MODABAT

A Clean Aviation Project

D3.1 - Battery System Architecture and Specification

Document No: MODABAT-DEL3.1
Document Title: Battery System Architecture and Specification
Issue N° & Date: 1.0 | 2026-05-31

Dissemination Level (Security)		
Public	Public, fully open, e.g. web	x
Sensitive	Sensitive, limited under the conditions of the Grant Agreement *Restricted to a specific group within the consortium (including the European Commission Services for key deliverables)* Restricted List: XXXYYY Ext. Restricted List: *N/A*	
Classified	Classified under Commission Decision No 2015/444:	
	– R-UE/EU-R (EU Restricted)	
	– C-UE/EU-C (EU Confidential)	
	– S-UE/EU-S (EU Secret)	

Document Verification & Approval	Name (printed & signature)	Beneficiary shortname	Date (dd mmm yyyy)
Lead Author	Fatma Khera	UNOTT	18-05-2026
Contributing Author(s)	*Surojit Sen (UNOTT), Matthias Hessmann (FHG), Javier Marco Gimeno (UPV), Angel Romero (AXT)*		
Verification (Confirms the technical contents of the document. The signatory must have the technical approval within their organisation)	Angel Romero Maxence Estrade	AXT ATR	2026-05-29 2026-05-29
Approval (Confirms that the document conforms to the specific WP expectations/requirements)	Martin Wenger	FHG	2026-06-02

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Document History

Issue	Date	Summary of changes
0.1	18-05-2026	First draft with structure
0.2	26-05-2026	Merged content partially – final refinement required
0.3	27-05-2026	All content merged, refinement #1 – ready for internal review
0.4	29-05-2026	Post reviewer comments from ATR and AXT
1.0	29-05-2026	Final version for submission

Abstract

This document refers to MODABAT deliverable D3.1 Battery System Architecture and Specification as defined in GA 101251224 for a hybrid-electric regional aircraft (ATR 72-600) application. This report establishes the project nomenclature, summarises the proposed battery system architecture, including mechanical, electrical and data interfaces and system components. The overall system has been broken into four sub-systems: battery pack (the battery core with battery cells assembled into a system), battery energy control system (BECS), battery management system/energy management system (BMS/EMS), and thermal management system (TMS). Each sub-system has a system diagram produced with description of the components and interfaces (with connected sub-systems) and design rationale. The proposed architecture follows a modular and technology-open approach, combining clearly defined subsystems with repeatable string- and module-level building blocks to enable scalability, adaptability, and the integration of future cell technologies.

The document specifies a battery system with 187.5 kWh energy content, a voltage range of 600–1020 V, and a 15 × 240s1p configuration, targeting aviation-relevant performance in terms of energy density, power capability, thermal control, and safety. In addition to describing the baseline architecture and subsystem responsibilities, the report discusses potential modifications for weight optimization, showing how automated assembly and integration could simplify module-level protection and reduce component count, wiring complexity, and system mass. The deliverable therefore provides the initial technical reference for subsequent MODABAT development activities and for further refinement of the battery system design.

Keywords

Battery, aviation, electrification, system architecture, interfaces, deliverable, report, Hybrid-electric aviation, aircraft battery system, battery system architecture, modular battery system, technology-open battery system, scalable battery system, weight optimized battery system architecture

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Information Table

Contract Number	101251224
Project Acronym	MODABAT
Project Title	**M**odular, scalable and technology-**O**pen **D**esign for future **A**viation **BAT**teries
Topic	HORIZON-JU-CLEAN-AVIATION-2025-03-FTA-01
Type of Action	HORIZON JU Innovation Actions
Start date of project	1 November 2025
Duration	24 months
Project Coordinator	FRAUNHOFER GESELLSCHAFT
Deliverable Number	D3.1
Deliverable Title	Battery System Architecture and Specification
Version	1
Status	Final
Responsible Partner (organization)	UNOTT
Deliverable Type	Report
Contractual Date of Delivery	31-05-2026
Actual Date of Delivery	31-05-2026
Dissemination Level	PU

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Partners involved in the document

Lines of Beneficiaries not involved can be removed.

Nº	Role	Member name	Short name	Check if involved
1	COO	FRAUNHOFER GESELLSCHAFT	FHG	X
5	BEN	THE UNIVERSITY OF NOTTINGHAM	UNOTT	X
7	BEN	AXTER AEROSPACE SL	AXT	X
9	BEN	UNIVERSITAT POLITECNICA DE VALENCIA	UPV	X
10	BEN	AVIONS DE TRANSPORT REGIONAL	ATR	X

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Table of Acronyms and Abbreviations

Acronym/Abbreviation	Description / Meaning
AC	Alternating Current
BESS	Battery Energy Storage System
BECS	Battery Energy Control System
BMS	Battery Management System
BTMS	Battery Thermal Management System
CAN	Controller Area Network (communication protocol)
DC	Direct Current
EMS	Energy Management System
FADEC	Full Authority Digital Engine Control
HV	High Voltage
HVIL	High Voltage Interlock Loop
HX	Heat Exchanger
IMD	Insulation Monitoring Device
LV	Low Voltage
MS	Mechanical Switch
RUL	Remaining Useful Life
SoC	State of Charge
SoH	State of Health
SSCB	Solid-State Circuit Breaker
TMS	Thermal Management System
TR	Thermal Runaway

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Disclaimers

The project is supported by the Clean Aviation Joint Undertaking and its members.

Clean Aviation is the EU's leading research and innovation program for transforming aviation towards a sustainable and climate neutral future.

As a European public-private partnership, Clean Aviation pushes aeronautical science beyond the limits of imagination by creating new technologies that will significantly reduce aviation's impact on the planet, enabling future generations to enjoy the social and economic benefits of air travel far into the future.

Visit the website to find out more about Clean Aviation: www.clean-aviation.eu

Funded by the European Union, under Grant Agreement No 101101999. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Copyright © 2025, MODABAT Consortium, all rights reserved.

This document and its contents remain the property of the beneficiaries of the MODABAT Consortium. It may contain information subject to intellectual property rights. No intellectual property rights are granted by the delivery of this document or the disclosure of its content. Reproduction or circulation of this document to any third party is prohibited without the consent of the author(s).

THIS DOCUMENT IS PROVIDED BY THE COPYRIGHT HOLDERS AND CONTRIBUTORS "AS IS" AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT OWNER OR CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS DOCUMENT, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Table of Contents

Introduction **7**

1 Battery Systems Overview **8**

1.1 Battery System Nomenclature 8

1.2 Battery System Specification 8

1.3 System Architecture Block Diagram 9

2 Battery Pack **13**

2.1 Function 15

2.2 Interface 16

3 Battery Energy Control System (BECS) **17**

3.1 Function 18

3.2 Interface 18

3.3 SSCB Technology Overview 19

3.3.1 SSCB Architecture 20

3.3.2 System-level SSCB 20

3.3.3 String-level SSCB 21

4 Battery Management System (BMS) **22**

4.1 Energy Management System (EMS) 22

4.2 Master Battery Management System (BMS-Master) 24

4.3 Slave Battery Management System (BMS-Slave) 25

4.4 Interface 26

5 Thermal Management System (TMS) **30**

5.1 Function 30

5.2 Interface 32

6 Battery System Architecture Modifications for Weight Optimisation **33**

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

List of Figures

Figure 1: Overview of the battery system architecture components 10
Figure 2: Block diagram legend showing the block diagram components and responsibilities 11
Figure 3: Block diagram of the MODABAT battery pack architecture 14
Figure 4: Block diagram of a single battery module with a 120s1p configuration 15
Figure 5: Block diagram of BECS architecture showing switches, fuses, current sensor and EMS ... 17
Figure 6: Block diagram of SSCB architecture showing key subsystems 20
Figure 8: Three-layered battery management strategy 22
Figure 9: Block Diagram of EMS acting as control and management unit on system level 22
Figure 9: Block diagram of the BMS-Master acting as control and management unit on string level 24
Figure 10: Block Diagram of BMS-Slave acting as monitoring unit on module level 26
Figure 11: Block Diagram of TMS showing controller, pump, filters, HX, manifolds and sensors 30
Figure 13 Simplified Battery String Architecture for Automated Assembly and Installation 34

List of Tables

Table 1: Definition of the battery system specification 8
Table 2: Summary of the Interfaces between the Aircraft and the Battery System 11
Table 3: Interfaces of Battery Pack 16
Table 4: Summary of system-level and string-level SSCB 18
Table 5: Functions of BECS 18
Table 6: Interfaces of BECS 18
Table 7: Protection technologies for aircraft applications 19
Table 8: Functions of EMS 23
Table 9: Functions of BMS-Master 24
Table 10: Interfaces of EMS and BMS (master and slave) 27
Table 11: Functions of TMS 31
Table 12: Interfaces of TMS 32

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

INTRODUCTION

This document presents the preliminary architecture and specification of the MODABAT battery energy storage system (BESS) developed for application in a hybrid-electric regional aircraft. It builds upon the system requirements defined in Deliverable D1.1 and establishes a coherent technical framework to support subsequent design, integration, and validation activities.

The battery system adopts a modular and technology-open architecture, designed to ensure scalability, adaptability, and compatibility with future battery cell technologies. The overall system is structured into four principal subsystems: the battery pack, the Battery Energy Control System (BECS), the Battery Management System and Energy Management System (BMS/EMS), and the Thermal Management System (TMS). Each subsystem is defined in terms of its functionality, interfaces, and architectural composition, supported by system-level diagrams and design rationale.

The battery pack provides the core energy storage capability and is configured as a set of parallel strings composed of series-connected battery modules. This modular configuration supports scalability, redundancy, and fault tolerance while enabling continued operation under degraded conditions. Each module integrates safety-relevant features, including thermal runaway containment, gas venting, and distributed sensing, to ensure compliance with aviation safety expectations and to enhance overall system robustness.

The BECS defines the electrical interface between the battery system and the aircraft powertrain. It enables controlled bidirectional power flow, system pre-charge functionality, and high-speed protection through the use of solid-state circuit breakers (SSCBs) in combination with mechanical switching elements and safety elements. This subsystem plays a central role in ensuring the safe energisation and isolation of the high-voltage network across all operating conditions.

