TULIPS

Demonstrating lower polluting solutions for sustainable airports across Europe

GRANT AGREEMENT NO. 101036996

START DATE 01.01.2022 END DATE 31.12.2025

D2.3

Functional modular battery farm and simulator for airsides distributed charging

Public

DUE DATE OF DELIVERABLE: 31/12/2023

SUBMISSION DATE 26/03/2024

Pipistrel Vertical Solutions d.o.o., Slovenia

REVISION	ORGANIZATION & PERSON	DATE
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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101036996.

I. DELIVERABLE INFORMATION

Deliverable Number	D2.3
Deliverable Title	Functional modular battery farm and simulator for airsides distributed charging
Work Package	WP 2
Date of Issue	26/03/2024
Version Number	V1.0
Nature of Deliverable	Report
Dissemination Level (Public / Confidential)	Public

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Keywords	Battery farm, charging simulator, modular charging system

Abstract

This report offers a detailed overview of development and production of the modular charging system for future electric aircraft. It briefly explores each subsystem, highlighting the components used in the demo. Additionally, it discusses future prospects for large-scale electric aircraft charging at airports.

II. DOCUMENT HISTORY

Date	Version	Modified by	Remarks
04-12-2023	0.1	PVS, Akshayan Sudharshan	Initial draft version
22/12/2023	1.0	PVS, Akshayan Sudharshan	Resvolved comments from NLR and SNBV. Briefly discussed about the fire test, including additional improvements to the content

EXECUTIVE SUMMARY

In TULIPS, specifically in Work package 2, three innovative demonstrations are performed by various partners in the consortium. The modular charging system is one of the 3 demos which is developed by the Pipistrel Vertical Solutions, located in Slovenia. The modular charging system is capable of simulating battery charging for the various future aircraft categories. Instead of using a real-world electric aircraft, such as Pipistrel Velis Electro, the modular charging system utilizes several Velis Electro batteries with hundreds of kilowatt-hours of energy. This energy storage system, also known as propulsion batteries, are certified by EASA (European Aviation Safety Agency) which ensures the safety and reliability of the modular charging system. The focus of this demonstration is to effectively perform the charging and discharging of the propulsion batteries. In addition, the modular charging system contains system interface between the batteries and the operator allowing the modules to be configured in series and parallel to derive the voltage and energy needed to represent various future battery electric and/or hybrid electric aircraft propulsion batteries. To charge the propulsion batteries, four proprietary Velis Electro chargers are used simultaneously with the desired power. The batteries are incorporated inside the standard ISO shipping container together with other essential components such as mechanical constructions, cooling system and, safety components to maintain the safety and the reliability of the propulsion batteries as well as the modular charging system.

This report provides information regarding the demo development of the modular charging system. In addition, the future perspective of the different charging technologies will be discussed.

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VI. LIST OF ACRONYMS

Acronym	Meaning
A	Ampere
AC	Alternating Current
BMS	Battery Management System
DPDT	Double Pole Double Throw
DPST	Double Pole Single Throw
EA	Electric Aircraft
EASA	European Aviation Safety Agency
GA	General Assembly
KOM	Kick Off Meeting
LSA	Light Sport Aircraft
OEM	Original Equipment Manufacture
PCB	Printed Circuit Board
PLC	Programable Logic Controller
SJB/BJB	Small/Big Junction Box
SPDT	Single Pole Double Throw
TBD	To Be Defined
TC	Type Certificate
VDC	Voltage – Direct Current
WP	Work Package

1 Introduction

The charging infrastructure needs to be developed and improved at airside to accelerate the utilization of battery powered electric as well as hybrid-electric aircraft. Currently, all airport system lack compatibility with varying electric aircraft voltages. While all electric and hybrid-electric aircraft, particularly those powered by batteries and hydrogen, currently face technological deficiencies, such as limited range and challenges regarding energy storage, their efficiency and environmental benefits are expected to drive a significant increase in the number of flights in the future. Rapidly emerging technologies such as high energy density lithium-ion batteries and solid-state batteries facilitates the development of such aircraft for the aeronautical applications. Therefore, an effective charging process is needed which aims to standardize the future electric and hybrid-electric aircraft while eliminating the logistical and financial challenges.

In order to realize the concept of charging multiple electric aircraft in a single point, a concept study and a preliminary design is performed in TULIPS, specifically in Work Package (WP) 2. Utilizing aircraft such as Pipistrel Velis Electro will not be cost effective and realistic to simulate charging of several types of propulsion batteries. In addition, to perform the charging, tremendous infrastructure is anticipated. Therefore, a demo is performed at Rotterdam The Hague Airport and Oslo Airport to show a modular battery charging concept that facilitates charging of future battery technology for various types of electric aircraft. The goal of the demo is to perform the charging/discharging of a mobile battery bank, with a capacity of hundreds of kWh and voltage range up to +1.5kV. The system must be capable of de-risk airport charging infrastructure investments by offering a scalable solution of charging future electric aircraft. To achieve the goal, a universal, voltage agnostic charging hardware will be developed and produced by Pipistrel Vertical Solutions. By using an aerospace certified propulsion battery, the charging process is simplified. This allows the consortium members to generate the identical outcome without impacting the infrastructure. In addition, the cost to perform such activity will be reduced.

This report is structured as follows. Chapter 2 describes the overall design of the modular charging system and provides technical details of the system itself. An insight of the future perspective of charging infrastructure is given in Chapter 3. Chapter 4 and 5 gives the conclusion and recommendations, respectively.

2 Modular charging system development

In this section, the overall design and the development of the modular charging system is discussed.

2.1 Requirements specification

A set of requirements are established to verify the functionality of the modular charging system. The requirements are separated into technical requirements and functional requirements. The modular charging system is divided into several sub-systems. Each sub-system consists of several components to provide the functionality necessary to simulate charging of various electric and hybrid electric aircraft configurations. Therefore, the technical and functional requirements are further divided into sub-system level in-order to differentiate the requirements. The technical and functional requirements are further divided into low level requirements that can be decomposed.

- Mechanical requirements
- Electrical requirements
- Thermal requirements
- Hardware (HW)/ Software (SW) requirements
- Safety requirements

To track and trace the requirement specifications of each subsystem, a compliance matrix is made. The compliance matrix contains the high-level requirements of each sub-system of the modular charging system.

2.1.1 The sub-systems of the modular charging system

The modular charging system is divided into four sub-systems which in combination with provide the functionality for the system. These sub-systems are propulsion batteries, electrical system, charging system, and command and control system. The modular charging system is designed to be easily transported to different locations seamlessly. To facilitate the mobility of the system the sub-systems are placed inside a cargo container which can be easily transported using the cargo-ship or truck.

2.1.1.1 Propulsion batteries

The modular charging system requires hundreds of kilowatt hours of capacity in order to simulate the charging of various electric powered aircraft. To facilitate the cost-effective part of the demo development the modular charging system uses the same energy source which is used in the Velis Electro aircraft. The Velis Electro battery is certified by the EASA, and therefore, is reliable choice to use in the modular charging system. This reduces the cost that is required to perform the R&D (research and development) and the costs that is required to certify the batteries.

