Proceedings of the ASME 2025 Conference on Smart Materials,
Adaptive Structures and Intelligent Systems
SMASIS2025
September 8-10, 2025, St. Louis, MO

SMASIS2025-167967

DEVELOPMENT OF STRUCTURAL INTEGRATED SUPERCAPACITORS WITH IMPLEMENTED ELECTRONICS FOR SPACE APPLICATIONS

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ABSTRACT

The market of small cube-like satellite is growing very fast. These satellites are comparatively cheap but are very limited in volume, weight and available energy. Energy is the most decisive factor for the duration of space missions and what kind of application can be run. The research focuses currently on the development of powerful and efficient batteries. Due to the chemical storage processes their lifetime is limited to much less than 30000 cycles. Furthermore, charge cycles and powerful peak power applications such as radar or robotics stress their performance. As result batteries have to be more powerful and bigger or will degrade faster. In contrast, supercapacitors use reversable physical processes of ion movement and orientation for energy storage. This reversible principle allows more than 1 million cycles. Therefore, they can be considered as maintenance-free, ideal for being integrated into composite structures. This approach of combining energy devices and structural elements offers great opportunities to save weight and volume, especially for small satellites.

This publication deals with the development of semi-finished thin-film supercapacitors which are integrated into fiber-reinforced plastics composites by autoclave processing. The supercapacitors are manufactured using aluminum collectors coated a with an activated carbon electrode. As electrolyte the ionic liquid 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide is used as electrolyte. Experiments show, that these supercapacitors can also be used as sensors for temperature and mechanical loads. Furthermore, the electronics has to be developed and will be also integrated into the composite to reduce electrical wiring, to improve electrical conductivity and to reduce the overall failure risk. The integrated supercapacitors become a smart component for plug and play application.

Within the project Decentralized Electrical supplied Electrical Propulsion (DEEP) a thruster system was developed using also structural integrated supercapacitors. The aim is to test the system on a DLR satellite mission 2030.

Keywords: Power composites, structure-integrated energy storage, supercapacitor, structural supercapacitor, smart component, electrical propulsion;

NOMENCLATURE

C	capacity	[F]
E	energy	[Wh]
I	current	[A]
t	time	[s]
U	voltage	[V]
Q	charge	[C]
w	width	[mm]
l	length	[mm]
h	height	[mm]
Y	young's-modulus	[MPa]
m	mass	[g]
V	volume	[µl]
A	area	[cm^2]

ABBREVIATIONS

AC	activated carbon
CAN	controller area network
COTS	commercial of the shelf
CPE	constant phase element

CV	cyclic voltammetry
DLR	German Aerospace Center
DoI	Degree of Integration
ECSS	European Cooperation for Space Standardization
EIS	Electrochemical impedance spectroscopy
EMIM	1-ethyl-3-methylimidazolium
EW	Electrochemical window
GFRP	glass fiber reinforced plastic
HySES	Hybrid Solar Energy Storage
IC	integrated circuit
IL	ionic liquid
ITFC	integrated thin-film (super)capacitor
PCB	printed circuit board
PPP	Peak Power Platform
R	resistor
SC	supercapacitor
SMD	surface mounted device
TFSI	bis(tri-fluoromethylsulfonyl)imide

INTRODUCTION

Energy storage in satellites is a crucial and expensive subsystem. While volume and weight are also important properties for space applications due to high costs (5500€/kg [18]) current trends of nano and micro satellites using miniaturization led on the one hand to some cost reduction but highlights on the other hand volume and weight optimized structures. An ideal solution can be the combination of two necessary subsystems such as the satellite structure and the energy system within one part. As soon as an integration of energy devices within structures is considered, the lifetime of the device is of decisive importance. A battery, as the most common energy device, suffers from their chemical energy storage process via ion diffusion. Due to ion absorption the formation of dendrites occurs which causes a destruction of the separation layer and therefore the battery degrades within comparable short period (achieved by a specific solid-state battery with 71% of capacity after 20000 cycles [35], commercial batteries degrade much faster). In contrast, supercapacitors are a highly efficient type of energy storage in terms of lifecycle and peak power currents. Supercapacitors feature some advantages especially for short-term power applications, such as robotics, radar, heating and energy conversion. Their high specific power densities up to 10-15 kW/kg [1] is an order of magnitude larger than lithium ion batteries [2]. However, due to the different storage processes, batteries feature higher specific energy density and higher volumetric power density. This is one of the main reasons why batteries are used for applications with demand for constant power. A further advantage of supercapacitors is their ability to be charged within seconds (depending on the current), to manage power peaks and that they can be manufactured from sustainable, lightweight and abundant materials such as carbon. Finally, supercapacitors can be discharged completely, a condition which should be absolutely avoided for batteries. Batteries need a specific thermal management with temperatures ranging from 15-35°C (Li-batteries [36]) for delivering their performance and having a long service time. Also, supercapacitors have a temperature-dependent behavior but show a more robust lifetime behavior even at rough conditions.

As soon as supercapacitors are charged within their electrochemical window (EW) they can show their greatest advantage, the almost endless lifetime. This characteristic can be explained with their energy storing mechanism. It is mostly based on physical, reversible effects, such as electrostatic-induced ion diffusion between charged electrodes. As a result, life cycles of $5 \cdot 10^5 - 3 \cdot 10^6$ without degradation are possible [2, 3]. This freedom from maintenance favors their integration into composites, namely a structural power composite, more than any other energy storage device.

Recent supercapacitor research is a wide field and deals with the optimization of their components, such as electrodes made of graphene [4], thin separators, electrolytes with a wide electrochemical window or a mix of supercapacitors and batteries [5] to combine their advantages and to compensate the disadvantages. However, other promising research focuses on their structural integration into load-bearing structures [6-9]. The lay-up of composites is ideal for the integration of additional functions such as energy storage. For a better understanding of the different types of integration strategies, Adam [10] introduced the *Degree of Integration* (DoI), also shown in figure 1. The DoI represents the level of multifunctionalization of an energy storage device.

DoI 0 represents the classical arrangement of two isolated systems.

In DoI I, the structure and energy device are still isolated systems, but the energy storage device fills enclosed free spaces of the structure.