A hierarchical battery management architecture is implemented to provide comprehensive monitoring and control across system levels. The EMS functions as the central supervisory controller, coordinating system-level power distribution, protection, and interaction with the aircraft avionics. It interfaces with multiple BMS-Master units, each responsible for string-level monitoring, control, and fault handling. At the lowest level, BMS-Slave units provide high-resolution measurements of cell voltages, temperatures, and safety indicators, including gas detection, enabling early identification of abnormal conditions and supporting rapid system response. This layered approach enhances system reliability, fault tolerance, and operational safety.

Thermal management is addressed through a dedicated liquid-based TMS, designed to maintain battery operation within defined temperature limits under all mission phases. The system provides both cooling and heating functionality, ensuring uniform temperature distribution and supporting cold-start capability. Integrated sensing and monitoring functions allow early detection of abnormal thermal or hydraulic conditions, contributing to safe and efficient system operation.

In addition to the baseline architecture, the document considers potential design optimisations aimed at reducing system weight and complexity. These include alternative configurations enabled by automated assembly and integration processes, which allow a shift in protection functionality from module level to string level. Such approaches reduce component count and wiring complexity while maintaining the required levels of safety and performance. Also, other optimisations could be implemented to add functionality, level up the existing or improve safety concerns.

Overall, this deliverable establishes the foundational architecture of the MODABAT battery system, defining subsystem roles, interfaces, and design principles. It provides the basis for further development, detailed design, and validation activities within the MODABAT project.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

1 BATTERY SYSTEMS OVERVIEW

This section gives an overview of the MODABAT specific nomenclature and the battery system specification for the hybrid electric aircraft architecture targeted in the MODABAT project. In addition, the battery system architecture is described. The high-level architecture description is followed by a description of the individual subsystems.

1.1 Battery System Nomenclature

This section defines the nomenclature that is used within the MODABAT project.

- A **Battery Cell** is considered a single electrochemical unit which exhibits a voltage across its two terminals and is used as the elementary unit of a battery module or battery system.
- A **Battery Module** is a sub-assembly of cells that are electrically connected in series, contained in a single enclosure that ensures that no fluids, flames, gases, smoke, or fragments can escape the enclosure (i.e. during thermal runaway).
- A **Battery String** describes the electrical connection of two modules in series, connected to the battery management system.
- A **Battery Pack** defines the combination of battery strings in parallel.
- The **Battery System (BESS)** is defined as the battery pack connected to the battery energy control system (BECS) and battery thermal management system (BTMS). The installation on an aircraft may include multiple battery systems to make up the energy storage system.
- A **Battery Management System (BMS)** describes an electronic system that manages a rechargeable battery (cell, module or pack), such as by protecting the battery from operating outside its safe operating area, monitoring its state, calculating secondary data, reporting that data, controlling its environment, authenticating it and/or balancing it.
- A **Battery Energy Control System** defines a supervisory energy management system that controls the energy flowing in and out of the battery pack and communicates with the BMS.
- The **Battery Thermal Management System** defines the subsystem responsible for maintaining the battery cells, modules and pack within their specified operating temperature range. The BTMS may include cooling, heating, sensing and thermal control components. BTMS communicates with BMS.

1.2 Battery System Specification

Table 1 gives an overview of the MODABAT battery system specification. The system specifications result from the battery system architecture (described in the next section) that was developed based on the targeted use-case of a hybrid electrical aircraft propulsion energy storage system for an ATR 72-600 aircraft and the results of the requirements defined in work package WP1. The battery system is intended to provide electrical energy during the climb and cruise phases of the aircraft, until it is fully discharged up to a minimal SOC. The battery system is intended to be a complementary energy source to support combustion-based propulsion.

Table 1: Definition of the battery system specification

Specification	MADABAT Implementation	MODABAT Target
Electrical		
Maximum Gravimetric Energy Density [Wh/kg]	260 (Targeted - Subject to system design implementation)	260
Energy Content [kWh]	187.5	150
Battery System Configuration	15 x 240s1p	-
Battery System Voltage [V]	600 – 1020	-

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Nominal Battery System Voltage [V]	830	800
Maximum Charge Current [A]	225	-
Maximum Charge rate	1C	2
Maximum Discharge Current [A]	675	-
Maximum Discharge Rate	3C	2
Peak Discharge Current for 30s [A]	1125	-
Peak Discharge Rate for 30s	5C	-
Cycle Life (80% SOH)	300	2000 (ATR requirement)
Mechanical		
Mechanical Dimensions [mm]	923 * 1300 * 737 (Targeted - Subject to system design implementation)	923 * 1300 * 737 (ATR requirement)
Battery System Weight [kg]	720 (Targeted - Calculated from MODABAT battery system implementation)	580 (calculated from MODABAT target values)
Environmental		
Operational Temperature Limits [°C]	+5°C to +35 °C	-

1.3 System Architecture Block Diagram

This section gives an overview of the high-level battery system architecture, represented by the block diagram depicted in Figure 1. The block diagram is also attached as a separate file to this document. Within MODABAT, the battery system architecture follows a modular and technology-open approach, accommodating for future cell technologies such as solid-state Lithium-ion batteries. Redundancy strategies, modularity and interfaces including electrical, mechanical, thermal and data interfaces can be adapted with minimal effort when transitioning to future cell technology.

The MODABAT battery system development focusses on the following sub-systems shown in Figure 1:

1. Battery Pack (1)
2. BMS (2) and EMS (3)
3. BECS (4)
4. BTMS (5)

In Figure 1, each sub system is highlighted by a dedicated colour.

The battery pack (green) – only 2 of 15 strings shown for clarity - stores the electrical energy of the hybrid electrical aircraft and provides electrical power to the aircraft during climb and cruise. It is electrically connected to the BECS (orange), which is the electrical power interface between the battery system and the aircraft powertrain.

The BECS performs load current switching, pre-charging, overcurrent protection and fault management on system level. The BECS is controlled by the EMS.

The EMS (blue) acts as the central supervisory control unit of the battery system. It communicates with the aircraft control system (i.e. FADEC) and with the BMS of every string to control the battery system operation accordingly. The EMS initiates protective actions when detecting failures or abnormal operating conditions and communicates them to the aircraft control system. In addition, the EMS is responsible for system level safety by monitoring the system current, isolation resistance, HV-DC-Bus voltage and an interlock line. Possible protective measures include not only warnings to superordinate aircraft control systems but also disconnecting

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

the battery system from the propulsion system. The BECS also communicates with the TMS for error handling and temperature feedback.

On string level, safe operation is ensured by the BMS (blue), which continuously monitors the battery cells inside each module. This includes voltage, current, gas and temperature measurements. The BMS communicates with the EMS and is capable of autonomously isolating individual battery strings upon failure detection.

The BTMS (purple) is interfaced to the battery modules via a cooling plate to maintain the battery cells within the specified operating temperature range by providing heating and cooling functionality as required.

The subsystems are described in more detail in the sections 2, 3, 4, and 5. The components inside the grey cross hatched lines, namely the traction inverter, low voltage (LV) power distribution unit, and aircraft venting system are not within the MODABAT development scope.

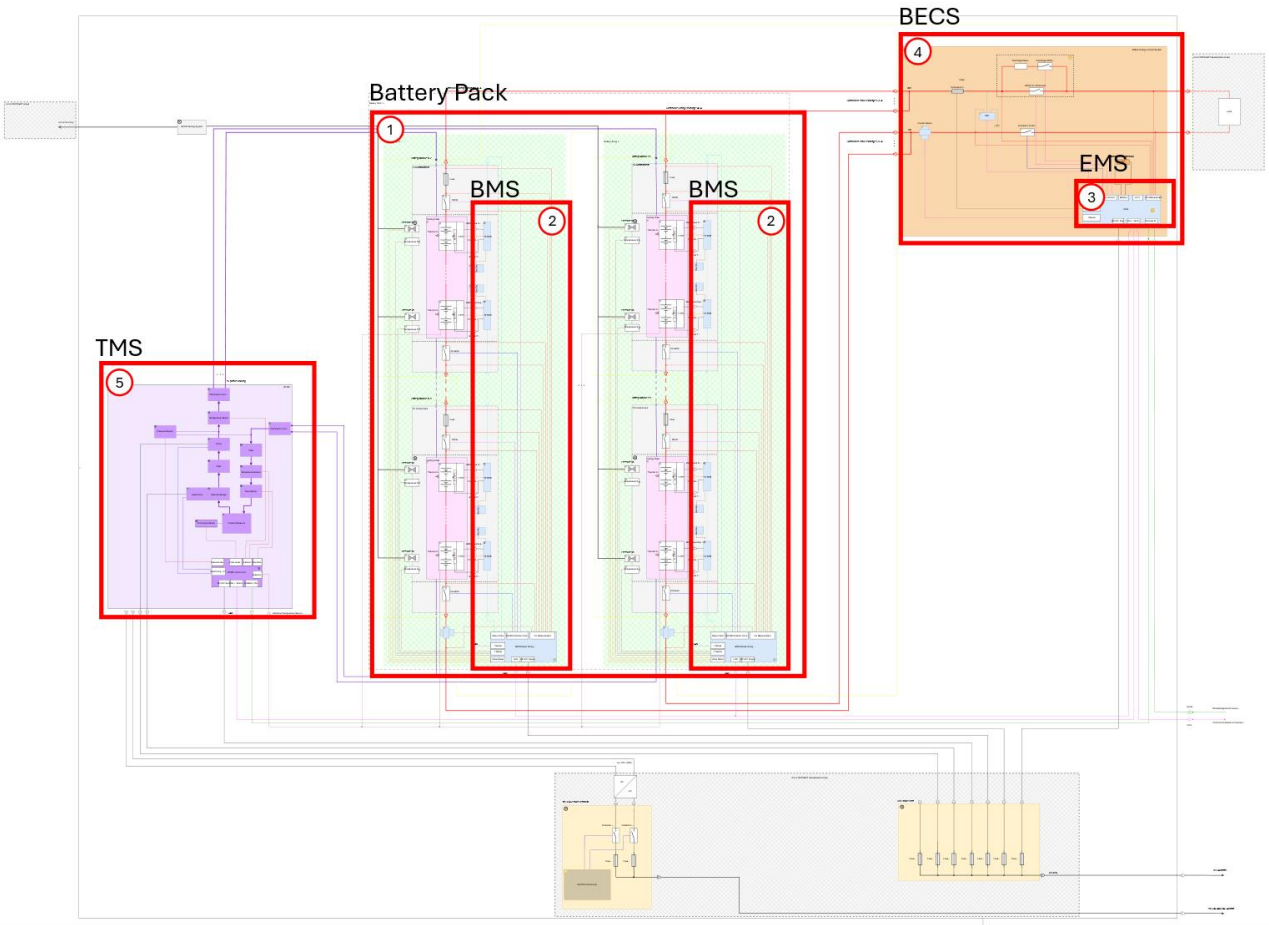


Figure 1: Overview of the battery system architecture components

A legend with all system components is presented in Figure 2. All electrical, mechanical and thermal subsystem components are shown together with the corresponding symbol inside the block diagram. The subsystem responsibilities between the project partners are also indicated via the colouring scheme.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

