MELISSA PROJECT: STRATEGY AND IMPLEMENTATION PLAN FOR 2025-2040

MELISSA

MICRO-ECOLOGICAL LIFE SUPPORT SYSTEM ALTERNATIVE

APPROVAL

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EXECUTIVE SUMMARY

The Micro-Ecological Life Support System Alternative (MELiSSA) project is the leading European initiative on modular, controlled and regenerative closed-loop life support systems. The project aims to generate knowledge and technology to reach the highest degree of autonomy in space, i.e. the reliable and efficient production of oxygen, water, food, nitrogen, and materials during deep space exploration missions, where otherwise terrestrial resupply would not be feasible nor safe for the crew. Besides this primary objective, the project fits in with a wider circular economy approach, in line with the Sustainable Development Goals (SDG) defined by the United Nations: the innovations stemming from the MELiSSA space applications serve the green transition for a more sustainable, resilient and fairer society. Eventually, leveraging on its multi-disciplinary approach, with both space and terrestrial applications, the project can be used to inspire, educate, and raise awareness on circular life support and resource management systems, while advancing key research areas through collaboration with European universities and institutions.

The MELiSSA project was initiated in 1987, and the latest project strategy was elaborated in 2019 [RD2]. Yet, the space and terrestrial context of the project has evolved significantly over the last decade. At the European Space Agency (ESA) level, the European exploration strategy (Explore 2040) and the commercialization strategy have undergone substantial updates. The project is also at a significant turning point at consortium level, with new stakeholders joining the Memorandum of Understanding partnership and evolution in the project's governance. The definition of a clear and up-to-date strategy is essential for the project to sustain its leadership position in the field of modular and controlled closed-loop life support systems in Europe and worldwide. In light of the recent changes that have occurred in the project's landscape, it is therefore appropriate to revisit its strategy and to confirm its short-, medium- and long-term objectives.

The MELiSSA project ambitions to position Europe at the forefront of sustainable human exploration by providing unique contributions for modular, controlled and regenerative closed-loop life support systems and by returning benefits to society to enable a green and circular transition. The project's strategy for 2025-2040 defines the top priority goals for space, terrestrial, and education and outreach applications for the period 2025-2040. Supporting the preparation of future space exploration missions has always been part of the project's DNA.

In addition, the present strategy recognises the development of terrestrial applications and green commercialisation as a necessary and enabling step for the longevity, growth and leadership position of the project.

The MELiSSA project's four strategic goals for 2025-2040 are:

(Goal 1) Being a global leader in the field of modular and controlled closed-loop life support systems

(Goal 2) Strengthening European unique capabilities in the field of advanced regenerative life support systems for space habitation

(Goal 3) Contributing to a more circular and sustainable management of resources on Earth and mitigating environmental changes

(Goal 4) Driving public awareness, nurturing the development of European STEM talents in the fields of closed-loop life support and circular systems and inspiring future sustainability leaders

The MELiSSA project strategy and implementation plan for 2025-2040 is consistent with ESA Agenda 2025, ESA Strategy 2040, ESA Explore 2040 exploration strategy, TEC 2040 Vision, ESA Technology Harmonization Roadmaps for Life Support and Additive Manufacturing technologies, the Advanced Manufacturing cross-cutting initiative, the Space for Education 2030 Vision and takes into consideration feedback from participating ESA Member States.

1. GLOSSARY

Advanced ECLSS	System ECLS functions for extended periods of time, typically integrating multiple sub-systems such as atmospheric control, water recovery, waste management, food production and habitat support. May include both regenerative processes and non-regenerative or partially regenerative components.
Circular economy	Circular economy is an economic system that is restorative and regenerative by design, aiming to gradually decouple growth from the consumption of finite resources (Ellen MacArthur Foundation). In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting.
Circularity	Practices that optimize resource use and minimize waste across the entire production and consumption cycle, emphasizing sustainability and economic efficiency.
Closed-loop ECLSS	ECLSS based on recycling, regeneration, and recovery of materials or elements. The closed-loop ECLSS implies that the use of significant expendables and consumables is excluded from the processes [RD1].
Deterministic model	A deterministic model refers to a mathematical model that can accurately predict certain characteristics or properties of a system or process of interest. For a given input, the model output is always the same, creating a form of determinism between inputs and outputs. As opposed to stochastic models, deterministic models allow prediction of the outcomes. Deterministic control is a prerequisite for the long-lasting and sustainable existence of the MELiSSA loop.
ECLS	Engineering discipline dealing with the physical, chemical and biological functions to provide humans and other life forms with suitable environmental conditions. The objective of ECLS is to create a suitable environment by controlling environmental parameters, providing resources, and managing waste products [[**RD*1***].
ECLSS	System that includes the hardware and software to perform ECLS functions [[**RD*1***].
Mechanistic model	A mechanistic model refers to a mathematical model based on physical, chemical and biological laws describing the elemental mechanisms and processes of the system of interest. As opposed to empirical models, mechanistic models allow the understanding of underlying mechanisms and the accumulation of knowledge.
Model predictive control	A model predictive control enables to control a process based on dynamic models of this process and bound by a set of constraints.
One health	A collaborative, multisectoral, and transdisciplinary approach—working at the local, regional, national, and global levels—with the goal of achieving optimal health outcomes by recognizing the interconnection between people, animals, plants, and their shared environment.

Open-loop ECLSS	ECLSS based on external resupply of resources [RD1].
Regenerative ECLSS	ECLSS based on recycling and regeneration of essential resources like water, oxygen, and food, hence minimizing the need for external resupply.

2. ACRONYMS

AD	Applicable Document
ALiSSE	Advanced Life Support System Evaluator
cMRL	Control Model Readiness Level
CELSS	Controlled Ecological Life Support System
COSPAR	Committee on Space Research
ECLS	Environmental Control and Life Support
ECLSS	ECLS System
ESA	European Space Agency
ICES	International Conference on Environmental Systems
IRL	Integration Readiness Level
ISS	International Space Station
LEO	Low Earth Orbit
LSS	Life Support System
MELiSSA	Micro-Ecological Life Support System Alternative
MPP	MELiSSA Pilot Plant
MRL	Model Readiness Level
NGO	Non-Governmental Organisation
RD	Reference Document
R&D	Research and Development
SDG	Sustainable Development Goals
STEM	Science, Technology, Engineering, and Mathematics
SSO	Swiss Space Office
TRL	Technology Readiness Level

3. PREAMBLE

"Great things are not done by impulse, but by a series of small things brought together"
Vincent Van Gogh

The MELiSSA (Micro-Ecological Life Support System Alternative) project was conceived in response to the growing need for sustainable and regenerative life support systems for long-duration space missions. The project was initiated in 1987 by a partnership between the French company MATRA and Belgian entities, SCK CEN and Ghent University, following a preliminary flight experiment onboard the Chinese rocket Longue March, based on two microbial cultures connected in the gas phase. While the project's concept was elaborated and published in 1988, the contractual activities with ESA only started in 1989 [RD3] [RD4]. The MELiSSA consortium has progressively grown over the years. Today, the project is structured around a Memorandum of Understanding [[**AD*1***] regrouping 16 participating parties, including ESA, who is responsible for the management of the project. The 15 other participating parties are: VITO (BE), IPStar B.V. (NL), University of Clermont Auvergne (FR), Universitat Autònoma de Barcelona (SP), Ghent University (BE), SCK CEN (BE), Sherpa Engineering (FR), University of Mons (BE), MELiSSA Foundation, Enginsoft (IT), University of Naples Federico II (IT), University of Antwerp (BE), NTNU Samfunnsforskning AS (NO), EAWAG (CH) and Nantes University (FR). The project is currently co-funded by ESA, the other MELiSSA participating parties as well as local and national authorities.

For the past sixty years, several space agencies have initiated life support technology developments. However, these efforts have been largely focused on partially regenerating new consumables from a single product, such as water recovery or oxygen production from carbon dioxide, without a comprehensive approach to the entire environmental control and life support system (ECLSS). As plans for extended missions beyond low Earth orbit (LEO), such as Mars, were considered, it became obvious that future deep space missions would require increasingly regenerative closed-loop ECLSS, since supplying part of or all the consumables from Earth would result in a tremendous cost and possibly safety risks for the crew. For these reasons, the MELiSSA project was initiated in Europe. In parallel, several attempts to develop regenerative closed-loop ECLSS were set in motion by other international key actors (Table 1).

While the use of traditional physico-chemical technologies, such as the ones operated onboard the International Space Station (ISS), provide some degrees of closure, these technologies are currently not capable of producing food or degrading organic waste. The provision of a qualitative and sustainable food source for astronauts on long-duration missions can only be achieved by biological means (e.g., higher plants or micro-algae cultivation). The prepackaged dehydrated food items used for missions aboard ISS indeed do not have a sufficient shelf-life to sustain longer-duration missions and crew's health and performance can be negatively impacted, for example, by an insufficient nutrient and vitamin intake. In addition to food production, the introduction of photosynthetic organisms has the advantage of providing a new set of solutions for atmosphere revitalization, water recovery and crew waste valorisation. Similarly, technologies based on microbial decomposers are also required for the efficient degradation and transformation of the wide range of complex solid and liquid waste produced by the crew, which may vary with crew activity or food intake. In a closed-loop system approach aiming for mass closure, the product of this degradation can be reused for the cultivation of higher plants and microalgae. Hence, all the above-mentioned closed-loop ECLSS initiatives have or are considering the integration of biological components, in some cases in complement to physico-chemical ones, to perform maximum, efficient and reliable metabolic resources regeneration and waste removal.

The technological challenges presented by closed-loop ECLSS require a stepwise approach. Most of the undertakings introduced in Table 1 focused first on photosynthetic atmospheric regeneration and then extended their concept to waste degradation and recycling, as a resource for biomass production. Among these initiatives, NASA and ESA are thought to be the only entities who have invested noteworthy efforts in a dedicated modelling approach. Today a large part of the system level endeavours have been abandoned. Except for two remaining projects: Lunar Palace 1 in China and MELiSSA in Europe [RD1] [RD2] [RD3].

In this worldwide context, the MELiSSA project is thought to have perdured over time thanks to its progressive stepwise approach backed up by a consistent system engineering methodology. The project progresses towards a highly engineered and modular life support system concept supervised by a dedicated control system based on mechanistic mathematical models. Meanwhile, the project successively seeks high efficiency and long-term stability for each component of the system. Considering this unique approach, MELiSSA assumes today a leadership position in the field of modular, controlled and regenerative closed-loop life support systems. Although MELiSSA is dedicated to finalising the integration and ground demonstration of its closed-loop concept at the MELiSSA Pilot Plant with relevant operational scenarios, the acceleration of flight hardware development will only gain amplitude once clear deep space crewed mission scenario and exploration goals are set by participating space agencies.