In DoI II, the energy devices are part of the structure, for example as layers, integrated thin-films or applied patches. Nevertheless, the systems can be considered as combined components that also work on their own. However, the energy devices can already influence the mechanical behavior of the structure positively or negatively.

The DoI reaches higher values when the energy-storing materials become small and light. This is the case when neat carbon fibers are used as electrodes, which represents a DoI of III. Here, the whole structure can be used as an energy storing device. Composites are particularly suitable for this task.

However, the highest DoI IV can only be reached by functionalizing the microscopic components of a structure, such as the carbon filaments of the carbon fibers or the fiber itself, and by using their specific excellent properties. In the following it will be shown that structural integrated supercapacitors are investigated in all degrees of integration.

The research on structural power composites started in 2004. Wetzel [11] reported the integration of energy supplies (battery, supercapacitor and fuel cell) and electronic devices into composites. This approach should significantly reduce the weight of military applications. His thin-film approach already reached a DoI of II to III.

Petersen integrated a thin-film supercapacitor (ITFC) into gas fiber reinforced plastic (GFRP) and also reached a DoI of II

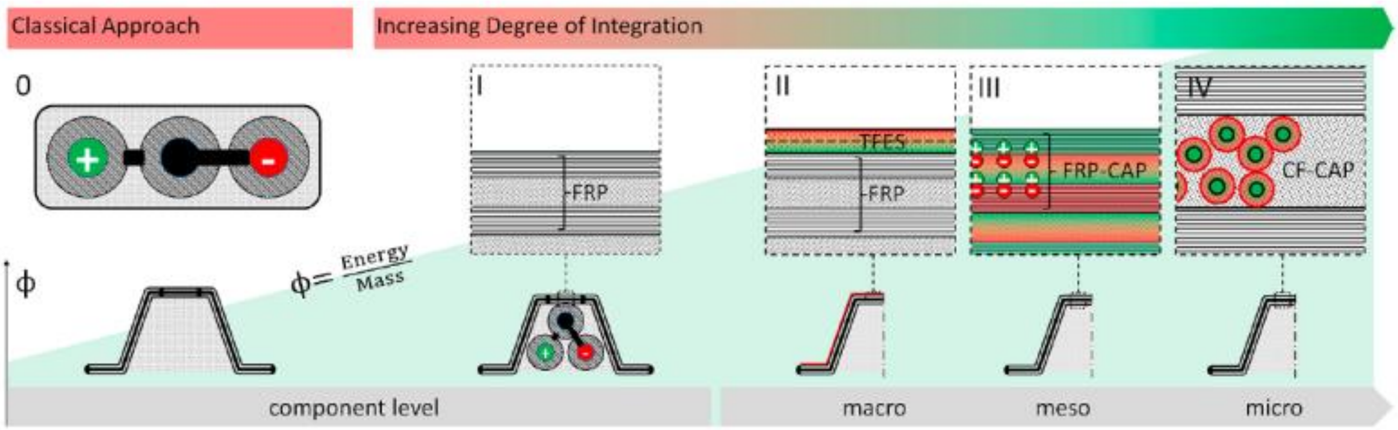


FIGURE 1: DoI-VALUES 0 TO IV, REPRESENTING DIFFERENT LEVELS OF INTEGRATION [10]

with additional sensoric effects such as detection of the temperature and mechanical loads [12].

An even greater scientific challenge seems to be the single-ply functionalization to reach a DoI of III. Quian [6] and Shirshova [7] developed carbon fabrics which are coated with carbon aerogel for higher specific surfaces. Furthermore, they developed an electrolytic matrix to build up a structural supercapacitor. Unfortunately, the energy composite shows neither good mechanical properties nor does it have a sufficient electrical performance.

According to several researchers [8, 13], the synthesis of a multifunctional matrix combining the two properties, ionic conductivity and stiffness, is a challenging task, see Fig. 2.

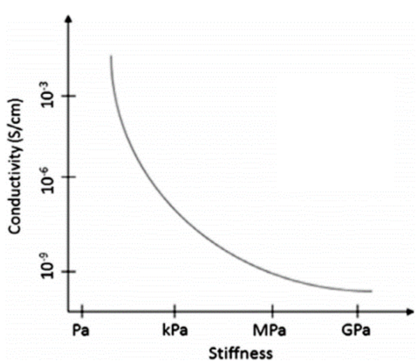


FIGURE 2: RELATIONSHIP BETWEEN IONIC CONDUCTIVITY AND STIFFNESS ACCORDING TO [8]

Ciocanel [8] defined the requirements for such an ideal structural energy storage material. Currently, there are two promising approaches for the multifunctional matrix of structural batteries, a strategy of which can also be applied to supercapacitors.

The first approach is the multifunctional matrix, combining ionic conductivity and mechanical stability in the same material. The second approach combines materials consisting of two different phases. The first ionic conductive phase is embedded within a second mechanical loadable structure phase [13, 14, 15]. Tu [13] used a multi-scale finite element simulation to find the best multifunctional bi-continuous electrolyte as resin for the composite. A structural battery based on these approaches achieved good mechanical and electrochemical performances [16].

The whole topic is summarized in several review papers [8, 23, 24, 26]. So far only a few full-scale demonstrators are presented, such as a Volvo S80 bootlid demonstrator [25] which never went into series production and a satellite positioning system using high torque wheels (HTW) with 14 integrated supercapacitors [27] developed in the DLR project Peak Power Platform. The third application, a solar panel with 12 integrated supercapacitors [28, 29]. Both applications still wait for their in orbit tests. However, on the 14th of January 2025 a cube satellite called InnoCube was launched to space carrying a structural battery [37] for tests in orbit. With NOVAC a first start-up was founded to commercially sell structural integrated supercapacitors, based on solid state electrolytes and integration in CFRP [38].