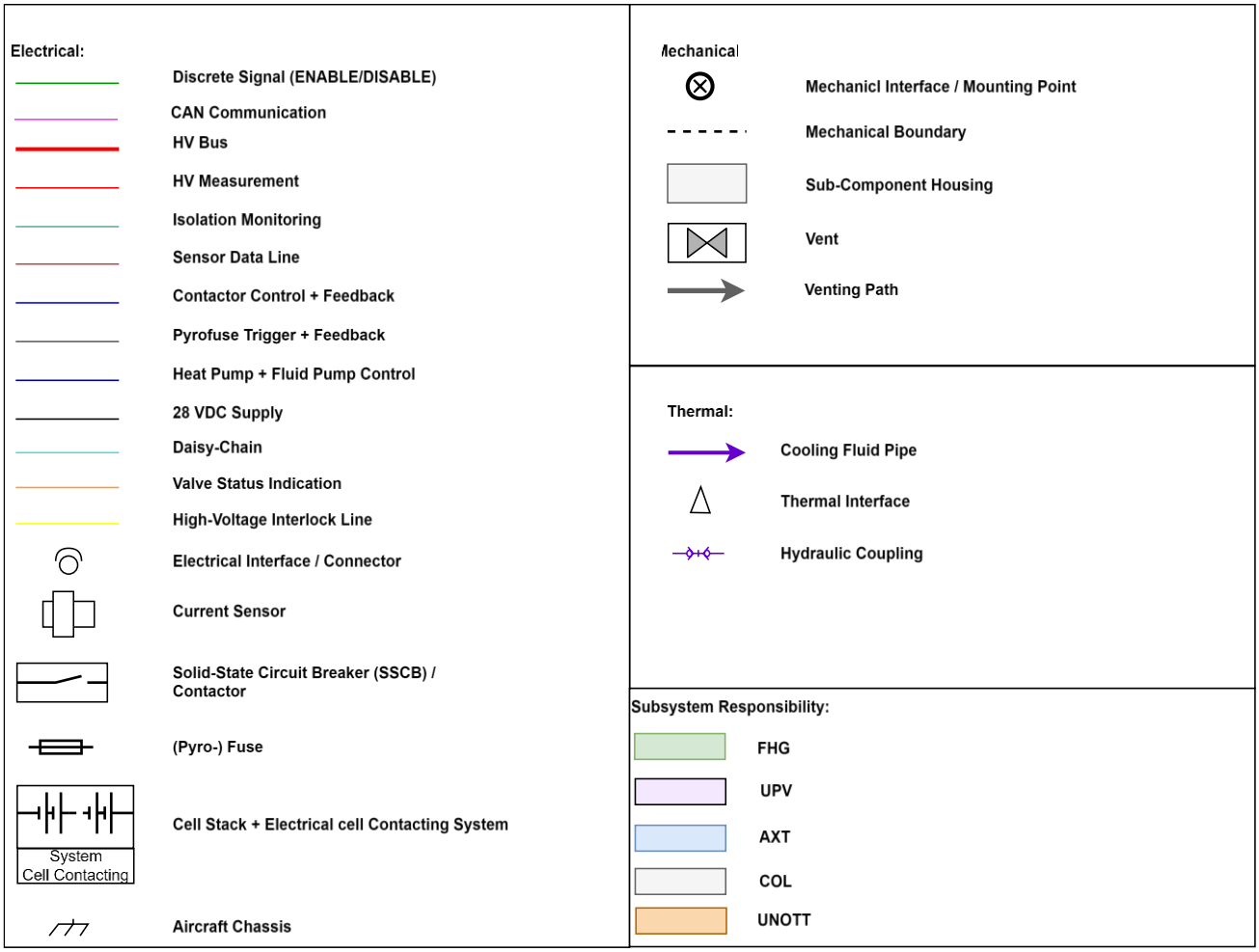


Figure 2: Block diagram legend showing the block diagram components and responsibilities

The battery system interfaces to the aircraft are listed in Table 2.

Table 2: Summary of the Interfaces between the Aircraft and the Battery System

Interface Name	Battery System Interface	Aircraft Interface	Description
Electrical			
830 V DC	BECS	Aircraft Powertrain	HV-DC-Bus for Electrical Propulsion Power
28 V DC LV	28V Power Distribution	28 V DC Aircraft LV Power Net	LV-Bus for Control Unit Power Supply
115 V AC	115 V AC Power Distribution	115 V AC Aircraft Mid-Level Voltage Power Net	BTMS Component Power Supply TBD

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Communication			
CAN-Bus	BECS	FADEC / Avionics control	Battery System EMS Communication to Aircraft
Analog Enable / Disable Signal	BECS	FADEC / Avionics control	Discrete ENABLE/DISABLE from Aircraft to Battery System EMS
Mechanical			
Mounting point	Battery System	Aircraft Fuselage	Implementation for BECS, Battery Pack and BTMS TBD
Venting System	Battery System Venting System	Aircraft Structure	Implementation TBD

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

2 BATTERY PACK

The MODABAT battery pack is shown in Figure 3. The battery pack consists of 15 identical battery strings in parallel. For simplicity, Figure 3 depicts two strings only. The battery pack follows a modular approach by identical separated functional subsystems, such as the battery modules. The battery pack can be scaled by adding or removing individual battery strings. Each battery string consists of two battery modules in series. Each battery module has a 120s1p configuration. Inside the block diagram, the boundary definition of a battery string is marked by a green cross hatched box. The voltage of each string ranges from 600 V to 1020 V and the energy content per string is 12.5 kWh at begin of life (BOL). All strings of the battery pack provide a separate electrical HV+ and HV- connector to the BECS. Mechanically, the modules of each string are mounted directly or indirectly (e.g. by an additional mechanical structure) to the aircraft fuselage, without an additional string containment. To comply with safety regulations such as DO-311 and MOC-3 SC-VTOL a thermal runaway (TR) proof containment and gas venting system is foreseen for each battery module of the battery string. In addition, TR propagation risk is mitigated by passive propagation materials inside the cell layer stack on module level and by an advanced BTMS. To prevent heat transfer via the BTMS thermal plates across the battery pack, each string is connected to the BTMS in parallel. Therefore, each battery module inside each battery string has its own thermal plate.

During normal operation, all strings are connected to the BECS simultaneously. Individual (dis-)connection of strings is not intended during normal operation of the aircraft battery system. Only in case of failure or maintenance, individual strings are disconnected by the BMS. Due to battery string redundancy on battery pack level, the battery system stays functional at decreased performance in case of individual strings being disconnected from the system due to failure. All HV power connectors of the battery pack are monitored via the EMS interlock line.

Each string is constantly monitored and controlled by a BMS consisting of one central BMS-Master and 20 local BMS-Slaves. Upon failure detection, the BMS-Master is responsible for disconnecting faulty battery strings from the battery pack via the contactor and SCCB. The BMS-Master monitors critical parameters, such as the current flow and high-voltage bus on string level, as well as fuse, SSCB and contactor statuses. Also, the BMS-Master receives information about the pressure valve status and additional battery string temperatures (in addition to the cell temperatures).