Country	Organization	Initiative	Concept	Status and Challenges
Russia	Institute of Biophysics (IBP)	Bios-1, -2 and 3 [RD5] [RD65]	Test facilities designed as part of the Soviet space program and located at the Institute of Biophysics, in Krasnoyarsk. Designed to include humans in a functioning, self-sustaining, closed ecosystem for continuous periods as long as one year. **Bios-1 (1965)**: A sealed 12m³ chamber for one human connected to an 18L algal cultivator growing *Chlorella vulgaris*. Aimed at gas circulation. The algae system contributed 20% of the oxygen and carbon dioxide balance by removing carbon dioxide and producing oxygen. Water recycling was introduced in 1968, increasing the system's closure to 80%. **Bios-2 (1968)**: A 3-component system constructed in 1968 where Bios-1 was attached to a 2.5x2.0x1.7m³ higher plant chamber for growing crops like wheat, beetroots, carrots, cucumbers and deals. A human crew could go into the higher plant chamber to attend and harvest the crops for consumption. This demonstrated the feasibility of direct gas exchange between humans and higher plants. **Bios-3 (1972)**: An underground, hermetic sealed 315m³ facility divided into 4 compartments including a crew area. Algae were initially used to regenerate air for three crew members. Later, the system was modified to include higher plant chambers growing crops such as wheat and sedge nuts. The system included hydroponic plant growth (63m² plant area) and recycled water for nutrients. Three 4–6-month closure experiments with two to three human crew were conducted in 1972-1973, 1976-1977, and 1983-1984. 100% of the water and air were provided. 25% of the crew's food came from lyophilized meat. Human waste was mostly not recycled, with feces dried and stored and water returned as vapor. Combustion was used for inedible biomass. The final experiment involved direct application of filtered hygiene water and urea to wheat plants. Gas concentrations remained stable, indicating a balanced ecosystem. Bios-3 used gravity dependent watering concept targeted for planetary surface settings.	Bios-3 test facility operated almost continuously from 1972 to 1980. Achieving stability proved to be a serious challenge in the Bios-3 experiments. The instabilities were mostly in microelements and microflora. Viruses and plasmids were not studied either, but they could also pose threats. BIOS-3 was discontinued due to the changing priorities in Soviet space exploration, as well as the high operational costs and difficulties in scaling the system for practical space missions. The lack of long-term funding and strategic direction contributed to its cessation.
USA	NASA	CELSS (Controlled Ecological Life Support System) [[**RD6**] [[**RD7**] [RD8] [RD9] [RD10] [RD11]	Research on the use of photosynthetic organisms to generate oxygen and food started in the 1950s and 1960s with the work of Jack Meyers et al. on algae for the US Air Force and NASA. Initiated in the late 1970s, the CELSS program aimed at providing research and technology to develop a regenerative life support systems for humans in space based on the use of higher plants. The program supported research at universities with a primary focus on the controlled environmental production of candidate crop plants. During the late 1980s and 1990s, research conducted by university CELSS researchers contributed to experiments at NASA's Kennedy Space Centre, where	Programme initiated in 1978. The BPC operated from 1988-2000. The CELSS Test Facility operated from the early 1990s until its decommissioning in 2004. Decommissioning was primarily due to a shift in NASA's research focus towards more integrated and practical systems that could be tested on the ISS and other space

		[RD65] [RD6] A Review of Recent Activities in the NASA CELSS Program, MacElory, R.D., Tremor, J., Smernoff, C.T., Knott, W., Prince, R.P., Advances in Space Research, Vol. 7, No. 4, pp(4)53-(4)57, COSPAR, 1987. [RD7]	tests were carried out in a 20m^2 atmospherically closed chamber (Biomass Plant Chamber (BPC)). Following this, human trials with regenerative life support technologies were conducted at NASA's Johnson Space Centre in the mid-1990s, including a 91-day test with four humans living in a closed habitat. An 11m^2 wheat chamber was atmospherically connected to a living habitat and provided the air regeneration needs of one human, while the needs of the other three crew members were supplied by physico-chemical technologies. The tests included nutrient recovery from inedible biomass. The crew habitat included a small lettuce growth chamber to supplement stowed food. The CELSS test facility used gravity dependent watering concept targeted for planetary surface settings. As a subsequent step, a large-scale bioregenerative test facility known as BIO-Plex was planned but never completed. NASA's large scale bioregenerative life support testing stopped in the early 2000s.	exploration platforms. Currently, NASA has no full scale, closed, integrated test facilities for regenerative life support research.
USA	University of Arizona (privately sponsored)	Biosphere 2 [RD11] [RD12] [RD65]	Facility conceived for large scale investigation of integrated life support systems and constructed close to Tucson, Arizona. A 1.2 ha atmospherically closed structure containing crew habitat modules, various ecosystems including plants and animals and a large 15m^2 cultivation area providing 83% of the food for the human crew. The first tests were conducted for a two-year period from 1991-1993 with eight crew members, then in 1994 with seven crew members. 100% of the water and air were provided. Human solid body waste were dried. Decline in atmosphere oxygen concentration was measured after facility closure in 1991.	Facility constructed in the late 1980s. The facility has not operated as a fully closed life support system since 1994. Biosphere 2 design was modified. The University of Arizona assumed ownership of the facility in July 2011.

Europe	ESA	MELiSSA [[**RD*13***] [RD14]	European project of modular and controlled regenerative closed-loop life support systems investigating waste processing using microbial systems, photosynthetic cyanobacteria and higher plants for biomass, O2 production and water recovery. The MELiSSA Pilot Plant (MPP) is an ISO9001 certified external laboratory of ESA located at the Campus of Universitat Autònoma de Barcelona (UAB), Spain. The MPP is devoted to the long-term and continuous feasibility demonstration of the MELiSSA closed-loop concept on the ground, under the supervision of a control system using knowledge-based models reproducing each compartment's individual characterization and intercompartment dynamic. The development of the facility aims for the integration of 5 compartments: microbial degradation of organic wastes (Compartments 1 and 2), nitrification (Compartment 3), air revitalization and edible material and oxygen production by cyanobacteria and plants (Compartment 4a and 4b respectively, with C4b consisting today in a $5m^2$ hydroponic culture plant chamber working with lettuce and kale as plant model) and the crew compartment, consisting of an animal isolator (Compartment 5). The MPP is developed in a stepwise approach, according to availability of fundamental knowledge, models, compartments and interfaces. In parallel to the MPP, a 2.16m2 research facility, Plant Characterization Unit (PCU), was developed in 2019 at the Laboratory of Crop Research for Space of the University of Naples (Italy). The MELiSSA PCU enables terrestrial scientific investigation and characterization of higher plants in view of their integration into a life support system for food production, air revitalisation and water purification.	Initiated in 1987. The first MPP operational activities started in a laboratory located at ESA ESTEC. In May 1995, the laboratory was transferred to UAB. In 2009, a new dedicated laboratory was opened at the UAB School of Engineering. Today the MPP operates with a mock-up crew of rats mimicking human respiration (compartments are aimed to be scaled up to achieve oxygen and water production equivalent to the needs of one human, with 20% concomitant production of food). As a subsequent step, the MELiSSA project ambitions to integrate a human crew compartment.
Japan	Institute for Environmental Sciences of Japan	CEEF (Closed Ecological Experiment Facility) [RD11] [RD15] [RD16] [RD17] [RD65]	CEEF was developed primarily to track radio isotopes through closed ecosystems but was also used to study controlled environment agriculture and human life support. Facility located in the Rokkasho Village of Aomori Prefecture and composed of three independent modules: a plant cultivation module ($150m^2$ cultivation area, a closed animal breeding and habitation experiment facility (goats) and a closed geo-hydrosphere experiment facility. Tests were conducted between 2005-2007 with two crew members and two miniature goats for periods up to four weeks during which the crew ate the food grown inside the facility while the two miniature goats also enclosed in the facility were fed inedible parts of the plants. Plants provided oxygen, water and 82% of the vegetarian diet for the two human crew members. Fecal matter was handled by pyrolysis and processed waste was carried out. Oxygen was provided to the crew members and goats from plant while solid amine was used for CO2 separation and reutilization in photosynthesis. CEEF used gravity dependent watering concepts targeted for planetary surface settings.	Construction of the facility started in 1994 and was completed in 1999. Human life support related tests conducted until 2007.

China	Beihang University	Lunar Palace 1 [[**RD*11***] [RD18] [RD19] [RD65]	Facility located at Institute of Environmental Biology and Life Support Technology, Beihang University, Beijing, China. The facility has currently a total area of 160m^2 and consists of two higher plant chambers and a crew module including four private bedrooms, a living room, a bathroom and an insect culturing unit. Lunar Palace 1 integrates higher plant cultivation, animal protein production, urine nitrogen recycling, and bioconversion of solid waste. A 105-day airtight test was conducted in 2014 with three crewmembers, where environmental conditions were maintained, 100% of the oxygen and water and 55% of the food were provided for three crewmembers (crop cultivation area of 69m^2), 20.5% nitrogen recovery from urine, 41% solid waste degradation (worm-assisted fermentation for inedible plant biomass and feces), and a small amount of insect *in situ* production were achieved. More recently, a 370-day closure experiment was performed including three consecutive phases of four crewmembers each.	Lunar Palace 1 facility was built in 2014 and upgraded for the 370-isolation test in 2016.

Table 1. World-wide Closed-loop Life Support Systems Initiatives

4. PROJECT DRIVING VISION AND STRATEGIC GOALS

Project Vision and Strategic Goals for 2025-2040

The MELiSSA project aspires to achieve the highest degree of system closure and sustainability in space, empowering crewed missions to operate with complete autonomy from Earth. Through maximized knowledge and innovation, MELiSSA strives to advance environmental and resource management on Earth and to establish itself as an inspirational leader in closed-loop life support systems on the global stage.

The MELiSSA project long-term vision translates into four strategic goals for 2025-2040 [[**RD*21***]:

(Goal 1) Being a global leader in the field of modular and controlled closed-loop life support systems

(Goal 2) Strengthening European unique capabilities in the field of advanced regenerative life support systems for space habitation

(Goal 3) Contributing to a more circular and sustainable management of resources on Earth and mitigating environmental changes

(Goal 4) Driving public awareness, nurturing the development of European STEM talents in the fields of closed-loop life support and circular systems and inspiring future sustainability leaders

Given its multi-application nature, the MELiSSA project is naturally called upon to respond to a wide range of needs and stakeholders, reflected in the four aforementioned goals. During the elaboration of its strategy, the MELiSSA consortium focused on defining distinct deliverables, as well as their specific completion timeline, corresponding to each of the strategic goals. These deliverables are detailed in the following chapters but may need to be revisited depending on the evolution of the MELiSSA project landscape and stakeholders.

5. MELISSA: A GLOBAL PIONEER FOR MODULAR AND CONTROLLED CLOSED-LOOP LIFE SUPPORT SYSTEMS

Project Strategic Goal 1

The MELiSSA project aims to be a global leader in the field of modular and controlled closed-loop life support systems.

Project Strategy for Goal 1

To ensure a credible and convincing leadership position on the international scene (**Goal 1**), the MELiSSA project aims to address the most elaborate example of a closed-loop ECLSS. The knowledge, expertise and know-how generated with such an exercise can later be flowed down and tailored to a wide range of space exploration scenario and applications. The project hence focuses on the following strategical approach:

1. Study, design, model and simulate a modular and closed-loop life support system based on transformation processes. This reference assembly of technologies, or loop, shall be seen as a key tool for the project to understand and control the behaviour of complex closed-loop systems. This loop shall also abide by the following guiding principles:
    - Recover oxygen, water and food from crew waste.
    - Follow a compartmentalised structure to allow a modular engineering approach, compatible with a wide range of use cases and mission requirements.
    - Follow a bottom-up approach at compartment level, coupled with a continuous evaluation of closure at system level.
    - Follow a technical approach relying on deterministic and mechanistic model-based system engineering.
    - Conform to sub-system and system evaluation based on the ALiSSE (Advanced Life Support System Evaluator) methodology.
2. Develop, assemble, demonstrate, validate and qualify the above-mentioned reference assembly on the ground, for a long duration, for relevant operational scenarios and up to one human in the loop (or representative).
3. Provide expert support for the design, modelling, simulation and evaluation of modular and controlled closed loop life support systems.
4. Thrive for excellence in scientific and engineering activities by:

- Maintaining constant exchange with international space agencies, key actors of the space and terrestrial industry and academia through conferences or working groups (e.g., COSPAR, ICES, MELiSSA Conference, International Water Association, etc.).
- Publishing scientific articles in high-quality scientific journals on a yearly basis (impact factor 2 or higher).
- Adopting and embedding Knowledge Management best practices across the project, including knowledge capture, sharing, and retention processes, to ensure the effective management and utilization of project knowledge throughout its duration [[**RD*22***].

Project Deliverables for Goal 1

The MELiSSA loop concept is elaborated in an iterative approach by the consortium. The concept considered at the time of publication of this strategy document is presented in Figure 1 and further detailed in Table 2. The proposed loop is based on both physico-chemical and biological processes (i.e., mechanical grinding, bioreactors, filtration, etc.) aiming at a total conversion of the organic wastes and carbon dioxide into oxygen, water and food. Over the last thirty-five years, the MELiSSA project has been following a very progressive approach of studying each individual compartment independently: from the selection of the transformation processes (including the selection of the most adequate living organism, either single or multi-cellular), their characterization and modelling using deterministic and mechanistic models up to the development of predictive control models. In parallel, efforts have also been dedicated to the modelling and simulation of the entire loop as well as to the development of predictive dynamic models of the interacting compartments into an interconnected network.