The presented work also focuses on a space application with the need of reduced volume and weight. Structural supercapacitors as part of a highly integrated electrical propulsion system is investigated and developed in the DLR-funded project Decentralized Energy supplied Electrical Propulsion (DEEP). Five institutes of the German Aerospace Center (DLR), the Institute of Integrated Systems, the Institute of Materials Research, the Institute of Optical Sensor Systems, the Institute of Aerodynamics and Flow Control and the Institute of Engineering Thermodynamics collaborate to develop a compact electrical propulsion system with a hybrid energy system for small satellites. As part of the hybrid energy system structural supercapacitors are design and equipped with electronics as smart component for plug-and-play application. The development of this smart component with possible additional sensoric features, based on earlier projects such as Hybrid Solar Energy Storage (HySES) and Peak Power Platform (PPP) will be presented in this paper.

1. MATERIALS AND METHODS

This section gives a detailed view on the materials used to build the supercapacitors and laminates. The results of various mechanical tests, such as interlaminar shear stress, tensile modulus and strength as well as four-point bending (4PB) can be found elsewhere [27-29].

1.1 Supercapacitor materials

The film supercapacitor consists of a separator membrane with a thickness of 20µm (Celgard 3501-4000M-AS40), which is supplied by the company Celgard, LLC (USA). A SEM picture in figure 3 a) shows the surface of the membrane with slot-like pores of 400-700nm in length and 30-50nm in width.

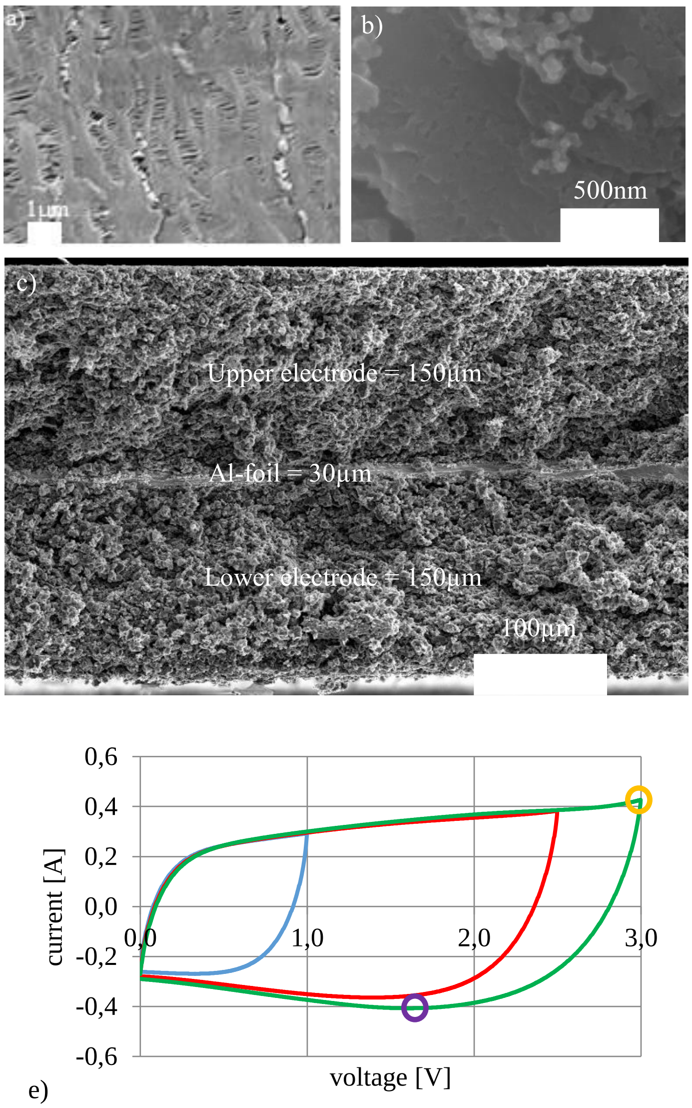


FIGURE 3: SEM PICTURES OF THE SC-COMPONENTS A) SEPARATOR CELGARD 3501 TOP VIEW B) DETAILED VIEW ON AC AGGLOMERATES WITH SOME PORES C) DOUBLE SIDE COATED COLLECTOR/ELECTRODE COMBINATION SUPPLIED BY SKELETON D) CYCLIC VOLTAMMETRY TEST OF [EMIM][TFSI] AT A SCAN RATE OF 20mV/s USING ACTIVATED CARBON AS ANODE AND CATHODE BETWEEN 0V AND +3V WITH FIRST REDOX-REACTIONS (CIRCLES)

The separator film is durable even to handle the compression and temperature during the manufacturing, dense, thick enough to avoid any short circuiting via electrode material passing the pores and permeable enough for the comparative big ionic ions (0,76-0,79nm for 1-ethyl-3-methylimidazolium bis(tri-fluoromethylsulfonyl)imide) to diffuse through the holes. In Fig 3 c) a cross section of the electrode-collector is shown.

The 30µm thick Al-collectors on which electrodes of activated carbon are coated (AC, thickness of 150µm) are customer-tailored produced and supplied by the company Skeleton Technologies GmbH (Estonia, Germany). The SEM picture in figure 3 b) shows details of the cubic agglomerates of activated carbon (AC) revealing some pores on the even surfaces of the agglomerates. However, a specific pore size cannot be defined. The electrode is coated on both sides of the collector for efficient stacking of the supercapacitor cells

The vacuum-assisted process to consolidate the composite and the area of application in space reduces the variety of possible electrolytes dramatically. Typical water-based electrolytes such as sodium chloride have high ion mobility due to their low viscosity, but they vaporize in vacuum as a result of their high vapor pressure (12.28hPa at 5°C-25°C). However, this feature is important for handling applications in space. There are several cases in which outgassing materials had caused failures of satellites. Mechanical properties of materials decrease due to outgassing [21], outgasses might contaminate devices e.g. optics [22, 23], or the outgassing can generate discharge breakdowns in high-voltage devices [22], seriously affecting the performance and reliability of the whole satellite.

Alternatively, there are ionic liquids which have very low vapor pressure and compared to water-based electrolytes, offer a wider electrochemical window (EW) of up to 6.1V [21] referring to the cathodic and anodic window. Actually, here the anodic window of 0V up to +4.5V is used. However, ionic liquids (ILs) consist of long charged molecules. Compared to water they feature higher densities and are more viscous, which causes higher internal resistances and therefore slower electrochemical behavior, but higher electrochemical stability.