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

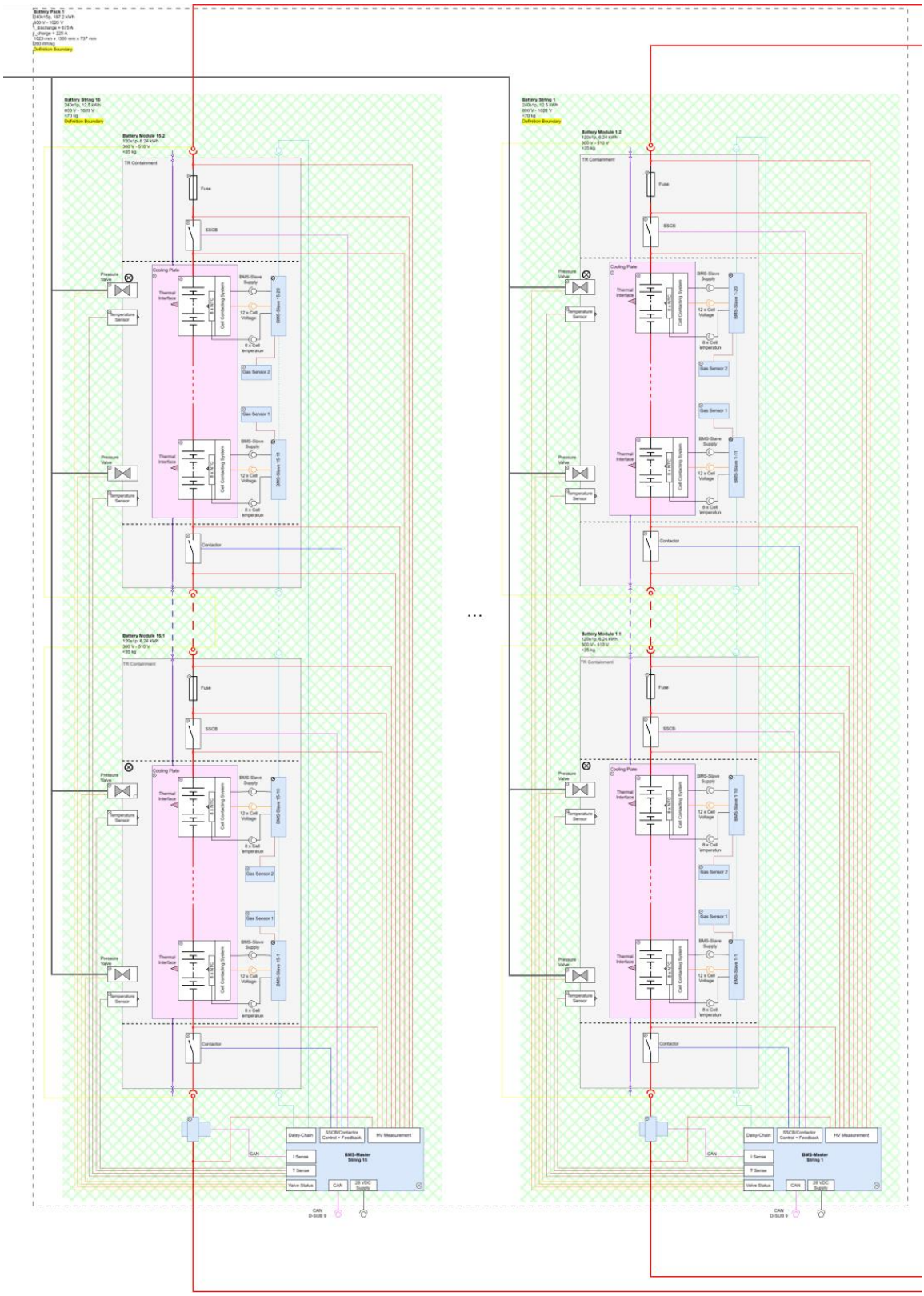


Figure 3: Block diagram of the MODABAT battery pack architecture

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

2.1 Function

In Figure 4, the battery module architecture is shown in more detail. The battery module consists of a thermal runaway proof containment (grey), a thermal plate of the BTMS (pink), the cell stack with a 120s1p configuration, and the BMS (blue). The containment of each module has two pressure valves, that establish the connection to the battery pack venting system and allow pressure release both during normal operation and during a TR event. As described in section 4, the valve status is constantly monitored by the BMS-Master. Also, additional temperature sensors are placed on the outer module containment to monitor the maximum temperature occurring during a TR event. The module is mechanically connected to the aircraft fuselage.

Each battery module is equipped with a fluid-cooled/heated thermal plate, that is used to maintain optimal cell temperature before and during operation and to assure a homogenous temperature distribution across all 120 cells of each module. The thermal plate is mechanically connected to the module containment. All cells inside the module are thermally connected to the BTMS thermal plate.

Each module contains 10 BMS-Slaves, constantly monitoring the individual cell voltages via an electrical interface. Each BMS-Slave measures 12 cell voltages and eight cell temperatures. Mechanically, the BMS components are connected to the module housing. To detect gas generation during abusive conditions, each battery module includes two gas sensors that are also monitored via the BMS-Slave.

To disconnect faulty strings from the battery system, each module has a SSCB on its positive pole and a mechanical contactor on the negative pole. The SSCB is used to quickly disconnect the faulty string, while the mechanical contactor ensures galvanic isolation. The switches on module level are controlled by the BMS-Master on string level.

Each battery module includes a passive fuse, that is triggered during a module- or string-level overcurrent event, without need of control for safety.

Both the switches and fuse are located outside the cell compartment of the containment to minimize the risk of the components being damaged or malfunctioning during a TR event. The electrical communication and power connection of each battery module is established via dedicated connectors. Touch protection will be installed to prevent HV access during handling of the modules (i.e. during installation and maintenance).

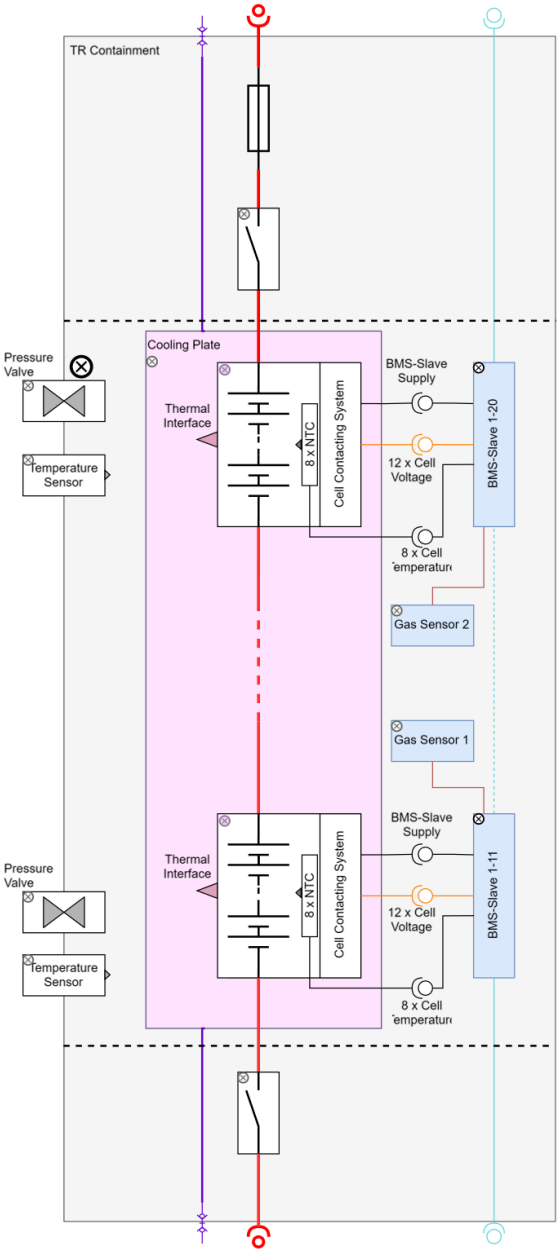


Figure 4: Block diagram of a single battery module with a 120s1p configuration

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

2.2 Interface

Table 3 below shows all the interfaces for the battery pack.

Table 3: Interfaces of Battery Pack

Interface	Connection A	Connection B	Description
Electrical			
28 VDC (LV supply)	BMS-Master (String Level)	28 V DC Aircraft LV Power Net	BMS-Master Power Supply
High Voltage Bus	Battery Pack	BECS	HV-DC-Bus to BECS
Interlock Line	Battery Pack	EMS	Monitoring Electrical Connector Status
Communication			
CAN-Bus	Battery Pack	EMS	CAN Communication to EMS
Mechanical			
Mounting Point	Battery Pack	Aircraft Fuselage	Implementation TBD
Venting System	Battery Pack	Aircraft Structure	Mechanical Connection from the Battery Pack Venting to the Aircraft Venting System
Thermal			
BTMS Piping	Battery Pack	BTMS	Cooling Fluid on String Level

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

3 BATTERY ENERGY CONTROL SYSTEM (BECS)

The following section describes the common BECS functions, specifications, and interfaces, followed by detailed specifications of the individual solid-state circuit breakers (SSCB) subsystems.

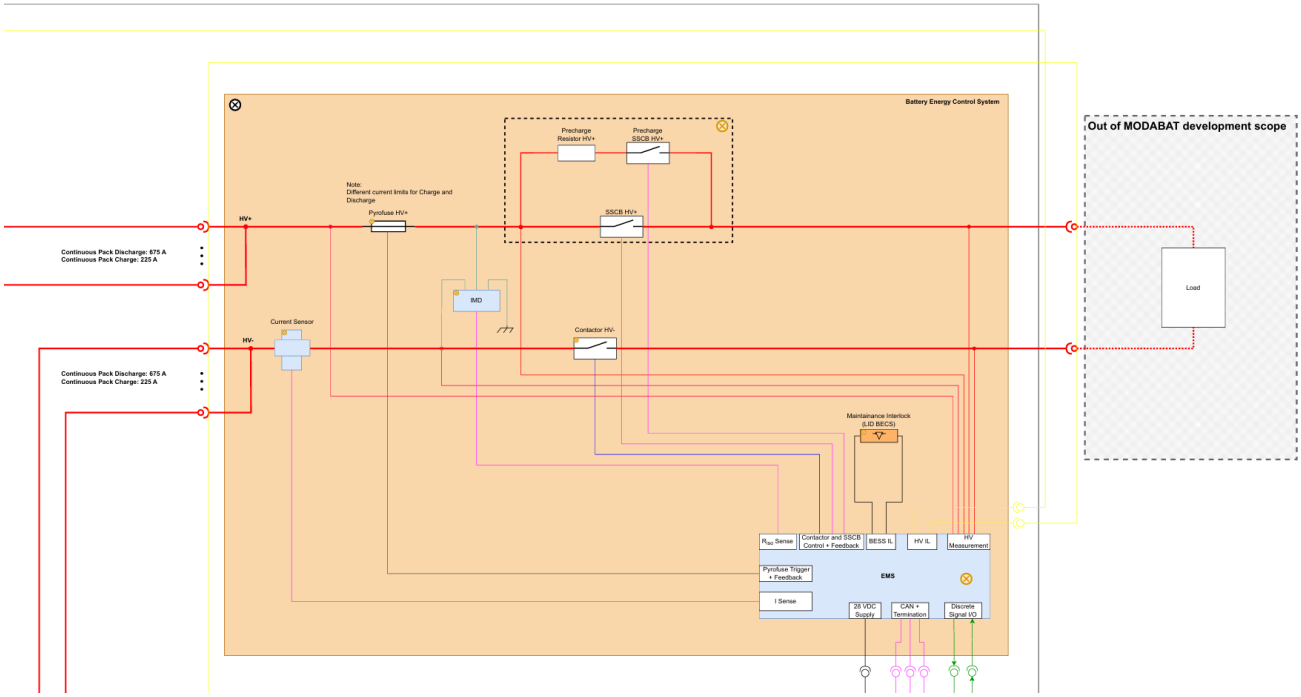


Figure 5: Block diagram of BECS architecture showing switches, fuses, current sensor and EMS

The system (Figure 5) is designed with an operating voltage range of 600 V to 1020 V DC. The nominal operating voltage is 830 V. The primary objective of the BECS architecture design is to correctly identify the location of the active (controllable switches) and passive (fuses, connectors and wiring) elements for safely and accurately controlling the flow of energy to/from the BESS. The overall objective is to:

- Maximise overall efficiency while minimising weight
- Perform the interrupt action under safety-critical failure conditions
- Safely connect the BESS to the Aircraft Powertrain
- Monitor the overall current flow of the BESS

At a system-level, the positive pole will have a precharge-integrated SSCB with in-built current sensing capability and rapid turn-off in failure conditions. The negative pole will have a mechanical switch (MS) controlled by the EMS. This means both poles have disconnection capability with the SSCB (positive pole) offering standalone rapid current interruption capability and MS (negative pole) offering galvanic isolation at a much smaller and lighter package.