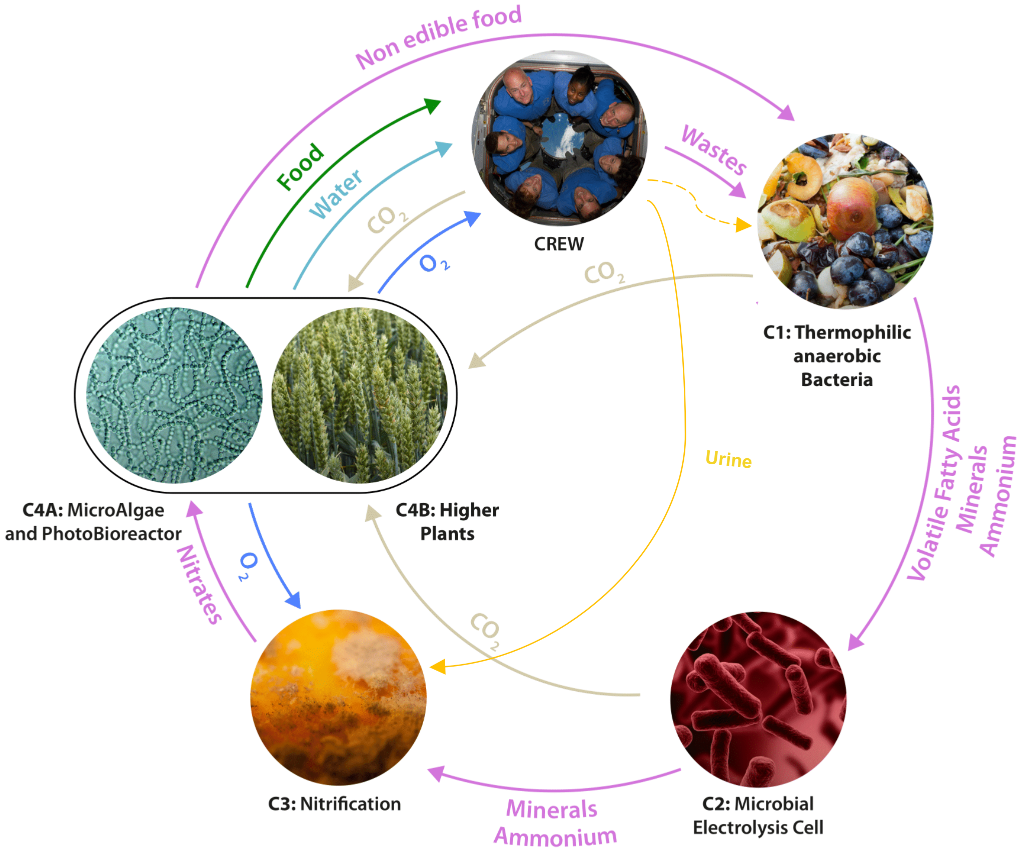

Figure 1. MELiSSA Loop Concept

Compartment	Technology	Function
C1	Thermophilic anaerobic fermentation bioreactor	Thermophilic waste liquefaction. Transforms complex organic waste into simpler molecules by anaerobic digestion in acidic conditions inhibiting methane production. Converts complex organic polymers present in waste into carbon dioxide and ammonium for further utilisation in photosynthetic compartments C4a/C4b and C2/C3, respectively. Volatile fatty acids (mainly acetate and butyrate) are produced as byproducts. First step in the MELiSSA loop. Determines the fraction of organic waste that can be recycled in the rest of the loop.

C2	Microbial electrolysis cell	Total conversion of the organic carbon (volatile fatty acids) coming from C1 into carbon dioxide for further utilization in photosynthetic compartments C4a and C4b.
C3	Urine nitrification bioreactor	Transformation of stabilised urine into nitrate-rich substrate for higher plants and micro-algae cultivation. Alternatively, urine may be (partially) fed to C1.
C4a	Micro-algae photobioreactor	Carbon dioxide fixation, oxygen generation, water recovery and food production.
C4b	Higher plant chamber	Carbon dioxide fixation, oxygen generation, water recovery and food production.
C5	N/A (crew)	Metabolic waste streams production, oxygen, water and food consumption.

Table 2. Compartments of the MELiSSA Loop and Associated Technologies

It is worth highlighting that most of the technologies considered in the proposed MELiSSA loop are also investigated by other space agencies (Annex 5510.1, Table 6).

The deliverables of the MELiSSA Project in relation to **Goal 1** are:

1. MELiSSA Loop Design and Simulation

The most-up-to-date MELiSSA loop design (Figure 1) is available publicly on the MELiSSA Foundation website (melissafoundation.org). To complement the MELiSSA loop design, the MELiSSA project also investigates complementary technologies to further valorise the ultimate by-products of the loop (e.g. production of bio-stimulants or biomaterials for 3D printing, production of nitrogen gas from urine). For clarity, these complementary technologies are not shown on Figure 1. However, the MELiSSA project is open to collaboration to further investigate these technologies.

The **MELiSSA Modelling, Simulation, Control and Evaluation Activities Roadmap** is provided in Annex 10.3.1. In consistency with the priorities identified in the MATHES CDF study [RD23], ESA Explore 2040 [RD27] and the ISECG Global Exploration Roadmap [RD24] [RD25], the mid-term modelling, simulation and control efforts are placed on developing a digital twin of a system showing maximum water and air loop closure, fresh food production and water recovery from solid waste degradation. Calibration and validation of the mechanistic models are performed in various research platforms available to the MELiSSA project (e.g., Plant Characterisation Unit, Algosolis Microalgae R&D Facility, Capture, ISS, etc.) for models of standalone transformation processes, and at the MELiSSA Pilot Plant, for models of transformation processes integrated into a larger life support system.

Mid-term objectives (in line with Explore 2040 strategy, see Chapter 6 on Space Applications):

- Analysis of the degrees of freedom, simulation and control (digital twin) of part of the MELiSSA loop (i.e., C3, C4a, C4b, C5: water and nutrient recovery from urine, air revitalisation and food production) for O2, CO2, CH4 and H2 components in the gas phase and H2O component in the liquid phase. Simulation to be performed both at steady state and in transient state for the study of the system's stability. Data-driven models shall be used for C5 and C4b when appropriate to account for variability.
- Analysis of the degrees of freedom, simulation and control (digital twin) of part of the MELiSSA loop (i.e., C3, C4a, C4b, C5: water and nutrient recovery from urine, air revitalisation and food production) in addition to water recovery from solid wastes for O2, CO2, CH4, H2 and H2O components in the gas and liquid phase. Simulation to be performed both at steady state and in transient state for the study of the system's stability. Data-driven models shall be used for C5 and C4b when appropriate to account for variability.

Long-term objectives:

- Analysis of the degrees of freedom, simulation and control (digital twin) of C1 and C2 (including C5 and C4b as solid waste producers) for C, H, O, N, P and S elements and for electrolytes in the gas, liquid and solid phase. Simulation to be performed both at steady state and in transient state for the study of the system's stability. Data-driven models shall be used for C5 and C4b when appropriate to account for variability.
- Analysis of the degrees of freedom, simulation and control (digital twin) of the entire MELiSSA loop (i.e., C1, C2, C3, C4a, C4b: solid waste transformation, water and nutrient recovery from urine, air revitalisation and food production) for C, H, O, N, P and S elements and for electrolytes in the gas, liquid and solid phase. Simulation to be performed both at steady state and in transient state for the study of the system's

stability. Data-driven models shall be used for C5 and C4b when appropriate to account for variability.

2. MELiSSA Pilot Plant

The MELiSSA Pilot Plant (MPP), an external ESA laboratory located on the campus of Universitat Autònoma de Barcelona, is a modular research and development platform enabling the testing of various ECLSS architectures corresponding to different simulation scenarios. In that regard, the MPP is a tool to generate knowledge and know-how serving different operational scenarios. The MELiSSA Consortium entrusted the MPP, to include a human-crewed ground facility for the development, assembly, demonstration, validation and qualification of the MELiSSA loop design. These tasks are performed in a stepwise approach according to the available fundamental knowledge, mathematical models, compartments hardware and interfaces generated within the MELiSSA project. The integration logic has been so far focused on the gas and liquid phases, starting with photosynthesis. Recent integration and demonstration achievements at the MPP are highlighted in Annex 10.2 Table 7. The foreseen future integration and testing steps are described in the **MELiSSA Pilot Plant Integration and Testing Roadmap** provided in Annex 10.3.2. In consistency with the priorities identified in the MATHES CDF study [RD23] and the ISECG Global Exploration Roadmap [RD24] [RD25], mid-term integration and demonstration efforts will be placed on operational scenarios demonstrating maximum water and air loop closure, fresh food production and water recovery from solid waste degradation.

3. Expert Consultancy and Collaboration

The MELiSSA consortium is available for expert consultancy or collaboration (e.g. but not limited to space agencies and organisations, aerospace and space industries, environmental and sustainability organisations, agricultural and food technology companies, water and waste management industries, health and biotechnology companies, research institutions and universities). Consultancy and collaboration request are facilitated through the MELiSSA Project Manager or the MELiSSA Foundation. A comprehensive overview of the consortium's expertise, along with the MELiSSA innovations to date, is available for consultation on the MELiSSA Foundation website (melissafoundation.org).

4. Knowledge Management and Technical/Scientific Material Sharing

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Even though MELiSSA was born as a space project, it encompasses today a much wider range of topics beyond human spaceflight. Particularly at a time where resource management, circular economy, environment protection and waste disposal have become priorities for a sustainable life on Earth, terrestrial applications as well as education and outreach act as a sounding board for the MELiSSA project [RD26]. Building up on the know-how and expertise acquired in the generation of the aforementioned deliverables, the MELiSSA project is hence well positioned to answer the needs of key stakeholders in space (**Goal 2**), terrestrial (**Goal 3**) and education and outreach sectors (**Goal 4**). In the following chapters, a detailed strategy and associated deliverables have been derived for each of these application areas which are interdependent and benefit each other.

The MELiSSA applications areas bring their own set of requirements, timeline and financial considerations, but synergies are key to the success of the project [RD26]. The mid and long-term human space exploration needs call for the development of innovative life support systems for space habitats, which directly inform short-term challenges for Earth-based industries, particularly in waste management, resource recycling, and sustainable agriculture. The multiple opportunities for terrestrial applications, in turn, provide complementary funding sources for technology maturation and valuable insights from real-world long-term testing grounds for space technologies, ensuring their robustness, reliability and effectiveness. Education and outreach efforts serve as a critical bridge, disseminating MELiSSA's scientific advancements to a broader audience, inspiring the next generation of researchers and engineers, and fostering public understanding and support for space exploration and environmental sustainability. This three-way interaction ensures that the project remains not only relevant to the evolving challenges of human space exploration but also a valuable contributor to Earth's sustainability agenda, while cultivating a highly skilled workforce to tackle these global challenges. This synergic approach also strengthens the project's technical, financial, and political resilience, maximizing its potential across all sectors, and ensuring long-term success and impact.