Each propulsion battery consists of 11 kWh of energy capacity. In total 32 aerospace certified propulsion batteries will be used to achieve the total capacity of 352 kWh. These propulsion batteries are repurposed that are previously utilized in old Velis Electro aircraft. The batteries also include the Battery Management System (BMS) which provides functionalities such as monitoring the voltage and temperature to ensure the safety and the reliability of the system during the charging and discharging process.

2.1.1.2 Electrical system

The electrical system consists of sub-system that is crucial to perform the charging and the discharging of the propulsion batteries. This includes several junction boxes, HV cables and connectors, and the physical hardware to configure the propulsion batteries prior to the charging and discharging process.

2.1.1.3 Charging architecture

The charging architecture also consists of several sub-systems to provide energy required to charge the propulsion batteries. The modular charging system utilizes the Pipistrel proprietary charging standards which is used in all low-end Part 23 Pipistrel electric powered aircraft. The commercial name of this charger is called Skycharge with the suffix M20. The proprietary charging system is illustrated in Figure 1. The Skycharge M20 is capable of providing maximum output power of 20 kW. The charger itself is mobile thus the handling is much convenient.

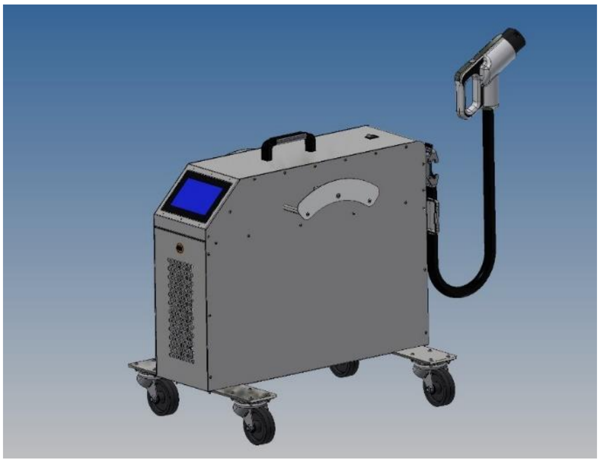

Figure 1 Skycharge M20

The modular charging system is designed to connect four Skycharge M20 in parallel to the propulsion batteries. This allows the system to be charged at the maximum power of the 80 kW since each M20 charger is capable of providing maximum power of 20 kW. The Table 1 provides the specification for the Skycharge M20 mobile battery charger.

Table 1 Skycharge M20 specification

Input	
Input voltage	130 Vac – 440 Vac
Recommended fuse	32A
Output	
Output voltage	150 Vdc – 440 Vdc
Maximum output current	60A
Maximum output power	20kW
Mechanical	
Dimensions	823mm * 530mm * 767mm
Weight	71kg

To connect four the skychargeM20 at the airports, the power grid at the airside needs to be modified if the allowable maximum power of the grid is less than 80 kW. As given in Table 1, each charger requires 32A fuse to connect to the chargers to the power grid. The charger must be connected to the power grid by means of an IEC 60309 three-phase 380 VAC connection. Therefore, 4 receptacles are required to connect the IEC 60309 three-phase plugs at the airports. Moreover, the chargers are not waterproof. To prevent the chargers from damaging in case of heavy precipitation, the chargers can be placed under a roof. However, this is not essential since the chargers can be placed inside the shipping container which resists water splashes during this condition.

2.1.1.4 Command and control system

The propulsion batteries and the charger architecture function together with the system controller of the modular charging system to perform the test scenarios defined by the operators. The command-and-control system uses PLC (Programmable Logic Control) to connect the propulsion batteries in series and/or parallel. This allows the operators to be more flexible when it comes to charging – offering possibility to reconfigure batteries from original configuration (on the aircraft) to simpler one, if necessary. The PLC used in the demonstrator version (SIEMENS S7-1200) can be expanded easily in terms of number of inputs/outputs, allowing it to include more batteries. Once batteries and chargers are connected to junction boxes, PLC will get information about each battery. connect them to specific configuration on level of one module, charge them, and reconfigure back to the original setup.

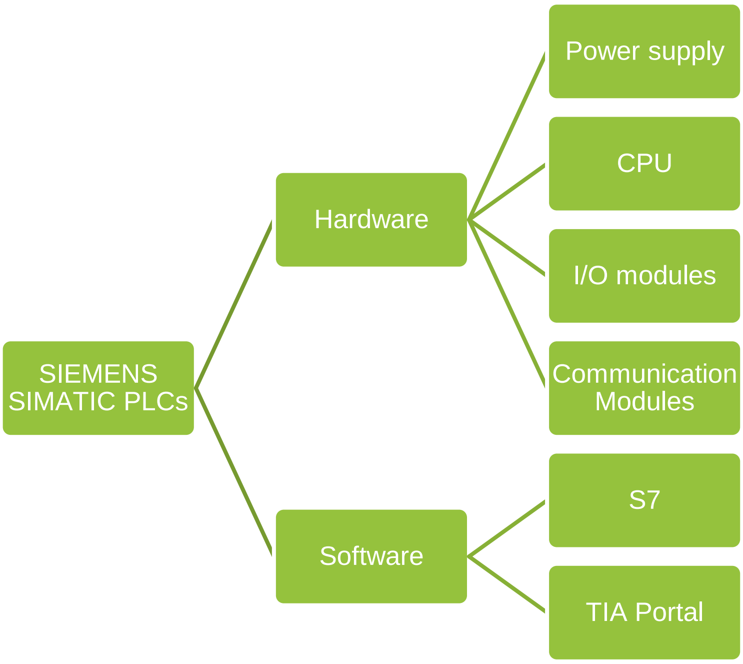

Figure 2 overview of the command-and-control system with SIEMENS SIMATIC PLCs

To achieve multiple voltage level and capacity of the modular charging system, SIEMENS SIMATIC S7 1200 Programmable Logic Unit (PLC) is used. SIEMENS provides many PLC units that can be used to control and automate many systems seamlessly. It is possible to attach I/O modules to the PLC in order to extend the number of I/O and connect additional batteries to the PLC through the junction box. The modules consist of many analog and digital inputs and outputs that can be used to control the system components. Voltage supply of 24Vdc for the PLC is also SIEMENS product – PM 70W, connected to 240V (AC). PLC is further connected to PN/CAN LINK, which is a communication gateway and allows connection of SIMATIC controllers to the CAN fieldbus over PROFINET. This way, with PROFINET cable, PLC is indirectly connected to PC (laptop), where TIA portal is installed and used for programming and deployment of program to PLC.

In order to perform specific control logic, TIA portal v18 is used for configuring, programming, testing, and diagnosing the controller. Software can also be used to have an interface between the PLC and the operator using the HMI (Human-Machine Interface) This allows the operator to easily configure the devices that are connected to the PLC with the help of external device such as, personal computer.

2.2 System architecture

In this section, a brief description of the system architecture of the modular charging system is given. This includes the complete electrical architecture with the related hardware, software and safety features.

The modular battery charging system consists of two types of junction box – small and big junction box, charging and discharging port. In small junction box, multiple aircraft, whose batteries have maximum voltage 400 Vdc (nominal voltage is 345 Vdc), can be connected either in series or parallel. This way is formed one *module,* whose voltage is within range 345 Vdc to 1600 Vdc, meaning that module can contain one to four batteries. Maximum eight of such modules can be charged through the HVDC bus in big junction box, if they are connected in parallel, or each module can be charged independently when connected to the charging port. Charging port allows four Velis Electro certified chargers – Skycharge M20 to be connected, while discharging is TBD. An overview of the system architecture is shown in Figure 3. Please note this overview excludes the charging architecture.