A similar half-and-half design has been adopted at the string-level; SSCB at the positive pole and MS at the negative pole. In theory, a single SSCB (at system-level) is capable of rapid current interruption; however, an additional string-level SSCB (sized for much smaller current, and consequently, better safety margin) is incorporated in the design at this stage of R&D to allow downgraded function of the BESS.

A summary of the SSCBs under design for system-level and string-level is provided in Table 4.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Table 4: Summary of system-level and string-level SSCB

Parameter	System-level SSCB	String-level SSCB
Current rating (continuous)	667 A	45 A
Current rating (peak for #s)	800 A for 10ms	75 A for 30s
Voltage rating	>1500 V	>1500 V
Turn off time	~10–500 µs	~5–200 µs
Additional feature	Self-contained current protection Integrated pre-charge circuit	Self-contained current protection

3.1 Function

The BECS performs three core functions as summarised in Table 5.

Table 5: Functions of BECS

Function	Implementation
Provides controllable power flow path to/from the BESS (bidirectional flow). This ensures safe and controlled connection and disconnection of the battery module to and from the DC-link during normal operation, startup, and shutdown cases.	Bidirectional SSCB at the system-level and string-level. Additional pre-charge path on the system-level positive pole to enable pre-charging of the DC Link capacitor downstream of the BESS.
Provides multi-layer protection of the system preventing any fault currents causing catastrophic failures such as thermal runaway of Li-Ion cells.	SSCBs provide rapid fault current interruption (10-500µs) at both system and string levels, providing a redundant layer of protection. Passive fuses provide further protection. Pyro-fuse ensures the energy cut-off in case of catastrophic failure. SSCB continuously monitors the circuit current to provide overcurrent, short-circuit, and thermal limit protection, and can be remotely reset.
Interfaces with the EMS (Energy Management System) – EMS is the supervisory controller for the BESS.	CAN communication with EMS to exchange component status information, including SSCB status, fault indications, and current measurements.

3.2 Interface

The BECS interface (Table 6) consists high voltage power connections, low voltage, and communication links, and are designed to ensure mechanical and electrical integration with the aircraft system.

Table 6: Interfaces of BECS

Interface	Connection A	Connection B	Description
Electrical			
28 VDC (LV supply)	BECS	Aircraft 28 V DC power net	28 VDC power supply from aircraft to energise the control systems in BECS (in common with EMS LV supply that). This LV power is required for control interface,

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

			sensing circuits, and communications.
High Voltage Bus	BECS	Battery Pack	High voltage/power connection to the battery pack via suitable HV connectors with HVIL functionality to allow flow of energy.
High Voltage Bus	BECS	Aircraft HV bus	High voltage/power connection to the aircraft via suitable HV connectors with HVIL functionality to allow flow of energy.
Interlock Line	BECS	EMS	Monitoring Electrical Connector Status
Communication			
CAN-Bus	BECS	EMS	Control (turn on/off system-level SSCB, MS, pre-charge) and diagnostic signals (SSCB current and status, precharge status, various fault flags) via CAN protocol.
Mechanical			
Mounting Point	BECS	Aircraft Fuselage	Implementation TBD
Thermal			
BTMS Piping	BECS	BTMS	Cooling Fluid for system-level SSCB (TBD)

3.3 SSCB Technology Overview

Table 7 is high level comparison of the fuse, mechanical switch (MS) and SSCB. The table highlights that SSCBs provide a major performance improvement, with switching up to 1000× faster than MS (10–100 ms). While fuses offer good power density and low cost, their lack of intelligence and reset capability makes them unsuitable as main protection. MS is robust but are constrained by slow operation and mechanical wear due to arcing. SSCBs provide fast protection, arc less, digital control, and supporting scalable designs for currents ranging from hundreds of amps to kA levels, making them the most suitable solution for future aircraft systems. However, they have some downsides such as high cost, larger volume and weight.

Table 7: Protection technologies for aircraft applications

Feature	Fuse	MS	SSCB
Type	Passive protection device	Manual or electromechanical	Semiconductor device
Losses	Low	Low	High / needs optimization
Resettable	No	Yes	Yes (Remotely)
Breaking time	slow (ms to sec)	Slow (tens of ms)	Very fast (µs–ms)
Current Monitoring	No	Limited versions	Yes
Protection Features	Overcurrent	Overcurrent	Overcurrent, thermal, over/under voltage
Size & Weight	Small/light 80-1000 kW/kg	May be bulky 20-50 kW/kg	Compact 10-120 kW/kg
Cost	Low	Low–Medium	Medium–High

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Reliability	Low (Aircraft) High (Automotive)	Mechanical wear over time (arcing, contact degradation)	High (no moving parts)
TRL	High TRL 8-9 (mature)	High TRL 8-9 (mature)	TRL 7–8 (developing/mature in some fields)

3.3.1 SSCB Architecture

The main SSCB and string SSCB consist of several common subsystems. However, the detailed specifications and ratings of the inner components are different. Figure 6 below highlights the key SSCB subsystems:

- **Semiconductor devices:** High-power SiC MOSFET modules are used to ensure efficient operation.
- **Gate drive and protection circuits:** Gate drivers with protection features such as desaturation (DESAT) protection.
- **Cooling system:** Cooling can be through natural convection or forced convection (air or liquid). Selecting the proper cooling is considered the primary factor that effecting the SSCB overall weight.
- **Overvoltage suppression circuit:** Implementation of protection elements (e.g., TVS, MOV or snubber networks) to limit voltage overshoot during fault interruption, lightning events or NEMP.
- **Thermal monitoring: Temperature** sensors that is embedded within the SiC modules or externally mounted on the heatsink.
- **Current sensing:** Current sensor plays the fundamental role and used for monitoring and fault detection.
- **Interface and control board:** this manages SSCB operation, monitoring, protection, and communication functions.
- **Other peripheral components** including connectors, busbars, wiring, supporting elements, enclosure. All of that is to enable the electrical connection and effective cooling.

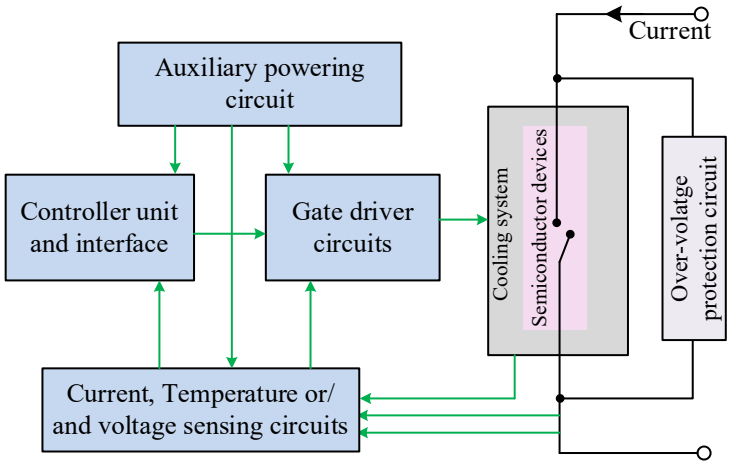


Figure 6: Block diagram of SSCB architecture showing key subsystems

3.3.2 System-level SSCB

The system-level SSCB form the switching interface between the DC-link and the components in downstream such as battery and emulator system. The electrical specifications are:

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

- For high-power up to 400 kW.
- The operating voltage range of 600 V to 1020 V DC.
- The nominal operating voltage is 830 V.
- Current rating is ~670 A (based on the minimum voltage rating)

In addition to the common BECS interface, the system-level SSCB connects to the aircraft power distribution system via the positive high-voltage bus (HVPOS) or negative high-voltage bus (HVNEG) with one input side and one output side.

Some preliminary physical characteristics have been calculated as below:

- **Interruption time:** ~10–500 µs, depending on the circuit parameters such as circuit stray inductance, current level, and the selected overvoltage clamped voltage level.
- **Approximate weight:** ~6–25 kg, depending on the selected semiconductor module, mechanical integration, and cooling method (passive or liquid-cooled design).

3.3.3 String-level SSCB

This SSCB form the switching interface between the DC-link and the battery modules.

The string SSCB is designed according to the battery module characteristics. The battery supports a high-rate continuous discharge current of 45 A (3C), and a peak discharge current of 75 A (5C) for a duration up to 30 s.

The electrical specifications are:

- The operating voltage range of 600 V to 1020 V DC.
- The nominal operating voltage is 830 V.
- Current rating is 45 A (at 3C)
- Peak current: 75 A (at 5C) for 30 s.

In addition to the common BECS interfaces, the string-level SSCB connects to the positive high-voltage bus (HVPOS) or negative high-voltage bus (HVNEG) on one side and to the battery module on the other side.

