ECSM

EUROPEAN CHARGING STATION FOR THE MOON PRE-PHASE A

Title : Executive Summary Report

Abstract : This document concisely summarises the work performed throughout the project and details the findings and conclusions.

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1 Introduction

1.1 Scope and Purpose

This document provides a concise summary of the work performed throughout the Pre-Phase A study of the European Charging Station for the Moon. This includes an outline of the background information, a brief description of the design specification development, including costing and scheduling, and highlights the project's major findings.

1.2 Document Structure

Section 1 introduces the document, details the structure and provides the relevant acronym and document information.

Section 2 summarises the work performed throughout the study detailed in the Technical Notes (TN).

Section 3 briefly concludes the work.

1.3 Acronyms

AD	Applicable Document
AstroSci	Astronaut Science Enabler
CDF	Concurrent Design Facility
CDHS	Command and Data Handling System
ECSM	European Charging Station for the Moon
EL3	European Large Logistic Lander
ESA	European Space Agency
EVA	Extravehicular Activity
EVA-IF	Extravehicular (or User) Interface
LDE	Lunar Descent Element
MBSE	Model Based Systems Engineering
PCDU	Power Conditioning and Distribution Unit
PeakPwr	Astronaut Science Enabler with Peak Power Capability
RD	Reference Document
RFCS	Regenerative Fuel Cell System
TN	Technical Note
TRL	Technology Readiness Level

1.4 Applicable Documents

AD1 Statement of Work European Charging Station for the Moon Pre-Phase A, ESA-E3P-EXPE-SOW-034, November 2021

AD2 European Large Logistic Lander (EL3) Generic Mission and System Requirements Document (GMSRD), ESA-E3P-EL3-RS-002

AD3 European Large Logistic Lander Missions Environmental Specification, ESATECEPS-SP-020864, 2.2, 12 Apr, 2021

AD4 International Deep Space Interoperability Standards, https://www.internationaldeepspacestandards.com

AD5 Coordinate Frame definition for the European Large Logistic Lander, E3PEL3-TN-001

AD6 ECSS-E-ST-10C Rev.1 – System engineering general requirements, 15 February 2017

AD7 ECSS Space Project Management - Project Planning and Implementation, ECSS-M-ST-10C Rev.1, March 2009

AD8	ECSS Space Project Management - Configuration and Information Management, ECSS-M-ST-40C Rev.1, March 2009
AD9	ECSS Space Project Management – Risk management, ECSS-M-ST-80C, July 2008
AD10	ECSS-M-ST-60C Space Project Management: Cost and Schedule Management, July 2008
AD11	ECSS Space Product Assurance – Safety, ECSS-Q-ST-40C, March 2009
AD12	ECSS Space Product Assurance – Hazard Analysis, ECSS-Q-ST-40-02C, November 2008
AD13	ECSS Space Product Assurance – Critical-Item Control, ECSS-Q-ST-40- 04C, July 2008
AD14	ECSS-E-TM-10-25 – Engineering design model data exchange – CDF (20 October 2010)
AD15	EL3 ECSM Mission pre-Phase A – Cost Estimate Template (MS Excel file) v10.1, ESA-TECSYC-CT-2021-026022
AD16	EL3 ECSM Mission pre-Phase A – Cost Requirements and Assumptions for Costing, ESA-TECSYC-RS-2021-026021
AD17	ECSM Technical Budgets Templates

1.5 Reference Documents

RD1	ECSM CDF Report CDF Study Report: CDF-218(A), August 2021
RD2	ECSM CDF – Final Presentation, May 2021 ESA UNCLASSIFIED
RD3	TN1 – ECSM System Requirements Document v1.0.0
RD4	TN2 – ECSM Design Rationale v1.0.0
RD5	TN3 – Architecture and Configuration Specification v1.1.1
RD6	TN4 – System Design v1.2.0
RD7	TN5 – Operations Concept v1.1.0
RD8	TN6 – ECSM Preliminary Technology Development Plan v1.1.0
RD9	TN7a – Costing and Consortium Structure v1.1.0
RD10	TN7b – Programmatic Dossier v.1.1.1
RD11	TN7c – Cost Report Including ROM Industrial Cost Estimate v1.1.0
RD12	TN8 – MBSE Approach and Lessons Learnt v1.0.0
RD13	TN9 – Commercialisation Options: Cost of Service Analysis v1.1.0