As shown in earlier publications [28-30], 1-ethyl-3-methylimidazolium bis(tri-fluoromethylsulfonyl)imide ([EMIM][TFSI], IL-0023-HP) supplied by Iolitec – Ionic Liquids Technologies GmbH, Germany – was chosen as the most promising electrolyte. The electrochemical advantages of [EMIM][TFSI] as an electrolyte were also used in [1, 8, 9].

Conducted cyclic voltammetry tests reveal the first irreversible chemical reactions with a small current peak at 3V (fig. 3 c) orange circle) and an increasingly larger counter-peak at +1.7V (fig. 3 c) purple circle) on the negative current side (see figure 3 c) green graph). This results in the definition of a maximum voltage of +3V or less. Typically, this maximum voltage should not be used for long cycling as the energy storage would start to degrade. However, space requirements of the European Cooperation for Space Standardization (ECSS, [30]) require a derating of 40% so that safe operations are ensured (see figure 3 c). Furthermore, [EMIM][TFSI] is highly compatible with the used electrode and diffuses fast into its pores.

1.2 Equations

Cyclic voltammetry (CV) tests are conducted using a potentiostat (Reference 3000 w/AE, Gamry Instruments, USA). The CV is conducted out at 20mV/s at a voltage range of 0V up to +1V. The capacity C, an important parameter of the electrochemical performance of supercapacitors, is calculated according to Eq. 2. However, the capacity, calculated by the current I and time variable voltage U, is not a specific value, since the capacity increases with the electrode area, small electrode distances and increasing current.

$$C = \frac{Q}{U} = \frac{I}{\frac{dU}{dt}} \qquad [F] \qquad (1)$$

To evaluate the efficiency of the used materials, the electrode mass, electrode area and the amount of ionic liquid can be considered (also see Eq. 2-4). By using these specific values, the efficiency of the material combination and cell manufacturing can be better compared to other research results.

$$C_m = \frac{C}{m} \qquad [F/g] \qquad (2)$$

$$C_A = \frac{C}{A} \qquad [F/cm^2] \qquad (3)$$

$$C_V = \frac{C}{V_{IL}} \qquad [F/\mu l] \qquad (4)$$

Further values of the electrochemical system, such as the maximum voltage, the material density or the electrical resistance (ESR) of the developed supercapacitors can be used to calculate the efficiency of storing energy. Therefore, the maximum energy E_{max} was calculated according Eq. 5.

$$E_{max} = 0.5 \cdot C \cdot U^2 \qquad [Wh] \qquad (5)$$

The maximum energy divided by the mass of the storing device results in the gravimetric specific energy according to Eq. 6.

$$E_{spe} = \frac{E_{max}}{m} \qquad [Wh/kg] \qquad (6)$$

1.3 Manufacturing and integration

The lay-up of the thin-film supercapacitor is schematically shown in figure 4, the whole manufacturing process in figure 5.

Two Al-collectors, coated with electrodes of activated carbon, are separated by one layer of separator. The electrode should be dried before processing to avoid moisture deposition. Furthermore, the electrodes must be sufficiently wetted with IL. However, the amount of IL on the electrodes is a decisive parameter. On the one hand, an insufficient amount of electrolyte reduces the ionic conductivity and therefore the serial resistance increases resulting in a reduced capacity. On the other hand, too much IL will be pressed out of the capacitor into the composite during manufacturing, which reduces the mechanical stiffness of the surrounding resin matrix. In our case a specific IL-amount of $8 \mu l/cm^2$ brought the best results. Due to the high specific surface area of the electrode and the viscosity of the ionic liquid, a complete wetting needs some time. A diffusion period that is too short results in less wetted electrodes that participate in the electrochemical processes. Furthermore, the remaining IL will reach into the composite, causing delamination during the manufacturing, as it interferes with the curing of the epoxy resin.

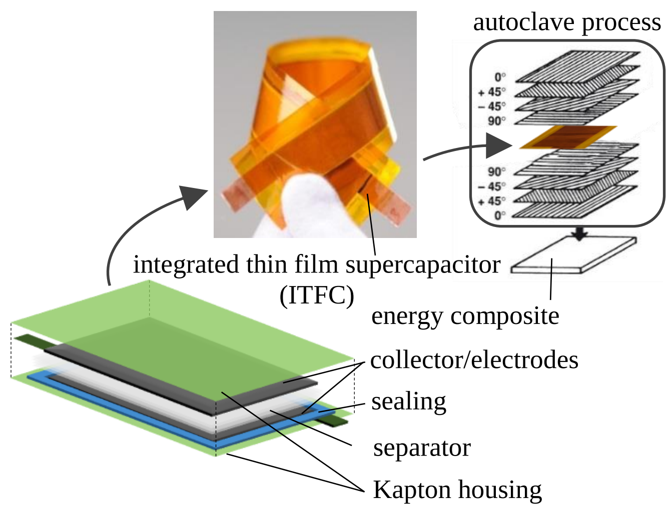


FIGURE 4: LAY-UP OF THE SUPERCAPACITOR CELL WHICH CAN BE HANDLED AS A FREE-STANDING, FLEXIBLE ENERGY STORAGE FILM THAT CAN BE INTEGRATED WITHIN THE LAY-UP OF A COMPOSITE TO BUILD A POWER COMPOSITE.