Some preliminary physical characteristics have been calculated as below:

- **Interruption time:** ~5–200 µs, depending on the circuit parameters such as circuit stray inductance, current level, and the selected overvoltage clamped voltage level.
- **Approximate weight:** ~0.5–3 kg, depending on the selected semiconductor module, mechanical integration, and cooling method (e.g., passive or liquid-cooled design).

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

4 BATTERY MANAGEMENT SYSTEM (BMS)

In MODABAT, a three-layer battery management and monitoring strategy has been adopted (Figure 7). At system level, an Energy Management System (EMS) is implemented to monitor, control, and optimize the operation and safety of the battery system. The EMS communicates with the 15 BMS-Master units, one per string, gathering information and errors from the battery string level. The BMS-Master (second layer) continuously monitors critical battery string parameters such as the battery string voltage, current, and containment temperature, ensuring operation within the defined safety limits. It also performs fault detection and state estimation functions on battery string level. In addition, the BMS-Master handles errors on battery module and battery string level and sends the information to the EMS. The Master-BMS communicates with all 10 Slave-BMS units on module level that are closest to the Li-Ion cells. Each BMS-Slave (third layer) directly acquires the battery cell data by reading 12-cell voltages and 8 temperature values, among other things that are explained in further detail later in this section.

This distributed architecture improves scalability, measurement accuracy, and system reliability, while reducing wiring complexity and enhancing modularity within the battery system.

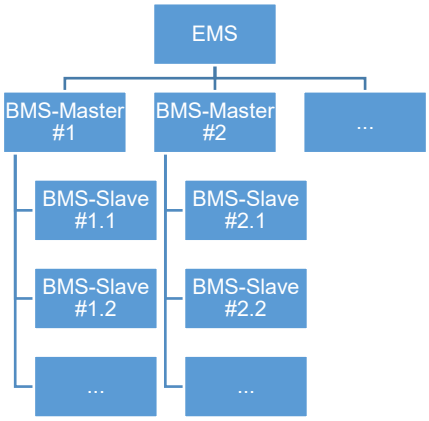


Figure 7: Three-layered battery management strategy

4.1 Energy Management System (EMS)

As shown in the system architecture, the EMS sub-system (Figure 8) is mechanically located inside the BECS enclosure; however, it is a sub-system of its own to constantly ensure safe battery system operation.

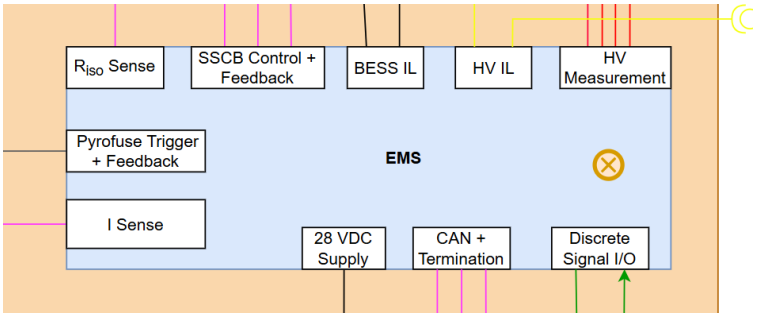


Figure 8: Block Diagram of EMS acting as control and management unit on system level

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

The key functions of EMS are noted as in Table 8.

The EMS ensures safe and efficient power distribution, supervises charging and discharging processes, and provides real-time diagnostics and protection functions. It interfaces with all relevant subsystems (i.e. BMS-Master and FADEC) to guarantee reliable operation under expected environmental and operational conditions.

The EMS is responsible for the supervision and control of the system level high-voltage (HV) power distribution and associated protection elements. This includes control of the HV+ SSCB, the HV− mechanical switch (MS), and the precharge circuit, which is used to safely energise the DC bus capacitors during system start-up and connection sequences. Furthermore, the EMS coordinates system-level protection strategies by managing switching sequences and ensuring controlled system energisation and de-energisation.

In addition, the EMS interfaces with key monitoring devices across the HV network. This includes the Insulation Monitoring Device (IMD), which continuously evaluates the insulation resistance and enables early detection of potential isolation faults. The EMS also controls the HV+ pyrofuse and receives its status feedback to identify fault activation events and support appropriate fault handling procedures. Also, the system level current measurement is acquired to support power management, protection, operational monitoring, and diagnostic functionality.

Table 8: Functions of EMS

Function	Implementation
Controls the power flow to/from the BESS (bidirectional flow)	SSCB (system-level positive pole), MS (system-level negative pole) and pre-charge switching devices are controlled by EMS via CAN signals.
Controls on/off state of various battery strings in the system	EMS communicates with the 15 BMS-Masters of the battery system (one per string) and can selectively connect/disconnect them based on SoC/SoH and potential failure detection.
Monitors system-level current value	EMS reads system-level current value in real-time via dedicated current sensor.
Detects various fault scenarios (e.g., overcurrent)	EMS sends fault-activation signals to various sources such as pyrofuse and SSCBs in case an over-current fault is triggered.
Detects HV insulation failures between the HV poles and chassis	EMS is interfaced with an IMD that constantly measures the insulation between the HV poles and chassis and shuts off all HV switches in case of fault.
Monitors cell-level diagnostic information	EMS communicates with the BMS-Masters (one per string) and receives cell voltages, temperature values, string-level current values, SoC, SoH, gas detection and various other indicators of thermal runaway.

The use of a pyrofuse is driven by the requirement for an emergency current cut-off capability in the event of a critical battery failure or hazardous operating condition. Unlike conventional protection devices, a pyrofuse is specifically designed to interrupt very high fault currents in an extremely fast and reliable manner, minimizing the risk of thermal propagation, electrical arcing, or catastrophic damage to the system.

This type of protection device operates by means of a pyrotechnic activation mechanism that is triggered when a severe fault condition is detected by the BMS or EMS. Once activated by the EMS, the pyrotechnic charge

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

mechanically breaks the internal conductor, creating a permanent and highly reliable disconnection of the high-voltage path.

Pyrofuses are typically used as a last-resort safety element in high-energy battery systems, where rapid isolation of the battery is essential to protect the equipment, surrounding systems, and personnel. Their operation is generally associated with critical events such as short circuits, severe overcurrent conditions, thermal runaway detection, crash events, or other emergency scenarios requiring immediate electrical isolation of the battery pack.

4.2 Master Battery Management System (BMS-Master)

The BMS-Master (Figure 9) is mechanically attached to the outer battery module containment and is responsible for supervising the complete battery string operation while coordinating the associated BMS-Slave units. Acting as the central control node at string-level, the BMS-Master gathers and processes battery cell information from the BMS-Slaves, which are connected through a differential, galvanically isolated daisy-chain communication. The BMS-Master controls the battery string based on the data that is acquired by the BMS-Slaves.

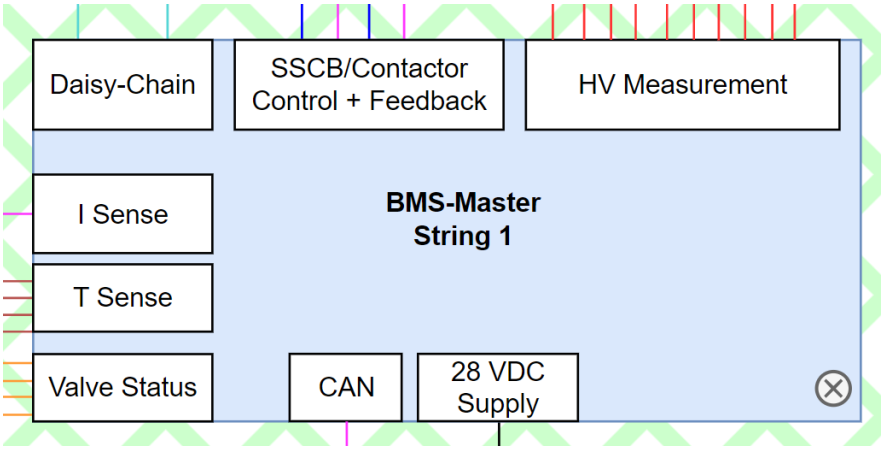


Figure 9: Block diagram of the BMS-Master acting as control and management unit on string level

The key functions of EMS are noted below in Table 9.

Table 9: Functions of BMS-Master

Function	Implementation
Controls the string power flow to/from the BECS (bidirectional flow)	SSCB (string-level positive pole), MS (string-level negative pole) are controlled by the BMS-. Control may be based on supervisory control information from EMS, or local fault-prevention measure based on cell and string level signals such as voltage, current and temperature.
Monitors string-level current value	BMS-Master reads string-level current value in real-time via dedicated current sensor.
Detects various fault scenarios	BMS-Master receives fault-activation signals from various sources such as string-level SSCB (overcurrent), EMS, and gas sensor.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Monitors cell-level diagnostic information	Each BMS-Master (one per string) receives cell voltages, temperature values from the BMS-Slaves. It calculates the battery states, such as SoC, SoH, and monitors additional sensors such as gas detection sensors and various other indicators of thermal runaway.

The BMS-Master is responsible for supervisory control, protection, and performance management at the battery string level. It operates within a distributed architecture, interfacing with lower-level sensing elements and higher-level system controllers to ensure safe, reliable, and efficient battery operation. The BMS-Master continuously monitors critical parameters such as voltage, current, and temperature, ensuring operation within the defined safety limits. It also controls the charge equalization on cell level (i.e. cell balancing), fault detection, and state estimation functions. The communication to the BMS-Slaves, responsible for battery cell data acquisition, is organized by the BMS-Master.

In addition, the BMS-Master directly controls the module power and safety elements, including the HV+ SSCB and the HV– contactor. It also monitors key operational parameters such as battery string current, containment temperature, and valve status information associated with the battery thermal runaway enclosure safety system. Furthermore, the BMS-Master receives feedback from both the HV+ fuse status line, allowing continuous supervision of protection device integrity and fault detection capabilities of each battery module. The BMS-Master also receives the status feedback from the switches (SSCB and contactor) on module level and manages communication with the EMS, transmitting consolidated battery status, diagnostics, and fault information to the upper-level control system.