2 Summary of the ECSM Pre-Phase A Work

2.1 Background and Introduction

The increased interest in lunar exploration has led to the development of the Global Exploration Roadmap, a consensus of member agencies of the International Space Exploration Coordination Group detailing phases for returning to and establishing a sustained human presence on the Moon. During the phase for expanding capabilities on the lunar surface, there will be a need to provide electrical power to any established architecture. The European Charging Station for the Moon (ECSM) is a proposed European-led solution.

For missions on the lunar surface, a key consideration is energy availability and, in particular, the ability to store power to survive and perform operations during the lunar night. The ECSM's envisioned purpose is to provide power to lunar surface assets, or Users, for a two-year baseline mission duration. The ECSM will be integrated onto the European Large Logistics Lander (EL3 – now known as Argonaut) and launched with the Ariane 64 rocket. The EL3 consists of the lander, known as the Lunar Descent Element (LDE), upon which the cargo and/or scientific payloads sit, interfacing with the LDE via a Cargo Platform Element.

The European Space Agency (ESA)'s Concurrent Design Facility (CDF) performed a study in which a baseline architecture, design concepts and initial requirements for the ECSM mission were outlined [RD1, RD2]. Through analysis of previous work on the topic and identifying the User needs, a reference mission concept and preliminary baseline design was established. Two primary missions, or use cases, were identified: the Astronaut Science Enabler (AstroSci) and the Astronaut Science Enabler with Peak Power Capability (PeakPwr). Both use cases use a deployable solar array to generate power for the Users and a Regenerative Fuel Cell System (RFCS) to store enough power for the ECSM to survive the lunar night. The power that each use case can continuously provide to the Users was identified in the CDF study as:

- AstroSci: Up to 7.7 kW during the lunar day
    - Up to 256 W can be provided during the lunar night

- PeakPwr: Up to 8.3 kW during the lunar day
    - An additional boost of 8 kW can be provided by batteries for up to 3 hours
    - When these batteries are charging, the maximum power provision is 7.1 kW
    - No power provision to Users during the lunar night

The ECSM payload will advance from its current concept, with a Technology Readiness Level (TRL) of 2, to an analytical proof-of-concept with TRL3, allowing ESA to present the ECSM as a credible potential payload for EL3. The primary objective of this activity is to successfully complete the pre-Phase A study and Design Review for the developed ECSM system. This includes requirements analysis, identification and execution of trade-offs, specifying a baseline design and operational concept for AstroSci and PeakPwr, detailing a programmatic outline for later phase development and evaluating the ECSM costs and customer value.

For this activity, tasks were completed through the implementation of Model-Based Systems Engineering (MBSE) [RD12]. A model is a simplified representation used to facilitate understanding of a concept or system. MBSE uses models to support the requirements, design, analysis, verification and validation activities throughout a system's development from concept to later life cycle phases. As opposed to the traditional document-centric engineering approach, the modelling approach uses a single source of truth that can be accessed by all stakeholders, containing interconnected models that allow changes to be propagated throughout the system.

2.2 System Requirements

The first phase of the work performed was a top-level analysis of the programmatic and mission requirements for the AstroSci and PeakPwr use cases [RD3], ensuring their completeness and feasibility in terms of paving the way for the design of an optimal system. These requirements were collated from the Statement of Work [AD1] and its Reference Documents (RDs), and then assessed, with comments made regarding modifications to the requirements, other observations or questions to be brought to ESA. These high-level requirements were then organised into system requirements, with categories including Design, Power, Interfaces, etc.

