EXC-SE²A: Call for Research Proposals in Research Area ICA C

Energy Storage and Conversion

1. Objectives of Call

Societies are becoming ever more interconnected and mobile and consequently are characterised by rapidly increasing air and land-bound traffic. Society requires new, substantially more sustainable and efficient energy supplies that meet its need for mobility. Sustainable aviation relies on reducing the present carbon footprint of aircraft and on developing sustainable and – if possible – zero-emission energy systems. Only a comprehensive and fundamental rethinking of energy supply concepts and technologies, rather than evolutionary research, will lead to a considerable increase in efficiency, specific energy and power, and sustainability. Key components are thought to be electrification, hybridization, and integration of batteries and fuel cells, and new combustion-driven fuel-conversion technologies. Every component on its own has considerable potential for improvement and the overall energy system even more so. On-board energy flows to be addressed in the analysis and subsequent improvements of the on-board energy system in addition to mechanical and electrical energy include heat and thermal energy associated with air, water (incl. humidity), and reaction products from combustion or fuel cells. Since some of the candidate devices for future on-board energy storage und conversion operate in narrow bands of temperature, pressure, and humidity (e.g. fuel cells, power electronics, electric motors), their needs for conditioning ambient conditions and operating conditions shall be addressed. Because the most promising energy system configurations are different for each flight scenario, a revolutionary change requires evaluating several new energy technology options and system architectures.

Projects within ICA C shall explore the most promising conversion and storage technologies and their interactions, focusing on increasing the specific energy/power, and efficiency while reducing emissions. The aim of the call is to set up a comprehensive research program along the following research hypotheses:

(1) Electrofuel blends can be designed for safe and efficient propulsion with low-emission on-board combustion. Their quality and purity must conform to specifications which ensure life and durability of the propulsion system.

(2) Electrofuels and LH_2 on-board infrastructure can be integrated with low-temperature heat sinks and high-temperature heat sources aboard the aircraft such that the aircraft and its subsystems can be concurrently optimized.

(3) All the thermal management systems of the aircraft can be optimally integrated and/or synergistically operated with a large performance benefit.

(4) Electrode structures and production methods allow Li-sulphur batteries at increased specific energy and specific power levels which are required by future aircraft requirements. Modifications of these batteries allow integration of such batteries into load-carrying aircraft structures.

(5) Fuel cell systems and batteries can be designed to meet the specific power density, efficiency, operational flexibility, reliability and durability which are required by future aircraft.

(6) Considerable weight reduction, sufficient redundancy, reliability, and durability life of the electric on-board systems and motors is possible to the level required by future aircraft.

(7) Advanced propulsor configurations for fully electrical or hybrid propulsion systems achieve the performance needed by future aircraft.

(8) Ambient air can be conditioned for passengers, electric cooling, fuel cells, and combustion by suitable on-board devices with performance parameters at the level required by future aircraft.

(9) Health and Safety Monitoring methods and prediction of MRO requirements for energy system components such as energy conversion and storage devices can contribute to the reliability and the minimization of degradation.

The research work will be structured into Research Units as detailed below.

Full exploitation of advances in energy technologies requires assessment at the fundamental level of the technologies and at the overall energy system and aircraft level. Researchers on single energy conversion and energy storage technologies need to deliver operating conditions and functionalities to the research group for the overall design of the energy system. The energy system analysis needs to cooperate intensively with ICA-B on the design methodology and assessment of aircraft to ensure that energy and function demand of the aircraft is known and that the main specifications of the energy system like volume, weight, content and requirements and constraints are taken care of. Furthermore, in cooperation with ICA-A it is necessary to assess the sustainability and costs of the technologies to guide developments in the right directions.