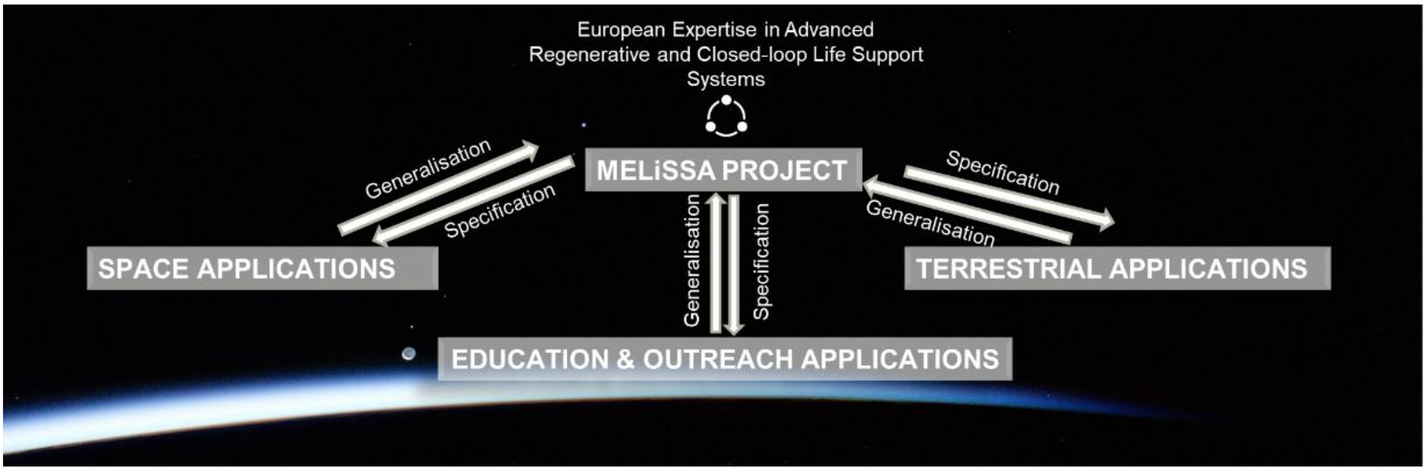

Figure 2. Areas of Applications of the MELiSSA Project and their Synergies

6. SPACE APPLICATIONS: PAVING THE WAY FOR NOVEL HABITATION SYSTEMS

Project Strategic Goal 2

The MELiSSA Project aims to strengthen European unique capabilities in the field of advanced regenerative life support systems for space habitation.

Project Strategy for Goal 2

Future ECLSS design will be driven in large part by mission scenarios (e.g., deep space, lunar surface, Martian surface). Depending on the chosen mission drivers, various ECLSS architectures could be considered to enable long duration missions outside the vicinity of Earth, where resupply logistics will differ from the current LEO strategy. These ECLSS solutions can be classified within a range bounded by two limit cases: embarking all the required metabolic resources with no recycling onboard, which would result in an unrealistic launch mass; or complete recycling of metabolic resources onboard, which would result in a high system complexity and mass.

It is anticipated that a future human deep space exploration campaign would be NASA-led, with multiple strategic opportunities for European contribution. One identified candidate area for ESA leadership is in the domain of habitation systems [RD27]. It is recognised that the first deep space habitat will utilize legacy ISS systems, upgraded to a next generation level and used in a hybrid combination with innovative technologies, which have the potential not only to recycle oxygen and water, but also to retrieve other vital elements (e.g. carbon, nitrogen, vitamins, minerals) and to provide food. Hence dramatically reducing the needed upload mass and further closing the life support system [RD20] [RD29] [RD30] [RD31].

To meet **Goal 2**, the MELiSSA Project proposes the following approach:

1. In alignment with the ESA Explore 2040 Strategy [RD27], driven by the Deep Space Habitat Simulator Initiative and the exploration-focused science habitation thematic workplan, the MELiSSA project advocates for de-risking the most critical technologies, or technology assemblies, to enable European leadership in hybrid ECLSS architecture configurations. The goal of technology maturation and de-risking is to ensure the availability of these technologies so that they can be considered for inclusion in deep space habitat ECLSS architecture trade-offs. From the preliminary set of requirements

formulated in the ESA MATHES Concurrent Design Facility study [RD23] and in consistency with GER-029 and GER-030 (Closed-loop Life Support Systems and Enhanced Reliability Life Support Systems [RD24]), the following high-level recommendations can be formulated for any deep space ECLSS architecture:

- Further closure of the air and water loop is critical.
- Fresh food production and water recovery, including from solid waste, must be considered.

Following these recommendations, the MELiSSA project seeks to derisk in priority the following functions (Figure 3) [RD33] [RD34] [RD35]:

- Atmosphere revitalization: aiming for further oxygen loop closure by transforming carbon dioxide into oxygen.
- On-board food production and preparation: aiming for fresh food complement production.
- Water and nutrient recovery: aiming for further water loop closure by processing yellow and grey water.
- Non-body solid waste processing: aiming for volume reduction microbial inhibition, long-term storage, biomaterial degradation and water recovery.
- Waste valorisation: aiming to reduce systems logistics (i.e., re-using ultimate byproducts of MELiSSA transformation processes for other complementary applications, such as bio-stimulants production for higher plant growth).
- Waste valorisation: aiming to increase technologies' maintainability (i.e. 3D-printed spare parts from biomaterials, chemical feedstock, biodegradable food and beverage packaging).
- Modelling, simulation, control and system evaluation: aiming to support ECLSS architecture design and trade-off analysis using the ALiSSE methodology.

Figure 3. Life Support System Functions to be Derisked for Space Applications

The proposed de-risking approach aims to bring technologies or assemblies of technologies to adequate maturity for integration into an operational system. This approach, which is mission-agnostic up to TRL 7 if the technologies or assemblies are not subject to scaling effects, relies on progressive steps of ground-based, LEO and cis-lunar/Moon surface testing, is two-fold (Figure 4):

- Bring selected technologies or assemblies of technologies up to TRL7 maturity by:
  - Pursuing continuous fundamental research on the ground to close science knowledge gaps.
  - Maturing and validating the simulation and control models of the transformation processes on the ground.
  - Investigating and demonstrating the stability of the transformation process (at function level) and of the living organisms responsible for the transformation, in space conditions (LEO and/or lunar environment) through exploration focused science experiments.
  - Validating the simulation and control models of the transformation processes in space conditions through exploration focused science experiments.
  - Flying technology demonstrators to validate the robustness and the reliability of critical sub-systems in LEO and/or lunar environment. Technology

demonstrators shall be representative versions of the technology foreseen to be integrated into a final operational system (i.e., representative in terms function, design or performance).

- Performing long duration human-in-the-loop integrated testing on the ground to demonstrate the performance, robustness and reliability of the technologies and to address closed-loop systems challenges such as technology connection at gas, liquid and solid phase, trace elements circulation or contaminants accumulation.

- Continue the effort to the point of TRL 9 fly-ready hardware for integration into future missions' operational systems.

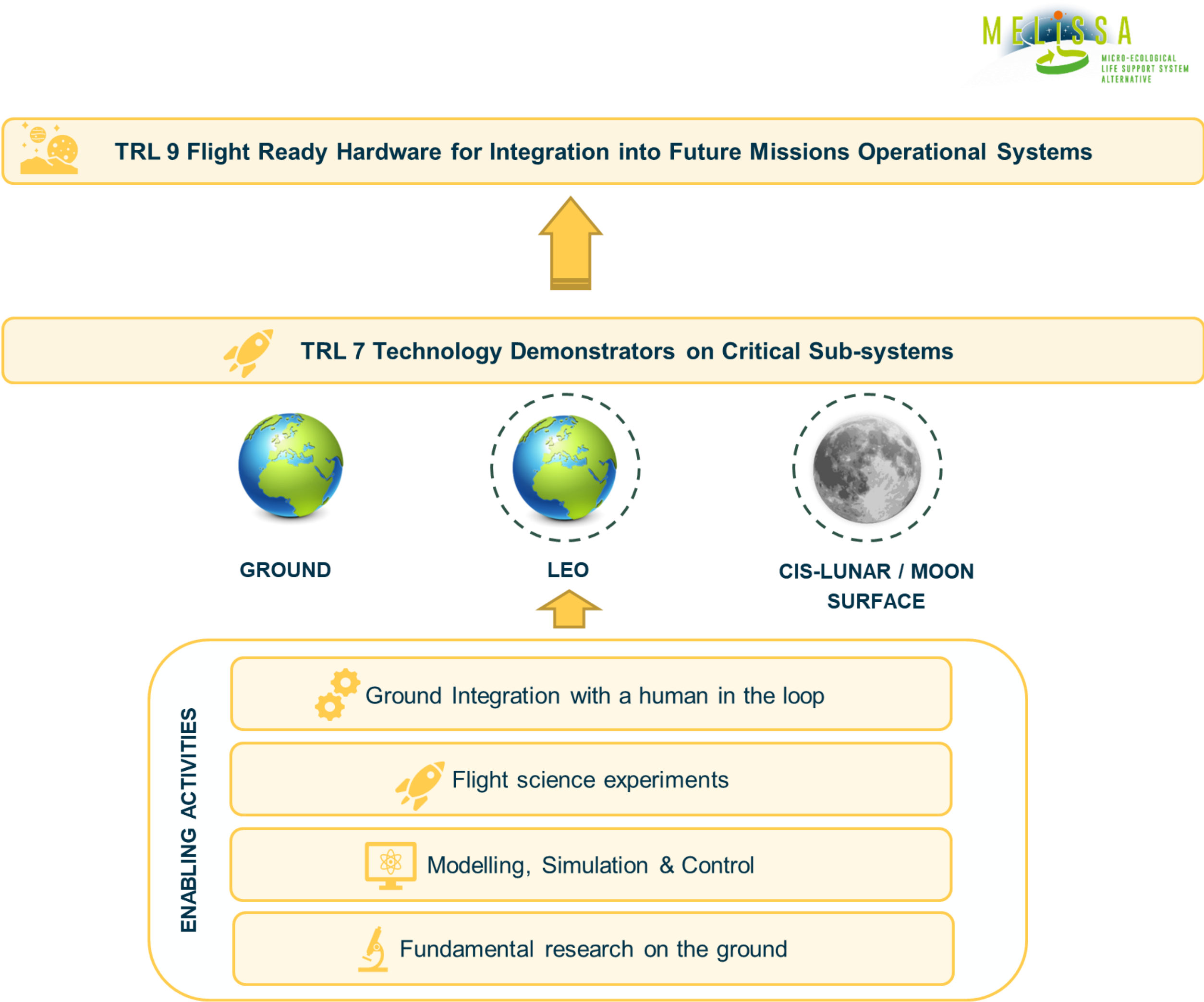

Figure 4. MELiSSA Derisking Approach for Technologies Maturation

2. The development of regenerative technologies requires collaboration across a wide range of disciplines and consideration of multiple domains that impact the physical,

physiological, psychological, and social well-being of astronauts. These include nutrition, comfort, mental health, exercise, radiation protection, waste management, closed-loop interaction between humans, microbes and habitat ecosystems, impact of the space environment and stress on the crew microbiota, and more. The MELiSSA consortium seeks to incorporate insights from these interconnected fields. Insights may be generated during the ESA Exploration 2040 exploration driven science studies.

3. The MELiSSA Project is committed to strengthen European unique capabilities in advanced regenerative and closed-loop life support systems in support of ESA Explore 2040 strategy. The MELiSSA Project expertise in the design, development, integration and evaluation of modular and controlled advanced life support system architectures can be leveraged to inform ECLSS architecture system studies and trade-offs.

4. Thrive for excellence in scientific and engineering activities by:
   - Maintaining constant exchange with international space agencies, key actors of the space industry and academia through conferences or working groups (e.g., COSPAR, ICES, MELiSSA Conference, etc.).
   - Publishing scientific articles in high-quality scientific journals on a yearly basis (impact factor 2 or higher).
   - Adopting and embedding Knowledge Management best practices across the project, including knowledge capture, sharing, and retention processes, to ensure the effective management and utilization of project knowledge throughout its duration [RD22].

Project Deliverables for Goal 2

The deliverables of the MELiSSA Project in relation to **Goal 2** are:

1. MELiSSA Flight Hardware Development

Based on a continuous evaluation through ALiSSE (Advanced Life Support System Evaluator) [RD36], the MELiSSA project took the initiative to consider some technology-push options for each of the functions identified in Figure 3. The technologies proposed for derisking are not studied independently but instead are to be considered as part of a closed-loop system development. Other technology options remain open depending on the still-to-be-defined baseline ECLSS architecture. Technology push options considered for derisking are identified in Table 3 and include, when applicable, the selection of one or more living organisms [RD2] [RD37]. The science knowledge gaps to close as well as the incremental demonstration steps leading to the development of operational systems are encompassed in Annex 10.3.3, **MELiSSA Flight Hardware Development Roadmap**.

2. Scientific collaboration with interconnected domains impacting the physical, psychological, and social well-being of astronauts

The MELiSSA consortium continuously seeks cross-disciplinary scientific collaboration to address the interconnected challenges associated with regenerative ECLSS development (e.g. but not limited to crew nutrition, comfort, mental health, exercise, radiation protection, waste management, closed-loop interaction between humans, microbes and habitat ecosystems, impact of the space environment and stress on the crew microbiota). Collaboration requests are facilitated through the MELiSSA Project Manager or the MELiSSA Foundation.