As well as the established User power provision needs, other key requirements identified are:

- All critical ECSM technologies shall reach TRL6 by the Preliminary Design Review
- The ECSM shall provide power to up to 3 primary external Users
- The system shall be able to provide high (120 V) and low (28 V) voltages to the Users
- The power generation system will be sized to provide power to the Users, store energy for night survival and sustain the ECSM subsystem equipment
- The ECSM design shall be compliant with the EL3 sizing and mass constraints
- The ECSM will operate in the expected mission environments
- The ECSM will be able to survive lunar night
- The system shall be safe for operation by Extravehicular Activity (EVA) crews

2.3 Design Trade-Offs and Architecture Configuration

During the CDF, numerous trade-offs were performed for informing the baseline mission designs. Those considered to require additional in-depth assessments, as well as any newly identified trades, were collated. A trade-space definition was established, in which each trade was categorised into a specific theme, such as Thermal, Structures, etc [RD4]. Each trade-off was given a technical description, along with the baseline design chosen in the CDF study (if indeed there was one). Finally, the options to be analysed, as well as the criteria with which they would be evaluated, and their respective weighting factors, were listed.

The trade-offs were evaluated using quantitative metrics and, in cases where values cannot be easily quantified or obtained, with qualitative metrics. For each trade study, a Decision Support Matrix, based on a Multi-Criteria Decision model, was used to provide a weighed value comparison of the options based on the trade criteria, from which an optimal choice was found [RD5]. For each optimal option identified, a further subjective evaluation was made to verify that the goals, objectives and constraints are fulfilled by the selected system

2.4 System Design

Using the inputs from the trade-off study, the preliminary design of the ECSM baseline for both the AstroSci and PeakPwr use cases has been detailed [RD6]. For each system, this involved the definition of baseline designs and subsystem components for the two missions, detailing how they are able to achieve the requirements and design drivers, along with a comparison of the differences between the AstroSci and PeakPwr configurations, a risk analysis and the technology development needs of the chosen equipment. From this, the mass, power and communications budgets of the two use cases were calculated, with appropriate design, development and harness margins applied where appropriate. A diagram of the completed ECSM design for the AstroSci configuration on the EL3 LDE is shown in Figure 1.

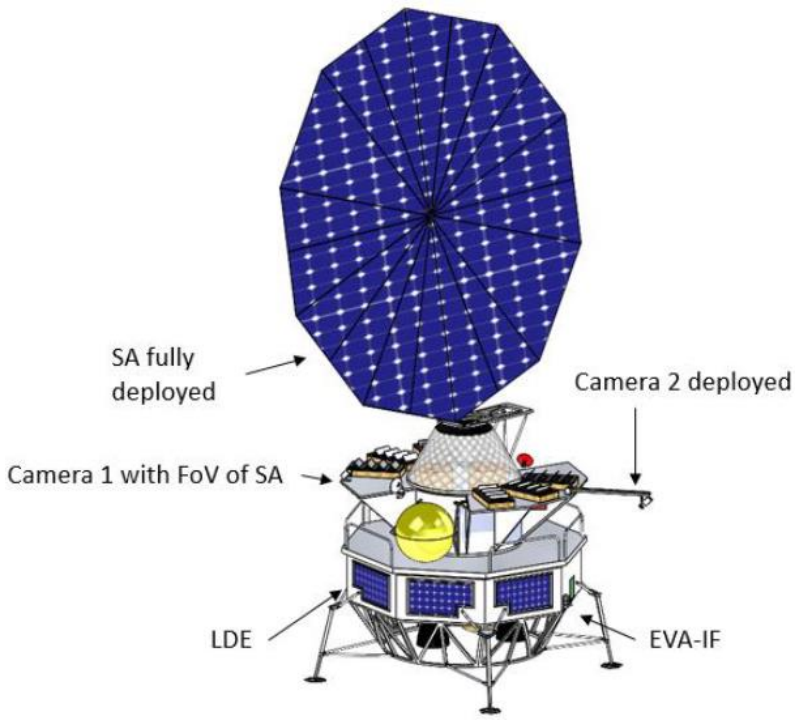

Figure 1 - ECSM AstroSci configuration with the fully deployed solar array

Sitting on top of the LDE, the ECSM is built around a primary central cylinder enclosure and deck structure, which serve as the overall system backbone and provides structural support. The former contains the primary Power storage systems, while the upon the deck is placed the Communications, Command and Data Handling System (CDHS), the Power Conditioning and Distribution Unit (PCDU), heat dissipating elements and two cameras. Additionally, the Extravehicular (or User) Interface (EVA-IF) is located on the side of the LDE.

