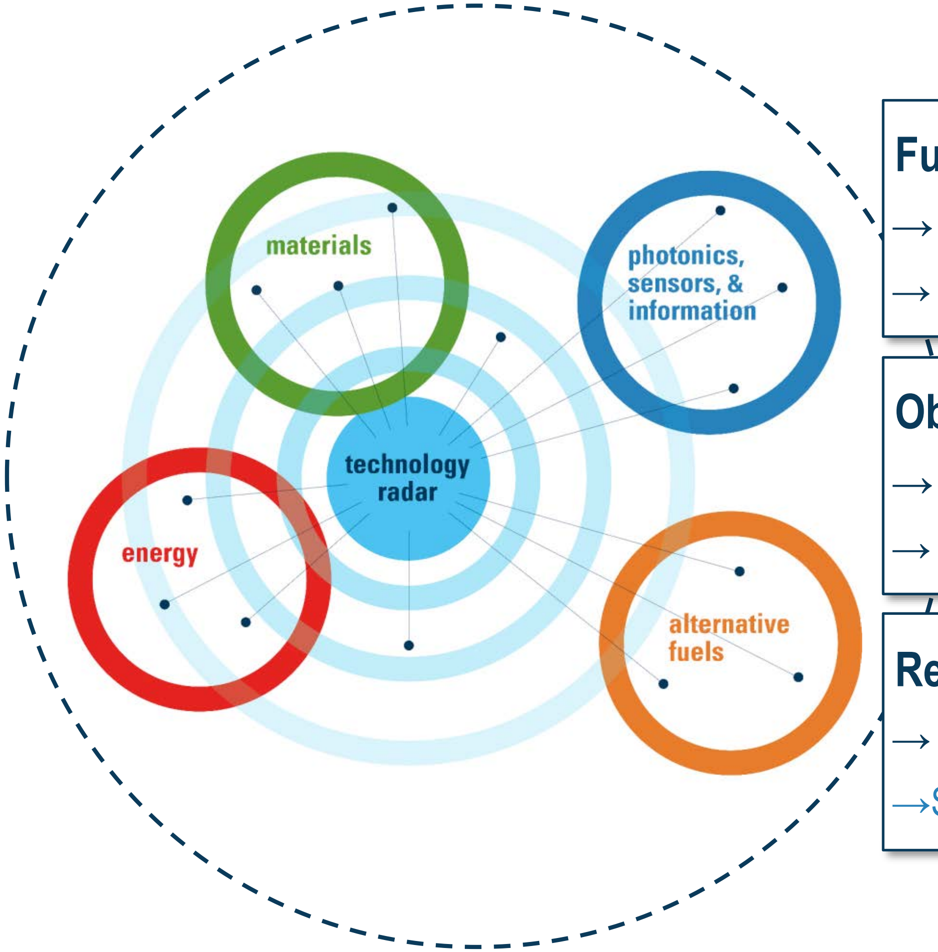
Technology Radar – Antenna for Weak Signals of Change



Function

→ Early identification of potentially significant innovation potentials

→ Long-term view (15 years +)

Objectives

→ Broad technology spectrum also beyond “classical” aeronautical disciplines

→ Bring step-change advances in cutting-edge R&D into aviation focus

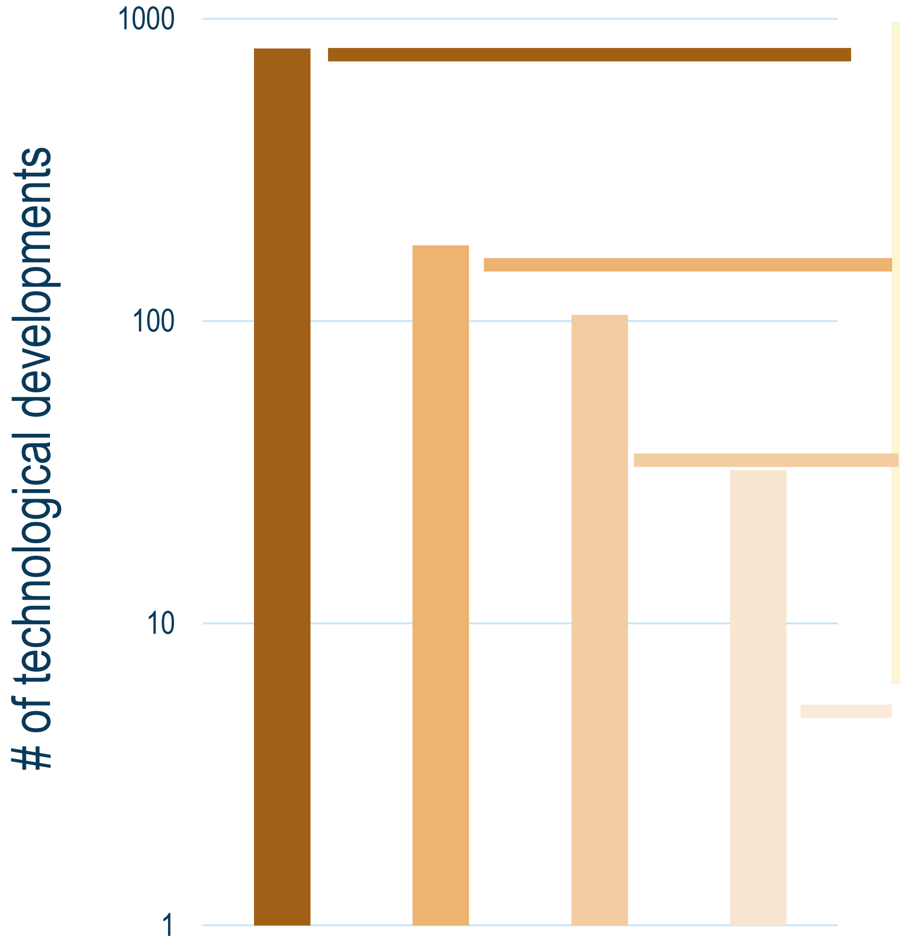
Relevance

→ Understand future technology options and ultimate performance potentials

→Strategic decision support & first mover advantage

Technology Radar – Identifying & Assessing Future Technologies

Unique, highly interdisciplinary, multi-step process to identify and assess a growing portfolio of potentially high-leverage technologies



Technology Scouting

- High-impact journals on cutting-edge research & forefront developments
- Scientific newsletters & websites
- Expert network

Pre-selection

Initial assessment & prioritization

- Interdisciplinary team of experts
- Continuous update of technology knowledge base

Activity of entire Bauhaus Luftfahrt team

Evaluation & Application

Industry, internal & third party projects

Future Technology Analysis

- Initial assessment for use in aviation based on scientific principles
- Integrated assessment exploiting combinatorial innovation

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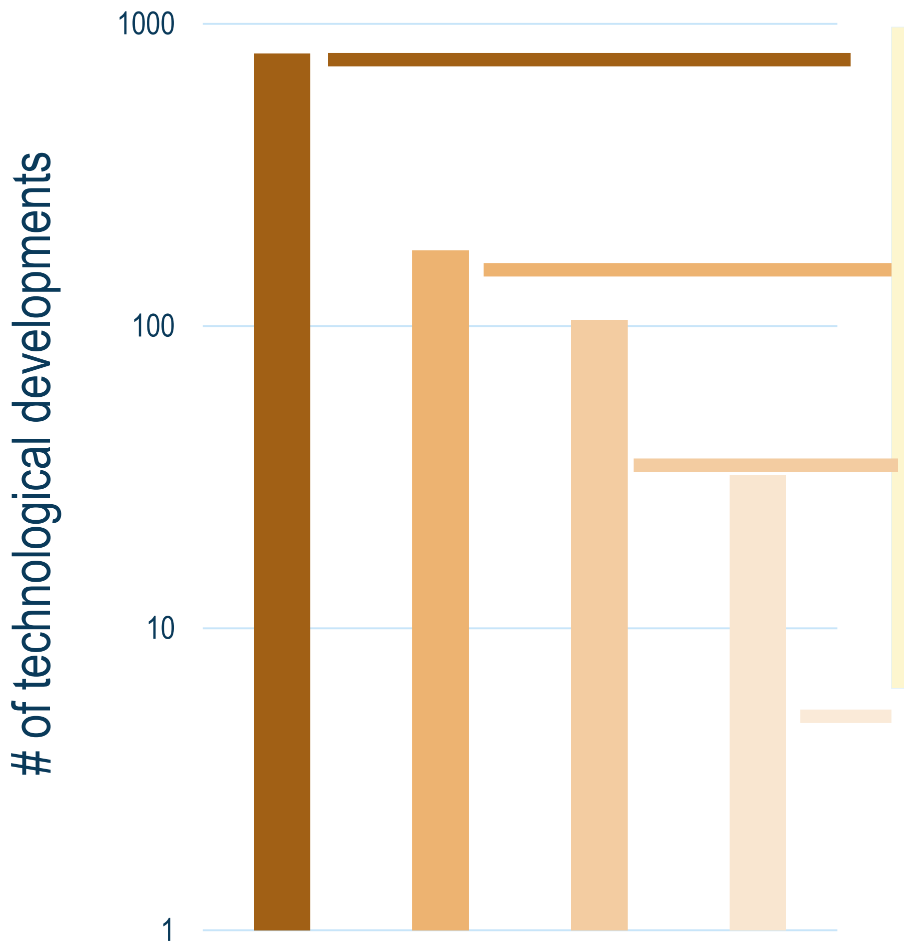