3. Expert Consultancy and Collaboration

The MELiSSA consortium is available for expert consultancy or collaboration (e.g. but not limited to space agencies and organisations, aerospace and space industries, research institutions and universities). Consultancy and collaboration request are facilitated through the MELiSSA Project Manager or the MELiSSA Foundation. A comprehensive overview of the consortium's expertise, along with the MELiSSA innovations to date, is available for consultation on the MELiSSA Foundation website (melissafoundation.org).

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	ECLSS Function	Technology showing potential to meet exploration goals	Living Organism	Technology Demonstrator (TRL as of 2025)
	Atmosphere Revitalisation	Photobioreactor	Arthrospira (a.k.a. Limnospira Indica)	BIORAT-1 (TRL 4)
	On-board Food Production and Preparation			
	Atmosphere Revitalisation	Food Production Unit	Tubers	PFPU (Precursor of a Food Production Unit) (TRL 4)
	On-board Food Production and Preparation			
	Water and Nutrient Recovery	Urine Nitrifying Bioreactor	To be determined	BIORAT-2 (TRL 3)
		Urine Inhibition and Nitrogen Gas Recovery Bioreactor	Heterotrophic bacteria, aerobic ammonium oxidizing bacteria, anaerobic ammonium oxidizing bacteria (to be determined)	NITROGENISOR (TRL 3)

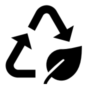
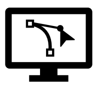
		Grey Water Treatment Unit	Not Applicable (Membrane-based technology)	GWTU (TRL 4-5)
	**Solid Waste Processing**	Non-body solid waste Compaction, Stabilisation and Biomaterial Degradation	To be determined for biomaterial degradation. Not Applicable for compaction and stabilization (physical methods based on mechanical force and heat, respectively).	BIOPACK (TRL 2-3 for compaction and stabilization, TRL 3-4 for waste degradation
	**Waste Valorisation to Reduce System Logistics**	Bio-stimulant production for plant growth	Arthrospira (a.k.a. Limnospira Indica)	To be determined
	**Waste Valorisation to Increase Technologies' Maintainability**	3D-printed spare parts from biomaterials, chemical feedstock, biodegradable (food & beverage) packaging	Not Applicable	To be determined
	**Modelling, Simulation, Control and System Evaluation**	Methodology for circular system design, modelling, simulation, control, evaluation (ALiSSE).	Not Applicable	To be determined

Table 3. Technology Push-Options Considered for Derisking [RD37]

7. TERRESTRIAL APPLICATIONS: TOWARDS A MORE RESILIENT AND SUSTAINABLE SOCIETY

Project Strategic Goal 3

The MELiSSA project aims to contribute to a more circular and sustainable management of resources on Earth and to mitigate environmental changes.

Project Strategy for Goal 3

In recent years, Europe has witnessed an increasing urgency in addressing several fundamental environmental issues, driven by escalating concerns over climate change, resource depletion, and environmental degradation. The European Union has recognized these challenges and made significant strides toward sustainability through initiatives like the European Green Deal, which aims to make Europe the first climate-neutral continent by 2050 [RD38]. Additionally, the growing focus on circular economy emphasizes the need for innovative solutions to manage waste, conserve resources, and reduce carbon emissions (Circular Economy Action Plan, European Parliament, 2020) [RD39]. This also aligns with the global framework established by the United Nations 2030 Agenda for Sustainable Development, which calls for urgent action to combat climate change and its impacts, while fostering sustainable economic growth (2030 Agenda for Sustainable Development, United Nations, 2015) [RD40]. As outlined in the European Environment Agency's report [RD41], addressing these multifaceted challenges demands the integration of cutting-edge innovations in areas such as resource management, renewable energy, and waste reduction. In that regard, ESA's Agenda 2025, and specifically ESA's Green Agenda, underscores the critical role of space technologies in addressing these environmental challenges [RD42] [RD43]. The agenda specifically highlights the importance of green commercialization, aiming to leverage space-based innovations to accelerate the transition towards a sustainable Europe.

MELiSSA's innovative approach for human space exploration aligns with core principles of circular economy, emphasizing resource conservation, waste reduction, and the sustainable management of essential materials. The project thus offers an obvious pioneering framework for advancing sustainability on Earth, bridging the gap between space exploration technologies and the urgent need for innovative solutions to address global environmental and resource management challenges.

The strategy of the MELiSSA project for Earth-based applications naturally includes a multi-faceted approach, spanning both commercial and humanitarian sectors, each with distinct but complementary goals. On the one hand, the commercialization of MELiSSA's innovations can create market-driven solutions that meet the needs of businesses, governments, and individuals, while also contributing to sustainability goals. On the other hand, the application of MELiSSA's innovations in humanitarian efforts ensures that it sustains initiatives that have a broader social and environmental impact, benefiting the most vulnerable populations, especially those in crisis or underserved regions.

This hybrid strategy is enabled by a diverse range of tools, already available to the MELiSSA project, namely:

- the ESA Technology Broker network which facilitates the transfer of technology for commercial purposes, using space technology to meet industrial challenges and terrestrial innovations to meet space ones.
- the ESA Phi-lab network which supports groundbreaking science and technology development with high commercial potential, offering co-funding and technical assistance to explore business concepts.
- the ESA Business Applications and Space Solutions (BASS) programme which supports the development of sustainable services and products utilising space assets (i.e., technology, data, knowledge), offering funding opportunities and expert support to entrepreneurs with ESA kick-start, feasibility studies and demonstration projects.
- MELiSSA spin-offs and industrial technology providers which offer a frame for technology maturation.

To meet **Goal 3**, the MELiSSA Project advocates for the following approach:

1. Boosting collaboration with the terrestrial sector
    - Facilitate exchange of knowledge through publications, workshops and conferences with external organisations and networks (e.g. European Innovation Council).
    - Foster collaboration with R&D platforms in the private sector to support the intensification of MELiSSA activities.
    - Foster interdisciplinary collaboration and networking between researchers, engineers and industries to create complete value chains.
    - Seek additional support from European bodies (e.g., European Commission).

2. Engaging in activities with commercialisation potential
    - Foster the generation of patents to share MELiSSA innovations.
    - Transfer knowledge by providing professional training on MELiSSA innovations.
    - Provide consulting services for businesses or institutions seeking to transition to more sustainable practices and to adopt circular economy principles.
    - Demonstrate and validate technologies' economic viability and scalability, for instance through pilot trials with users/customers in a real utilisation environment in the frame of the ESA BASS programme (Figure 5)
        - Step 1
            - Identify terrestrial sectors facing similar sustainability challenges.
            - Identify transferable technologies.
            - Implement pilot technology transfer projects for the identified sectors.
            - Foster the creation and development of spin-offs to enable the commercial maturation of technologies.
        - Step 2
            - Raise interest of the key resource management industries and technology transfer pioneers to scale-up successful pilot projects to full-scale implementations in diverse environments.
            - Create sustainable integrated economic models "from waste to valuable bioproducts".
            - Support the commercialization and industrial deployment of technologies.

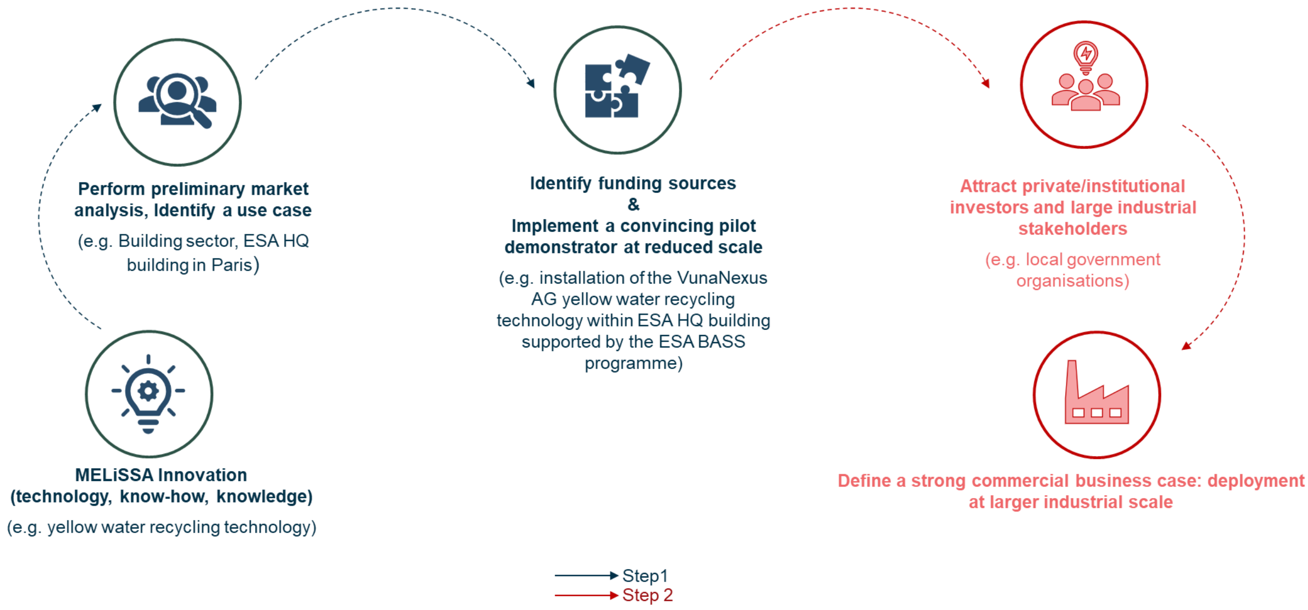


Figure 5. Pilot Technology Transfer Projects and Technology Scale-up

3. Engaging in humanitarian and non-commercial activities
   - Seeking collaboration with Non-Governmental Organisations (NGO) (e.g., international aid or environmental organisations such as Belgian NGO Congodorpen [RD44]) or government-backed sustainability programs (e.g. the Netherlands Water Partnership financed by the Dutch Ministry of Agriculture, Nature, and Food Quality [RD45]).
   - Supporting the development of sustainable communities (e.g., promoting sustainable food and water systems).
   - Supporting disaster relief, emergency response or under-resourced areas (e.g. promoting temporary/mobile solutions for water purification, food production in areas suffering from chronic malnutrition and waste management in emergency settings).
   - Supporting environmental conservation (e.g., promoting temporary/mobile solutions for decentralized and sustainable management of resources; promoting regenerative solutions to reduce environmental footprints).

4. Thrive for excellence in scientific and engineering activities by:
   - Maintaining constant exchange with key actors of the terrestrial industry and academia through conferences or working groups (e.g., MELiSSA Conference, International Water Association, etc.).

- Publishing scientific articles in high-quality scientific journals on a yearly basis (impact factor 2 or higher).
- Adopting and embedding Knowledge Management best practices across the project, including knowledge capture, sharing, and retention processes, to ensure the effective management and utilization of project knowledge throughout its duration [RD22].

Project Deliverables for Goal 3

The deliverables of the MELiSSA Project in relation to **Goal 3** are:

1. Collaboration with the Terrestrial Sector: Innovation and Knowledge Sharing

The MELiSSA consortium is available for expert consultancy or collaboration (e.g. but not limited to environmental and sustainability organisations, agricultural and food technology companies, water and waste management industries, health and biotechnology companies, research institutions and universities). Consultancy and collaboration request are facilitated through the MELiSSA Project Manager or the MELiSSA Foundation. A comprehensive overview of the consortium's expertise, along with the MELiSSA innovations to date, is available for consultation on the MELiSSA Foundation website (melissafoundation.org).