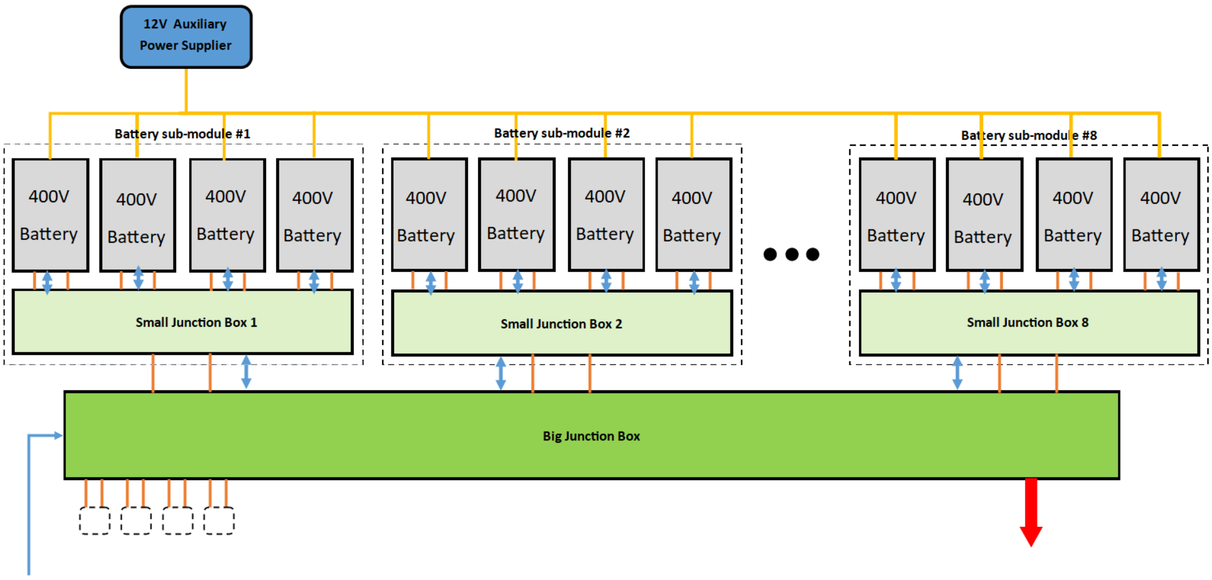

Figure 3 Overview of the Modular Charging System architecture

2.2.1 EASA certified propulsion batteries

To simulate multiple aircraft propulsion batteries charging, the modular charging system incorporates 32 aerospace certified batteries. In the following section, a brief overview of the propulsion battery that is provided.

The Velis Electro is the world's first electric powered aircraft to receive Type Certificate (TC) from the European Aviation Safety Agency (EASA). With an endurance of 1 hour including the reserve time, the two-seater propeller driven aircraft is the Velis Electro is one of the efficient aircraft in Light Sport Aircraft (LSA) category. Each Velis Electro module consist of 96 of these cells in series and 12 in parallel. In total, each pack consists of 1152 cylindrical cells. The battery operates to the voltage of nominal voltage of 345 VDC by configuring 96 cells in series. The Velis Electro battery is capable of providing maximum continuous power of 40 kW.

The Velis Electro uses primary the cylindrical form factor cells, which is well-known for the ease of manufacturability and relatively low cost in production. In addition to the cells, the propulsion battery consists of several components which ensures the reliability of the battery functions. One of the main components is the Battery Management System (BMS). The BMS is the main PCB (Printed Circuit Board) that controls and monitors the state and the health of the propulsion battery. Moreover, the BMS also provides the safety features for the propulsion battery. For example, if a thermal runaway occurs the BMS performs the appropriate steps to prevent the catastrophic failure of the aircraft. The propulsion battery also consists the enclosure and other mechanical components to support the structural integrity.

As explained in the previous, the Velis Electro battery incorporates several cells in series to derive 345 VDC and the rated capacity of 11 kWh at 23 ℃ and 20A of discharge rate. The battery is capable of providing a maximum continuous discharge power of 40 kW. Table below contains the brief specification of the Velis Electro propulsion battery system.

Table 2 - Velis Electro battery specification

Parameter	Value
Minimum voltage	260 VDC
Maximum voltage	~400VDC
Maximum discharge current	120A
Nominal operating temperature range	-0℃ - 60℃
Recommended temperature range for storage	-0℃ - 30℃
Allowable SOC range for normal operating conditions	30% – 80%
External dimensions	546 x 265 x 375 mm

The battery incorporates two 135A rated contactors to prevent internal failure. Moreover, the thermal type main HV fuse prevents overcurrent conditions of the battery stacks. Using current sensors, the modular charging system is actively protected to detect any over current conditions, thus provides additional layer of protection. The active, passive safety features of the Modular charging system is briefly elaborated in the Section 2.2.5.

2.2.2 Electrical architecture

Junction box, referring to whether the small or big, is equipped with relays to provide flexibility in terms of battery connection in one module or modules to charging port.

Each battery has its own SPDT relay (level 1 in Figure 9), making switching from series to parallel possible. Furthermore, each combination of two batteries (series or parallel) can be combined with another group of two – forming one module that consists of maximum 4 batteries. Additional SPDT relay (level 2 in Figure 9) is necessary to accomplish this. As mentioned, voltage level of one module can be in range from 345 V (in case of parallel connection of four batteries) to no more than 1600 V (in case of series connection of four batteries). Eight of such modules can be connected to the big junction box, where it is possible to charge them as independent modules or to connect them in parallel and charge through HVDC bus. Switching from independent to parallel charging option is done with DPDT relays (Figure 10). Even though batteries have their own BMS, which provides internal protection (for overcurrent, temperature, overvoltage, undervoltage...), each module of batteries will have current measuring device, that will report measurements to Programable Logic Control unit. This current sensor will be connected to PLC with analog input device, without any amplifiers needed in that case. Relays dedicated to one module of batteries will be placed in small junction box (SJB) as in Figure 9, which furthermore will be connected independently or in parallel with other modules in big junction box (BJB) as in Figure 10. All relays are governed by PLC (big junction box controller), which will be informed about each module’s current, as well as currents of all modules which are connected in parallel, through respective sensors as explained. Furthermore, coil of each relay is triggered by PLCs 12V or 24V control signal. Level 1 relays' contacts must be rated for maximum charging current of 40 A. Relays' contacts at level 2 have to handle currents from 40 A (in case of series connection) up to 160 A (in case of parallel connection). Finally, contacts of DPDT relay on HV bus must be rated for maximum current 1280 A, when all of eight modules are charged in parallel.

Modules in parallel are connected to HVDC bus and charged simultaneously, with a priori elimination of disbalance in modules. This means that parallel connection demands equal voltage of each battery (+/- 2V for Velis Electro batteries), resulting in charging the battery/module with lowest voltage (SOC can be compared as well) to the voltage level of second least charged battery/module. Then, these are connected in parallel and charged to the next lowest voltage level of battery/module until charged - fully or rest state, if specified so.

