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Development and Qualification of a Scalable and Modular COTS-based Li-Ion Battery System for Satellites in Low Earth Orbit

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Abstract

This paper introduces a commercial-of-the-shelf (COTS) - based lithium ion battery system for satellites in low Earth orbit (LEO). The aspects of modularity and scalability in system design are outlined. Further, a market study of existing battery systems for satellites was analysed to compare the specifications and functionality.

The fundamental building block of the presented battery system is a cell module that consists of eight battery cells. By stacking multiple battery modules either the electrical capacity and current capability or the terminal voltage can be adapted to the satellite's requirements. This modular approach also makes the battery system redundant. The software is also responsible for communication between battery modules and analysis of the state of the battery cells with sensors for temperature, current and voltage of each cell. The COTS battery system is developed to reduce manufacturing price and increase functionality of future satellites. Development and testing of the battery system are supported by the fundamental knowledge of batteries at the DLR's Institute of Engineering Thermodynamics. The approach of using mostly COTS components including the battery cells influences system architecture, electronic design, software and the qualification process. The battery system has the ability to measure temperature, voltage and current of each battery cell. This allows for further functions like adaptive cell balancing, state of charge and state of health estimation. The goal of a highly functional battery system is to give the operator knowledge of the remaining useful life of the satellite.

Keywords: Battery Management System, Modularity, Scalability, COTS, Satellite Power

Nomenclature

U_{System}	System Voltage
I_{System}	System Current
U_{Module}	Module Voltage
I_{Module}	Module Current
$n_{Modules,serial}$	Number of serial modules
$n_{Modules,parallel}$	Number of parallel modules

Acronyms/Abbreviations

BMS	Battery Management System
BOL	Begin of Life
COTS	Commercial of the Shelf
C-Rate	Capacity Rating
DLR	German Aerospace Centre
DOD	Depth of Discharge
EoCV	End of Charge Voltage
EOL	End of Life
FDIR	Failure Detection, Isolation and Recovery
GEO	Geostationary Earth Orbit
I2C	I-Squared-C
IC	Integrated Circuit
LEO	Low Earth Orbit
Li-Ion	Lithium-Ion
MEO	Medium Earth Orbit
OBC	On-Board Computer
PCB	Printed Circuit Board
PCDU	Power Control and Distribution Unit
RUL	Remaining Useful Life
SOC	State of Charge
SOH	State of Health
TRL	Technology Readiness Level

1. Introduction

Today LEO satellites take on a wide range of tasks: e.g.: communication, scientific experiments, manoeuvring, Earth observation and data processing – processes which rely on electrical power supply. Thus, the electrical power system, and specifically the battery system, secures safe and reliable satellite operation. A battery system usually consists of battery cells, electronics, auxiliary components and a structural integration. The battery cell mainly defines the energy density of a battery system. There are different cell chemistries with different advantages and disadvantages. In the past decade, the Lithium-Ion (Li-Ion) cells made a breakthrough in terrestrial applications [1] and are now also used in most satellite and spacecraft energy systems.

Space systems are usually more conservative in their development process because of their remote operation with limited maintainability and harsh environmental conditions. Flight heritage, which means with a lot of in-orbit experience, is important when it comes to the selection of components and subsystems. Especially due to space radiation, flight heritage is valued for reliable, predictable and safe operation. This causes older technologies to be used longer for spacecrafts than in other applications. A new approach in space engineering has changed the focus towards commercial components in recent years [2]. Modern components, for example in the battery system, can offer great improvements. The battery cells have increased energy densities. Also, the electronic components add immensely higher functionality for battery management like state estimation or adaptable behaviour. Lastly, systems built from commercial components have lower production costs. The downsides of commercial components are increased workload on component selection, system design with redundancy in mind and qualification of components and systems.

The CubeSat market has a variety of companies that are selling small battery systems (<1kg) with commercial-of-the-shelf (COTS) Li-Ion battery cells. These systems reach high energy densities (>120Wh/kg) and are very compact. The electronic components are also COTS and the systems can be purchased at low prices (<10k€) and with flight heritage.

Commercial battery systems for larger satellites (Compact Satellites and larger) use components for the cells and electronics that are radiation hardened and specialized for space environment. Some of these single components are often more expensive than an entire CubeSat battery system (up to 500k€ including qualification and certification) and they offer less power density or functionality. The advantage of course is their reliability and wide range of possible missions (from LEO to lunar missions).