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Technology PULL – Generated by Ambitious Climate Targets

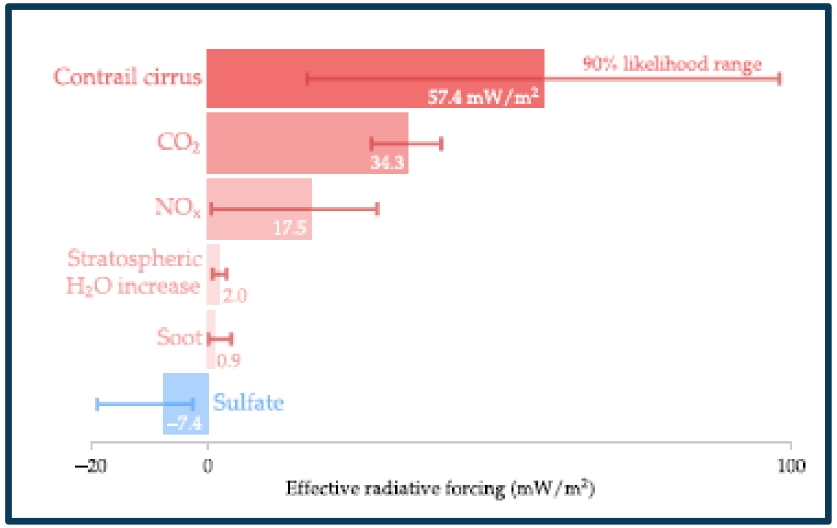
Key demands

- **Transition to 100% renewable energy carriers**
- **Non-CO_2 impact mitigation (contrails, NO_x) → critical**
- **Efficiency gains** → scale down emissions (yet no full elimination)
- **Robust technology decision-making → universal climate impact metrics**, uncertainty quantification & propagation
- **Accelerated adoption → AI-driven optimization & digitization**

***Task*: Identify key technology advances at the intersection of aviation demands (Technology PULL) & cutting-edge research (Technology PUSH)**
→ Next slides

Address full climate impact

- **Essential to mitigate beyond CO_2**
- **Contrails and NO_x are dominant contributors to radiative forcing, but uncertainties remain high**



[Adler, Martins, *Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts*, Prog. Aerosp. Sci., *(2023)*, based on Lee et al.,*The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018,* Atmos. Environ. (2021)]

Technology Pull versus Push – Technologies on the Radar

Energy technologies

PULL: Cleaner high-performance propulsion technologies

PUSH: Recent advances in

1. **High T Polymer Electrolyte Fuel Cells (HT-PEFCs)**
2. . **Proton Ceramic & Solid Oxide Fuel Cells (SOFCs)**
3. **Lithium Metal Batteries (Li–S, Li–Air, etc. & solid-state variants)**
4. **Anode-free metal batteries**
5. **High T superconductor technologies**

⋮

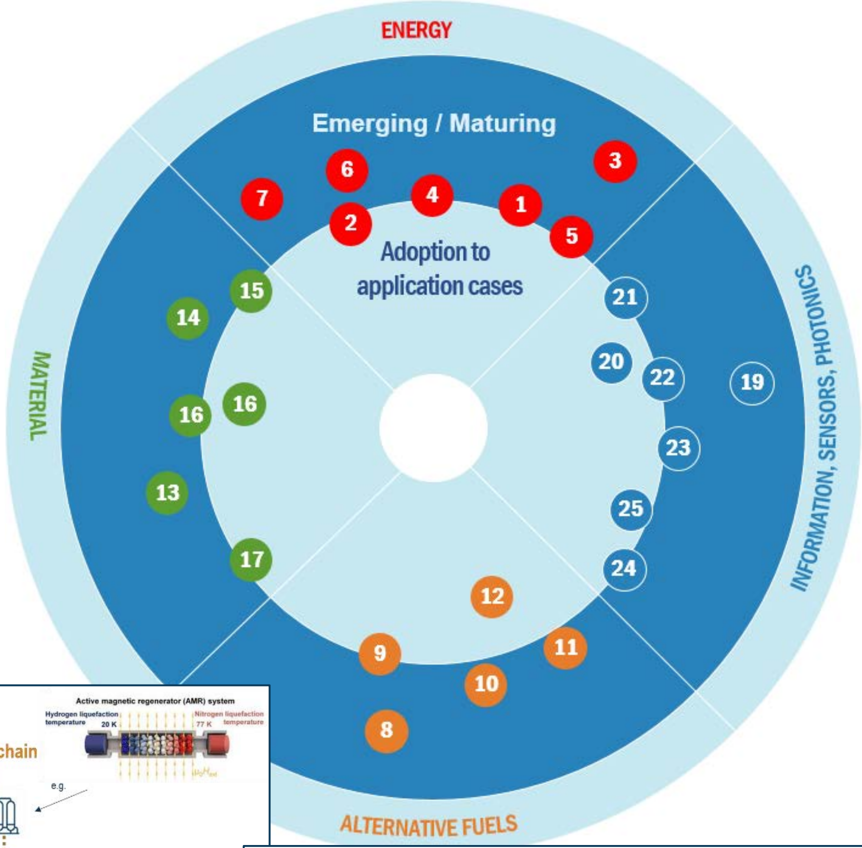
Alternative Fuels (Liquid H_2, SAF)

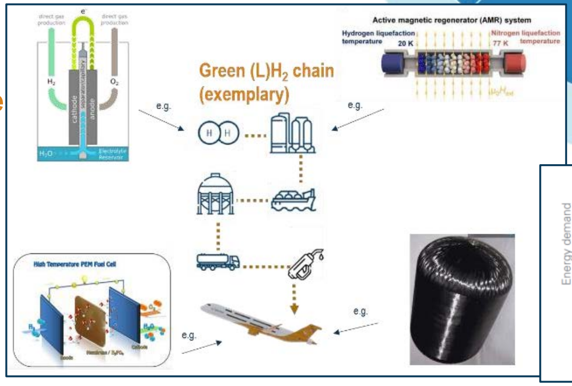
PULL: *Scalable, resource & cost-efficient provision*

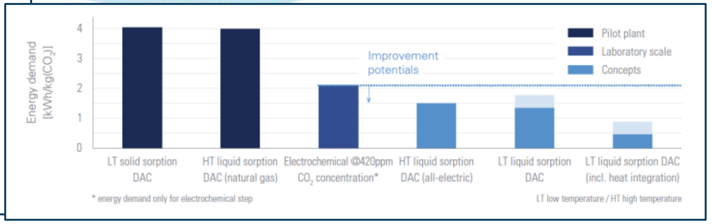
PUSH: *Recent advances in*

8. **Natural / geologic H_2**
9. **Intermittent energy storage**
10. **Low & high T electrolysis**
11. **Magnetic refrigeration for H_2 liquefaction**
12. **Direct Air Capture (DAC)**

⋮







Material technologies

PULL: Light / high-performance / multifunctional / tunable / renewable

PUSH: Recent advances in

13. **Structural & isolation materials for cryogenic applications**
14. **Fiber-reinforced, nano-enhanced & bio-derived composites**
15. **Shape memory materials**
16. **(Hydrogen) electrolyte & electrode materials**
17. **Multi-material & continuous fiber 3D printing**

⋮

Information, Sensors & Photonics

PULL: *Smart / connected / adaptive / efficient / resilient*

PUSH: *Recent advances in*

19. **Physics-informed Machine Learning**
20. **Generative AI & transformer AI models**
21. **AI-powered Generative Design**
22. **AI-based real-time monitoring & control**
23. **Neuromorphic (computing) computing / sensing**
24. **Quantum(-Inspired) Technologies**

⋮

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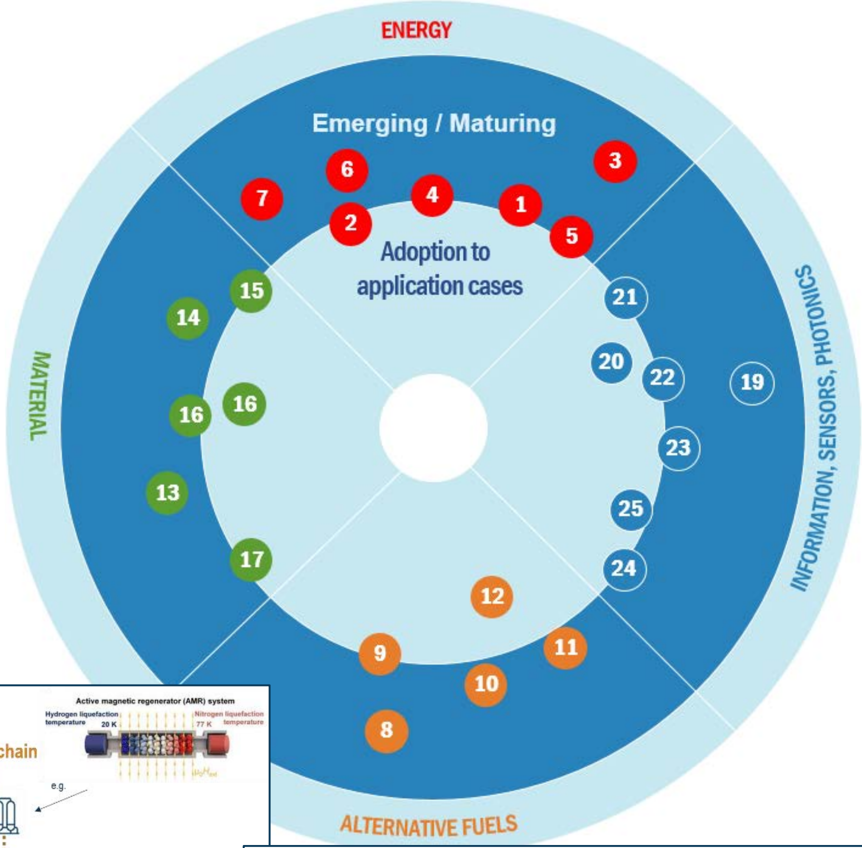