The BMS-Master also incorporates sufficient processing capability to execute advanced prognostic and health-monitoring algorithms aimed at improving battery reliability, availability, and safety throughout its operational lifetime. By continuously analysing operational data such as cell voltages, temperatures, current profiles, balancing activity, gas detection events, and historical usage patterns, the BMS-Master can run prognostic models to estimate battery degradation trends and predict potential failure conditions before they occur.

These prognostic functions may include advanced estimation of State of Charge (SoC), State of Health (SoH), Remaining Useful Life (RUL), aging behaviour, thermal stress accumulation, and anomaly detection based on both real-time measurements and historical operational data. The integration of these capabilities within the BMS-Master processor enables localized and fast decision-making without relying exclusively on external systems.

This predictive approach enhances maintenance planning, improves operational safety, reduces the risk of unexpected failures, and contributes to optimized battery utilization and lifecycle management in high-reliability applications.

4.3 Slave Battery Management System (BMS-Slave)

Inside every module, each 12 serial cells are monitored by a dedicated BMS-Slave unit, which continuously monitors each individual cell voltage and up to eight temperature measurement points as shown in Figure 10.. This distributed monitoring approach enables accurate detection of abnormal operating conditions at an early stage and improves the overall safety and reliability of the battery system.

In addition to electrical and thermal supervision, the BMS-Slave incorporates safety monitoring features associated with thermal runaway detection and containment. For this purpose, the BMS-Slave is capable of detecting the presence of gases generated during the initial stages of a thermal runaway event through the use of a dedicated gas sensor. This functionality provides an additional early-warning mechanism, allowing the system to identify cell venting or decomposition events before a more severe failure develops.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Furthermore, the BMS-Slave can also monitor the status of the pressure relief valve associated with the TR venting containment system. This allows the system to determine whether the venting mechanism has been activated and provides valuable diagnostic information related to internal pressure events or containment operation.

The combination of electrical, thermal, gas, and venting supervision at subpack level significantly enhances fault detection capability, supports safer battery operation, and contributes to the mitigation and containment of thermal runaway propagation within the module.

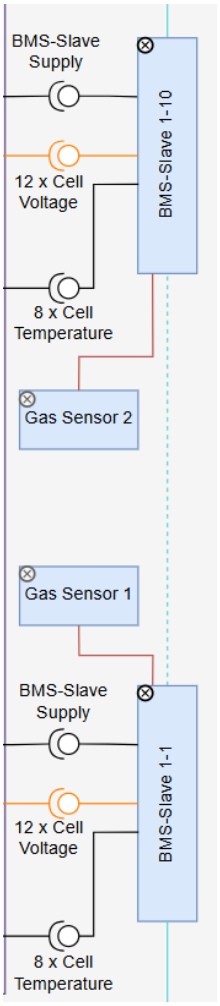


Figure 10: Block Diagram of BMS-Slave acting as monitoring unit on module level

4.4 Interface

In Table 10 below, the interfaces of BMS and EMS are defined. A CAN communication protocol has been selected for the BMS-Master and EMS communication. CAN is selected to ensure high noise immunity, deterministic behaviour, and compatibility with distributed battery management architectures typically required in high-reliability and high-voltage applications. The BMS-Slave to BMS-Master communication is established via a differential, galvanically isolated daisy-chain.

Communication strategy with aircraft is of critical importance and hence a two-tier process has been adopted: discrete I/O signals and CAN protocol. The discrete I/O interface provides fast and deterministic exchange of

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

critical control and status signals, such as system enable commands, fault indications, emergency shutdown requests, and operational interlocks. In parallel, the CAN bus communication enables the transfer of more detailed operational data and diagnostics, including system status, power availability, fault reporting, and monitoring information. This dual communication approach enhances both system robustness and functional safety by combining the simplicity and reliability of discrete signalling with the flexibility and data bandwidth provided by the CAN bus protocol.

Table 10: Interfaces of EMS and BMS (master and slave)

Interface	Connection A	Connection B	Description
Electrical			
28 V DC LV	EMS	Aircraft 28 V DC Power Net	EMS Power Supply
High Voltage Bus	EMS	High-Voltage Bus	System level SSCB, Contactor, Fuse Monitoring
Interlock Line	EMS	Battery System Connectors	Monitoring of Electrical Connector Status
Switch control	EMS	Contactor HV-	System Level Contactor Control + Feedback
Interlock Line	EMS	Battery System Connectors	Connector Monitoring
Maintenance Interlock	EMS	Position Switch	BECS Enclosure Lid Monitoring (Maintenance)
Pyrofuse Trigger	EMS	Pyrofuse	System Level Fuse Trigger
28 V DC LV	BMS-Master	Aircraft 28 V DC Power Net	BMS-Master Power Supply
High Voltage Bus	BMS-Master	High-Voltage Bus	String and Module Level SSCB, Contactor, Fuse monitoring
Switch control	BMS-Master	Module - Contactor	String and Module Level Contactor Control + Feedback
Valve System	BMS-Master	Pressure Valve	Venting System Monitoring
Cell voltage	BMS-Slave	Battery Cell	BMS-Slave Power Supply and Cell Level Voltage Monitoring

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Cell Temperature	BMS-Slave	Battery Module Temperature Sensors	Cell Level Temperature Monitoring
Gas Detection	BMS-Slave	Gas Sensor	Module Level Gas Detection
Communication			
CAN-Bus	EMS	FADEC / Aviation Control	CAN Communication to Aircraft
CAN-Bus	EMS	BMS-Master	CAN Communication to BMS
CAN-Bus	EMS	SSCB HV+	System Level SSCB Control + Feedback
CAN-Bus	EMS	Current Sensor	System Level Current Monitoring
CAN-Bus	EMS	IMD	System Level Isolation Monitoring
CAN-Bus	EMS	TMS	Communication with TMS for control and monitoring
Analog ENABLE/DISABLE Signal	EMS	FADEC	Discrete ENABLE/DISABLE Signal from Aircraft to EMS
Analog ENABLE/DISABLE Signal	EMS	BTMS	Discrete ENABLE/DISABLE Signal from EMS to BTMS
CAN-Bus	BMS-Master	SSCB Module+	Module Level SSCB Control + Feedback
CAN-Bus	BMS-Master	Current Sensor	String Level Current Monitoring
Differential Daisy-Chain	BMS-Master	BMS-Slave	BMS-Master and BMS-Slave communication
Mechanical			
Mounting Point	EMS	BECS Housing	Implementation TBD
Mounting Point	BMS-Master	Battery Module Containment	Implementation TBD

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Mounting Point	BMS-Slave	Battery Module Containment	Implementation TBD

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

5 THERMAL MANAGEMENT SYSTEM (TMS)

Figure 11 below shows the TMS coolant loop defining how the cooling fluid is circulated and monitored. The diagram presents the closed loop with the required temperature sensors, pressure sensor, pumps, filters heat exchanger, and BTMS control unit.

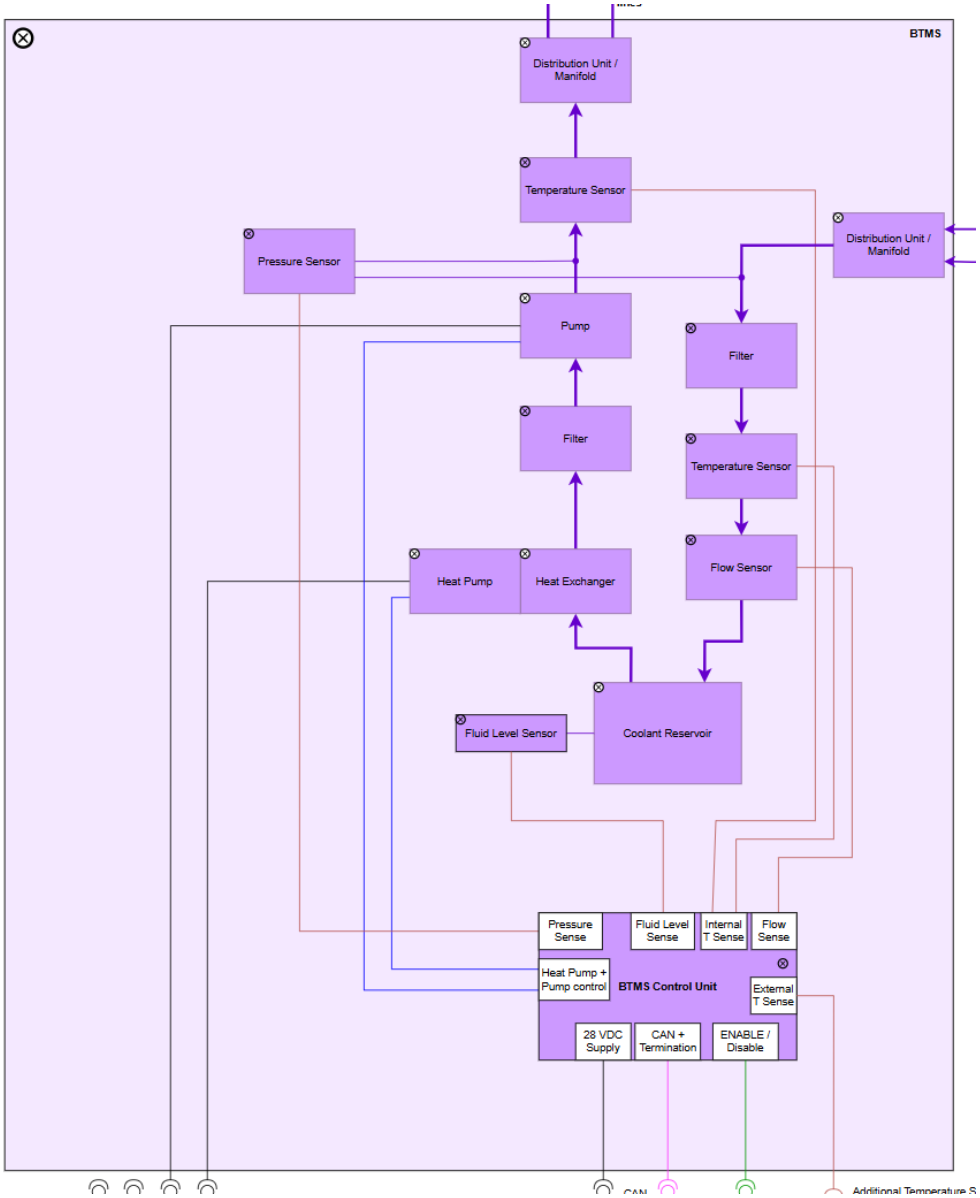


Figure 11: Block Diagram of TMS showing controller, pump, filters, HX, manifolds and sensors