With the research into the satellite battery systems the energy density and functionality of smaller systems should be extended into larger systems with the use of scalability and modularity. The battery system in development will use COTS components and feature a modular and scalable approach. Both the capacity and voltage of the system will be adaptable by selecting the necessary amount of battery modules for the mission. Modularity and scalability of proven systems will be compared to the system architecture of the DLR concept.

In chapter 2 modularity and scalability are defined and a market study of battery systems is analysed. The resulting DLR battery system is presented in chapter 3. Chapter 4 concludes the content of this paper.

2. State of the Art Battery Systems

In order to gather enough information on the current state of satellite battery systems, a large collection of smaller (<1kg), medium (1kg - 5kg) and large (>5kg) systems for different types of satellites is compared in a market study. Further, a literature study is conducted to gain an insight into the possible implementation of modularity and COTS components into battery modules. The chances, risks and necessity of modularity will be discussed. Finally, the market study is compared to the literature research to state the necessary features of future battery systems.

2.1 Modularity and Scalability

The general idea of modularity and scalability is to design a system for different requirements or applications. A higher capacity requirement (in the example of a battery) can then be done by adding battery modules or scaling the system up with a predefined step-size. For a better understanding the definitions, advantages and disadvantages of these aspects will be described first.

Modularity is interpreted differently across literature. A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Clearly there are degrees of connection, thus there are gradations of modularity. In other words, modules are units in a larger system that are structurally independent of one another, but work together [3].

In [4] it is stated that a modular product is made up of modules acting as building blocks. The more of the components that fit into these modules, as opposed to lying around independently, the more modular a product is.

Modularity in systems can be seen in two different ways. There are [5] two possible ways to use the concept of modularity. The *ideal-modular* approach splits every function group of a system into one module (see Figure 1). For a battery system the modules could be a battery pack, the electronics that takes care of the battery management, a thermal system and some structure. The *ideal-integral* approach on the other hand uses modules that are interchangeable. Here a battery system would consist of different battery modules. Each battery module has battery cells, electronics and components for thermal and structure (see Figure 2). The modules together deliver the necessary power.

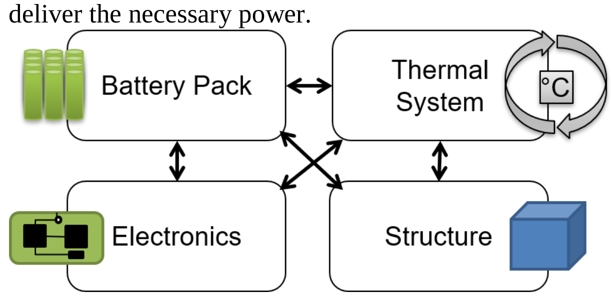

Figure 1: Ideal-modular System

The modularity could, however, also be described in layers. In the upper layer there are the battery modules that are connected in parallel and in the lower layer each of the battery modules consists of functional modules for battery cells, electronics and so on.

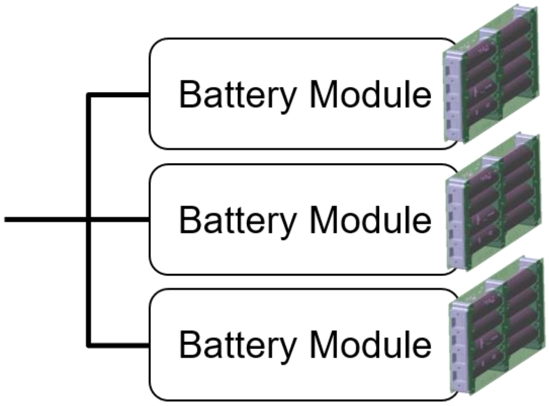

Figure 2: Ideal-integral System

The advantages of modularity are reusability of design [6], replicability, product development without touching the entire system and simplified testing (due to module tests). The disadvantages of modularity are that a good planning and system design is necessary and the weight of the system might be higher due to the separation into smaller parts.

Scalability in a battery system is a concept that allows to cope with increasing or decreasing requirements. For a battery system the change in capacity or in nominal voltage is of relevance for meeting the requirements of different satellite applications. There are two possibilities of scaling [7]. *Horizontal scaling* would include more (or less for down-scaling) modules of the existing one to cope with the change in requirements. In *vertical scaling* the system is scaled by changing the singular components (e.g. using larger battery cells) (see Figure 3).