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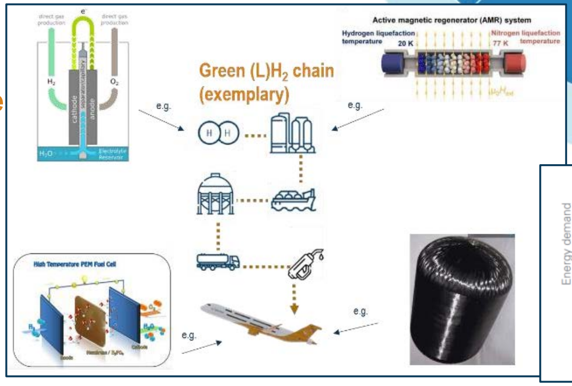

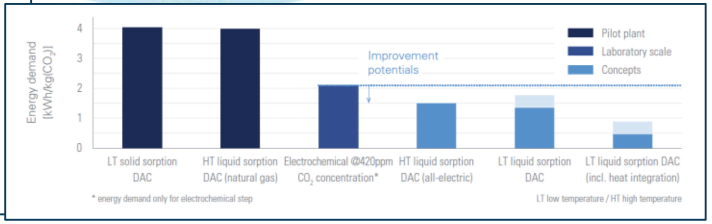

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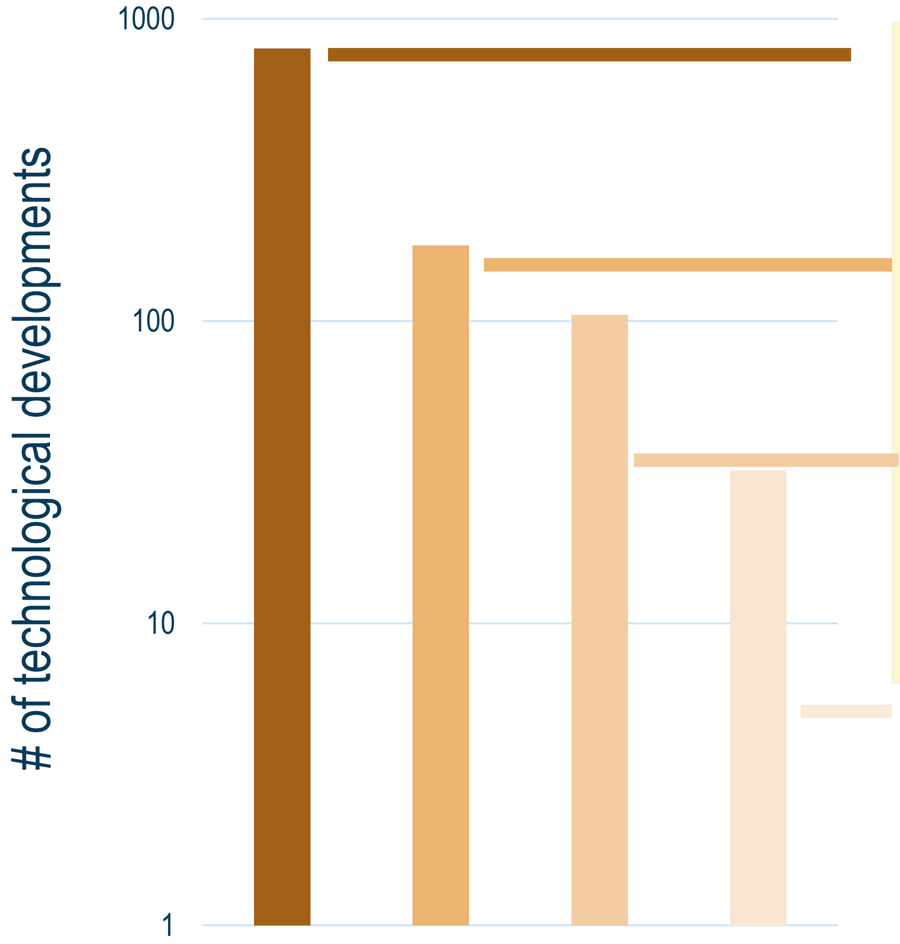

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Future Technology Analysis (FTA) – Aim, Approach & Relevance

Aim: Assess performance potentials[1]

- Of emerging technologies *under aeronautical conditions*

Approach: Future Technology Analysis

- Universal metrics identify step-change advances & key trade-offs
- Benchmarking reference values, ultimate performance potentials
- Scaling & risk analysis adaptability to aeronautical applications
- Uncertainty quantification for robust technology decisions

Relevance of future proof, scientific knowledge

- Early identification of aviation-relevant potentials
- Inform decisions, guide integrated system studies

Component / device level (→ FTA), e.g.

Materials	Energy	Alternative Fuels
Bio-derived composites for aircraft structures	Next-Gen Batteries Next-Gen Fuel Cells Thermoelectric systems	Direct Air Capture for scalable synthetic fuel production Technology along the $L(H_2)$ life cycle

Integrated assessment, e.g.

Integrated aircraft level assessment	Integrated propulsion system & aircraft level studies	Integrated techno-economic & life cycle studies supporting fuel strategies

Extended modeling exploiting combinatorial innovation

Mission & fleet → transition scenarios

[1] E.g. in BHL industry partner project (Airbus, MTU, Liebherr Aerospace, IABG) > 50 high-priority technologies analysed since 2009

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Electrochemical Propulsion – Climate Benefits & Scalability

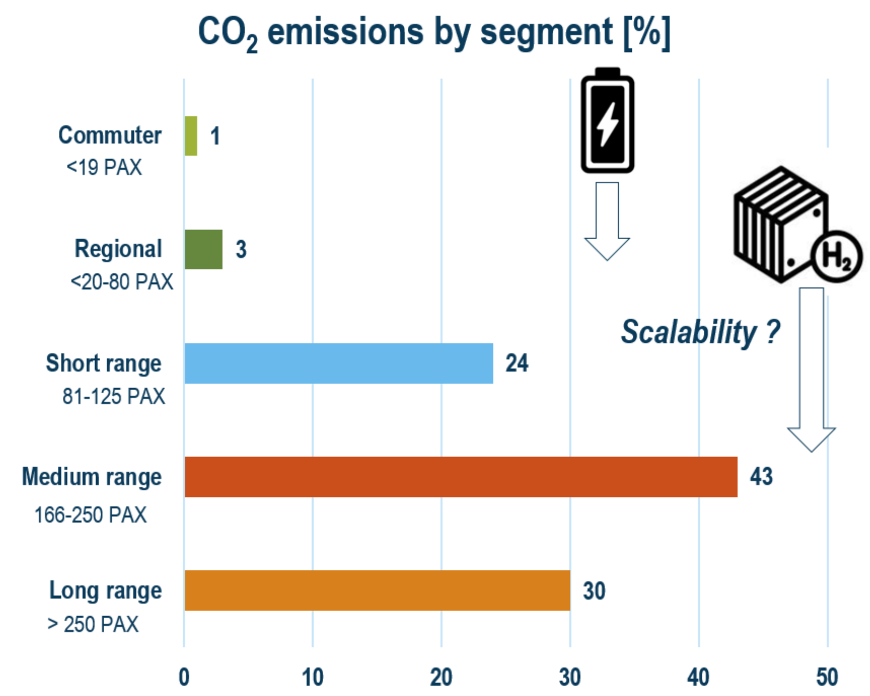
Battery electric flight

- **Zero in-flight emissions (life-cycle impact still key)**
- Severely limited by range cf. next slide

Fuel-cell (FC) electric flight

- FCs only emit heat & water
- **Potential for contrail-free operation** by water management[1]
- **No CO_2 & NO_x[1] emissions**
- Feasible for regional aircraft, scalability beyond?