2. Structure of Research Units

2.1 Design methodology for aircraft energy supply systems (ICA-C1)

2.1.1 Objectives

The goal of the call is a methodical approach for choosing and dimensioning an appropriate energy supply concept for any given specific propulsion concept based on technologies mentioned above. All types of energy and required media have to be considered simultaneously, such as electrical, thermal and chemical energy streams as well as compressed air. The approach derives system-oriented research targets from the results of ICA A and ICA B, transfers them into requirements to the research on components in ICA C and feeds the resulting component and energy system performance and requirements back to ICA A and B.

2.1.2 Work content

The favoured design methodology originates from process systems engineering approaches and consists of two elements. The first is a model-based description of all relevant interdependencies. For this purpose, a system model of the on-board energy supply is formulated and utilized for optimisation. The component expertise within ICA C will be employed to derive a system model of the on-board energy supply. Special focus should be given to the simultaneous consideration of all energy and media streams, being relevant for the propulsion concepts under consideration. The description of each component and the corresponding energy and media distribution systems should be carried out on an abstract level, required for the overall system optimization. Intense interaction with component experts within ICA C is required, who design components and energy/media distribution systems on a more detailed level. At the systems level, the energy and media flows between the different components shall be balanced by means of an energy management strategy including the required subsystems, particularly the heat management and cooling which is the focus of C5 below, in order to fulfil the performance requirements during the entire operation. In addition to the technical description, together with ICA A an economic assessment shall apply methods such as factorial estimating. Scale and time indices shall be applied since they allow for a reliable estimation of investments for technologies at an early planning stage. Operational requirements and implications of different solutions on subsystem level shall be assessed in a step-wise procedure using the competencies of the systems research group in ICA B. Computational modules for aircraft design as developed by ICA B will be imported, while appropriate computational modules for energy storage, conversion, and propulsion shall be provided to ICA B.

The second element comprises the application of numerical optimisation methods to the system model in order to identify the most promising system structure and the dimensions of each component. At this stage, the uncertainties regarding technical and economic parameters originating from the component research, which is executed in parallel, are considered by means of stochastic methods. Finally, through this second step, a certain energy and operational requirement originating from the aircraft will be translated into a suitable energy supply concept, associated with problem-specific parameterised weight and size, cost estimates, efficiency measures, thermal management, and infrastructure requirements, which will be fed back into the research of ICA A and B. This will ensure complete integration of the energy system and aircraft design. As a further outcome, sensitivity analysis will assist us in deriving problem-specific research targets for the energy system component development.

2.1.3 Estimate of resources within Research Unit

The overall personnel resources for establishing the Research Unit are 1.5 doctoral researchers.

2.1.4 Call coordination

The call to establish Research Unit ICA-C1 is monitored by a Call Coordination Team consisting of PI Jens Friedrichs, Managing Director Doris Pester, and ICA C Coordinator Joerg Seume. The team members will serve as points of contact for any question concerning this call.

2.2 Advanced energy storage (ICA-C2)

2.2.1 Objectives

New material and processing concepts shall be applied for the preparation of lithium-sulphur cells. These will include minimisation of passive materials, carbon-sulphur composites with solid-ion electrolyte on the cathode side, solid-ion conductor as separator, and a pre-defined internal interface design. These cells shall have high specific energy exceeding 0.6 kWh/kg, reasonable specific power, high cycling stability, and good safety characteristics. A complementary approach of integrating energy storage functions into the structure shall be pursued through the investigation of energy storing composites for batteries. This would provide combined weight reduction of the structure and battery of at least 10%. Both strategies together pave the way for battery-powered aviation.