2.4.1 Power Generation, Storage and Distribution

The power-generating and storing devices are the solar arrays, RFCS and batteries. For both the AstroSci and PeakPwr configurations, the Azur Space QJ 4G32C solar arrays were sized to generate the power needed to supply the external Users, charge the RFCS and batteries and power the various ECSM subsystems, taking into account degradation losses after a two-year mission. For both configurations, a small battery pack of ABSL I28 batteries is used to assist with system start-up and deployment. For PeakPwr, another much larger battery pack was included, sized to produce the additional 8 kW boost in power. A PCDU is used to regulate the incoming power, and ensure safe supply of the required voltages to external Users and the ECSM’s subsystems. Power is provided to the Users via the EVA-IF, an aluminium panel consisting of three connectors to which harnesses of up to 500 m length can be attached.

The RFCS is a method for storing energy for use during the lunar night, when the solar arrays cannot be used, and offer advantages over batteries due to their scalable nature. The RFCS utilises stored hydrogen and oxygen in a fuel cell to produce electricity, water and heat. The generated power is used to ensure the ECSM can survive the lunar night and, in the case of AstroSci, also provides a small power supply to the Users. As such, the RFCS’ fuel cell stacks have been sized accordingly for both missions. Additionally, the waste heat generated by the RFCS can be utilised through a thermal interface with the ECSM to act as a heat source that can further assist with lunar night survival. During the day, the RFCS is charged by applying power to an electrolyser, splitting the water back into hydrogen and oxygen.

2.4.2 Thermal and Structural Design

The thermal control system has been designed to ensure proper temperature control of all elements in the ECSM, ensuring they remain within their operational and survival temperature ranges by dissipating excess heat during the day and providing heat during the night. By taking into account the thermal needs of the mission's hot and cold cases, and the use of conduction, insulation and heating hardware, and the subsystems' locations, the relevant thermal control systems have been sized. This includes Louvered Radiators for heat dissipation, a Pumped Fluid Loop for controlling the RFCS waste heat, Heat Pipes for facilitating heat transfer, Electric Heaters for lunar night survival and passive insulation systems such as Multi-Layer Insulation.

The structures system has been designed to ensure acceptable structural support is provided for the ECSM and LDE, provide protection against stresses, shocks and the lunar environment and integrate a variety of deployment and pointing mechanisms. The Primary structure, as discussed in Figure 1, includes the primary load bearing elements, enclosure and mounting surfaces. Secondary structures identified are the supports for the solar arrays, RFCS gas tanks and the EVA-IF panel, while tertiary structures include brackets and local reinforcements. The materials, sizes and subsequent masses of each of these structures has been determined.

2.4.3 CDHS and Communications

The CDHS is responsible for receiving and processing the telemetry uplinked from the ground station, and the data sent from the various sensors and electronics, as well as sending telecommands to the subsystems and other dedicated telecommand/telemetry modules. The CDHS consists of a flight computer, a custom input/module for the various data interfaces and a mass memory module. The CDHS will oversee several control loops, such as heater operation and drive mechanism control, and has levels of various levels of autonomy.

The communications subsystems allow downlink and uplink of data to and from the ECSM to Earth. This is done either through direct transmission to ground stations, or via the Lunar Gateway relay system, assumed to be operational by the time of the mission, when the Earth is not in sight. The data rates of the telemetry, telecommand and video feed data have been calculated, allowing the correct utilising of the X and Ka-band frequencies, and identification of the required equipment, including the transceivers, transponders, amplifiers and antennae.

2.4.4 Mobile ECSM and Lunar Surface Communications Hub

As an additional consideration, two additional systems were considered as potential complementary design options. The first is a mobile ECSM, in which the system could be unloaded from and towed away from the LDE by a rover. This would provide greater flexibility with regards to the landing location with respect to the Users and reduced harness needs. The second is the Lunar Surface Communications Hub, which would be used to provide surface-to-surface communications between surface and orbital assets.