[1]offering benefits over H_2 combustion



[Based on data of DiiOMI database and ICCT report (2018)]

Technology Pull: Electrochemical propulsion as enabler of zero in-flight emissions → scalability key for maximized leverage

Technology PUSH: Key advances in batteries & FCs with perspectives for improved scalability for (hybrid-)electric flight → Next slides

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Batteries for Electric Propulsion in Aviation – Key Metrics

Key metrics with inherent trade-offs

- Specific energy & power, C-rate, efficiency & cycle life

Range determined by specific energy

- Usable energy reduced to ~26% of new cell-specific energy[1]
  → cell-to-pack-scaling, safety, cell aging, minimum flight reserve required

Peak power demands takeoff, climb

- Require sufficient specific power & C-rate for fast energy delivery with limited cost in specific energy (cf. Ragone diagram)

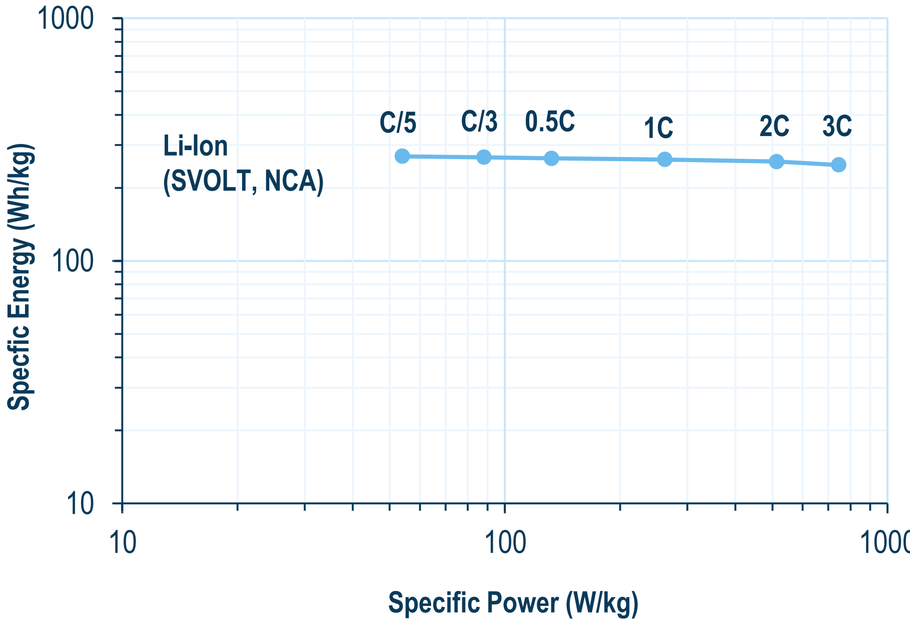
Mass determined by energy or power demand

Efficiency with trade-offs in rate capability & cycle life

- Different loss mechanisms → ⚠ heat losses, cooling demand
- Propulsion chain: high conversion efficiency

Ragone diagram

- Fundamental trade-off btw energy density & discharge power capability → limited by cell chemistry (cf. next slides)
- Commercialized Li-Ion: balanced trade-off



Good rate capability & power performance

[1] [Viswanathan et al., *The challenges and opportunities of battery-powered flight*, Nature (2022)]

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Key Trade-offs & Maturity in Next-Gen Batteries (1/2)

Battery type	TRL (estimate)	Specific energy (cell) [Wh/kg]	Rate capability	Cycle life	Volumetric energy density [Wh/l]
Li-ion (NMC, NCA)	9 (commercial)	200-300	High	High (1000-3000 cycles)	cf. later discussion
Li-Metal*	4-7 (emerging)	300-500 (lab)	Moderate	Medium	
Li-Sulfur	4-5 (prototypes)	400-500 (lab)	Low-moderate	Medium	
		1000 (forecasted)	Tbd	Low (current estimate)	
Zinc-Air	4-5 (early stage)	300-400 (lab) 500+ (forecasted)	Low	Medium	
Li-Air	3 (experimental)	1000+ (forecasted)	Low	Low	

Higher-energy, less mature batteries (e.g. Li-Air, Li-S) currently show unfavorable trade-offs in rate capab. & cycle life

* Including advanced Li Ion batteries with conventional intercalation cathode, but Li metal anode

Key Trade-offs & Maturity in Next-Gen Batteries (2/2)

Battery type	TRL (estimate)	Specific energy (cell) [Wh/kg]	Rate capability	Cycle life	Recent key advances
Li-ion (NMC, NCA)	9 (commercial)	200-300	High	High (1000-3000 cycles)	Incremental improvements
Li-Metal*	4-7 (emerging)	300-500 (lab)	High	Medium - high	*Stabilized Li metal anode* *Anode-free designs*
Li-Sulfur	4-5 (prototypes)	400-500 (lab)	High	High	*Stabilized Li-S & anode-free → x10 in cyclabililty, ultra-high rate capability*
		1000 (forecasted)	Tbd	Low (current estimate)	
Zinc-Air	4-5 (early stage)	300-400 (lab) 500+ (forecasted)	Low	Medium	Reachargability & air-cathode stability
Li-Air	3 (experimental)	1000+ (forecasted)	Moderate	Moderate	*1000-cycle breakthrough at high performance*

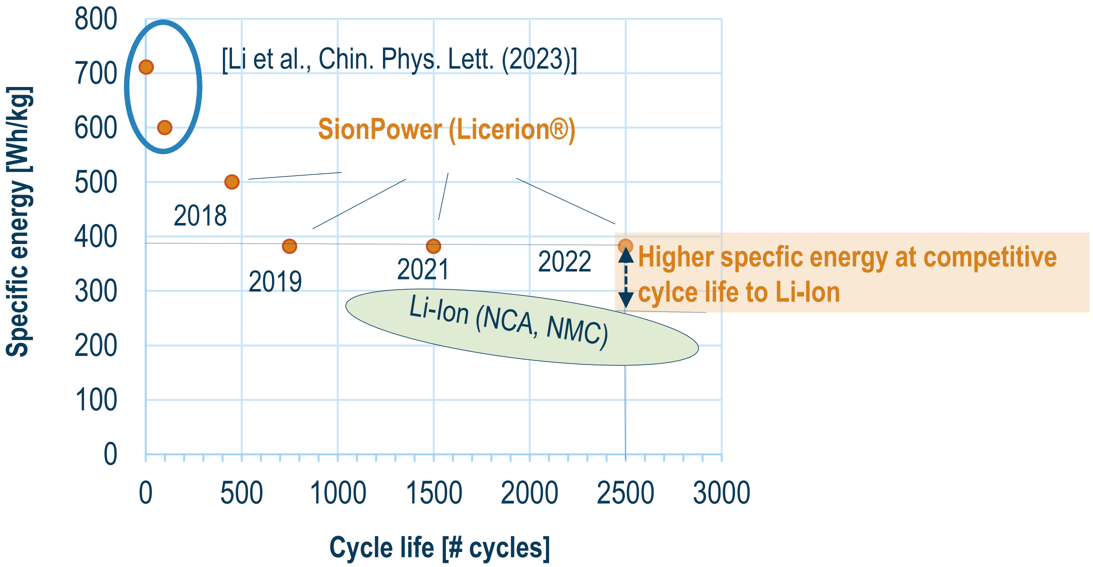
Recent advancements address stability, cycle life and power / energy density improvements → Next slides

* Including advanced Li Ion batteries with conventional intercalation cathode, but Li metal anode

Li-Metal – Key Progress for Improved Performance Trade-offs

Stabilized Li-metal anode dendrite-free operation

Exploitability of very high capacity & low electrochemical potential

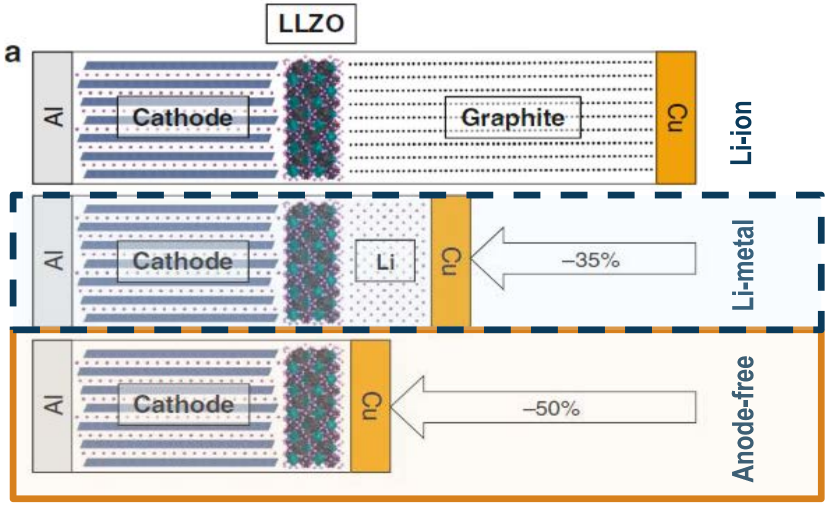


- **Balanced energy vs. cycle life for liquid-electrolyte variants**
- **Near-term target*: 400 Wh/kg, >2500 cycles**
- **⚠ Record-high reported values typically at *low* cycle life**

*E.g. SionPower, SES, Li-metal anode, conventional intercalation cathode

Anode free designs

Both for liquid & solid electrolytes, adaptable to various chemistries



Solid electrolyte example – Lithium Lanthanum Zirconium Oxide (LLZO)
[Molaiyan et al., Adv. Funct. Mater. (2023)]

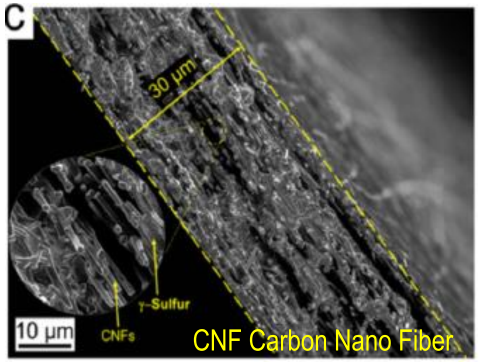
- **Near-term target**: ~ 300 – 500 Wh/kg**
- **Significant *volumetric* energy density gains**
- **⚠ Cycle life → current performance ~O(100) cycles**