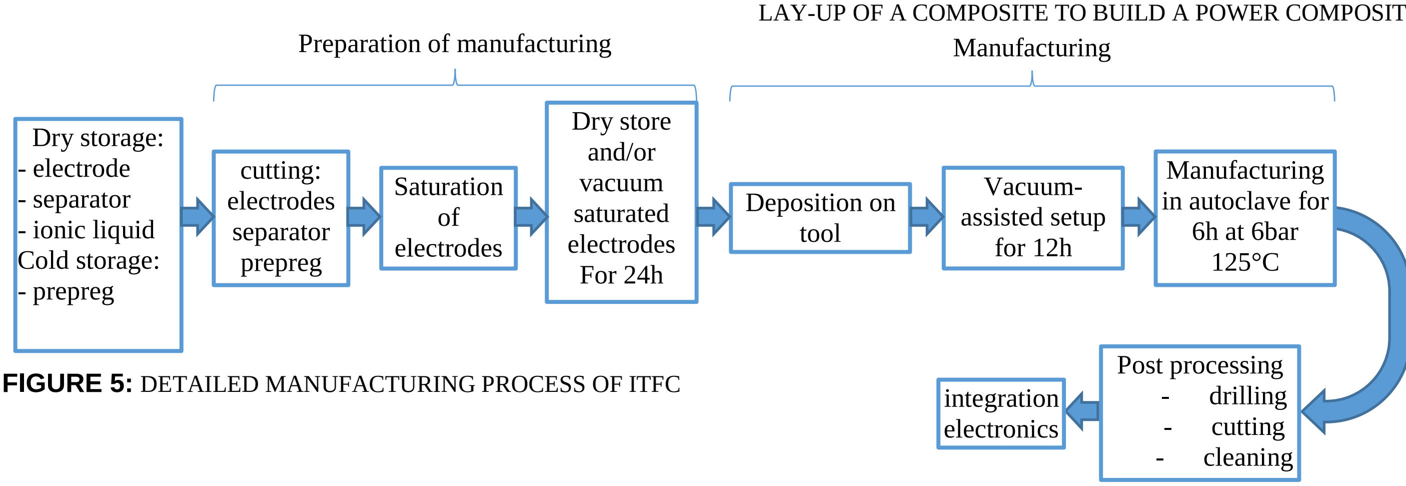


FIGURE 5: DETAILED MANUFACTURING PROCESS OF ITFC

As a barrier between IL and epoxy, a 20µm thick polyimide film is used (Kapton-160FN616, DuPont de Nemours Inc., USA) as housing. This film is modified with an FEP-fluoropolymer on both sides, which enables the polyimide to bond very firmly to the composite.
Unidirectional impregnated glass fiber layers are used as electrical insulation (Hexply 913, Hexcel Corporation, USA). The composite is processed vacuum-assisted within an autoclave at a pressure of 6 bar at 125°C for approximately 6 hours.

1.5 Design of demonstrator

The lay-up of the SC demonstrator is planned to fit to an 8U cube satellite. Therefore, its dimension must fit into 20x20cm. In this case a dimension of 19x19cm was chosen to integrate the power composite into the frame of a 8U cubesat or even use the plate as the frame itself. According to the system requirements six supercapacitors connected in series have to be used. As requirement of the electronics the supercapacitors have to be separated, instead of being stacked. In a stacked setup the supercapacitors would use both sides of the coated collector as electrodes for individual supercapacitors. The planned setup here needs to separate all supercapacitors in order to decouple the supercapacitors from each other as result of their different performance. In worst cases, the electronic could decouple misperforming supercapacitors. The top and bottom composite is made of 4 layers of GFRP (Hexply 913, Hexcel Corporation, USA). The supercapacitors are integrated within two frame-layers and two separation layers between the supercapacitors are used. In total 30 layers of GFRP are used. Their lay-up is shown in figure 5.

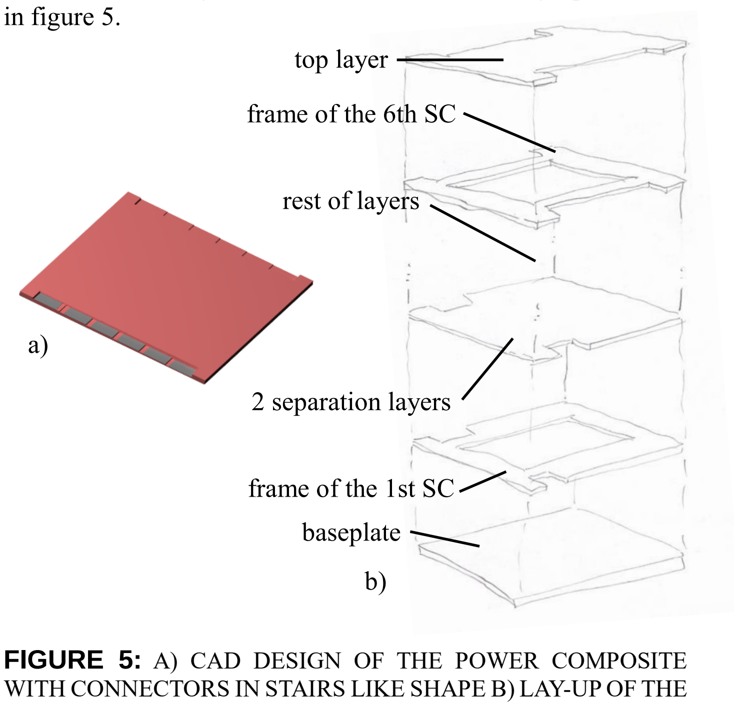


FIGURE 5: A) CAD DESIGN OF THE POWER COMPOSITE WITH CONNECTORS IN STAIRS LIKE SHAPE B) LAY-UP OF THE COMPOSITE LAYERS TO BUILD THE POWER COMPOSITE

1.6 Sensoric effects

In order to utilize a supercapacitor as a strain or temperature sensor, in-depth knowledge of its components is required. It is important to know the materials used and their morphology. In this work, carbon-based electrodes with aluminum collectors are used. Furthermore, the separator is a polypropylene membrane (Celgard, 3501-4000M-AS40), the electrolyte an ionic liquid (IoLiTec, EMIM TFSI).
The detailed analysis of the electrode is described in [39]. A potentiostat from Gamry Instruments Inc. (REF 3000, USA) is used for the impedance spectroscopy. The impedance spectra are analyzed using a fitting. The model used for this fitting is shown in Figure 6. Further information on how this is setup and the associated justification can be found in [39, 40].
The model consists of three constant phase elements (CPE) which are connected in parallel with a resistor (R). These elements are used to describe the porous electrode of the supercapacitor. The three CPE-R elements describe pores of different sizes. Furthermore, there is a CPE which describes the double layer of the supercapacitor as well as a resistor which considers resistive parts of the supercapacitor, such as the ionic conductivity, resistances of the electrode or also contact resistances. Last is an inductive part, which only serves to consider inductances of the wiring as well as the current collector.