2.2.3 Charging architecture

In the modular charging demo, the proprietary chargers of the Pipistrel are utilized to charge the propulsion batteries. In this section, a brief description is provided about the Skycharge M20.

The Skycharge is the mobile charger primarily used to charge the Velis Electro aircraft. The rated capacity of the Velis Electro battery is roughly 20 kWh. Since, the Skycharge can provide up to 20 kW power technically the Velis Electro can fully charge in 1 hours. However, during the charger optimizes and trades between charging time, ambient temperature robustness and battery system lifetime. Therefore, the charging time will be not constant. Together with the system controller, the charger can provide various current values to charge the Velis Electro battery, depending on the environment conditions such as ambient temperature. As mentioned in previous section, 32 aerospace propulsion batteries are utilized to achieve simultaneous charging of Velis Electro and charging various types of electric powered aircraft in a single point. To charge the 32 batteries, 4 Skycharge M20 chargers is used. Therefore, in total, the modular charging system is capable of charging each battery around 4 hours.

The GB/T charge port is equipped with the Skycharge M20. At the time of the development, there was no standardization in aviation regarding the charging port. Therefore, the charge port is derived from the automotive industry standards to be compatible within other Pipistrel aircraft such as Thaurus Electro. The charging plug is shown in the Figure 4. The compatible charging socket for the GB/T charge port is the standard IEC62196 Type III. These ports are located on inside the shipping container.

Figure 4 The GB/T charging plug used by Pipistrel

2.2.4 Mechanical and thermal design considerations

To ensure the structural integrity of the propulsion batteries several aluminium extrusion profiles are used together with the related fasteners. Using these components, the propulsion batteries can be easily assembled and disassembled inside the shipping container. A CAD (Computer Aided Design) overview is given in Figure 5. As illustrated in Figure 5, the batteries are placed inside a 20ft standard shipping container. This allows the system to be transported easily to the desired locations. In addition, the container protects the modular charging system components from the ambient environmental conditions. The dimensions of the 20ft standard container are provided in Table 3. A detailed technical drawing of the overall system is provided in Appendix E:.

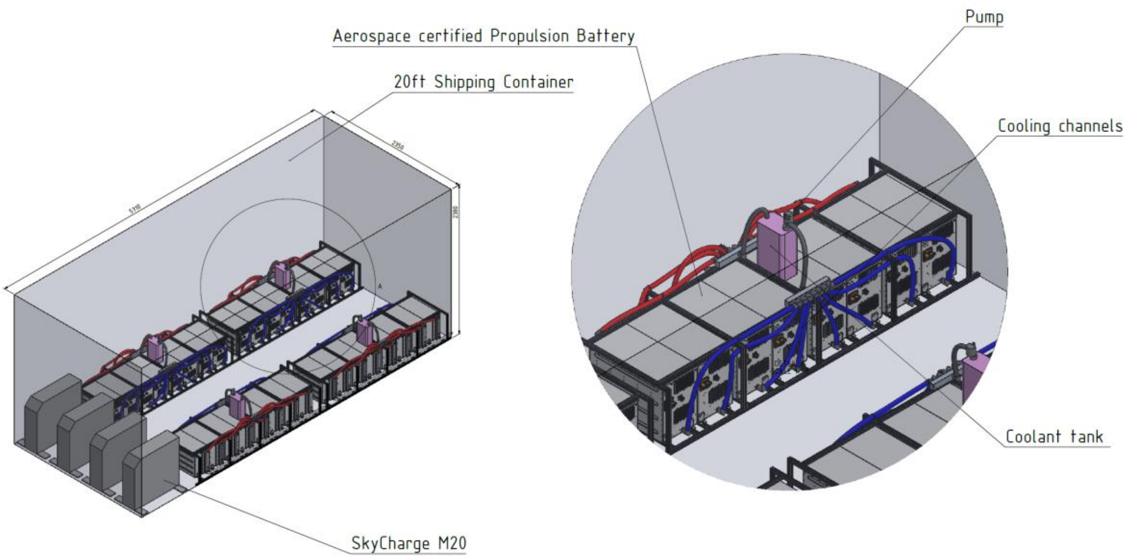

Figure 5 Technical drawing overview of the Modular Charging System

Table 3 20ft shipping container data

Parameter	Value	Unit
Maximum external dimension L x W x H*	7,5 x 2,50 x 2,60	m
Volume capacity	33,10	m^3
Empty weight	2200	kg
Load capacity	27800	kg
Total estimated weight	6500	kg

**Maximum external dimension includes the total length with door open on one side to facilitate input cables*

An overview of the single unit which consists of 8 propulsion batteries including the cooling channels with single reservoir and the heat exchanger is described in this section. Since each module is charged around 2,5 kW power, the heat dissipation during the demo will be lower. However, the ambient temperature will greatly influence the performance of the battery charging. Under the direct sunlight conditions, the inner temperature of the shipping container might reach above 60℃. Therefore, the active cooling is necessary during the charging phase. By reducing the discharge time, the current draw of the battery will increase which requires cooling of the battery module.

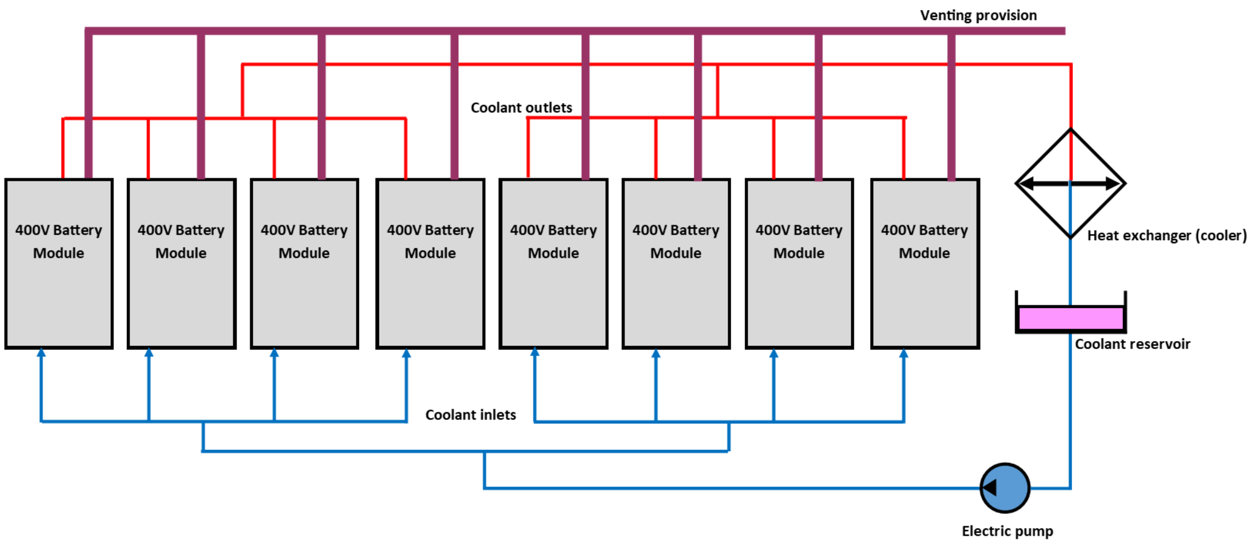

Figure 6 Thermal design architecture of the single unit battery pack

In modular charging system, the cooling system in the modular charging system is arranged in each 8 propulsion batteries.