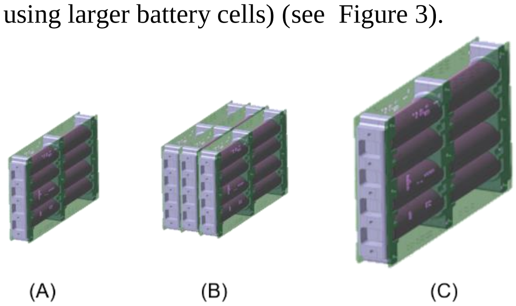

Figure 3: Original System (A), Horizontal Scaling (B), Vertical Scaling (C)

Horizontal scaling of a battery module can be done by paralleling or serializing the modules. By connecting modules in parallel the capacity and current capability of the system increased. By connecting the modules in serial, the voltage of the system is increased. A combination of parallel and serial modules is also possible and improves redundancy.

$$U_{System} = U_{\text{Module}} * n_{Modules,serial} \qquad (1)$$

$$I_{\text{System}} = I_{\text{Module}} * n_{Modules,parallel} \qquad (2)$$

Vertical scaling, on the other hand, features a less complex system complexity (less communication and interfaces due to the single module).

The paper in [8] concludes: “The scalability needs should be analysed to define the depth of modularity. The scaling stages define the module size.” In conclusion, modularity enables scaling of the system and the required scalability defines the modules.

2.2 Market Study

The market study focuses on existing battery systems for satellites and has been conducted by gathering the information on the database of SatSearch [9] for all the manufacturers that have made their relevant metrics available. Further datasheets with information about commercial battery systems was found in [10-12].

The data are grouped into two sections. Firstly, the fundamental metrics of these systems start with goal application, type of battery cell and configuration of the cells. Further, energy capacity and energy density allow a comparison between the systems. The fundamental metrics can be found in Table 1.

The second section is more focused on the functionality of the system. The availability and type of balancing, heating and protection are investigated. Moreover, the possibility of modularity, scalability and voltage scaling is investigated. Lastly, radiation tolerance, which gives an impression of the built-in components, and temperature tolerance are compared. The goal of this analysis is to gather knowledge for improvements on the DLR battery system and identify gaps and niches for satellite battery systems.

Among the 30 investigated battery systems there are small ones that are focused on the CubeSat market and larger ones that are used in compact satellites. The smaller systems generally follow the COTS approach whereas the medium and large systems follow a more robust and conservative selection of electrical components. The larger systems, on the other hand, can also be used by Medium Earth Orbit (MEO) or Geostationary Earth Orbit (GEO) applications. The same observation can be made for the battery cells. Commercial 18650 cells are used in the CubeSat systems and specially developed cells (mostly by the company SAFT) are used by the larger systems.

The aspect of ideal-integral modularity is feasible with most CubeSat systems as they can be used in parallel to increase the capacity. The larger systems focus more on a combination of horizontal and vertical scaling. The battery cells stay the same, but the battery structure grows. The ibeos B28 battery system for example can be bought

Table 1: Market Study of Existing Battery Systems for Satellites (15 of 30 investigated systems)

Name / Manufacturer	Weight [kg]	Volume [l]	Configurations	Energy Capacity [Wh]	Grav.Energy Density [Wh/kg]
GomSpace BPX	0,5	0,33	Flexible	75	150
Pumpkin BM2	0,7	0,50	Flexible	100	143
SAFT 4S1P	0,7	0,59	4S1P	64	91
SVC 39501	1,0	0,91	-	22	22
Skylabs Nanoeps	1,9	1,67	Flexible	158	82
BST Bat-110	3	2,48	-	172	57
Redwire Nova	3,3	3,15	8SNP	455	138
EaglePicher15,5Ah	4,0	1,58	8S5P	446	113
SatSearch VLB	4,5	3,30	8SnP	346	77
SAFT LEO	5	4,99	8S4P	512	102
Ibeos 50VkWHR	7,5	5,93	12S6P	1000	133
Ibeos B28	8	5,70	8SnP	1100	138
EaglePicher SAR	28,2	27,95	8S2P	3315	118
EaglePicher SAR	63,5	47,52	9S4P	6660	105
SAFT MEO/GEO	69,6	68,92	Flexible	9100	131

in steps from 135Wh (815g) to 1100Wh (8000g) with a full structure surrounding the interior. There is also a SAFT MEO/GEO system that allows for a full configuration of serial and parallel cells.