**E.g. SAMSUNG, Quantum Scape

Li-Sulfur – Key Progress for High Specific Energy, Power & Cycle Life

Stabilized Li-S avoiding side reactions (polysulfide shuttle) + dendrites with step-change advance in rate capability

E.g. via sulfur-carbon cathodes & carbon nanotube anodes (not shown)



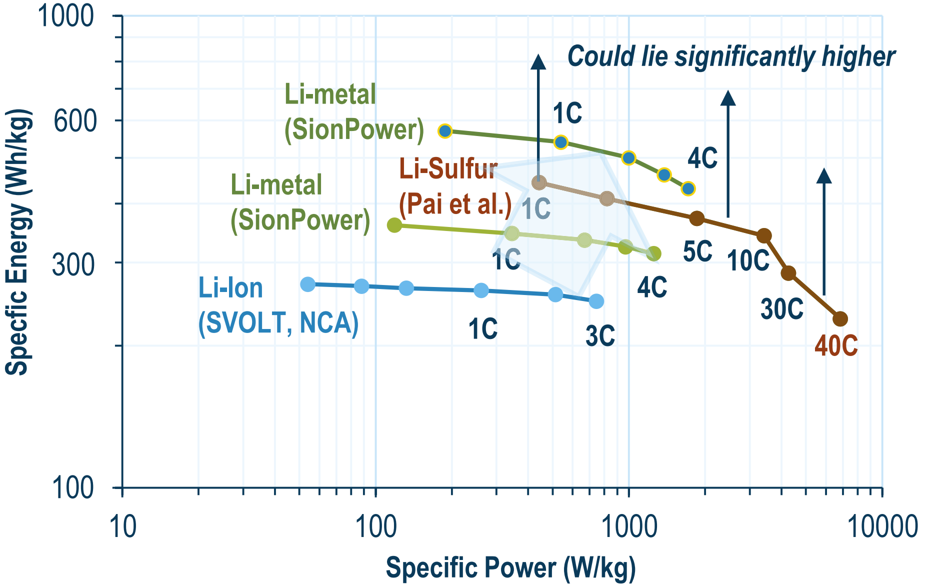
Nano-confined Sulfur contained in cathode (γS-CNFs) stable at room T in carbonate electrolyte:
4000 cycles at 0.5 C

Exceptional rate capability
with comparatively high specific energy even at
Ultra-high C-rates of 40C (!)
→ Ragone diagram

[Pai et al., Communications Chemistry (2022); Liu et al., Advanced Functional Materials (2024)]

Ragone diagram based on data from Pai et al., SionPower, SVOLT

Note: Technologies of different maturity levels



- **Step-change improvement in cyclability (> x 10) & rate capability: e.g. Zeta Energy 2030 target: 450 Wh/kg, 2000 cycles, up to 10C[1]**
- **Anode-free designs: perspectives for offseting lower *volumetric* energy density than Li-ion**
- **⚠ Scalability: manufacturing complexity**

[1]Optimized for automotive applications

Li-Air – Key Progress Towards Tapping High Energy Potential

Lab-scale breakthrough in cycle life & rate capability at high specific energy

- First demonstration of **full $4e^-$ reaction at room T** via solid-state nanocomposite electrolyte[1]
- **Significantly improved power output capability & round-trip efficiency**
- **Up to 685 Wh/kg (cell)*, 1000 / 350 cycles for 0.5C / 1C**

→ **More than order of magnitude improvement in cycle life at high performance**

- **Forecast: 1200 Wh/kg (cell)***

[1] [Kondori et al., Science (2023); Cheng et al., Nature Communications (2025)]

Key ways forward for optimizing system-level gains & closing maturity gaps

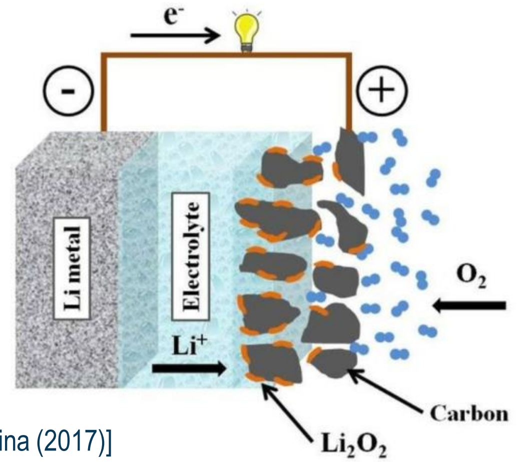
- **Consideration of trade-offs cell vs pack level → will diminish net gains wrt. Li-Ion**

→ **Lightweight oxygen management & system integration**

→ **Optimized charge transport** (electrolyte, cathode architecture) to further **improve power / rate capability**

→ **Improved cathode stability**

Reaction (e.g.)	Theoretial specific energy (Wh/kg) (active mass level)	Characteristics
$4e^-$ (Li_2O formation)	~3000	Improved conductivity, rate capability
$2e^-$ (Li_2O_2 formation)	~1765	Limited cycle life



[Mozhzhukhina (2017)]

Air cathode – key trade-off cell vs pack level
✓ No stored cathode reactant → reduced mass (cell)
⚠ Oxygen supply → adds weight, volume (pack level)

* Note: oxygen supply not included → penalties at pack level (cf. RHS), which reduce net gains wrt. Li-Ion technology

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Agenda

- Bauhaus Luftfahrt Technology Radar
- Technology Pull versus Push
- Future Technology Analysis
- Signals for Innovation Potentials
  - Batteries
  - Fuel Cells
- Summary & Conclusions
- Outlook

Fuel Cells for Electric Propulsion in Aviation – Key Metrics

Key metrics

- **Stack & system specific power, efficiency & durability**

Range

- Determined by stored (L)H_2 → energy and power decoupled

Peak power demands **takeoff, climb**

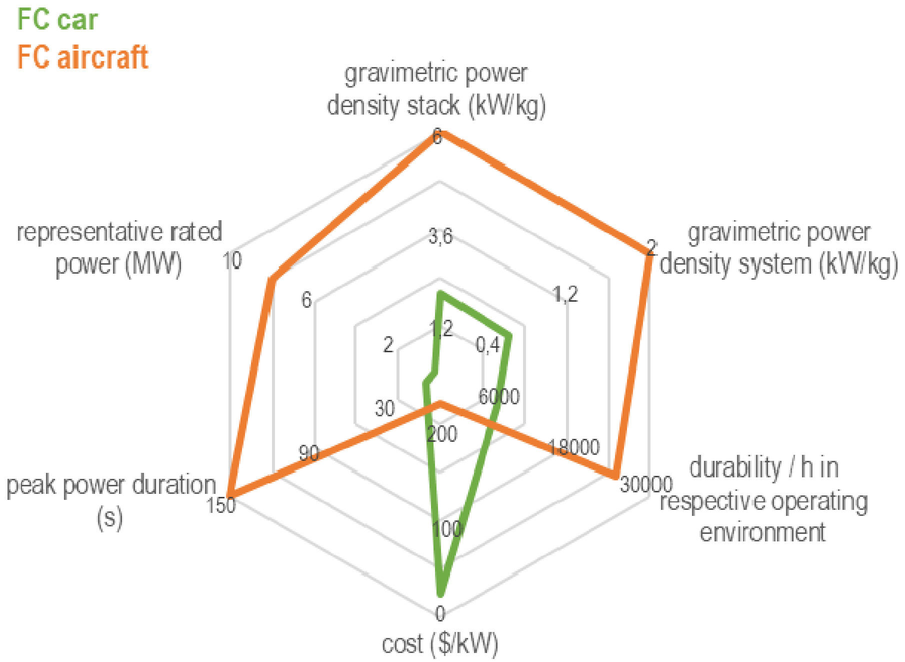
- Require high **specific power at system level**
- System-specific power is a key scalability challenge
  (FC stack power density, BoP[1], LH_2 tank → weight & drag penalties)

Durability **challenging under aviation-typical load profiles**

Efficiency → **next slide**

- Propulsion chain: higher conversion losses than battery-electric, yet potential efficiency benefit wrt. H_2 combustion

Performance targets FC AC vs FC car



[Ebner, Koops, *Potentials of Prognostics and Health Management for Polymer Electrolyte Fuel Cells in Aviation Applications*, Aircr. Eng. Aerosp. Technol., (2022)]

[1] BOP Balance Of Plant (water, thermal & power management & reactant supply)

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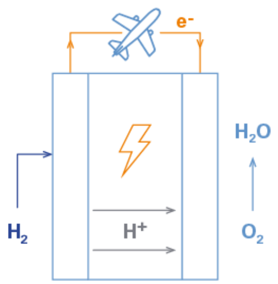
Hydrogen Fuel Cell Technology Options



Low Temperature Polymer Electrolyte Fuel Cell (LT-PEFC)

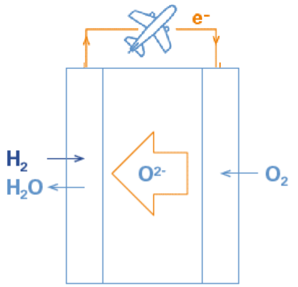
(~60-80°C)