2. Pilot Technology Transfer and Maturation Projects in Preparation for Commercialisation

The MELiSSA project has already resulted in the development and maturation of a wide range of innovative technologies for Earth-based applications. These technologies, some of which have been further advanced by MELiSSA spin-offs, and others by external technology providers who have leveraged MELiSSA's foundational knowledge and expertise, represent valuable contribution to multiple sectors. The MELiSSA project aims to develop at least one technology transfer and maturation pilot per identified synergic terrestrial sector in preparation for commercialisation (Figure 6). In this perspective, the ESA BASS programme provides an ideal frame for the development of a viable business case, backed up by the data of pilot trials. For consideration, a non-exhaustive list of transferable technologies is outlined in Table 4. The list of existing MELiSSA spin-offs and external technology providers to date, together with the relevant patent publication numbers, is provided in Table 5.

3. Knowledge Management and Technical/Scientific Material Sharing

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The path towards the development and scale-up of pilot transfer projects is depicted in Annex 10.3.4 **MELiSSA Technology Transfer and Commercialisation Roadmap**.

Figure 6. Identified Synergic Terrestrial Sectors Facing Sustainability Challenges

		Sector						
Technology	**Estimated TRL for Earth-based Applications**	**Maritime**	**Building**	**Environment**	**Events**	**Agrifood**	**One Health**	**Humanitarian**
Organic waste recycling (kitchen waste, faecal matter)	3-7	x	x	x	x	x		
Volatile Fatty Acids (VFA) valorisation	3-5		x	x				
Small-scale methaniser	6		x	x				
Bio-facades (microalgae production in buildings facades for CO2 and yellow water valorisation, thermal isolation and microalgae production for multi-application such as feed, food, biomaterials etc.)	5		x	x				
Intensified photobioreactor (intensified microalgae production for multi-	5			x		x	x	x

applications such as feed, food, biomaterials etc.)								
Use of microalgae as bio-stimulant	4			x		x		x
Use of microalgae as biomaterial	3			x				
Production of micro-organism for health applications (anti-cholesterol)	4						x	
CO2 capture from carbon intensive industries (e.g. cement factories, wine and beer brewery)	5		x	x				
Transformation of urine into fertiliser	9		x	x		x		
Yellow water recycling	3-5	x	x		x			x
Grey water recycling (shower, sink, dishwasher, washing machine, swimming pool, sauna)	9	x	x	x	x			x
Black water recycling	3-5	x	x	x	x			

Vertical Farming/intensive higher plant chamber	4-5					x		
Support to energy balance performance	N/A	x	x	x				
Support to modelling and control of complex processes	N/A	x	x	x				
Support to design, modelling and evaluation of complex circular systems	N/A	x	x	x	x			

Table 4. Non-exhaustive List of MELiSSA Transferrable Technologies for Earth-based Applications

	MELiSSA Spin-off	**External Technology Provider**	**Field of Activity, Technology and Patents**	**Technology Transfer Success Stories**
SEMiLLA IPStar BV (semilla.io)	x		Technology transfer partner and participating party of the MELiSSA consortium. SEMiLLA IPStar is committed to leveraging space technology for sustainable solutions on Earth, addressing challenges in water purification, sanitation, nutrition, and circular	○ SEMiLLA IPStar supported spin-offs ezCOL BV and SEMiLLA Sanitation BV. ○ Brewery Waste to Protein (La Trappe Pilot Project): In partnership with the La Trappe brewery in the Netherlands, SEMiLLA IPStar established a pilot facility that uses purple bacteria to convert brewery wastewater into high-protein biomass. This microbial protein serves as a sustainable

				alternative to traditional animal feed ingredients like soy and fishmeal, offering a more environmentally friendly solution for aquaculture and livestock industries. ○ NextGen Circular Water Systems: As part of the EU-funded NextGen project, SEMiLLA IPStar contributed to large-scale demonstrations of circular water technologies across Europe. These initiatives focus on water reuse, energy recovery, and nutrient recycling in urban and rural settings, aiming to transform wastewater treatment plants into resource recovery hubs. ○ SEMiLLA Circular Economy Hub – Málaga, Spain: SEMiLLA IPStar is developing a Circular Economy Hub in Málaga in collaboration with the University of Málaga and the Technology Park of Andalusia. This hub serves as a platform for research, education, and innovation in circular economy practices, focusing on sustainable urban development and the integration of space-derived technologies into everyday applications. ○ Barapullah Water Treatment Pilot – New Delhi, India: In New Delhi, SEMiLLA IPStar is involved in the LOTUS project, which aims to demonstrate holistic wastewater management approaches along the Barapullah drain. The project focuses on recovering water, energy, and nutrients from urban wastewater, contributing to

				improved sanitation and resource management in rapidly urbanizing areas.
SEMiLLA Maritime Solutions (semillamaritime.solutions)	x		MELiSSA technology transfer spin-off targeting circular water treatment in maritime environments. Supporting technical entities: Hydrohm, FIRMUS and SEMiLLA Sanitation.	In a project supported by ESA, SEMiLLA Maritime Solutions has constructed a demonstration container in collaboration with Hydrohm and FIRMUS.
SEMiLLA Sanitation Hubs BV (semillasanitationhubs.com)	x		A spin-off from SEMiLLA IPStar that developed mobile sanitation units that convert urine, greywater, and blackwater into clean water and nutrients. These systems are designed for deployment in disaster zones and remote areas, addressing critical public health challenges and supporting the United Nations' Sustainable Development Goal 6 for clean water and sanitation.	○ From ground pollutions to food solutions in Uganda: the Circular Refugee Camp (CRC) consortium, consisting of SEMiLLA Sanitation, SkillEd, and two local companies won the 2022 Water for Food Proposal. The consortium received financial support for their project from the Water for Food Programme, initiated by the Netherlands Water Partnership and financed by the Dutch Ministry of Agriculture, Nature, and Food Quality [RD45]. ○ Silvolde project (NL): the realization of sustainable, climate-adaptive homes. A locally closed water cycle is one of the objectives: the washing machine washes with rainwater, domestic wastewater is treated.
ezCOL BV (ezcol.com)	x		A spin-off from SEMiLLA IPStar that developed a bacterium (Rhodospirillum Rubrum) capable of reducing LDL cholesterol by up to 50%. Originally researched for astronaut nutrition, this bacterium has undergone successful	ezCOL has successfully raised over 2.000K€ in cash and 2.300K€ in in-kind contributions. Their achievements include conducting pre-clinical studies on the cholesterol-lowering capabilities of R. Rubrum in various animal species, such as chickens, eggs, mice, rats,

			Phase IIa clinical trials with Maastricht University and is being positioned for use as a food supplement or pharmaceutical product. Relevant patent publication numbers: o US/2020/0101120A1 o NL/2024/271B1 o NL/2026/903B1 o US/2022/0331373A1	and pigs. Additionally, they have collaborated with the University of Maatstricht (NL) to conduct clinical studies in human volunteers. Notably, in 2024, ezCOL has licensed all its intellectual property to Curador S.A., which is currently engaged in negotiations for a joint venture with a spin-off of the University of Mons.
SEMiLLA Health BV	x		Subsidiary of ezCOL. Relevant publication number: o NL/2028/872B1 o WO/2023/009000A1	
Hydrohm BV (hydrohm.com)	x		Electrochemical process development company which provides innovative and sustainable solutions for resource recovery and wastewater treatment. Relevant patent publication numbers: URIDIS technology o To be completed	o URIDIS yellow water treatment pilot installed on the recreational domain 'De Blaameersen' in Gent. Belgium from July to September 2021. o Two URIDIS yellow water treatment pilots were installed at two schools during summer 2022: campus Sint Hendrik (Leiepoort) in Deinze, Belgium and College O.-L.-V.-ten Doorn in Eeklo, Belgium.
FIRMUS (firmus.net)		x	Company which develops membrane-based technologies for grey water treatment.	o Grey water recycling at Concordia research station in Antarctica. More than 8 million Liters of grey water recycled since 2005. o Grey water recycling at the Rolland Garros Tournament since 2020. More

			Relevant patent publication numbers FIRMUS Grey Water Recycling System: ○ 2020/3111825 (4171788)	than 30 000 Liters of grey water recycled at each tournament edition. ○ Mosa Ballet School, Liège, Belgium. More than 100 000 Liters of grey water recycled. ○ Laundry Company Anett, Ardennes, France. More than 4 100 000 Liters of grey water recycled. ○ Swimming pool and changing rooms of Monaco Yacht Club. More than 2 800 000 Liters of grey water recycled. ○ - Monaco Oceanography Museum. More than 40 000 Liters of grey water recycled.
VunaNexus AG (vunanexus.com)		x	Sister company of Vuna GmbH, spin-off of EAWAG. Company focusing on microbial-based urine treatment technology and fertiliser production. Relevant patent publication number (Vuna process): ○ WO/2018/100069	○ Yellow water recycling at ESA Head Quarters as an ESA BASS demonstration project. More than 8900 liters of yellow water treated, and 160 liters of fertilizer produced in February 2025 since installation. ○ Yellow water recycling in two pig farms in Switzerland aiming to reduce ammonia emissions by 80% and to reduce synthetic nitrogen imports. ○ Yellow water recycling on the campus of Pictet Bank, Geneva.
AlgoLight (algolight.com)		x	Company focusing on the controlled and intensified production of microalgae through an innovative PRIAM patented photobioreactor technology. Relevant patent publication numbers: PRIAM-Algolight ○ FR1661496A	To be completed

			○ WO2018096107 ○ US16463893	
To be completed		x	Company focusing on the valorisation of micro-algae into products with added value for a wide range of applications including health. Relevant patent publication numbers: AlgoFilm, a thin-layer photobioreactor with high volume productivity. ○ FR0956870 ○ US20120252112A1	To be completed

Table 5. List of MELiSSA Spin-offs and External Technology Providers to Date

8. EDUCATION AND OUTREACH APPLICATIONS: PROMOTING STEM TALENTS AND INSPIRING SUSTAINABILITY LEADERS

Project Strategic Goal 4

The MELiSSA project aims to drive public awareness, nurture the development of European STEM talents in the fields of closed-loop life support and circular systems and inspire future sustainability leaders.

Project Strategy for Goal 4

To meet **Goal 4**, the MELiSSA project advocates for the following approach (Figure 7) [RD46]:

1. Communicating on the project's achievements

The MELiSSA project aims to increase public awareness of technological advancements and potential space and Earth-based applications through consistent and targeted communication. The project actively participates in high-profile outreach events, conferences, and media campaigns to reach a wide audience. This includes engaging with scientific publications, educational platforms, and media outlets to disseminate the results of MELiSSA's cutting-edge research and developments as well as successful project milestones. Additionally, MELiSSA's website, social media platforms, and public reports are used as dynamic tools for continuous communication with external stakeholders, demonstrating the project's positive impact on space exploration and sustainability.

2. Engaging a broad community

The MELiSSA project strives to engage a wide community of professionals, researchers, industry partners, and the public to create a collaborative environment that encourages shared knowledge and interdisciplinary solutions. In this regard, conferences facilitate the exchange of knowledge between international experts, industry leaders, and researchers. MELiSSA-related conferences shall cover emerging topics in space-based regenerative closed-loop systems and Earth-based circular systems. In addition to the conferences, networking events shall be organized between the participating parties of the MELiSSA consortium and external stakeholders to encourage collaboration, the formation of partnerships, and the exploration of synergies between various sectors.

3. Training and inspiring future generations

With the aim to ensure efficient knowledge transfer over the years, the project seeks to equip future generations with the knowledge and skills required to address the circularity challenges of tomorrow, particularly in the field of life support systems for space exploration and sustainable systems for Earth applications. MELiSSA's strategy aims to bring space-related technologies into the educational sector, fostering STEM engagement and encouraging students to explore how space innovations can provide solutions to critical issues on Earth. In that perspective, MELiSSA ambitions to offer a diverse range of educational opportunities fostering interest in space technologies, circularity and sustainability and empowering the next generation of engineers, scientists and leaders.

4. Thrive for excellence in teaching and outreach activities by**:**
    - Maintaining constant exchange with academia through conferences or working groups (e.g., MELiSSA Conference).
    - Adopting and embedding Knowledge Management best practices across the project, including knowledge capture, sharing, and retention processes, to ensure the effective management and utilization of project knowledge throughout its duration [RD22].