Looking at the functionality of electronics and software it has to be said that most systems do not offer satisfactory data values to derive insights on the cells. The most basic balancing is implemented in small and large systems alike. The cells can be balanced over a shunt resistor at one prefixed voltage. The SatSearch VLB offers a smart balancing which also uses a shunt resistor but can balance at any voltage. This gives more options when operating the satellite, extends the lifetime of the satellite and also helps with the passivation of the battery cells. The skylabs Nanoeps even offers an active balancing that can move energy from once cell to the other to balance them.

Only three battery systems offer state of charge (SOC) and state of health (SOH) calculation. The pumpkin BM2 and SATrevolution BMS calculate the SOC via coulomb counting. The space vector corporation's Li-Ion Battery 39501 can offer SOC and SOH, but it is not apparent how these are determined.

Most systems communicate their data via CAN, RS-422 or I2C. The ibeos 50V and B28 on the other side simply offers the connectors to each cell to read out the values with a separate device.

Most systems do not state a radiation tolerance level. They are, likely, only made for short LEO missions with low requirements for radiation tolerance. For a five of the systems the TID value is between 20 and 30 krad, which allows 5-year LEO missions. An outlier is the EaglePicher SAR-10197 that offers radiation tolerance of up to 3000 krad.

2.3 Results of the Market Study

15 of the 30 investigated systems offer limited modularity or scalability for their capacity and current capabilities. The others are not made for changes in configuration. Only 7 of the 30 systems allow for a change in their voltage level. It has to be said that the voltages for CubeSats and larger satellites are normally at 14.4V or 28.8V. The smaller battery systems offer ideal-integral modularity, which is limited to parallel

operation. Usually a CubeSat would use only one or two battery modules. These small systems offer limited functionalities. In these systems the power of the cells is provided without single-cell monitoring and only analog balancing. That also makes the concept of modularity easier to follow.

The scaling options for some larger systems are not directly visible. However, since they also include the structure in their system they could be classified as scalable instead of modular.

Looking at the systems from the ideal-modular perspective, it can be said that mainly the electronics and with-it microcontroller and software are very limited for most battery systems. The electronics are mostly analog and software not used. This means that software can not simply be changed to accommodate a new requirement in operation. Additionally, new battery cells or chemistries can only be implemented and used with changes in to the electronics layout. Most systems are not made for changes but rather for one specific purpose and application.

The overall energy density can be improved in the future. Battery systems should move towards 200 Wh/kg with better cells and improved designs. The functionality, supported by commercial components, can be increased as well. Satellite operators can benefit from better understanding of SOC, SOH and remaining useful life (RUL). The experiments can easier be scheduled and the life time and disposal of the satellite can be planned in advance.

In conclusion, there are lots of different systems with certain sizes and goal applications. The functionality towards data and certain modularity is not existent for the most part. Nonetheless, there are also a few impressive state-of-the-art battery systems.

3. DLR Battery System Concept

3.1 Requirements

The battery system that has been developed at the DLR shall bring some unique characteristics to improve the state-of-the-art for spacecrafts.

- Electronics with microcontroller and software for collection and processing of data
- Software with failure detection, isolation and recovery (FDIR)
- Single Cell voltage, current and temperature measurements for deep understanding and scientific research on cell behaviour in orbit
- Smart balancing with adaptable End of charge voltage (EoCV)
- Extendibility of system capacity, current and voltage
- Calculation of SOC and SOH (to give satellite operator a good understanding of the RUL)

There are some fundamental requirements so that the system can be a possibility for satellites listed in Table 2.

Table 2: Fundamental Requirements of the Battery System

Architecture	Modular, scalable
Energy Density (System)	Gravimetric: >140Wh/kg
Cell Chemistry	Li-Ion
Cell Type	18650 (COTS)
Cycle Stability	>12000 Cycles (with 20%DOD)
Energy Efficiency	>95%
Temperature Range	0 - 40°C (operational) -20°C - 55°C (storage)
Interface	CAN
TRL	7
Qualification	• Electrical • Structural/Mechanical • Thermal • Radiation

With the stated goals a design for the battery system has been created. The concept is based on an ideal-modular battery module. This allows for changes in BMS or cells. The modules can be connected to a battery system in an ideal-modular way. Yet, the structure surrounding the modules can only be scaled up.