Theoretical: 50-60%
Practical: 45-55%

High Temperature Polymer Electrolyte Fuel Cell (HT-PEFC)

(~120-200°C)

Theoretical: 55-70%
Practical: 40-50%



Solid Oxide Fuel Cell (SOFC)

(~600-1000°C)

Theoretical: 60-85%
Practical: 50-60%

- Increasing operating temperatures
- Improved reaction kinetics
- Increasing theoretical efficiency
- Facilitated thermal and water management (no humidification required, cf. next slides)
- Fuel flexibility beyond (L)H_2
- Increasing combined heat & power potential
- Increasing challenges in thermal stability
- Decreasing load response
- Decreasing Technology Readiness Level (TRL)*

* For mobile applications

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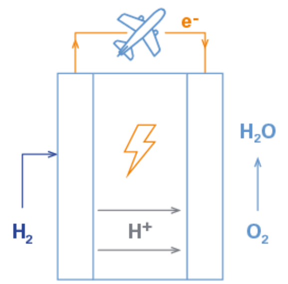
Hydrogen Fuel Cell Technology Options



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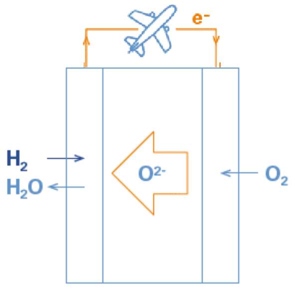

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Comparing HT- to LT-PEFCs focus: water & thermal management & component weight differences

Potentials & Indicators

Higher operating temperature (T)

- ✓ Higher efficiency potential cf. last slides
- ▪ Different membrane types & further advanced materials

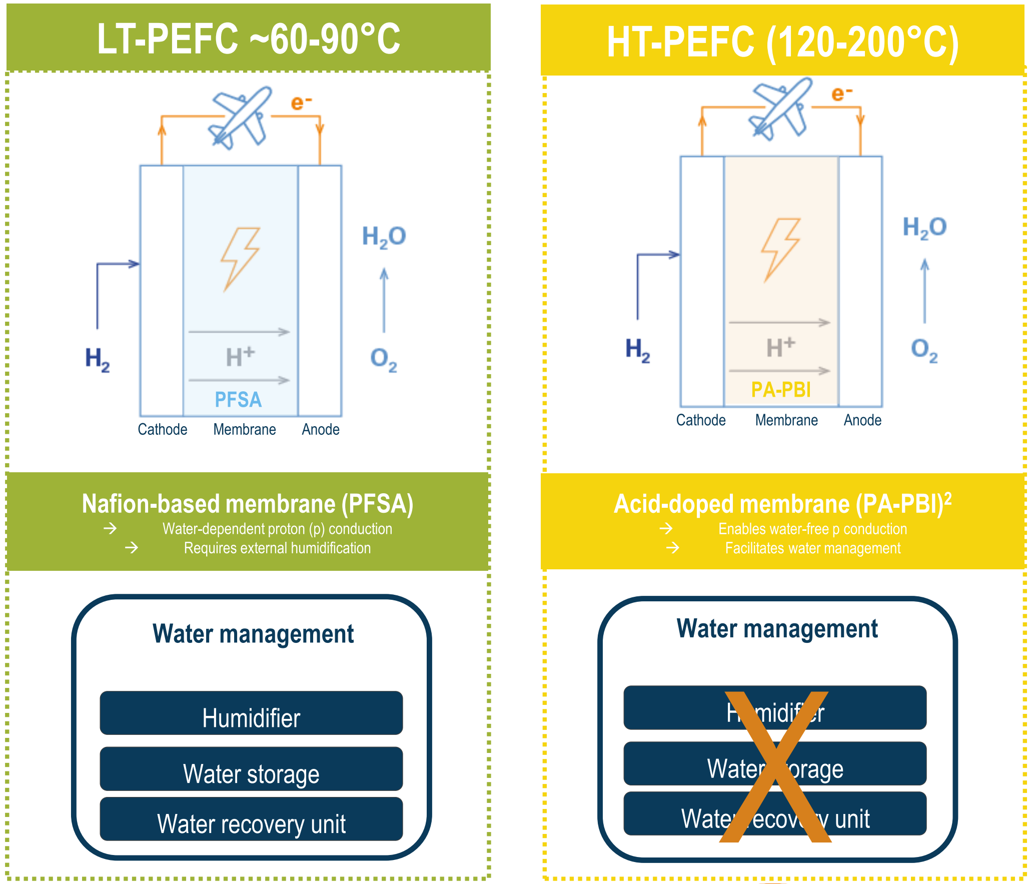
Novel working principles

- ▪ Water-free proton conduction in acid-doped polymer membranes (e.g. PA-PBI)[2]
- ✓ Enabling high-T operation *without* external humidification
- x Requires handling corrosion (acid leaching)[2]

High-level implications

- ✓ **Significantly lower BOP[1] weight**
- ✓ Eliminated need for complex water management subsystems
- ✓ Facilitated thermal management cf. next page
- ✓ Potential for improved scalability to larger aircraft cf. later slides

Reduced BOP weight & complexity

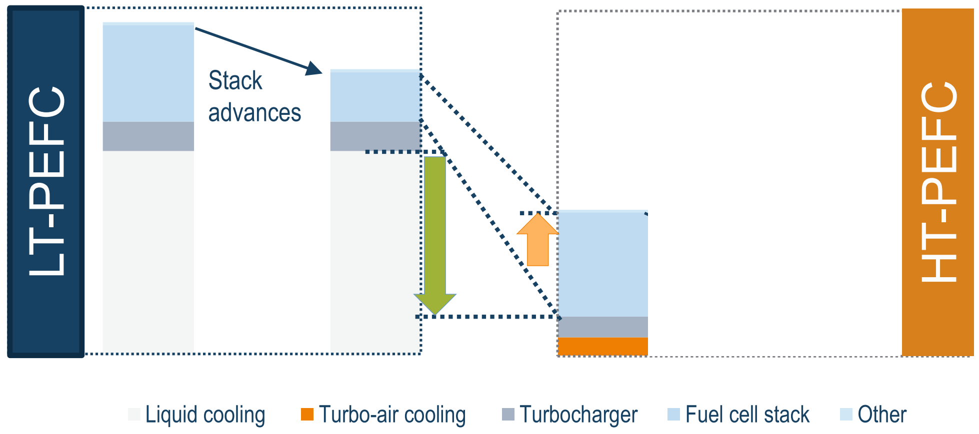


[1] BOP Balance Of Plant (water, thermal & power management & reactant supply); [2] Recent progress to handle corrosion (acid leaching) under various operating conditions

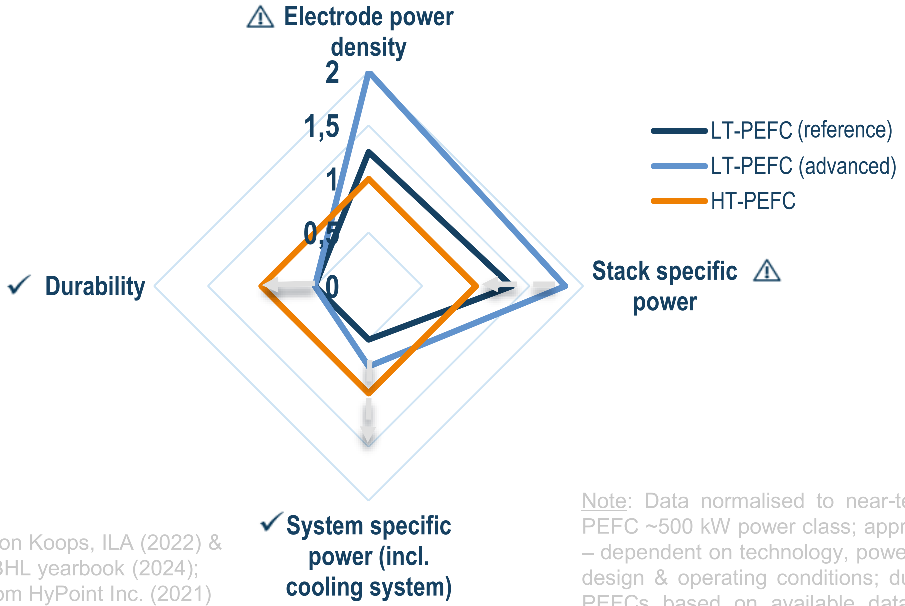
HT-PEFCs vs LT-PEFCs – Potential for System Level Advantages

Thermal management system weight

- High T operation enabling novel cooling concepts vs conventional liquid cooling, e.g.
- Turbo-air cooling using compressed air for cooling (depicted)* & oxygen supply to enhance efficiency ⟶ offsets compression energy demand (not depicted)
- Phase-change cooling ⟶ efficient multi-MW-scale HT-PEFC integration



Key trade-off & system-level perspectives



Based on Koops, ILA (2022) & Fikry, BHL yearbook (2024); data from HyPoint Inc. (2021) (acquired by ZeroAvia in 2022), ZeroAvia (2024); Hyzon

Note: Data normalised to near-term target HT-PEFC ~500 kW power class; approximate values – dependent on technology, power class, system design & operating conditions; durability for LT-PEFCs based on available data for LT-PEFC (reference); hence for LT-PEFC (advanced) to be considered as estimate

* Detailed modelling & simulation needs to ensure that cooling is effective over the full envelope & assess scalability, while quantifying potential penalties (pressure drop, compressor power, efficiency & integration impacts), including any auxiliary power & buffer-storage (battery) requirements.