2.2.2 Work content

For batteries, the proposed project will investigate the manufacturing and processing of glassy and ceramic-based electrolytes (LLZO, sulphides, and tri-phosphates) and of hybrid electrolyte systems with polymers for identifying electrode and separator composite structures for high-energy aviation battery cells with load-bearing properties. Key topics that are continuously evolving through concurrent research on car batteries include (1) scalable chemical/mechanical processes to form composite solid electrolytes with defined microstructure, particle size and morphology; (2) post-processing techniques, such as granulation, to obtain structured composites consisting of electrolyte and carbon hosts; (3) interface design to reduce resistances and increase stability of the Li-metal anode by surface modification, functional thin films and gradient interfaces; (4) scalable processes for manufacturing electrodes, separator layers, and resulting cells with specific structures to improve performance, and mechanical strength for structural application in aviation. The extrinsic system properties required, such as energy and power densities, are obtained from ICA B, and the performance shall be matched to the energy system. Model-based analysis and pre-selection of the composition and structure of surfaces, electrodes, and cells is a prerequisite for identifying the most promising, high-performance cell configurations for air transport system. Existing electrode and battery models shall be extended, adapted, and parameterised to analyse and identify promising cell and electrode designs. The structure and material specifications identified as yielding the most promising configurations shall be experimentally validated and pave the way for producing these next-generation structures and materials. Together with ICA A and ICA B, the processes shall be rated on their economic and ecological feasibility. Parallel investigation of structural energy storage shall be pursued focussing on battery cells with load-bearing properties and higher energy densities. This shall be carried out by developing carbon fibre-reinforced composites with highly structured (e.g. nano-modified) solid-state electrodes that will need to be investigated further regarding their density, ionic conductivity and mechanical performance.

2.2.3 Estimate of resources within Research Unit

The overall personnel resources for establishing the Research Unit are 3 doctoral researchers.

2.2.4 Call coordination

The call to establish Research Unit ICA-C2 is monitored by a Call Coordination Team consisting of PI Gabriele Raabe, Managing Director Doris Pester, and ICA C Coordinator Joerg Seume. The team members will serve as points of contact for any question concerning this call.

2.3 Sustainable, low emission energy conversion (ICA-C3)

2.3.1 Objectives

Using sustainable liquid-fuel combustion shall proceed in two steps: The first objective is to identify CO_2-neutral electrofuels with combustion properties similar to those of kerosene. These "drop-in fuels", as they are referred to, can be used for aviation in modified combustion turbines. Further potential motivates a second and more challenging objective of synthesising and investigating tailor-made electrofuel that will allow the application of the lean pre-mixed prevaporised (LPP) combustion concept with acceptably low probability of pre-ignition, flashback, and combustion instability. This will result in sustainable aviation with zero CO_2 and soot particle emission as well as very low NOX emissions.

Adaptive compressors contribute to sustainable aircraft propulsion by enabling fuel cells or gas turbine-based generators to achieve higher power density and higher efficiency over a wide operating range. Shape-adaptive and flow-controlled compressors will help to overcome the aerodynamic limits of conventional compression systems. All approaches to active flow control will enhance operational flexibility and efficiency of individual stages and will readjust the flow to downstream stages, thus improving stage matching. Additionally, active flow control could allow the compressors and propulsors to switch into turbine —windmilling mode in order to recover energy during aircraft deceleration. A comprehensive analysis at the system level is required, as for instance the propulsors will likely be distributed throughout the aircraft in a modular fashion while the power conversion unit shall be central for reasons of power density.

2.3.2 Work content

The vision of emission-free combustion with sustainable electrofuels requires chemical reaction studies and property comparisons with respect to self-ignition. Laboratory flame experiments shall establish the combustion properties and stability of selected electrofuels including blends. Experiments with increasingly preheated fuel-air mixtures shall establish pre-ignition and flash-back limits of electrofuel for the LPP concept. Emissions shall be tracked down to ultra-low emission levels. In parallel, numerical simulation of combustion shall be done including use of the Large Eddy Simulation technique, and reaction and ignition modelling shall be empirically validated against the experimental setups. This will allow up-scaled application predictions for future aircraft propulsion systems.