This strategy is enabled by a diverse range of tools, already available to the MELiSSA project, namely:

- The ESA_LAB network, an initiative which enables partnerships between ESA and Universities in the Engineering and Business domains, with the purpose of fostering research and innovation in European space activities, their sustainability, and to expand Europe's commercial talent capacity for a future skilled workforce (ESA Agenda 2025). The MELiSSA project is already contributing to the ESA_LABs set up with CentraleSupelec (France) and ISAE-SUPAERO (France) (commercialisation.esa.int/esa-labs/).
- The European Space Education Resource Office (ESERO) project, ESA's main way of supporting early years, primary and secondary education community in Europe (esa.int/Education/Teachers_Corner/European_Space_Education_Resource_Office)
- ESA Academy, which develops and maintains a portfolio of targeted training programmes (esa.int/Education/ESA_Academy/)

Figure 7. MELiSSA Project's Key Objectives for Education and Outreach

Project Deliverables for Goal 4

The deliverables of the MELiSSA Project in relation to **Goal 4** are:

1. Communication of achievements

- The MELiSSA project's progress and achievements are showcased on the MELiSSA Foundation website, available at: melissafoundation.org
- The MELiSSA project's progress and achievements are showcased on the main social media platforms (*MELiSSA Space Research Program* account):

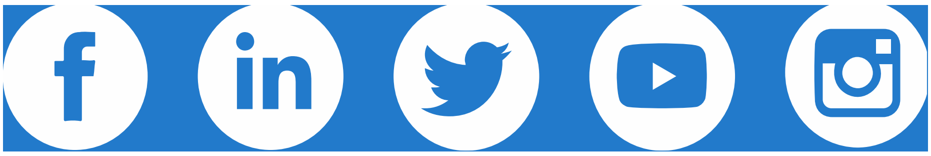

Figure 8. MELiSSA Presence on Social Media

2. Community Engagement

The MELiSSA Conference is an event held biennially, bringing together scientists, engineers, industry leaders and students to present the latest findings and technological advancements in closed-loop life support systems for space exploration and circular systems for sustainable living on Earth. The MELiSSA conference is a forum for sharing knowledge; fostering partnerships between academic institutions, industries, and governmental organizations and for providing a platform for students, researchers, and professionals to network and collaborate on future projects. The programme of past and upcoming conferences is available online:

- 2016: melissafoundation.org/page/LAUSANNE2016 (Lausanne, Switzerland)
- 2018: melissafoundation.org/page/roma (Rome, Italy)
- 2020: melissafoundation.org/page/FULLYVIRTUAL2020 (Online)
- 2022: 2022melissaconference.org (Toulouse, France)
- 2025: 2025melissaconference.org (Granada, Spain)

3. Training and inspiration of future generations

The MELiSSA Project offers the following educational opportunities:

- Dedicated lectures and courses within European elementary, secondary and higher education institutions where MELiSSA experts deliver targeted educational content.
- Supervised students' projects in the frame of the ESA_Labs initiative and internships that enable students to actively contribute to on-going cutting-edge research and development, fostering a deeper understanding of MELiSSA challenges, applications and progress.
- Dedicated PhD and Post-doctoral program (MELiSSA Pool of PhDs and Post-doctoral) ran every four years and including at least one year at the premises of one of the MELiSSA participating parties.
- MELiSSA Summer University**,** an intensive training program held typically every three or four years, offering PhD, post-doctoral students and young professionals with intensive hands-on learning experience.
- Collaboration with educational partners to maximize educational impact through strategic collaborations by offering specialized courses and training modules that are aligned with the project's objectives. As an example, the ESA Academy "Life Support Systems Solutions from Space for Earth" training course, the first in the "Space for Earth" series, is a two-week training session developed by ESA's Education Office in collaboration with the MELiSSA project. The pilot edition was held in 2025.

4. Knowledge Management and Technical/Scientific Material Sharing

All MELiSSA project related technical notes, meetings presentation and minutes of meeting are stored in a MELiSSA dedicated repository (exchange.esa.int/restricted/melissa-partner/), managed by ESA and accessible to all other MELiSSA participating parties. MELiSSA Technical Notes that were produced more than 10 years ago are shared publicly on the MELiSSA Foundation website (melissafoundation.org/page/melissa-technical-notes). The list of MELiSSA related scientific publications is shared publicly on the MELiSSA Foundation website (melissafoundation.org/page/melissa-publications). Third parties, including institutions, academia or industry, may attend the public part of the bi-yearly MELiSSA board meetings, upon prior agreement with the MELiSSA Project Manager. The MELiSSA consortium organises a dedicated MELiSSA Conference every two years with the aim of sharing the achievements and perspectives of the project and bringing together the latest science, technology and best practices to the advanced life support and circular systems community at large.

The proposed timeline for education and outreach activities is encompassed in Annex 10.3.5 **MELiSSA Education and Outreach Activities Roadmap**.

9. CONCLUSIONS

For nearly sixty years, crewed space missions have focused on creating a life-supporting environment. Today, however, the challenge has evolved. The ambition is no longer about solely sustaining human life but about reducing dependence on transported resources, i.e. producing oxygen, water and food from mission waste and consequently pushing the limits of human space exploration by allowing longer and more sustainable missions.

Initiated 35 years ago to support the paradigm shift of going from a linear approach, based on waste removal, to a circular approach favouring resource recovery, MELiSSA is now strategically positioned to address these challenges. Biological transformation processes, while more complex than physico-chemical ones, hold a wider potential for waste transformation and resource production, once understood, characterised and controlled. In that regard, lessons learned from past space life support developments underscore the importance of a thorough characterisation of such multi-phase processes. Over the last three decades MELiSSA has thus dedicated major efforts to tackle technically and scientifically demanding developments. To mention but a few examples, mastering advanced undertakings such as the modelling and control of complex microbial communities, the control of 3D biofilm construction, the optimization of heterotrophic nitrification, the modelling and reconstruction of DNA sequences or the modelling of closed-loop systems are a foundational reason behind the longevity of MELiSSA's research and development effort.

Meanwhile, as interest has grown in green technologies and the circular economy, MELiSSA's innovations have become increasingly relevant across industries, spanning biotechnology, chemical engineering, and environmental sustainability. By uniting space exploration and terrestrial sustainability within a single strategic framework, and by pursuing high-level scientific and technological ambitions, the MELiSSA project provides an invaluable platform for the development of future STEM leaders and innovators equipped to address the complex challenges of tomorrow.

The MELiSSA project hence stands as a unique, multi-disciplinary, and multi-application initiative that exemplifies European collaboration. MELiSSA is a flagship project that perfectly illustrates ESA's mission: to explore the universe and improve life on Earth for exclusively peaceful purposes. Yet, the project is now at a crucial juncture as competition in both space and Earth-based circular systems is intensifying, and the project must therefore act swiftly to maintain its leadership. Over the next 15 years, MELiSSA will focus on accelerating and scaling its technologies, transitioning from pilot demonstrations to full operational systems in space, and from pilot projects to industrial-scale deployment on Earth. Achieving European leadership and creating an operational breakthrough on a larger scale, with a true European dimension, and strengthening its partnerships with both space and resource management industry leadership will be pivotal for the project's success.

10. ANNEXES

10.1. Current Life Support System Research and Development Initiatives Known to Date

Table 6 provides a non-exhaustive overview of the research and development activities conducted by space agencies worldwide. This table does not provide an indication on the maturity level of such activities.

	MELiSSA C1 or equivalent	MELiSSA C2 or equivalent	MELiSSA C3 or equivalent	MELiSSA C4a or equivalent	MELiSSA C4b or equivalent
ASI	Waste treatment technologies, similar to C1 [RD48] [RD67]				Plant chambers for food production [RD2] [RD47] [RD67]
AEE					
BELSPO			Urine nitrification [RD55]	Algae-based photobioreactors [RD2] [RD60]	
CNES	Organic solid waste recycling with mushrooms and with black soldier fly larvae, no direct work on C1 [RD47]		Urine and fatty volatile acids recycling into food/feed protein or bioplastics, no director work on C3 [RD47]		Plant chambers for food production [RD47]
CNSA		Microbial fuel cells, no direct work on C2 [RD53]			Plant chambers for food production [RD68]
CSA					Plant cultivation for food

					production [RD69]
DLR	Waste recycling and biological waste treatment [RD49]		Urine nitrification [RD59] Nitrogen mineralization with trickling filters [RD2]	Algae-based photobioreactors for atmosphere revitalization and food production [RD2] [RD61]	Plant chambers for food/oxygen production [RD63] [RD64]
JAXA					Plant cultivation for food production [RD70]
LSA			Urine nitrification [RD73]		
NASA	Advanced waste treatment systems, including anaerobic digestion processes [RD50] [RD51] [RD52] [RD58]	Microbial fuel cells and microbial electrolysis cells [RD54]	Urine nitrification /denitrification and wastewater recycling systems [RD56] [RD57] [RD58]	Algae-based photobioreactors [RD62]	Plant chambers for food/oxygen production [RD66]
NOSA					Plant cultivation for food production [RD47] [RD71]
SSO			Crop production on substrate of human urine origin [RD72]	Algae-based photobioreactors [RD2] Micro-algae cultivation [RD72]	Plant cultivation for food production [RD2] [RD72]

Table 6. Worldwide Life Support Systems Research and Development Interest

10.2. MELiSSA Pilot Plant Integration Steps and Accomplishments

Integration Step	Integration Goal	Main Achievement
Integration Work Package 1 (2015-2016)	Gas closure of C4a and C5 [RD74]	• The efficiency and robustness of the oxygen production control in C4a was demonstrated during one year of operation for: a) constant oxygen set-points in C5 and b) sequential tests, including different oxygen set-points in C5 with the same cohort of three rats, in order to demonstrate the performance of control system in dynamic conditions responding to the evolution of consumers' needs (depending on activity, day/night cycles). • C5 compartment successfully characterized: a) hardware verification, and b) hosting rats under safe conditions for the animals (good health status reported). • Tightness of C4a-C5 gas-loop system compliant with requirements, critical for demonstration purposes • Comprehensive gas analysis performed both for C4a and C5 gas phases; ammonia and methane monitored on-line. No impact on Limnospira performance compared to stand-alone operation.
Integration Work Package 3 (2017-2018)	Liquid connection between C3 and C4a [RD75]	• The integration of C3 and C4a in the liquid phase was demonstrated to be technically feasible and stable over the long term with robustness, recovering from several perturbations. • Complete ammonium removal and stable nitrate production was obtained for 300 days, at several combination of dilution rates and two light intensities at different ammonium loads. • Oxygen production met the needs of three rats. Higher dilution rates improved oxygen productivity.
Integration Work Package 4 (2017-2018)	Gas closure of C4a and C5 including liquid	• The integration of C3 and C4a in the liquid phase to meet the oxygen requirements of three rats in C5, for different oxygen setpoints across different dilution rates demonstrated stable oxygen production adapted to the dynamics of the rats' activity (day and night).

	connection of C4a and C3 [RD75]	• The system proved its robustness in front of perturbations. Light intensity was regulated to compensate for the lack of oxygen production when C4a was stressed by other factors, such as nitrite punctual accumulation. • Nitrification in C3 remained stable and efficient, at different ammonium loads, meeting the nitrogen needs of Limnospira in C4a without compromising system performance. • Respiratory quotient (carbon dioxide/oxygen) values matched those expected from literature and those obtained within WP1, confirming animal physiological stability. Carbon dioxide concentration in the isolator was kept below safe limits for the rats.
Integration Work Package 6 (2020-2021)	Gas closure of C3, C4a and C5 including liquid connection of C3 and C4a [RD76] [RD77] [RD78]	• The light control of C4a to adapt oxygen production to the rats' respiration needs across varying inflow rates, nitrogen loads, and oxygen setpoints was successfully demonstrated. Oxygen production by C4a met the needs of both C5 (crew) and C3 (nitrification) in all test conditions, with light intensity well below the maximum available. • The use of an oxygen enrichment unit allowed increasing the partial pressure of oxygen in C3 to fulfil the oxygen needs of C3 consortium to obtain complete nitrification at high ammonium loads. • Carbon dioxide levels in C5 were generally kept below critical thresholds. • System robustness, gas tightness, and animal health were maintained throughout all tests.
Integration Work Package 2 (2023)	Gas closure of C4b and C5 [RD79] [RD80]	• The operation in closed gas loop of C4b and C5 was demonstrated, adjusting the photosynthetic activity of the plants to provide the required oxygen to satisfy the demand of the animals (3 rats). • The dynamic adjustment of the light intensity in C4b and the flow between the two compartments was successful to control different oxygen levels in C5 or controlling a constant oxygen level in C5 by different oxygen levels in C4b. • Biometric analysis of plants and rats' health were both within normal boundaries.