***Key trade-off*: Higher stack weight (lower electrode power density) of HT-PEFCs vs. *much lower* BoP weight ⟶ perspectives for net system-level gains, with ~2 kW/kg (near term)**

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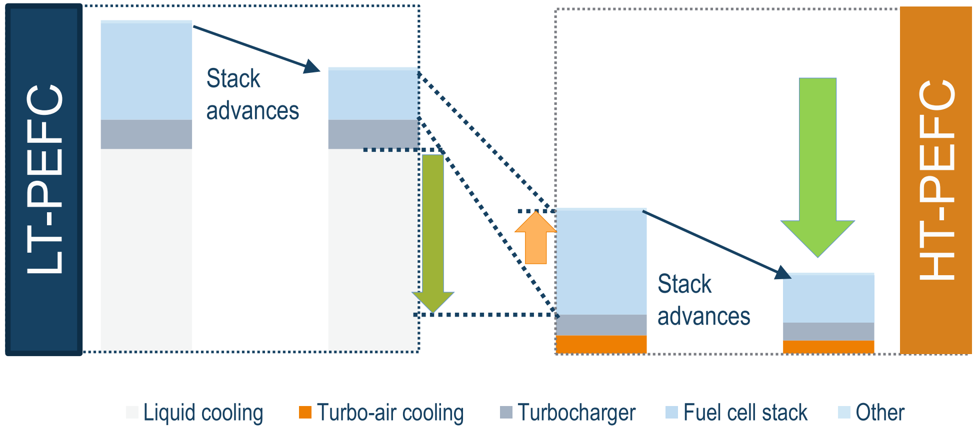
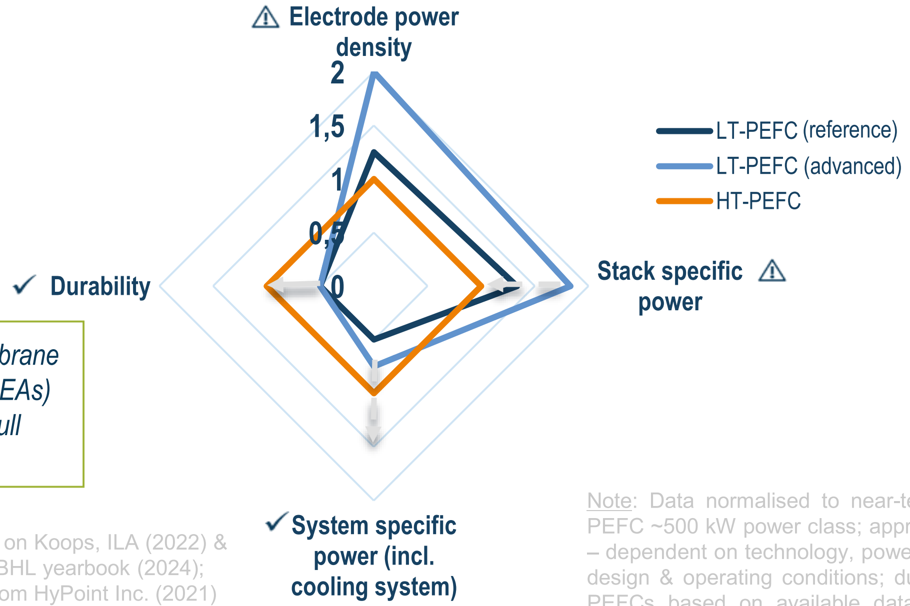


Future advances in Membrane Electrode Assemblies (MEAs) → large lever to exploit full potential of HT-PEFCs

Key trade-off & system-level perspectives



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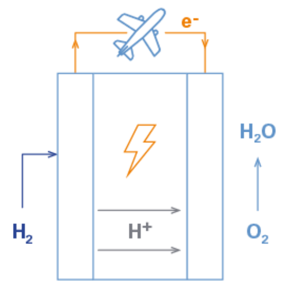
Hydrogen Fuel Cell Technology Options



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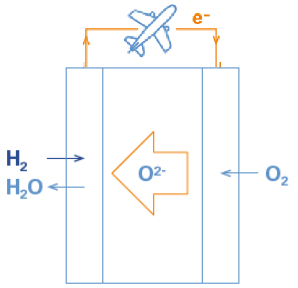

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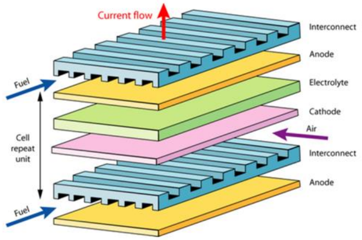
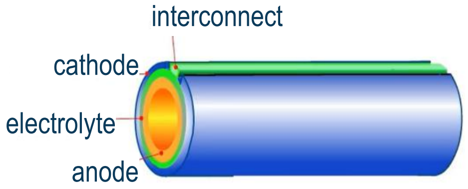
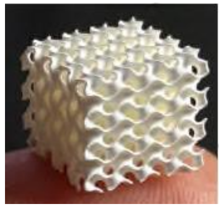
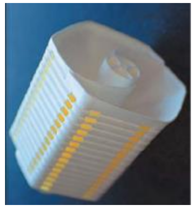
SOFCs – Key Progress towards Applicability for Aviation

[Based on data from Nehter et al. *Solid Oxide Fuel Cells for Aviation, ECS Trans.* (2023); Martos et al., *3D printing of reversible solid oxide cell stacks for efficient hydrogen production and power generation*, J. Power Sources (2024); DoITPoMS, 2020, available online: https://www.doitpoms.ac.uk/tlplib/fuel-cells/printall.php]









Metric	Planar SOFC	(Micro)-tubular	Monolithic
Specific power	Poor	Good (small diameter)	Good (expected)
Startup & shutdown time	Poor (stack)	Good	Medium (expected)
Internal cooling possibilities	Poor	Good	Good – medium
(Thermo-)mechanical stability	Poor (stack)	Good	Good – medium (expected)
TRL	High (commerical)	Medium - low	Low (experimental)

Previous focus on *planar* SOFCs in stationery applications, e.g. for Combined Heat and Power (CHP) applications

Lower maturity SOFCs with abstracted geometries come with more favorable trade-offs in aviation-relevant metrics

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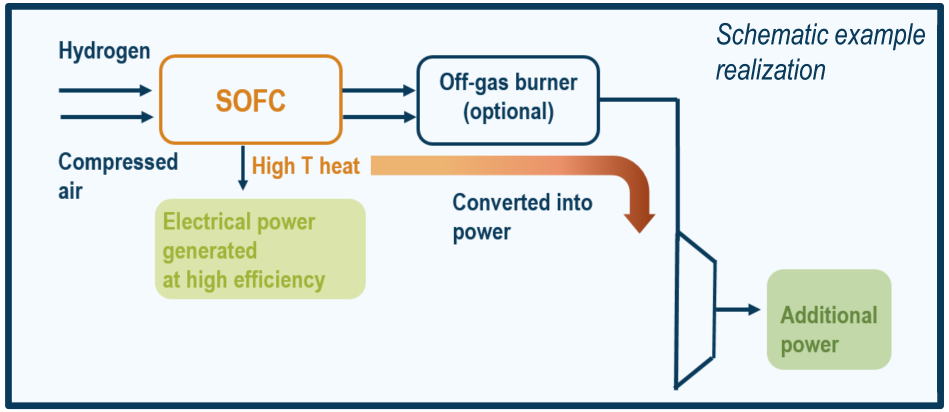
Synergistic SOFC – Gas Turbine Hybrids – Perspectives & Enablers

Perspectives of synergistic hybrids

E.g. highly integrated SOFC – Gas Turbine (GT) architectures[1]

- No CO_2 & essentially no No_x emissions
- High overall efficiency → emission & tank scaling



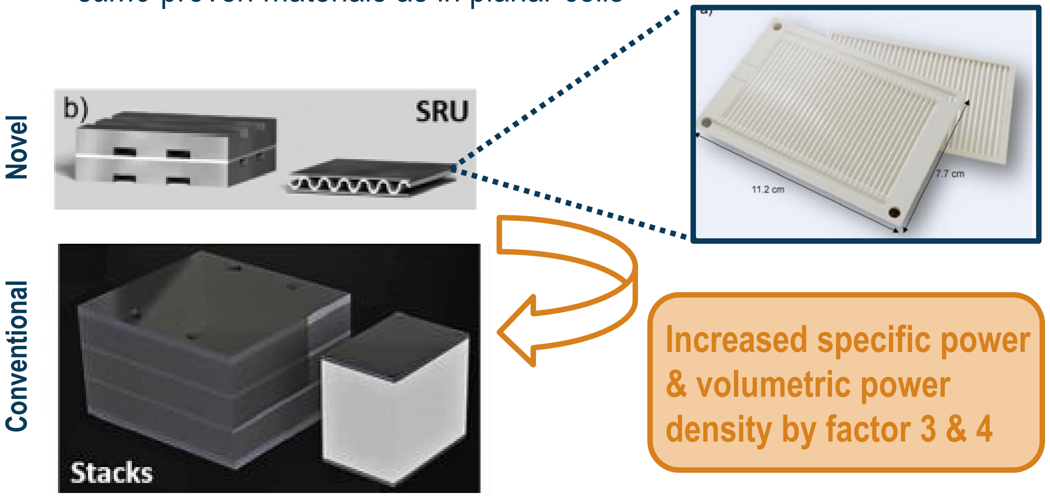
Adapted from Nehter et al. *Solid Oxide Fuel Cells for Aviation, ECS Trans.* (2023)