2.5 Concept of Operations

A baseline operational concept for the ECSM has been defined [RD7], allowing identification of the high-level timeline throughout the mission duration and a description of the operational modes foreseen for the system, with particular focus placed upon the power supply to Users, preparation for lunar night survival and the User Interfacing modes. Additionally, three scenarios critical to the successful operation of the ECSM have been identified: connecting a User to the ECSM power supply, deployment and commissioning of the system after it has landed on the lunar surface and maintenance and/or repairs of the solar array regulator module should it fail. These scenarios have each been meticulously planned out, with all expected interactions and required steps to perform the tasks identified.

2.6 Technology Development and Programmatic Dossier

The ECSM is a complex system composed of many subsystems and components that have not yet been qualified for or used in lunar missions. To ensure the mission is completed within the established timeframe, the critical systems, i.e. those with a TRL below 6, have been identified [RD8]. The potential risks associated with their development, such as long development times associated with low TRLs or the need for custom modifications, have been outlined. For each of these technologies, a schedule and description of the necessary development needed to reach TRL6, along with the expected timeline to progress to TRL8.

Following this, a programmatic assessment of the development of the system design has been made [RD10]. The expected activities to take place during Phase A, B1/B2, C and E have been summarised, including the definition of the mission concept baseline, refinement of the system architecture, procurement of items, the system design and construction, and testing and verification of the Electrical Qualification and Flight Models. From this, a preliminary master schedule for each phase, the major reviews and the Model testing, has been outlined. Additional subsystem technical risks, such as lunar dust contamination and reliability, as well as risks to the overall system cost and sustainability, have been identified and listed in a risk register, along with their potential impacts and possible mitigation actions. A risk management plan will be utilised, allowing the risks to be identified, planned for and controlled.

2.7 Cost Analysis and Commercialisation Options

The total cost estimate of the ECSM accounts for the ECSM development and construction, launching onboard Ariane 64 and the personnel needed to operate it for the mission duration [RD9, RD11]. The critical technology development costs were based on supplier information and expert opinions. The development costing was estimated by considering hardware purchases for each Phase, risk contingencies, testing facilities, ground support equipment and required manpower. From these inputs, a rough order of magnitude cost estimate was then calculated.

The launch costs were based on assumptions regarding the use of Ariane 64 to launch the EL3 into a direct lunar transfer orbit. Finally, the operational expenditure, i.e. the cost of ground station personnel required to maintain and operate the ECSM, as well as interact with Users, was estimated, by considering the manpower required for each operational mode. Based on these values, a minimum cost per Watt of the electricity supplied by the ECSM was estimated. The perceived value of this to customers was then discussed, highlighting the User benefits of utilising the ECSM, both in terms of tangible mass savings, such as the removal of their own power generation systems, and the potential for increased User mission scope and outputs.

Finally, the near-future commercial opportunities for the ECSM were identified [RD13]. The projected power needs of various technologies in development for lunar activities, such as In Situ Resource Utilisation and Excavation and Construction, were documented. For each of these activities, a list of potential customers was compiled, and the expected service duration for these customers was examined, in particular for long-term missions led by space agencies.

3 Summary

The European Charging Station for the Moon is a proposed payload for future use in the next phases of establishing human presence on the Moon, envisioned to provide power to multiple Users on the lunar surface. Two configurations have been considered, each of which are able to provide more than 7 kW to up to three Users during the lunar day: the Astronaut Science Enabler, which can also provide 260 W to Users using its RFCS during the lunar night, and the Astronaut Science Enabler with Peak Power Capability, which uses an additional battery pack to provide an additional boost of 8 kW for up to three hours during the lunar day.

The work performed in the pre-Phase A study has included a refinement of the collated requirements and the definition of a trade space for the completion of a detailed trade-off study for various design aspects, which has resulted in the detailed design of the AstroSci and PeakPwr configurations, both in terms of their overall configurations and the subsystem designs. From this, the operational modes have been established, the critical technologies have been identified, a programmatic dossier detailing the development, launch and operational costs has been created, and the perceived value of the ECSM power provision to customers has been discussed.