A fully adaptive compressor will exploit the synergies between shape adaptive compressor blades and active flow controls. Study targets are unstable 3D aerodynamics, the robustness of highly-loaded transonic airfoils against local shape variation, and aeroacoustics. Design studies shall focus on possible improvements from fibre composites, integrated macro fibre composite (MFC) actuators, and MFC concepts for cantilevered stator blades. Moreover, inter-stage mass-flow recirculation shall be realised that is needed for active stage matching in active flow control. The combination of adaptive-shape compressor blades and active flow control shall be demonstrated experimentally in a multi-stage research compressor lab with suitable infrastructure for experimental research on aviation engine compressors, such as variable pressures for simulating variable altitudes. The topic shall tentatively be addressed via establishing a Junior Research Group. Selected compressor system configurations shall be experimentally validated at the Dynamics of Energy Conversion laboratory at Leibniz University Hannover. The Junior Research Group Adaptive Compressors comprises the lead and two doctoral researchers, subject to a separate Call for Applications.

2.3.3 Estimate of resources within Research Unit

The overall personnel resources for establishing the Research Unit are 6 doctoral researchers and one JRG lead position.

2.3.4 Call coordination

The call to establish Research Unit ICA-C3 is monitored by a Call Coordination Team consisting of PI Friedrich Dinkelacker, Managing Director Doris Pester, and ICA C Coordinator Joerg Seume. The team members will serve as points of contact for any question concerning this call.

2.4 Electrifying aircraft (ICA-C4)

2.4.1 Objectives

Integrated design of the electric power system and electric propulsion drives of aircraft requires interdisciplinary cooperation involving both electrical and mechanical engineering, as well as multiple objectives optimization of specific power, weight, efficiency, and acoustics. An increase in specific power of 40% compared to separate designs of power electronics, electric motors, and turbomachines is targeted. For the propulsion drive, direct fan drives without gearbox as well as high-speed drives equipped with a gearbox can be addressed as a solution. Application of improved or new materials, like for instance thin leaves of cobalt iron alloys instead of iron sheets, can be used for increasing the specific power of electric machines. With the application of superconducting components in the excitation system of electric motors, specific powers of 45 kW/kg shall be targeted.

The objective for electronic power conversion is to achieve a weight versus reliability optimum at the system level. New options for multi-MW converters with output voltage levels of several kV shall be addressed using high-voltage SiC power electronic devices. This approach shall be compared to other options based on lower-voltage wideband-gap devices and more complex (multi-level) converter topologies. Converter weight reduction by innovative air or liquid cooling is foreseen to be around 50% and will need to be evaluated at the system level together with ICA B. At the component level, weight reduction, reliability and durability of power semiconductors, passive components and packaging materials for instance insulation shall be targeted. The overall goal for the research on electrical wiring is the design of a lightweight, safe, reliable, fail operational and efficient power transmission system. Health and safety monitoring methods and prediction of MRO requirements can contribute to the reliability and the minimization of degradation. Low-loss and lightweight transmission of about 4 MW over approx. 25 m shall be targeted. As an alternative to high-voltage aluminium wiring, the use of a superconducting on-board electric grid and suitably adapted power electronics and electrical machine shall be considered. The interaction between the electric machine, the power electronic converter and the onboard elements is to be worked out to achieve the maximum power density.

2.4.2 Work content

The weight of electric motors and power electronics is dominated by losses and the performance of cooling systems needed for continuous power and overload operation. Heat sources are located in wires due to ohmic losses, in iron core leaves due to magnetic losses, in semiconductors due to switching losses, and in filter components. Therefore, analysis and optimization shall be performed at both the system and component levels. System analysis shall use thermal network models that focus on the operating profile and its heat-generation mechanisms. For quantification of model parameters and for experimental validation, the E^2AGLE environment which will be developed in an own call can be used.