The coolant hoses interconnect the main coolant splitter and the inlet and the outlet of the propulsion battery module cooling channels.

- Air Comprime 20 bar compressed air hose (Inner diameter:16 mm, wall thickness 3.5 mm)
- NORMAQUICK PS3 Quick Connector NW 12 - 90 degrees
- Norma FBS 19 spring clamps
- Coolant reservoir
- Pump (Bosch)

2.2.5 Safety features

In this part, the safety aspects of the modular charging system are briefly provided. To ensure the safety of the modular charging system operations. The main safety feature is that the battery modules are able to be disconnect itself when the abnormal condition is detected by the BMS.

2.2.5.1 Active protection mechanism

The modular charging system needs to be reliable and safe while performing the demo since the demo is performed at the airfield. The system contains active as well as passive protection features to prevent unexpected failure and to keep the system safe during the operations.

The active protection features are primarily performed by the Battery Management System (BMS). Some of the features are given below:

- Overvoltage protection
- Undervoltage protection
- Protection against overtemperature
- Cell balancing

On top of these protection features the battery is capable of self-test to validate the system during start up.

2.2.5.2 Passive protection mechanism

BMS thermal runaway protection has been incorporated in the Velis Electro propulsion batteries. Each battery module consists of venting provision with a membrane attached to the enclosure. During normal operating conditions, the membrane will remain sealed and prevents the dust and other foreign objects from entering the enclosure. In the event of thermal runaway, the membrane will be ruptured due to increasing pressure and the smoke and toxic gases can be released safely to the outside environment.

2.2.5.3 Protections in modular charging system

On top of the active projection features from the BMS, the propulsion batteries also contain passive protection features to prevent the system to get into the catastrophic failure. This allows to switch the relays safely with proper synchronization.

Additional protection features of the Modular charging system is provided below.

- Thermal runaway
- External short circuit
- Short circuit of a cell
- High Intensity Radio Frequency susceptibility
- Isolation resistance
- Dielectric strength
- Temperature distribution
- BMS accelerated aging
- Current distribution

Figure 7 current sensor used to protect the batteries from over-current situation.

This protection is implemented together with the command-and-control system using PLCs to act as a fail-safe system. The current sensors not only allow to trigger the relays but also to safely disconnect the battery in the event of a failure which prevents other battery to be failed in this scenario.

3 Proof of function

By the time of writing this report, the standardization of the charging is still under progression. The SAE international is the world's leading authority in mobile standards development. Specifically, for the light electric aircraft, the connection set of conductive charging (AS6968) which establishes the design and minimum performance requirements has a potential use case. The international technical committee on aviation charging. SEA AE-7D plays a crucial role in addressing the limitations and challenges in aviation charging. However, it encounters hurdles in creating universal standards that cater to the diverse and evolving needs of electric aircraft. The SAE AE-7D's efforts are focused on harmonizing charging protocols and connectors, but they must contend with rapidly advancing battery technologies and varying voltage requirement. The (Original Equipment Manufacturers) use the automotive standards such as IEC 61851-1(General requirements) for the charging elements that interconnects the Electric Vehicle (EV), charging station and communication protocols. The standards for the DC fast charging covered in IEC 61851-23. In this chapter, the clarification and the proof of function of the Modular charging is briefly discussed.

3.1 Battery farm

As mentioned, one of the tree aspects of charging infrastructure is the charging interface. The charging interface consists of a plug-receptable combination. Based on the rated maximum charge voltage and charging current values the appropriate charging connector is chosen. In automotive several charging connectors are used across the globe. Figure 8 illustrates these chargers with cutout figures with their related regions. A brief explanation of each charging types is given in the following section.

Figure 8 Various charge ports available widely across the globe

Depending on the required charging power, the charging types can be categorized. The AC (Alternating Current) charging, also referred to as Level 1 charging system offers low charging power. In case of DC (Direct Current) charging, the maximum charging power can be much higher than 100 kW. The current types allow to charge up to 350 kW.

3.2 Future-scale battery simulator

As discussed in the previous section, the aviation sector faces a prominent scenario in adopting the standards of the conductive charging system. The current rated supply voltage for the AC charging system is 1000 V AC. The rated supply voltage for the DC charging system is 1500 V DC. In comparison, the majority of the aviation OEM charging system adopts either 400 VDC or 800 VDC charging capabilities.

To create a compatible system where from aircraft side multiple range of voltages are accepted, a unique architecture needs to be designed for the propulsion battery system. From the charging architecture perspective, each charger can incorporate multiple only a certain range of rated voltage. For example, the Velis Electro has its own proprietary charging architecture. The Pipistrel M20 Skycharge is rated up to 440 VDC since Velis electro incorporates 400 VDC propulsion battery system. However, the charger is only compatible with the 400 VDC propulsion battery system. Due to the voltage discrepancy, the 400 VDC chargers are not compatible with 800 VDC and +1500 VDC propulsion batteries. Therefore, the modular charging system is designed to utilize the Velis Electro batteries to simulate a system that represents aircraft propulsion battery architecture along Sky Charge M20, which provides the power to charge these batteries. In total, 32 Velis Electro batteries are placed inside the container that represents aircraft.

3.2.1 Test locations

The demo 2.3 is planned to be performed in two airports. The initial demo is expected to take place at Rotterdam the Hague Airport (RTHA) located in The Netherlands. In terms of operational traffic, RTHA considered to be medium to high. In contrast, the demo is also performed in Oslo to study the impact on large scale charging in high volume air traffic airports.

3.2.2 Test scenarios

Sustainable aviation can be further improved by designing light weight and efficient aircraft. The two main types of aircraft configurations are all-electric and hybrid electric aircraft. The Modular charging system can charge multiple aircraft propulsion batteries in a single point. In summary, the universal, voltage agnostic charging hardware simulates Battery Electric Aircraft (BEA), Hybrid Electric Aircraft (HEA) and, Electrical Vertical Take-off & Landing (eVTOL) which represents the real work scenarios such as, simultaneous charging of multiple Velis Electro (16 x 20 kWh battery), eVTOL charging for Urban Air Mobility application, charging of 19-seater commuter aircraft, respectively. An overview of the representative charging scenarios is shown in Table 4.

Table 4 Representative charging scenarios for future aircraft

Representative scenario	Voltage level	Real world application
Simultaneous charging of multiple 20 kWh batteries	400 V	Simultaneous charging of Velis Electro

Charging of single 200 kWh battery with dual charging system	800 V	eVTOL charging for Urban Air Mobility application
Charging of single 150 kWh battery with dual charging system	1,5+ kV	Charging of 19-seater commuter aircraft (HEA)

3.2.3 Test plan

To systematically execute the demo a test plan is established by utilizing systems engineering approach. The modular charging system demo test plan is given in Appendix C:.

3.2.4 Battery fire test

To conclude the demonstration of the Modular Charging System, a vital assessment will be conducted to test the system's thermal resilience. This involves exposing the modular charging system propulsion batteries to a controlled fire test. This test crucial to assess the emergency response capabilities. The exact location of the test is yet to be determined.