A single module without a housing and two, four and sixteen modules with housing are being used as reference. The raw numbers can be seen in Table 3.

3.2 Hardware

The battery modules use commercial components that are available in high quality at an affordable price (most

Table 3: Specifications of the DLR battery system

Configuration	Weight [kg]	Volume [l]	Energy Capacity [Wh]	Grav. Energy Density [Wh/kg]
DLR (1 Module)	0,7	0,34	104	152
DLR (2 Modules + Housing)	1,5	1,36	207	142
DLR (4 Modules + Housing)	2,7	2,22	414	151
DLR (16 Modules + Housing)	10,3	7,42	1658	161

components are below 10€). The battery cells used are standard cells (NMC) of size 18650. Due to the modular design, the developed modules can be used to implement various system configurations. Firstly, the modules can be connected in parallel to increase the system capacity and current capability. Secondly, series connection of multiple modules allows the nominal voltage to be adapted to the requirements of the satellite. The maximum of eight cells in one module equates to a nominal voltage of 28.8V.

The battery system contains a battery management system (BMS) that balances the serially connected cells, monitors the charging and discharging currents and analyses the operating status of the cells. The values and status messages can be communicated to the on-board computer (OBC), power control and distribution unit (PCDU) or even shared between the modules. Additionally, a command can be sent to the modules to change operation of balancer, heater or state machine.

In Figure 4 the printed circuit boards (PCBs) with electronics are visible in green. The electronic components are directly connected with the battery cells (in pink) and include all necessary components to manage the cells. The centrepiece of the BMS is a microcontroller that is flashed with the software and commands the other electronic components via SPI and one-wire bus. The microcontroller, sensors, balancing units and safety devices are selected with the radiation environment in mind. The components had either been previously tested for radiation or have a rad-hardened counterpart.

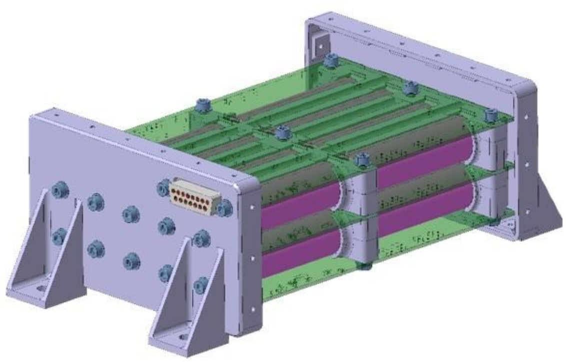

Figure 4: Battery system consisting of two battery modules and surrounding structure

Another important component is the balancing unit, which can individually measure and balance each cell at any voltage. Moreover, there are components for communication via CAN, temperature measuring, current measuring, latch-up protection, voltage regulation, heating and a back-up balancer.

The battery system's temperature sensors, structural components and heaters are used to regulate the temperature. This mostly passive thermal management ensures that the battery cells can be operated in an acceptable temperature window in a satellite environment (see requirements table).

The cell holders physically connect the battery cells with the PCBs and the thermal wedges support the thermal surface between battery cells and outside structure to increase conduction. The PCBs also act as structural components and give the system stability. The thermal wedges and included heater elements can be seen in Figure 5 and in Figure 6.

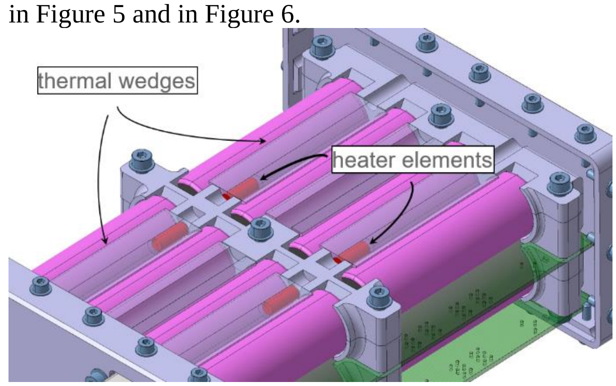

Figure 5: Isometric View of the Battery Cells, Thermal Wedges and Heater Elements of a Battery Module