Advanced approaches for component cooling shall be identified and assessed based on system analysis in close collaboration with C5. Possible candidates are forced-air cooling of machine housings, direct liquid cooling in motor slots, and direct liquid cooling of semiconductors. Component analysis may be performed on a comprehensive geometrical level by applying Reynolds-Averaged Navier-Stokes (RANS) flow solvers and hybrid turbulence representations. Improvement of channel geometries and surface character as well as active flow control shall be analysed for increasing heat transfer, while at system level the network shall exploit the synergies of an integrated cooling system. The system approach shall also quantify the benefits of low-temperature cooling for lightweight power electronics and electric motors and using the low cooling temperatures avail-able due to liquid hydrogen storage for cooling superconductive power supply rails (cables, adapted power electronics and machines). Mechanical strength and rotor dynamics shall be further developed by simulation and closely linked to the electromagnetic approaches explored. These approaches may be based on new analytical and numerical design methods that will be extended to aviation-oriented electric drives. Model validation may be supported by tests large testbeds.

Converters with new high-voltage SiC devices shall be designed and evaluated in the laboratory to realise power electronic systems at higher voltage levels. They will be compared to multilevel converter topologies using lower-voltage wideband-gap components (SiC or GaN). Increased robustness against temperature and power cycles is needed because of higher temperature swings. Higher packing density of small chips also needs to be investigated for SiC and GaN semiconductors (approx. 50 mm^2 because of lower production yields). Important research topics are here the balancing of multiple fast switching semiconductors to achieve a symmetric and unchanged slew rate and otherwise reliability and safety aspects. Material and packaging/cooling improvements may be investigated for semiconductors, passive components and construction materials.

Lightweight and efficient DC power on board avoids problems of reactive power, but requires a different design for overcurrent protection. Other promising concepts that shall be investigated and developed in combination with battery systems integrated into the mechanical structure include current collectors, distributed DC/DC-converters, and superconducting on-board net-work element. The operation of coupled electric capacities on common DC links is an important research topic here. The requirements shall be considered in functional and structural models (system analysis and electromagnetic compatibility). The energy system topology, protection concepts, fault scenarios, and dynamic loads shall be modelled and further developed.

2.4.3 Estimate of resources within Research Unit

The overall personnel resources for establishing the Research Unit are 4 doctoral researchers.

2.4.4 Call coordination

The call to establish Research Unit ICA-C4 is monitored by a Call Coordination Team consisting of PI Regine Mallwitz, Managing Director Doris Pester, and ICA C Coordinator Joerg Seume. The team members will serve as points of contact for any question concerning this call.

2.5 Aircraft thermal management system (ICA-C5)

2.5.1 Objectives

Aim of this additional section within the cluster area C is to establish a design methodology for an integrated thermal management system within a future electric airplane. A 'thermal management system' has to collect thermal energy from dissipative energy conversion and storage devices within the plane, has to identify the potential for internal heat recovery and integration and reject the remaining waste heat into the ambient air surrounding the plane. The distributed heat sources rely on stable and constant temperatures, each on its own individual temperature level, while the temperature of the ambient heat sink varies significantly during the flight mission.

2.5.2 Work content

The basic idea for the design methodology for such a thermal system with heat integration and recovery is to aim for a modular approach. In such an approach, components and subsystems of a possible thermal system, such as heat exchangers, compressors, pumps, valves, pipes, and heat pipes will be identified and assembled to create the most suitable thermal system for the specified airplane by means of simulation and iterative improvement. This integrated thermal system will be subject to optimization procedures for weight, efficiency, reliability, life, and design integration into the airplane. The latter will proceed in close collaboration with the overall energy system integration into the aircraft with B5 via C1. While C1 focuses on energy balances, C5 sets the targets for optimisation.

Modules such as the heat exchanger network, heat pipes, pumps, compressors, and thermal fluids and subsystems such as vapor compression cycles, Rankine cycles, and single-phase cooling loops will be modelled for purposes of design and optimization based upon state-of-the-art characterisation. Vapor compression and expansion equipment will be explored as an option of moving heat to different temperature levels or extracting work from heat available. The thermal system will condition ambient air for passengers, electric cooling, fuel cells, and combustion by suitable on-board devices with performance parameters at the level required by future aircraft. For state-of-the-art heat exchangers, by contrast, computational modules are provided for thermal system analysis which capture the main features of different types of heat exchangers at the 1-D level to be included into the overall thermal system program to be developed in C5 and B4. C5 shall also support ICA C4 in their challenges of cooling electric devices with high power densities.