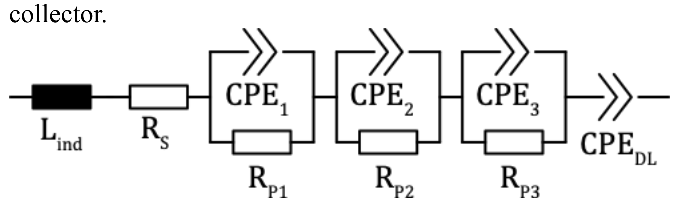


FIGURE 6: EQUIVALENT CIRCUIT DIAGRAM FOR MODELLING A STRUCTURAL INTEGRATED SS WITH IONIC LIQUIDS AND CARBON ELECTRODES. LEAD INDUCTANCES ARE MODELLED L_{ind}. ALL SERIAL RESISTANCES SUCH AS COLLECTOR; ELECTRODE; SEPARATOR OR ELECTROLYE RESISTANCE ARE EXPRESSED R_S. THE DIFFUSION PROCESSES WITH CHARGE TRANSFER DESCRIBE THE SERIAL CONNECTION CONSISTING OF CPE-R ELEMENTS. CPE_{DL} IS USED TO REPRESENT THE DOUBLE LAYER.

1.7 Electronics

The DEEP project aims to create an overall system to make an ionic propulsion system accessible to the small satellite market. The high-performance requirements of the electric propulsion system are being met with a hybrid energy storage consisting of a structural integrated supercapacitor and conventional battery. The supercapacitor is integrated into a fiber composite structure and can therefore not only buffer electrical peak currents, but also contribute to the overall mechanical system. For example, as the wall of the satellite.
Naturally, individual supercapacitors provide voltages of between 2 and 4 volts, which in turn is not sufficient for the operation of an electric propulsion. This is why six supercapacitors are being used in the DEEP project. As these are

all integrated in a fiber composite component, there is no increase in the complexity of the mechanical connection, because no holding structure for the supercapacitors is needed. However, there are a number of challenges for the electrical integration. All supercapacitors must be balanced, monitored, charged and discharged. These tasks are solved with an electrical circuit that is mechanically integrated onto the fiber composite panel. The resulting overall system thus forms a smart component.

This can be operated with a constant DC voltage. The cell balancing takes place automatically. In order to reduce the probability of failure in the event of a cell defect, cells can be masked with the help of the smart component. These will then no longer participate in the energy system. Furthermore, the Smart component records all cell voltages, currents and temperatures in order to communicate this information to the satellite via the integrated controller area network (CAN)-bus interface. Thanks to the integrated health monitoring, the system is able to react to critical events such as excessive voltages, temperatures or currents.

In order to minimize the system weight, the electronics are mounted on a flex printed circuit board (PCB). This significantly reduces the weight of the circuit board, as a thin polyimide film can be used instead of a 1.5 mm thick glass fiber prepreg.

Normally, a balancer would be connected to the supercapacitors using cables. This results in additional weight due to the wiring as well as the plug contacts. In the case of the smart component developed in this work, attention is also paid to minimizing weight. Due to the board design, cables and connectors can be completely omitted. As shown in Figure 7, the flex circuit board is located on the entire surface of the supercapacitor panel. This allows the current from the collector of the supercapacitor to be fed directly into the balancer via a screw connection.

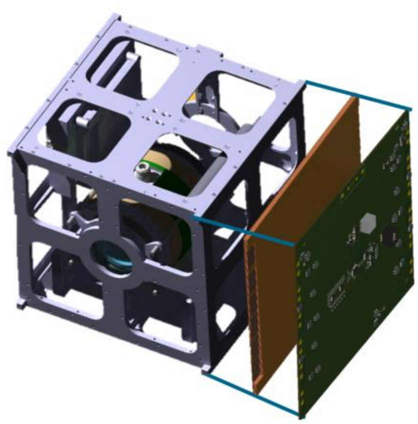


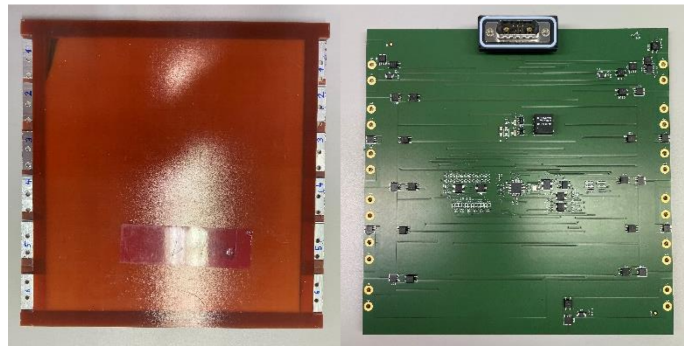
FIGURE 7: EXAMPLE OF A SATELLITE STRUCTURE: THE ELECTRONICS (GREEN) ARE GLUED ONTO THE GFRP STRUCTURE (ORANGE) WITH INTEGRATED SUPERCAPACITORS.

2. RESULTS AND DISCUSSION

In this section the realized demonstrators will be presented Finally, aspects for further optimization are discussed.

2.1 Realized demonstrator

The realized demonstrator along with the realized electronics are shown in figure 8. Due to quality assessment (figure 9) the six integrated supercapacitors were tested via CV at a scan rate of 20mV/s and 2V. The aim of the study was to determine how similar their performance would be and if the supercapacitors are performing according to the calculations. In figure 7 the results of the CV ist shown.



a) b)

FIGURE 8: REALIZED DEMONSTRATOR A) POWER COMPOSITE B) ELECTRONICS

It can be seen, focused on the individual capacitor, the charge and discharge value are very similar with a small loss of capacitance during discharging due to resistances. The discharging is the most important value since it describes the capacity, which can be made available for any kind of application. However, it can also be found, that the two capacitors (1st and 6th SC) located nearer to the outside, the top side and lower base plate, showed almost half of the performance compared to the inner SCs (24F vs. 40F).