5.1 Function

The TMS performs the following functions (Table 11):

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Table 11: Functions of TMS

Function	Implementation
Thermal management	The TMS manages the battery thermal state to be within safe operating limits and ensure uniform distribution of the cell temperature. This can be done by proper sequence of cooling, heating and preconditioning processes to bring cells within the required temperature range during ground and flight
Coolant system	The TMS circulates the coolant through the system using a pump. It is required to keep the cell temperatures within a module should not exceed 5ºC difference. The TMS extracts the heat from the battery cells using heat exchanger. The TMS heats the coolant when required for cold-start conditions.
Monitoring, detecting, and localization the faults	The TMS monitors the key parameters such as temperature, pressure and flow rate. Based on that, abnormal conditions, overheating, leakage and other issues can be early detected and localized.
Control and communications	The TMS controls the TMS main components such as pump and communicates with EMS to exchange component status information through CAN protocol.

The selection and placement of thermal and pressure sensors within the thermal management system (TMS) have been defined to ensure effective monitoring of cooling performance, early fault detection, and safe battery operation. The current strategy focuses primarily on temperature monitoring of the cooling fluid at key locations throughout the system. Temperature sensors are positioned at the outlet of each individual module cooling plate to detect abnormal thermal behaviour, such as the onset of thermal runaway, which would manifest as a localised temperature increase. Additional sensing is implemented downstream of the TMS outlet manifold, prior to the heat exchanger (HX), to assess the required level of cooling to be applied. Further temperature measurement is carried out after the heat exchanger and before the coolant reservoir to verify that the fluid has been cooled to the desired temperature. A sensor is also included within the coolant reservoir itself, where a heater is installed to support cold-start operation; this allows monitoring of fluid heating and ensures appropriate temperature rise under low-temperature conditions. Finally, temperature sensing is considered downstream of the pump to account for any temperature increase induced by pump operation. Added to that, the TMS has communication with the EMS to exchange information as temperatures, errors and status.

With respect to pressure monitoring, the current concept includes the possible placement of a pressure sensor downstream of the pump, although its necessity is still under evaluation. Instead, the primary strategy for hydraulic integrity monitoring relies on flow sensors located at the inlet and outlet of each cooling plate. By comparing flow rates across these points, discrepancies can be identified, enabling the detection and localisation of potential leakages within the cooling circuit.

The cooling loop architecture is configured to ensure efficient thermal management and uniform temperature distribution across all battery modules. The coolant circuit begins at the reservoir (deposit) equipped with a heater, which supports both normal operation and cold-start conditions. From the reservoir, the coolant is driven by the pump, after which it enters an inlet manifold where the flow is distributed in parallel across the individual module cooling branches. Each branch consists of a module inlet valve, cooling plate, and module outlet valve, allowing controlled flow through each module. The coolant from all branches is then collected in the outlet manifold, before passing through the heat exchanger (HX) where excess heat is removed, and finally returning to the reservoir to complete the cycle.

During specific operating modes, such as system warm-up or controlled heating phases, a bypass line is implemented downstream of the pump, allowing coolant recirculation directly back to the reservoir. This

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

configuration ensures that the fluid can be heated to the desired temperature before being distributed to the cooling plates, thereby preventing the introduction of cold coolant into the battery during cold-start conditions.

A parallel flow configuration is adopted for the module cooling plates to maintain consistent thermal conditions across all battery modules. In contrast to a series configuration, where coolant temperature would progressively increase as it passes through each module, parallel distribution ensures that each module receives coolant at approximately the same temperature. This maintains a higher and more uniform temperature gradient between the battery cells and the coolant, resulting in more effective heat transfer. Consequently, this approach reduces temperature imbalances between modules, improving overall system performance, consistency, and battery lifespan.

5.2 Interface

The TMS interface is summarised below (Table 12).

Table 12: Interfaces of TMS

Interface	Connection A	Connection B	Description
Electrical			
115 VDC	TMS	Aircraft 115 V DC power net	High power supply to drive the TMS pump
28 VDC (LV supply)	TMS	Aircraft 28 V DC power net	28 VDC power supply from aircraft to energise the control systems in TMS. This LV power is required for control interface, sensing circuits, and communications.
Interlock Line	TMS	EMS	Monitoring Electrical Connector Status
Communication			
CAN-Bus	TMS	EMS	Temperatures, errors, status information via CAN protocol.
Mechanical			
Mounting Point	TMS	Aircraft Fuselage	Implementation TBD
Thermal			
BTMS Piping	TMS	Battery Pack	Coolant inlet and outlet between TMS and battery pack. This includes manifolds, connectors and the required pipes/hoses.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

6 BATTERY SYSTEM ARCHITECTURE MODIFICATIONS FOR WEIGHT OPTIMISATION

In this section, possible modifications for an overall battery system weight optimization are discussed. Based on the targeted use-case and the WP1 requirements definition, the battery system architecture, presented in section 1.3, is developed to allow manual installation and handling of individual battery modules. As the battery module voltage exceeds 60 V DC, additional protective measures for touch protection including an electrical isolation of the battery poles via switches are required.

In the case of an automated battery system assembly and manufacturing process, certain optimizations can be implemented. For the following optimizations, the following assumptions are considered:

- Battery module handling, assembly, and integration are performed exclusively by automated equipment or trained service personnel under controlled conditions.
- The aircraft integration of the battery pack requires no handling of individual battery modules.
- During normal operation and maintenance individual battery modules are not replaced.
- No manual access to live conductive parts of individual battery modules is possible during normal operation or battery system assembly.
- Touch protection is always ensured at battery pack and system level.
- Fault detection and disconnection are implemented on string level, not on module level.
- String-level protection devices remain in place to isolate faulty strings in case of overcurrent, cell over- and undervoltage, cell overtemperature, short circuit, or insulation failure.

Under these assumptions, module-level switches can be omitted. Consequently, protection and fault isolation are shifted from module level to string level, resulting in reduced component count, lower system weight, simplified module design. This mainly affects the numbers of switches for each individual module per string. Following this approach, each battery string includes a single SSCB at the HV+ pole for fast disconnection combined with a single mechanical contactor on the HV- pole for galvanic isolation of the string. Also, the number of fuses can be reduced to one per string.

As a result, these measures also reduce the number of HV-measurements on string level, as less switches and fuses must be monitored during operation. This would reduce both the overall wiring complexity and string weight.

In Figure 12, a simplified architecture of the battery string is depicted. Individual cell voltage measurement, temperature monitoring, string current measurement, gas detection, and valve status monitoring are still valid.

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

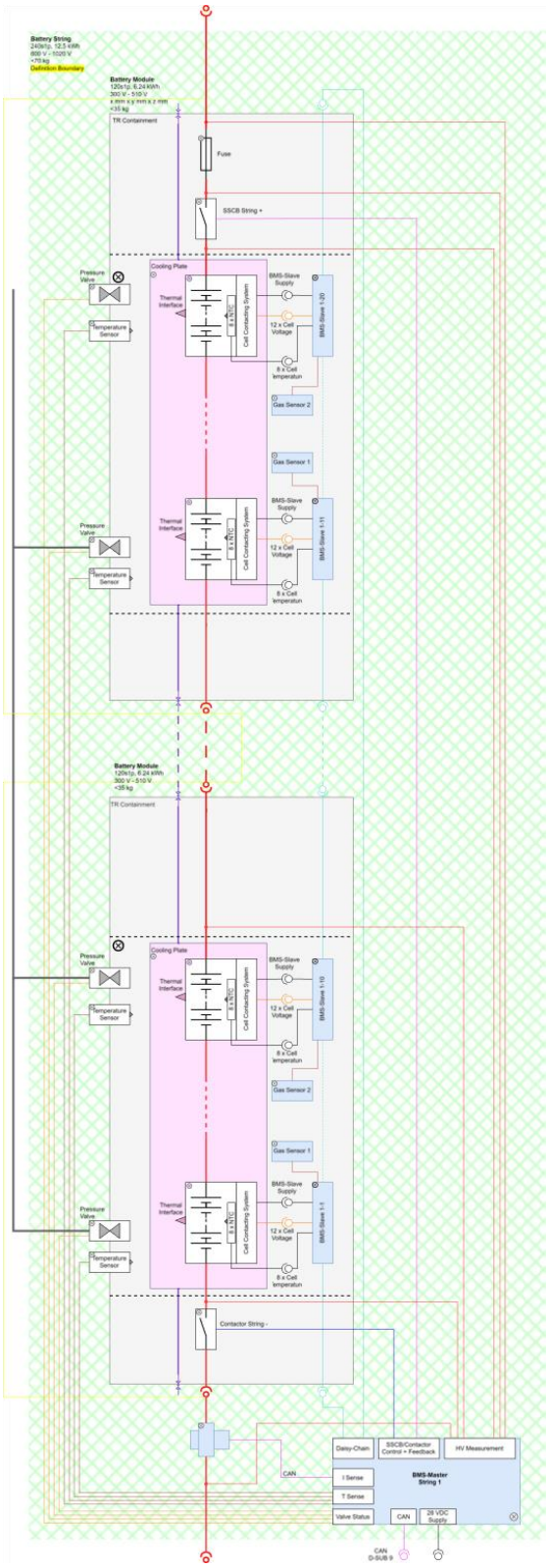


Figure 12 Simplified Battery String Architecture for Automated Assembly and Installation

CLEAN AVIATION

Funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101251224. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.