The rejection of the remaining waste heat of the optimized thermal system has be integrated into the external surfaces of the aircraft, notably in close collaboration with B5. Especially the design and subsequent modeling of a condenser which rejects large amounts of heat to the ambient needs a special focus.

Dedicated research projects shall be initiated for those components which require fundamentally new features or performance parameters beyond existing technology. This is likely to be the case for cooling electric devices with high power densities and fuel cells.

In order to achieve compact heat exchange with high thermal performance, phase change cooling is desirable for the main heat exchanger and other heat exchangers throughout the aircraft. This leads to apparatus with a free gas/liquid interface and sloshing may occur. To fix the liquid phase to a certain extent, capillary structures within the two-phase region may assure the function of the heat exchanger in strong accelerating or retarding situations. Such internal channel structures, which have to be designed considering wettability and capillary forces of specific working fluid involved, can favorably designed and fabricated using additive manufacturing techniques. These and related issues shall be addressed, either in the The Junior Research Group "Evaporative cooling of main components in electrified aircraft", if it is formed, or by other PIs in C5.

The Junior Research Group "Evaporative cooling of main components in electrified aircraft" comprises the lead and two doctoral researchers, subject to a separate Call for Applications.

2.5.3 Estimate of resources within Research Unit

The overall personnel resources for establishing the Research Unit are 6.5 doctoral researchers and one JRG lead position.

2.5.4 Call coordination

The call to establish Research Unit ICA-C5 is monitored by a Call Coordination Team consisting of PI Jens Friedrichs, Managing Director Doris Pester, and ICA C Coordinator Joerg Seume. The team members will serve as points of contact for any question concerning this call.

2.6 Aviation fuel cells (ICA-C6)

2.6.1 Objectives

The goal is to identify aviation-specific fuel cell solutions through improvements at the material level, electrode level, membrane level, cell level, and/or stack level. Improvements of the related subsystems (cathode air compression and air humidification, anode recirculation including water separation, cooling, exhaust enthalpy utilization) must be designed and integrated into aircraft to improve specific power and efficiency to levels which are required by future aircraft while ensuring sufficiently reliable, long-term, and flexible operation.

2.6.2 Work content

The specific power and energy of fuel cell systems must be increased while ensuring robust and long-life operation. To achieve these goals, systematic multiscale, model-assisted analysis is needed. The analysis shall reveal potentials and limitations of a wide range of system configurations, material configurations, operating strategies including heat management, and future R&D demands. At the system and stack or cell level, questions of modularisation, process integration, and topology must be answered for various stages of flight as well as for interactions with and requirements from other aircraft components.

While current fuel cell operation requires creating ground-level conditions at all altitudes and ambient conditions the aircraft may encounter during a mission, the design of aviation fuel cells should relax these requirements by making fuel cells more resilient, i.e. tolerant of a larger range of temperatures, pressures, pressure ratios and temperature gradients across the membrane, and humidity such that the energy spent and the equipment necessary can be reduced. This may be achieved by improving upon existing fuel cell materials, electrodes, membranes, cell designs, and stack designs. They shall be adapted to aircraft-specific requirements of power, energy density, and expectations of component life and reliability.

Improvements of the related subsystems (cathode air compression and air humidification, anode recirculation including water separation, cooling, exhaust enthalpy utilization) must be designed and integrated into aircraft to improve specific power and efficiency to levels which are required by future aircraft while ensuring sufficiently reliable, long-term, and flexible operation.

2.6.3 Estimate of resources within Research Unit

The overall personnel resources for establishing the Research Unit are 3 doctoral researchers.

2.6.4 Call coordination

The call to establish Research Unit ICA-C1 is monitored by a Call Coordination Team consisting of PI Gabriele Raabe, Managing Director Doris Pester, and ICA C Coordinator Joerg Seume. The team members will serve as points of contact for any question concerning this call.