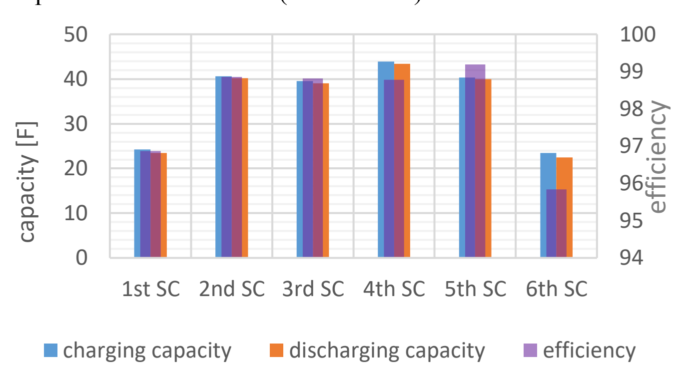


FIGURE 9: CYCLING VOLTAMMETRY RESULTS OF ALL SIX INTEGRATED SUPERCAPACITORS REVEALING SOME REDUCED PERFORMANCE OF THE SCS LOCATED CLOSER TO THE OUTSIDE LAYERS, THEIR INDIVIDUAL EFFICIENCY IS SHOWN ON THE RIGHT AXIS.

One probable cause is the surface pressure during curing. The inner areas can be pressed more efficiently by the surrounding material, which remains even after curing of the composite and leads to a higher capacity. However, it is also possible that air and moisture will penetrate the outer areas more quickly, leading to a reduced capacity. Investigations into this are still ongoing. Some specific details of the demonstrator are given in table 1.

TABLE 1: SPECIFIC VALUES OF THE DEEP-DEMONSTRATOR

	DEEP-demonstrator
Total mass [g]	336
Total volume [cm^3]	68.6
Specific electrolyte volume [µl/cm^2]	0.8
C_m [F/g total mass]	0.62
C_m [F/g capacitor]	4.5
C_A [F/cm^2 capacitor]	0.16
C_V [F/cm^3 total vol.]	3.4
Emax [Wh per capacitor]	88
Esp [Wh/kg total mass]	1307
Esp [Wh/kg per capacitor]	8971

2.2 Realized electronics

The electronics in the DEEP project are manufactured from COTS (commercial of the shelf) components for reasons of cost and availability. A microcontroller (ATMEGA328P-AUR) controls the balancing, communication and acquisition of sensor data centrally. It receives its commands from the PCDU via CAN-bus. A CAN-bus controller from Microchip Technology (MCP2515) and a transceiver from the same manufacturer (MCP2551) are used. Balancing is carried out using semiconductors to avoid having to rely on heavy relays. Furthermore, a constant direct current is generated from the satellite bus voltage for charging the supercapacitors. Due to the placement of the circuit board, the surface temperature of the supercapacitors can be measured directly using surface mounted devices integrated circuits (SMD ICs). A current sensor (ACS713ELCTR-20A-T) is used to record the current during balancing and discharging. The information obtained is not only used to monitor the balancing but can also be used to react to current or temperature peaks. In this case, the process is interrupted to prevent damage to the supercapacitors.
As already mentioned, the supercapacitors are contacted using screws. A CAD-model can be seen in figure 10.
These are inserted into the holes on the left and right side and thus connect the circuit board with the integrated supercapacitors. Cables and plug contacts are thus substituted.

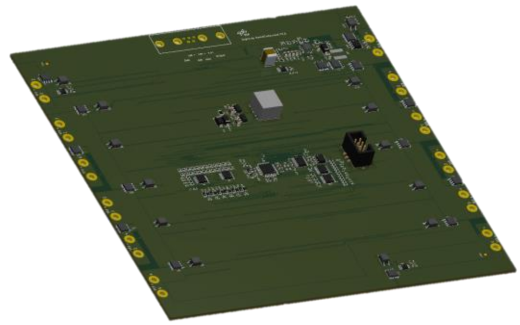


FIGURE 10: THREE-DIMENSIONAL REPRESENTATION OF THE ELECTRONICS: THERE ARE HOLES AT THE LEFT AND RIGHT EDGES THAT CONNECT BOTH MECHANICALLY AND ELECTRICALLY TO THE SUPERCAPACITORS. THE ELECTRICAL CONNECTION TO THE SATELLITES IS LOCATED IN THE CENTER OF THE UPPER PART OF THE CIRCUIT BOARD.

2.3 Measurements of temperature and mechanical stress

In order to evaluate the influence of the mechanical load as well as the influence of the temperature on the integrated supercapacitor and to be able to measure it later, extensive impedance measurements must be carried out. In this publication, the focus is on the results of the impedance measurement under mechanical or temperature load. The verification of the model and the necessary measurements are described in [39, 40].
Figure 11 shows the influence of a mechanical load on the impedance curve of an integrated supercapacitor. The sample is a GFRP flat bar with 2 integrated supercapacitors. The location of the capacitors is in the middle of the top or bottom side in the 2nd fiber layer. The reason for this position lies in the experiment carried out. A four-point bending is to be investigated. This offers both a compression and a tensile area that is also free of shear forces. Figure 9 shows that the supercapacitor under tensile load undergoes a significant change in impedance. The supercapacitor on the compression side does not experience any change in impedance. The cause can be found in the type of load, which outcome can be seen in Figure 12. A four-point bending test with an integrated supercapacitor was tested until failure. It can be clearly seen that the fibers on the compression side bulge. This in turn means that the supercapacitor integrated there has no compressive force between the electrodes. On the tension side, the electrodes still lie against each other and are also pressed against each other during the test. This compressive force can in turn be held responsible for the change in the impedance spectrum.

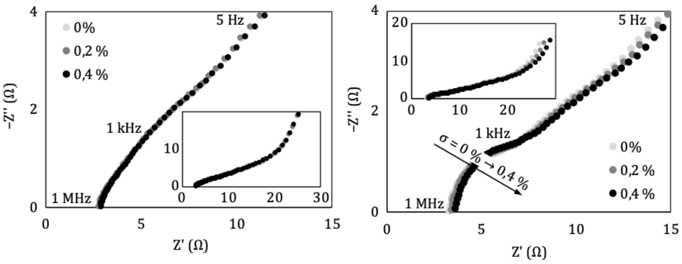


FIGURE 11: MECHANICAL LOAD INFLUENCE ON THE IMPEDANCE: THE FREQUENCY RANGE FROM 0.1HZ-1MHZ IS SHOWN IN SMALL. THE FREQUENCY RANGE BETWEEN 5HZ AND 1MHZ IS SOWN ENLARGED IN EACH ILLUSTRATION. THREE IMPEDANCES ARE SHOWN AT 0%, 0.2% AND 0.4% EDGE FIBER STRAIN. A) SUPERCAPACITOR LOCATED ON THE COMPRESSION SIDE OF THE BENDING SAMPLE. B) CHANGE IN THE IMPEDANCE SPECTRUM OF A SUPERCAPACITOR ON THE TENSION SIDE.