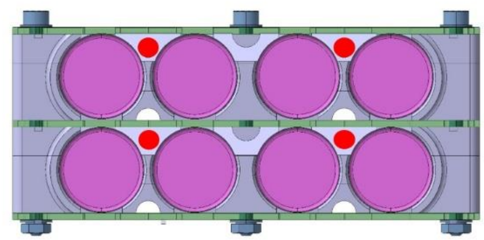

Figure 6: Side View of the Modular System

3.3 Software

The microcontroller of the system runs the software. Together with integrated circuits (ICs) of the system the operation of a smart battery management, with the ability to balance any cell at any voltage level, becomes possible. The general tasks of the battery management can be seen in Figure 7. The raw battery cells are shown in green. A direct power line (orange) from the battery cells to the outside cannot be interrupted by the management system. Consequently, a failure or power loss of the electronics will not cut the power from the satellite. The management system (blue) will monitor the system and the cells with voltage, current and temperature sensors. Further, the data from the electronic components is monitored. This data will be analysed and used for calculations (SOC, SOH) and a state machine, which changes states depending on the data and then allows or inhibits certain actions depending on the state. The state and sensor values will influence the management of the cells like heating or balancing.

Values, states and error messages will be communicated to the outside. Input is also possible to change the behaviour of the battery system. Possible states are idle, balancing, charging, discharging and emergency.

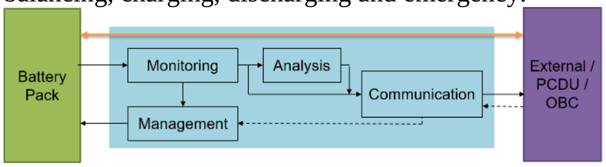

Figure 7: Tasks of the BMS Software

The software uses the modularity of the system for the failure detection, isolation and recovery (FDIR). A module's monitoring values can be compared to the neighbouring modules. If for example the current sensor suddenly shows unreasonably high values the microcontroller can compare with the CAN messages on the bus of the other modules. This allows for plausibility checks between the modules.

The average consumption of the electronics is 66mW. The modules can be powered externally (for an additional layer of safety) or powered directly by the battery cells. Even with an error or no power delivered to the BMS the battery cells can still be used safely due to a back-up balancing system.

The system has been tested electrically, in a thermal vacuum (between -20°C and 35°C) and under a load environment (sine 15g and random vibrations). Further, the next qualification goals are radiation tests and an extended thermal vacuum test campaign.

4. Discussion

The specifications of the previously described battery system concept are stated and compared in Figure 8.

The single module is in the top-right corner of the energy density graph. Most systems in that cluster are smaller CubeSat batteries. These usually come without a housing. The multi-module systems are higher than most systems when it comes to gravimetric energy density. The volumetric energy density can be improved. The housing is creating too much unused space on top of the modules and improvements need to be made. A trend towards >180Wh/kg can be seen for an improved housing concept or for systems with even more modules.

The advantages of this system over most of the compared ones is the compact system with many sensors and smart components to analyse the battery cells. The commercial battery cells offer high energy density. Also, long-term cycling tests are being conducted to have data on how much depth of discharge is possible for a certain cycle life. This knowledge can be used in combination