4 Conclusion

In accordance with the established functional and technical requirements, a universal, voltage agnostic charging hardware is designed by Pipistrel Vertical Solutions d.o.o. to simulate future electric aircraft charging in a single point. The system is also known as Modular Charging System. The system consists of 32 aerospace certified propulsion batteries that are derived from the world's first type certified aircraft Velis Electro. Each battery contains 11 kWh rated energy that provides the total energy of 352 kWh. Using SIMENS PLC solutions and the related electrical components, the system allows to represent charging scenarios for the battery packs of Battery Electric Aircraft (BEA), Hybrid Electric Aircraft (HEA) and Electric Vertical Take-off & Landing (eVTOL) with 400 VDC, 800 VDC and, 1500+ VDC maximum charge voltage propulsion batteries, respectively. The complete system is placed inside a 20ft shipping container which enables the system to be transportable. To facilitate the charging process, the Modular charging system incorporates 4 Pipistrel Skycharge M20 mobile chargers. Each Skycharge M20 provides 20 kW of maximum power resulting maximum charging power of 80 kW.

In DemonsTrating lower pollUting soLutions for sustaInable airPorts acrosS Europe (TULIPS), task 2.3 demonstrates the innovative charging solution which can be used as a future-proof method to scale up the infrastructure necessary for the emerging sustainable aviation. The demonstration is performed in Rotterdam The Hague Airport and, subsequently in Oslo Airport.

Many innovative solutions are widely available for automotive electric mobility mass-market-capable. However, the standards for the aeronautic applications are still under development, especially for the conductive charging system. Due to the lack of international standards and uncertainties in the market for electric and hybrid electric aircraft charging systems, Original Equipment Manufacturers (OEM) have no incentive to develop their own charging system. It causes resistance in the technological development and prevents further improvement in charging infrastructure at airside. The modular charging system bridges this gap by reducing the infrastructure needed to perform a demonstration with significant cost reduction. Moreover, the emerging future electric vehicles are still under development. Therefore, using real aircraft is not feasible to perform such an extended charging demonstration. The modular charging system uses several propulsion batteries to simulate simultaneous charging of up to 16 Velis Electro. In addition, the propulsion batteries can be configured electrically in series, parallel or in combination of both to achieve equivalent energy which can represent charging of HEA and eVTOL aircraft.

5 Recommendations

The modular charging system is capable of providing the total charging power of 80 kW. Therefore, the estimated charging time is 4,5 hours. Many future electric aircraft demand fast turnaround times. To simulate such scenarios, the charging power needs to be increased further by increasing the number of chargers used in the charging system. Alternatively, power electronics can be used to achieve such high charging powers. Further modification is required from the propulsion batteries, as well as grid in airside to achieve such fast-charging demonstration.