Demands for multi-level optimization: SOFC materials, cell & stack technologies, stacking & integrated designs

Exploit geometrical degrees of freedom

E.g. offered by advanced 3D printing

- For scalable fabrication of complex-shaped solid oxide cells – *here*: using *same* proven materials as in planar cells



Martos et al., J. Power Sources (2024)

Manufacturing progress as key enabler for significant gains in power density & geometric flexibility for integration

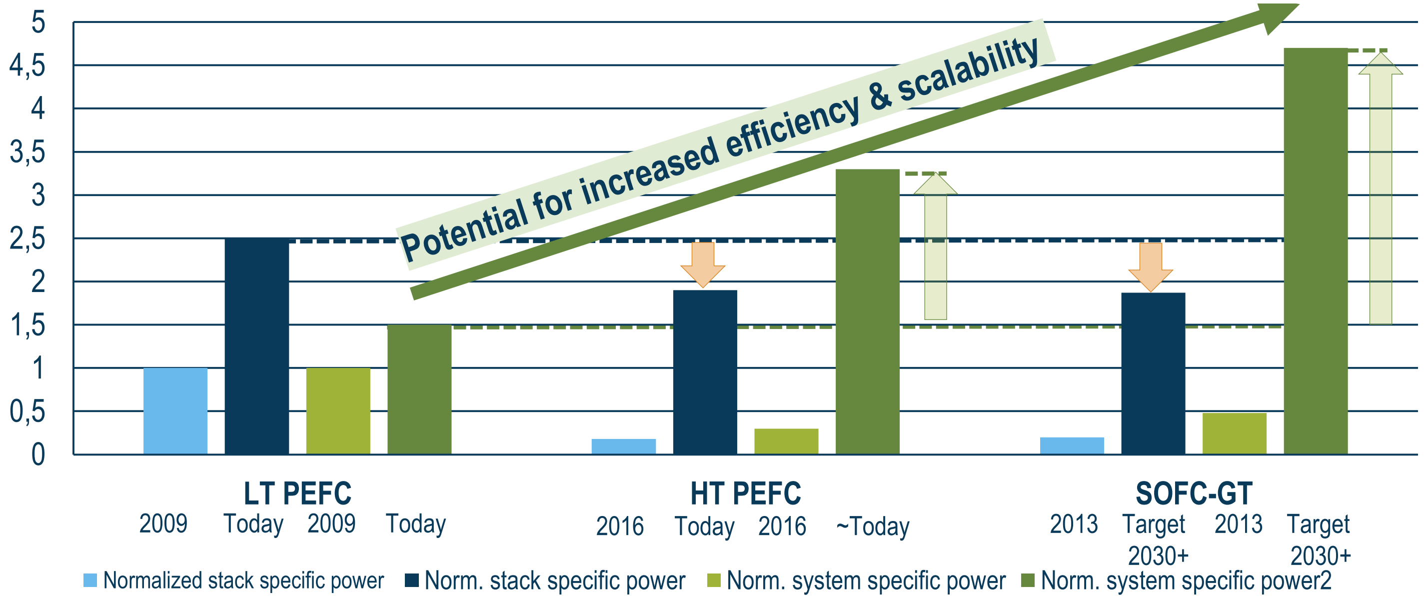
[1] HYLENA, *Horizon Europe*, *Airbus*, *TU Delft, LEPMI, DLR, LUH, BHL*

Evolution of FC Technologies – Performance Benchmarking Over Time

Progress in materials, designs & manufacturing as enabler

- Higher operating T → efficiency & system specific power gains
- Scalability: 150 kW (2009) → multi-MW potential
- Especially for SOFC-GT hybrids with waste heat integration for enhanced performance[1]

Normalized stack & system specific power



[1]Promising alternative hybrid conceps explored at BHL:
- Use SOFC water emissions to significantly enhance turbine efficiency & power output at significantly lower NO_x emissions, with potential benefits extending to long-haul applications[1]

Note: Specific power metrics normalized to fixed baseline, traditional LT-PEFCs in 2009 at 150 kW, to highlight technological progress, accounting for higher power outputs over time
⚠ Indicative values: stack and system specific power depend on cell type, system architecture and rated power; detailed modelling and simulation are required to assess scalability and system-level trade-offs

[[1] Nickl et al., German Patent Application DE 10 2020 107 905 A1 (2020); Seitz et al., *Initial Assessment of a Fuel Cell—Gas Turbine Hybrid Propulsion Concept*. Aerospace (2022); Seitz "Rapid Aircraft-Level Evaluation of Revolutionary Propulsion Concepts", 13th EASN International Conference, 2023]

Summary & Conclusions

Electrochemical propulsion enables zero in-flight emissions, scalability to larger AC critical for maximized leverage

Next-gen Batteries

- **Li-metal with intercalation cathodes & Li-Sulfur**: 400–500 Wh/kg (cell) near-term potential with cycle life & power / rate capability approaching Li-ion, but commercial scalability requires validation
- **Li-Air**: highest projected specific energy 1000 +Wh/kg (cell) with breakthroughs in cycle life & power, but key trade-off cell vs. pack level & low TRL → advance oxygen management, cathode stability, power capability & system integration
- **Short-to mid-term**: for significant range extension → exploit integrated design synergies and/or hybridization

Next-gen Fuel Cells

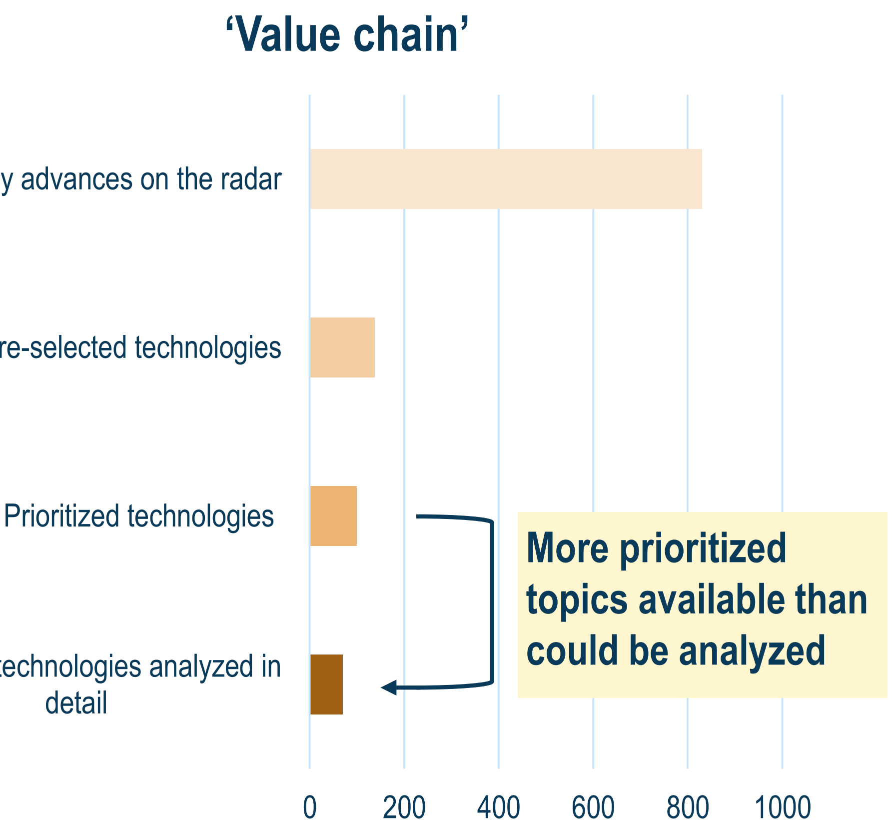
- **Higher operating T** → improved efficiency, facilitated heat/water management & reduced BoP weight → **better scalability for larger aircraft**
- **HT vs. LT-PEFC**: advanced cooling concepts & membrane electrode assemblies key enablers for **system-level advantages**
- **SOFC-GT hybrids**: high efficiency from SOFC electric power & gas turbine waste heat recovery

→ **Multi-level optimization** (SOFC & hybrid): manufacturing progress key enabler for higher power density & geometric flexibility

Outlook – Technology Radar at the National Level

- Continuously growing portfolio of potentially high-impact technologies
- Transfer BHL scouting & initial assessment process to the national level[1]
- LuFo VII-1 – ATLAS[1] (11/2025 – 10/2028)

[1]Air Transport Analysis and Technology Synergy Study



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The project is funded by the Federal Ministry for Economic Affairs and Climaty Action of Germany under the funding code 20M2438J.

[1] https://www.bauhaus-luftfahrt.net/en/projects/project-atlas-accelerating-the-transition-to-sustainable-aviation