FIGURE 12: CLOSE-UP OF A FOUR-POINT BENDING TEST UNDER LOAD. THE FORCE APPLICATION ELEMENTS ARE AT THE TOP OF THE PICTURE. THE SPECIMEN IS LOCATED SHORTY AFTER THE SPECIMEN BREAK. THE DISPLACEMENT WAS MEASURED USING AN INDUCTIVE DISPLACEMENT TRANSDUCER (PIN IN THE LOWER PART OF THE IMAGE).

The same samples that were used for the mechanical tests are also used for the temperature measurements. To heat up the sample, it is clamped in a temperature control device. Once a constant target temperature has been reached, the impedance measurement is performed. Figure 13 shows the impedance spectra for three temperatures (8 °C, 10 °C and 12 °C). A clear influence due to the temperature can be seen here. As the electrolyte has a strongly temperature-dependent conductivity, this is to be expected.

Once the elements of the equivalent circuit diagram have been fully described by temperature and mechanical tests, this model can be used to calculate either the temperature of the sample from the impedance spectrum or, alternatively, the mechanical load. Further information on this can be found in [39, 40]. In [40] it is also described how to separate the temperature influence from the mechanical in the impedance spectrum.

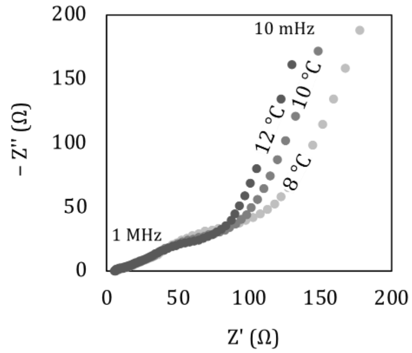


FIGURE 13: IMPEDANCE CURVES OF A STRUCTURAL INTEGRATED CAPACITOR AT THREE DIFFERENT TEMPERATURES (8°C, 10°C, 12°C). A CHANGE IN TEMPERATURE LEADS TO A STRONG CHANGE IN IMPEDANCE, ESPECIALLY IN THE LOW-FREQUENCY RANGE.

CONCLUSION AND OUTLOOK

This paper describes the development and application of thin-film supercapacitors integrated in a composite structure as part of an electrical propulsion system. Furthermore, it was also equipped with electronics in order to simplify the application, to utilize the supercapacitors via specific electronics more efficiently, to avoid additional wiring and to reduce the risk of mechanical failure during launch and mission in orbit. Additionally, the inherent behavior of the supercapacitors can be used as thermal and mechanical sensors in order to rise their order multifunctionalization and to avoid heavy, complex and expensive structural health systems (SHM). Their compact setup allows to become a part of small cube satellites and adds capabilities that would never have been possible due to their weight and volume limitations.

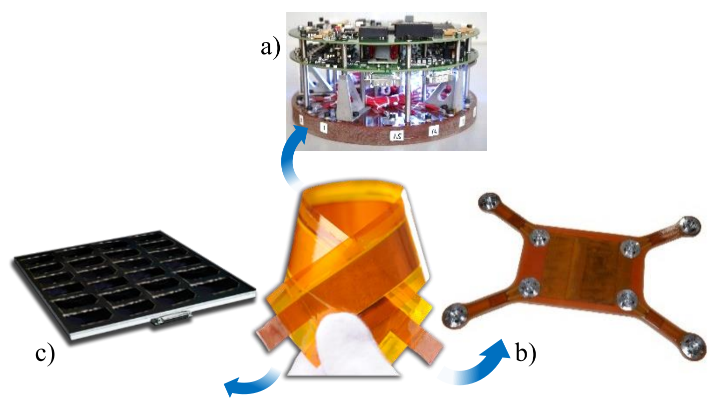


FIGURE 14: REALIZED FULL-SCALE APPLICATIONS USING STRUCTURE-INTEGRATED THIN-FILM SUPERCAPACITORS. A) 14 ITFCS INTEGRATED INTO THE BASE PLATE OF A HIGH TORQUE WHEEL [26]. B) MULTIFUNCTIONAL PANEL USING TWO ITFCS AS POWER SOURCE FOR VIBRATION CANCELLING [33]. C) SOLAR POWER-STORING SANDWICH PANEL OF THE DLR HYSES PROJECT

However, in terms of more lightweight design polymeric ionic liquids could avoid parasitic masses such as the separator and could further increase the mechanical performance of the SCs. Additionally, using polymeric electrolytes pre-manufactured supercapacitors could allow the manufacturing of patches which can be checked for their quality before integration. Supercapacitors with low performance can be identified and replaced before integration to avoid variation as shown in fig. 9. The specific parameters of the manufacturing causing the performance variations have also to be investigated further for more reliability.

ITFCs might not reach higher levels than DoI II because of their component character, but their robust behavior, their scalability, volume and weight savings in different realized applications (see figure 15) highlights this approach to be a promising candidate for further applications. The lay-up of the ITFC is designed to accommodate varying components such as electrode, ionic liquid or separator as soon as new, more powerful materials are available, enabling higher performances.

ACKNOWLEDGEMENTS

This work is part of the DLR-funded project GigaStore. The modified High Torque Wheel was developed within the project Peak Power Platform. Further research is done within the DLR projects Hybrid Solar Energy Storage and Multifunctional Satellite Panel and Decentralized Energy Supplied Electrical Propulsion, which all deal with integrated supercapacitors within space structures. We would like to acknowledge the funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC 2163/1 - Sustainable and Energy Efficient Aviation – Project-ID 390881007**.** Tribute has to be paid to Phillip Freytag for his contribution on this topic.

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