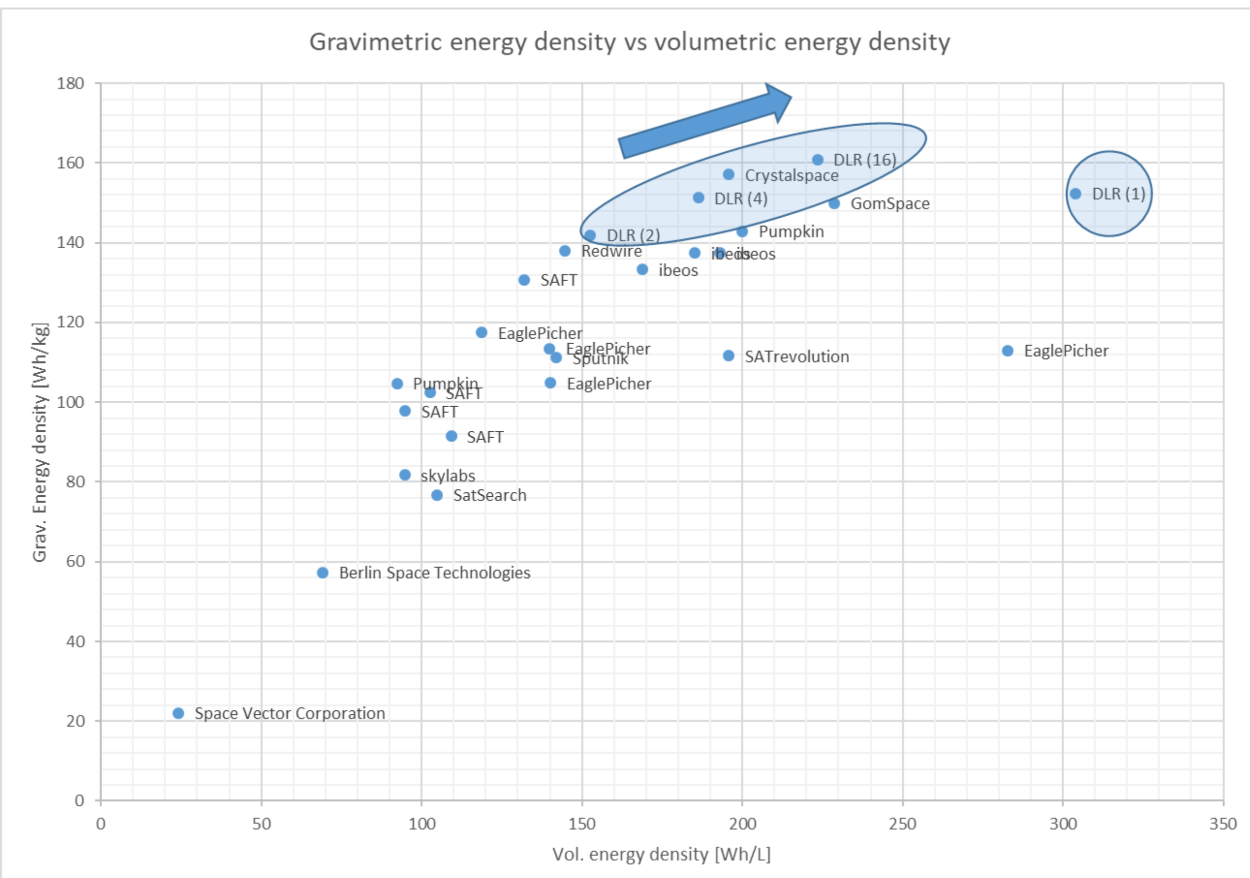

Figure 8: Comparison of gravimetric and volumetric energy density of the market study with the DLR system

with the sensor data to calculate the SOC, SOH and RUL of the battery system and therefore the satellite. With improvements a large system can get to >180Wh/kg and >250Wh/l while monitoring every single cell and offering modularity. Moreover, the system can be used in the future for new cell chemistries.

The open point of the system that has yet to be cleared is the lack of flight heritage. Qualification campaigns for thermal and radiation are planned for the end of 2022. Electronics, structure and miscellaneous parts are making up more than 50% of the entire system's weight. This ratio has to be improved, so that the majority of the weight is allocated towards the battery cells.

The idea of a modular and scalable battery system for satellites was presented and is definitely possible. Even with higher complexity due to electronics and interfaces the system can compare to the other battery systems. With more satellite missions being conceptualized each year a modular battery system can already be of help from the feasibility study. During the early phases first calculations can be run to determine the possible requirements to the power system. With predefined modules the weight, volume and power capabilities of the battery system can quickly be calculated.

5. Conclusions

The DLR battery system offers improvements regarding raw parameters like energy density, but also regarding functionality with adaptive balancing and sensors for complex SOC and SOH calculation. Specifically, the deep rooting knowledge on battery cells that supports the development can be used to improve and understand the system in flight. After all, improvements to the volume of the system need to be made and the interoperability of the modules has to be used to mitigate errors. Qualification campaigns in vacuum and radiation will finally prove the reliability of the system under space conditions.

However, it has to be said that large jumps in energy density cannot be expected without the use of a new cell chemistry. The functionality with regards to balancing and RUL are more significant with the new battery concept presented in this paper.

With these steps the system can eventually be taken a step further and considered for MEO or GEO applications as well. Due to the elaborate component selection most of the electrical components can simply be replaced by their rad-hard counterparts with the same footprint. The cost of component and therefore system will be higher in that case. The system is supposed to fly in a two-module configuration inside of a LEO CubeSat in 2023. Future papers will describe the qualification process.

Acknowledgements

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