Appendix A: LIST OF REFERENCES

Appendix B: ELECTRICAL ARCHITECTURE

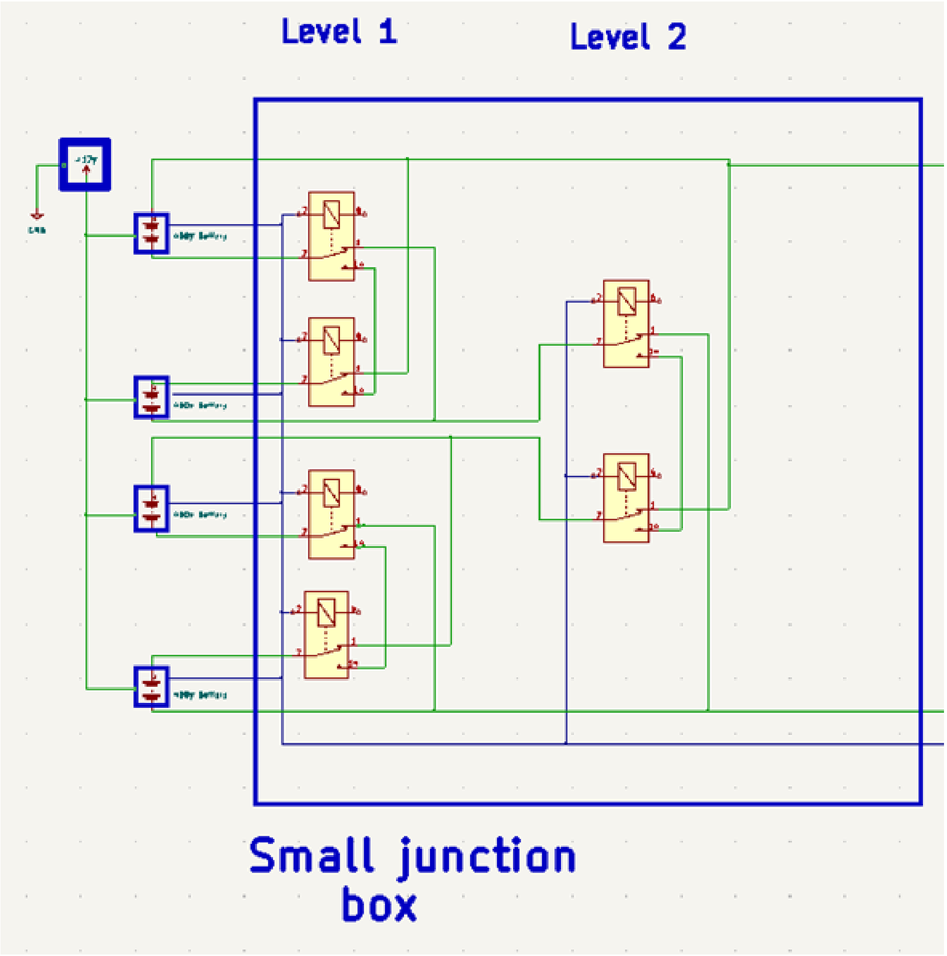

Figure 9 Small Junction Box design

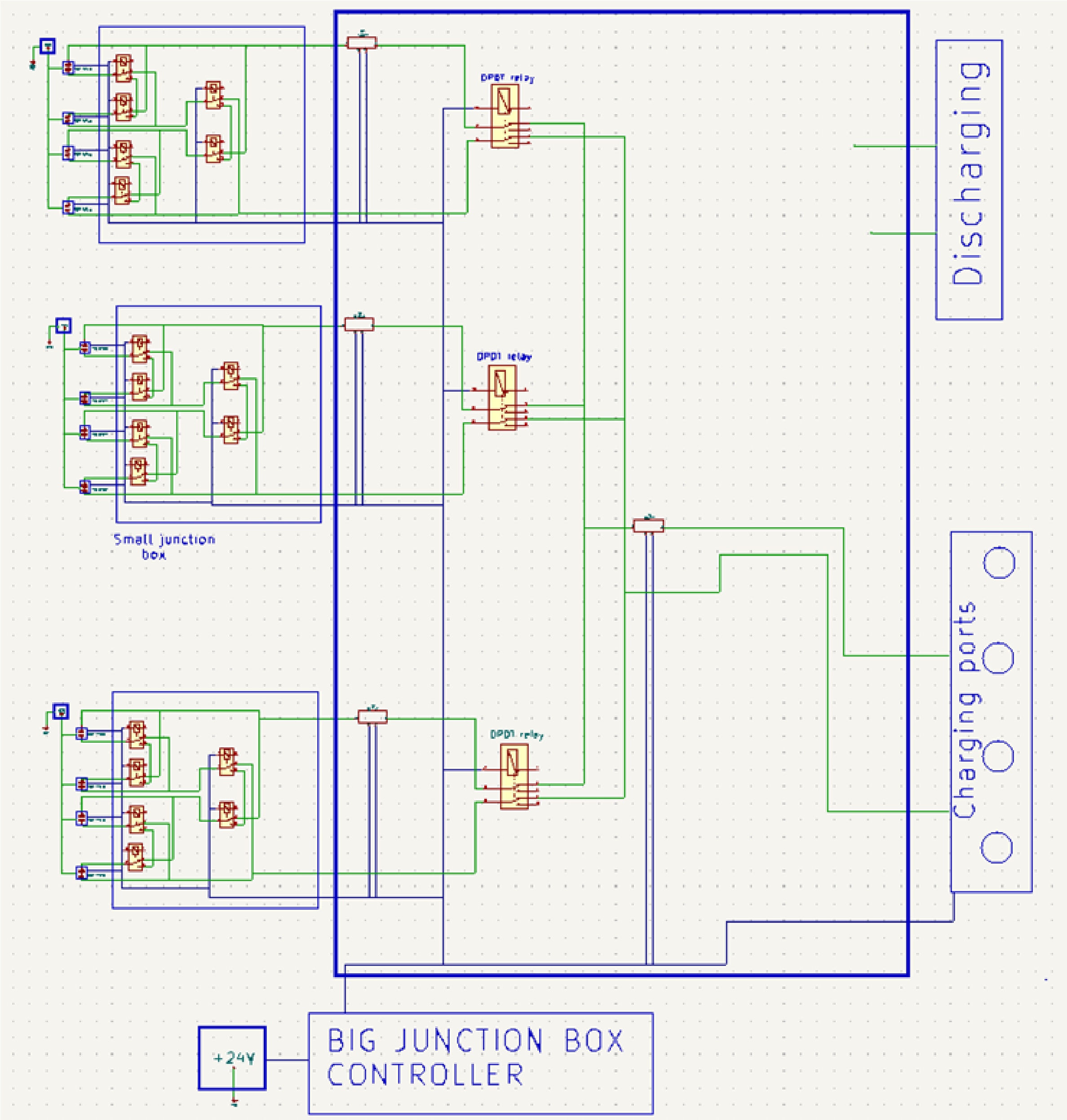

Figure 10 Big Junction Box design

Appendix C: TEST PLAN - MODULAR CHARGING SYSTEM DEMO

1. Objectives and scope

To validate the proposed solution of the modular charging system, following features are tested in both Rotterdam The Hague Airport and Oslo Airport during the demo. The demo consists of several test scenarios that can be validated with a single charging process of the modular charging system. Using the proprietary Pipistrel chargers, the 32 propulsion batteries will charge to the maximum charging voltage in parallel. During the charging process, the related data such as State of Charge, charge voltage and temperature will be acquired for the validation purposes. Subsequently, the propulsion batteries are reconfigured to simulate the 800 VDC and 1500+ VDC to achieve the desired battery voltage. Following the demo in Rotterdam The Hague Airport, the demo is also performed in the Oslo Airport in Norway.

The scope of the demo is limited to the charging of 32 propulsion batteries using Skycharge M20, which provides maximum power of 20 kW. To eliminate significant charging time, 4 Skycharge M20 chargers will be used in the demo. Therefore, the modular charging system is capable of providing the maximum power of 80 kW. During the charging process, each propulsion battery will be charged approximately 2,5 kW power. Since the estimated rated energy of each propulsion battery is 11 kWh, the estimated duration of the charging process will be 4,4 hours.

2. Test Equipment and Materials

The batteries will be assembled with other equipment 20ft shipping container: the complete modular charging system will be incorporated inside the 20ft shipping container. Therefore, the modular charging system is easily transportable by road, rail or inland waterway. In order to simulate the batteries of various capacities from small LSA aircraft such as Velis Electro to all the way up to the 19-seater commuter aircraft.

The modular charging system is designed to charge 32 aerospace certified simultaneously by connecting the propulsion batteries in parallel. To charge the propulsion batteries 4 Skycharge M20 charges are utilized. To facilitate the reconfiguration of the propulsion batteries PLC (Programmable Logic Controllers) are incorporated in the system. After the charging process, high resistive electrical components are used to discharge the propulsion batteries by converting the electrical energy into heat energy.

3. Test Setup

As discussed in the chapter 3, the demo is performed in 2 test locations. In each location, the test setup is identical. In Rotterdam The Hague Airport, the electrical connection for the chargers is provided from the grid connection from a location near the taxi way and Zeventembaan. In Oslo Airport, the electrical connection is provided directly from the connection that is used in Hanger 8.

4. Test Procedures

The procedure can be divided in several parts. Before the initiation of the charging process, the components need to be assembled to make sure that the modular charging is ready for the demonstration. Electrical components such as cables and HV connections shall not cause short circuit. Moreover, each components needs to be evaluated for potential fault before initiating the charging. Therefore, all components are checked by the Pipistrel technicians.

The demo is initiated by connecting the 3-phase plug of each charger to the grid available in airport. After connecting the 3-phase plugs, the charge receptacles are connected to the socket outlets in the big junction box. During the charging process each battery is connected in parallel to that small junction box. Subsequently, the connections of each small junction box are also parallel to the big junction box. After the confirmation of HV connection between charger and the controller, the pre-charge sequence is initiated. This balancing sequence charges all propulsion battery to the identical voltage. This concludes the initiation procedure of the modular charging system.

The charging process is assisted partially by the PLC (Programmable Logic Controllers) which enables the balancing of each individual propulsion batteries. Moreover, the PLC enables the reconfiguration after individual battery reaches the maximum charge voltage. This marks the end of the charging phase.

As mentioned in the previous section, the PLC is used to achieve the 800 VDC and 1500+ VDC configuration by connecting the propulsion batteries in series. However, prior to the reconfiguration the voltage of each propulsion battery is measured for the validation. The reconfiguration is performed by the operator that keeps the track of the battery parameters such as SoC (State of Charge), temperature, charging power, etc.

The post-test procedure consists of discharging and disassembling of the batteries and other components of the modular charging system.

5. Safety Precautions and emergency procedures

- Make sure cables to not interfere with other airport operations.
- Store portable chargers in a dry area and ensure they are not exposed to excessive moisture.
- Do not force disconnect the chargers.
- If smoke is observed stay away from the shipping container since batteries may self-ignite
- Vacate the area around the shipping container.
- Douse the fire with as much as water as possible in order to delay fire propagation.
- Expect to use approximately 1000L of water per battery pack.

Appendix D: TEST LOCATIONS

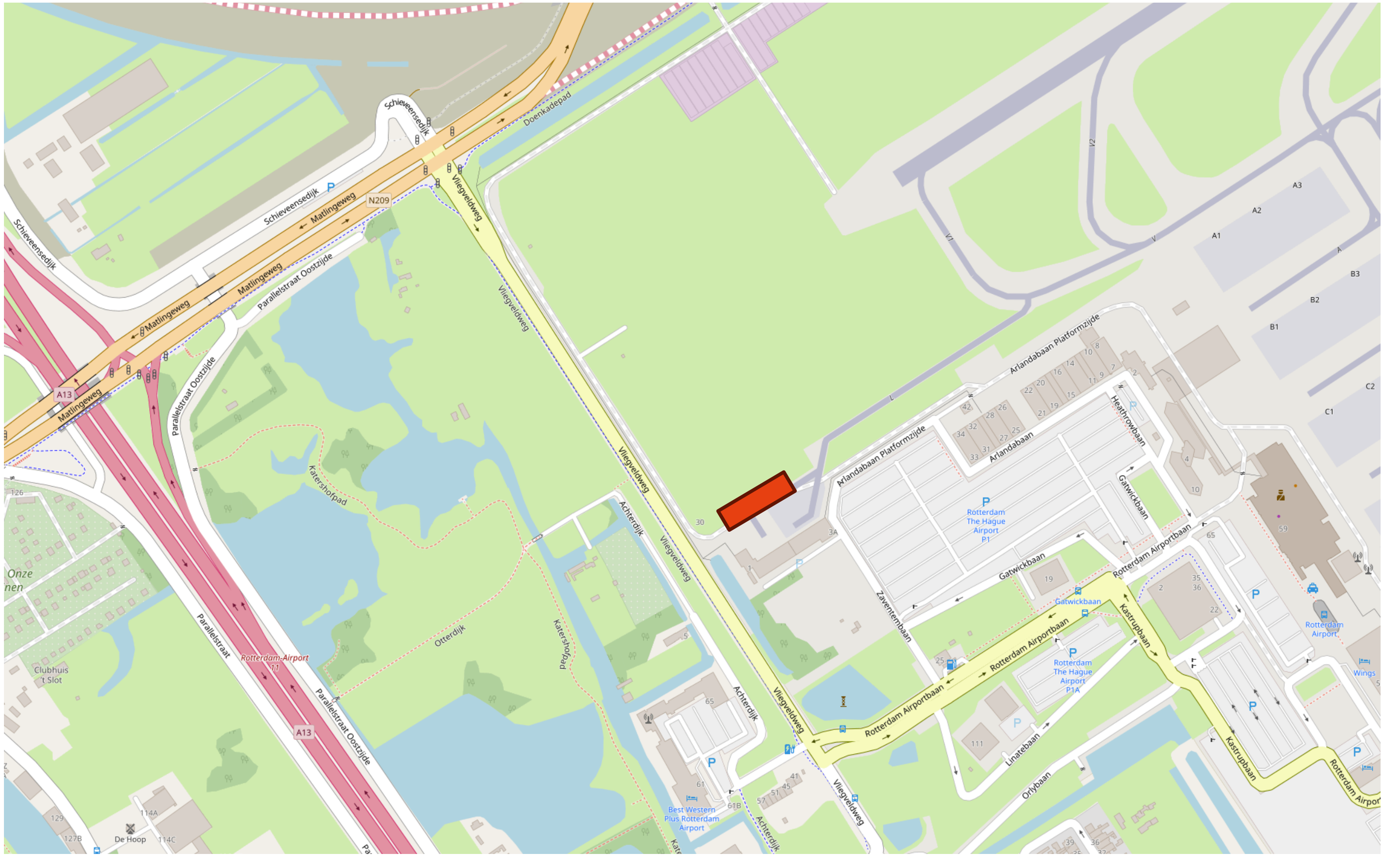

Figure 11 Rotterdam The Hague Airport aerial-view (Demo location indicated in red mark)

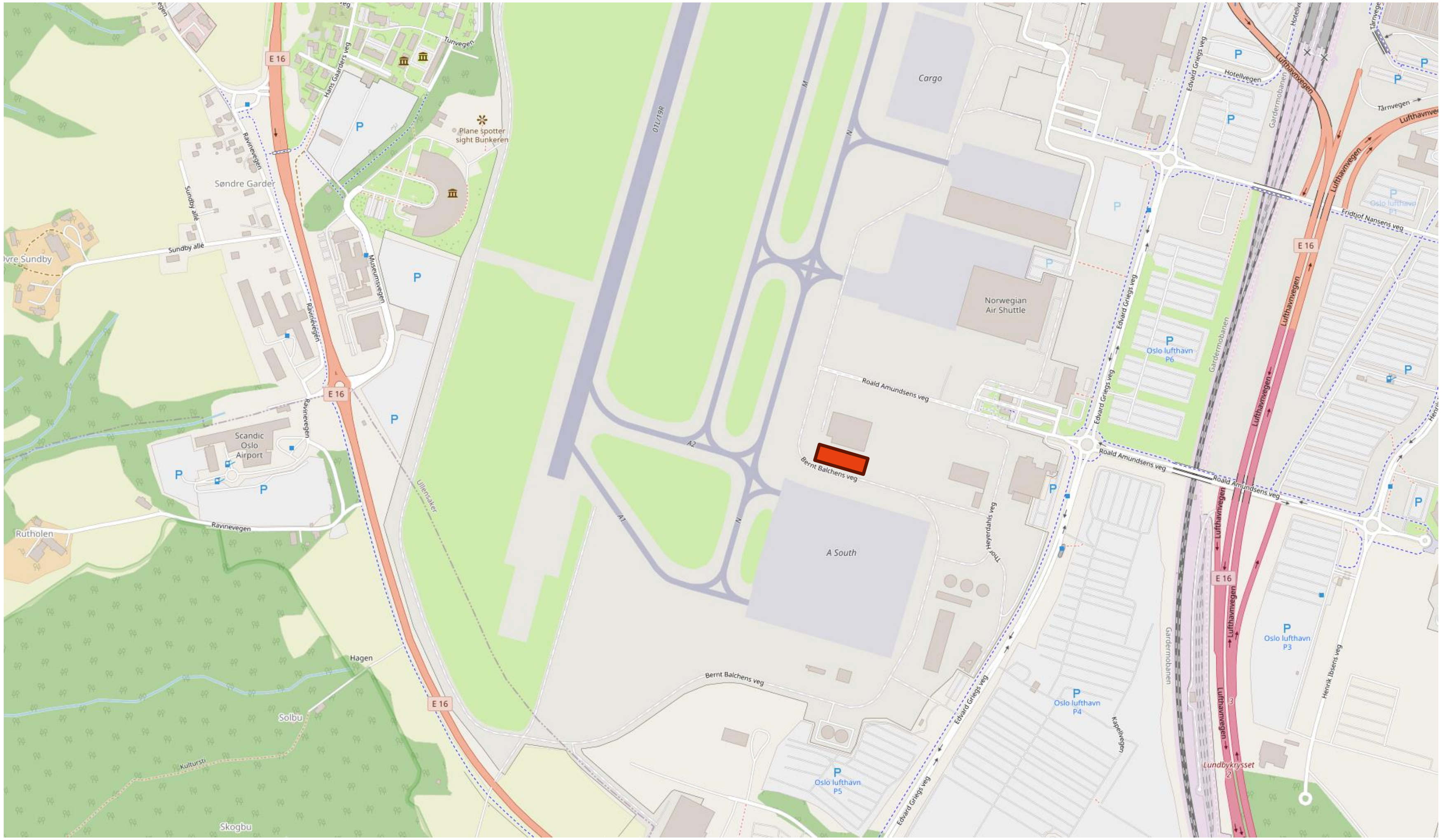

Figure 12 Oslo Airport aerial-view (Demo location indicated in red mark)

Appendix E: TECHNICAL DRAWING – MODULAR CHARGING SYSTEM (ISOMETRIC-VIEW)