Integration Work Package 5 (2023)	Gas closure of C4a, C4b and C5 [RD81]	• A comprehensive understanding of operational boundaries has been gained when employing C4a&b as oxygen producer compartments connected to an oxygen consumer (C5). • Successful control of oxygen concentration in C5 was achieved when a closed control loop in C4a was used, with several oxygen setpoints in C4b. • Some of the tested conditions allowed to identify the operation limits of the system. Particularly, high concentration values of carbon dioxide affect oxygen production in C4b and high illumination levels in C4a provoke photoinhibition.

Table 7. MELiSSA Pilot Plant Integration and Demonstration Achievements

10.3. MELiSSA Project Implementation Plan

LEGEND

- MELiSSA Milestone
- Explore 2040 Milestone
- Decision point
- LEO (blue), lunar (grey), and Mars (orange) mission needs or demonstration opportunities according to the mission portfolio elaborated in the Implementation Plan

- On-going or completed activities
- Activities in preparation of CM25
- CM25 proposal or TDE/GSTP 2027 work plan proposal
- Projected CMIN28+ proposal

- Projected ISS Flight
- Projected Flight on board Deep Space Habitat analogue in LEO
- Projected integration into Deep Space Habitat operational ECLSS

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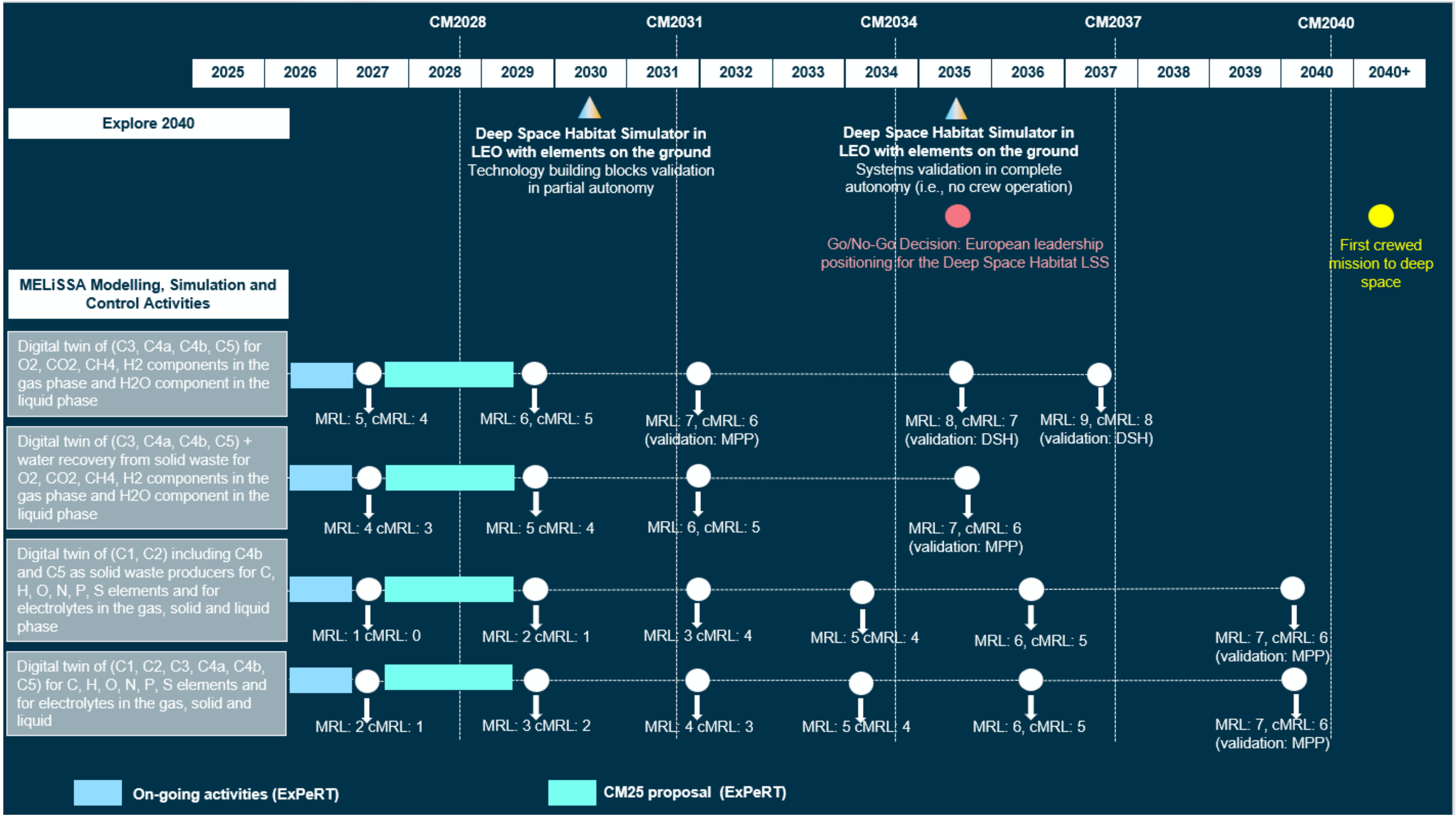
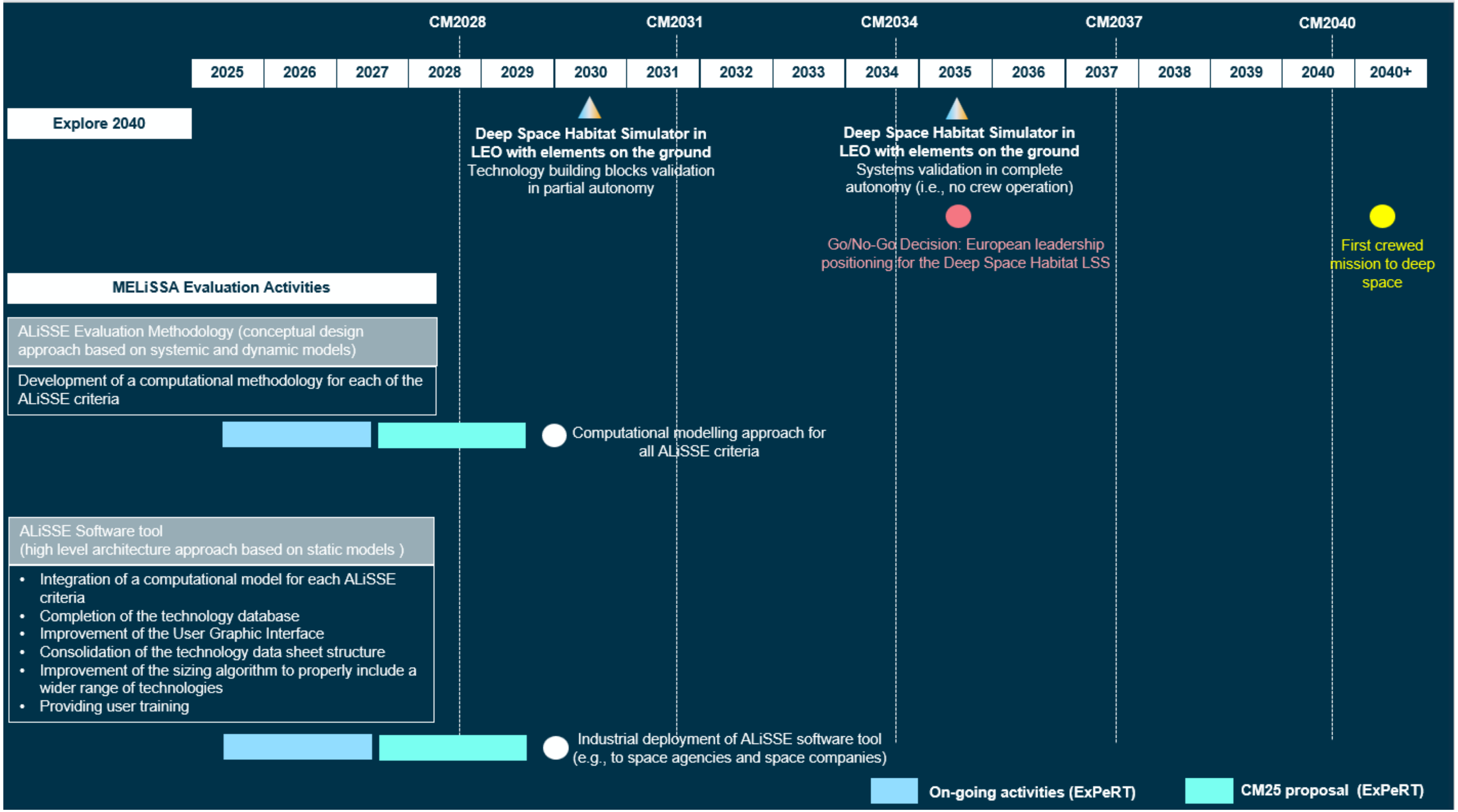
10.3.1. MELiSSA Modelling, Simulation, Control and Evaluation Activities Roadmap




CM2028
CM2031
CM2034
CM2037
CM2040
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2040+
Explore 2040
Deep Space Habitat Simulator in LEO with elements on the ground
Technology building blocks validation in partial autonomy
Deep Space Habitat Simulator in LEO with elements on the ground
Systems validation in complete autonomy (i.e., no crew operation)
Go/No-Go Decision: European leadership positioning for the Deep Space Habitat LSS
First crewed mission to deep space
MELiSSA Evaluation Activities
ALiSSE Evaluation Methodology (conceptual design approach based on systemic and dynamic models)
Development of a computational methodology for each of the ALiSSE criteria
Computational modelling approach for all ALiSSE criteria
ALiSSE Software tool
(high level architecture approach based on static models)
• Integration of a computational model for each ALiSSE criteria
• Completion of the technology database
• Improvement of the User Graphic Interface
• Consolidation of the technology data sheet structure
• Improvement of the sizing algorithm to properly include a wider range of technologies
• Providing user training
Industrial deployment of ALiSSE software tool (e.g., to space agencies and space companies)
On-going activities (ExPeRT)
CM25 proposal (ExPeRT)

MRL and cMRL SCALES

DEPOYMENT	9	Model validated at operational scale with the required accuracy and confidence for the required range of variables
DEPOYMENT	8	Model demonstration at relevant scale
DEPOYMENT	7	Model validation and demonstration at different scales: lab scale, pilot scale
DEVELOPMENT	6	Numeric model analysis: sensitivity analysis
DEVELOPMENT	5	Numeric model calibration: identification of unknown parameters
DEVELOPMENT	4	Development of the numeric model: I/O vectors, variables, parameters
RESEARCH	3	Formulation of the assumptions and hypotheses of the model
RESEARCH	2	Establishment of the general theoretical framework and approach
RESEARCH	1	Definition of the general characteristics and objectives of the model: range of applicability, requirements, knowledge, scale-up and down

Model Readiness Level

DEPLOYMENT	9	Control Model proven at BLSS level
DEPLOYMENT	8	Control Model demonstrated in integrated operational environment: integrated in spaceflight BLSS
DEPLOYMENT	7	Control model demonstrated in operational environment: spaceflight of the system controlled
DEVELOPMENT	6	Control Model demonstrated in integrated operational/relevant environment: integrated in lab/relevant BLSS
DEVELOPMENT	5	Control model demonstrated in lab/relevant environment: limited to the perimeter of the system
DEVELOPMENT	4	Control-model development
RESEARCH	3	Numeric theoretical-system model demonstration in lab/relevant environment (calibration/validation)
RESEARCH	2	Numerical-theoretical system model development
RESEARCH	1	Mathematical theoretical-system formulation of the model: Variables(action/measured/predicted); perimeter / level of description; Theoretical analysis of the system of interest

Mechanistic Mass Balanced Control Model Readiness Level

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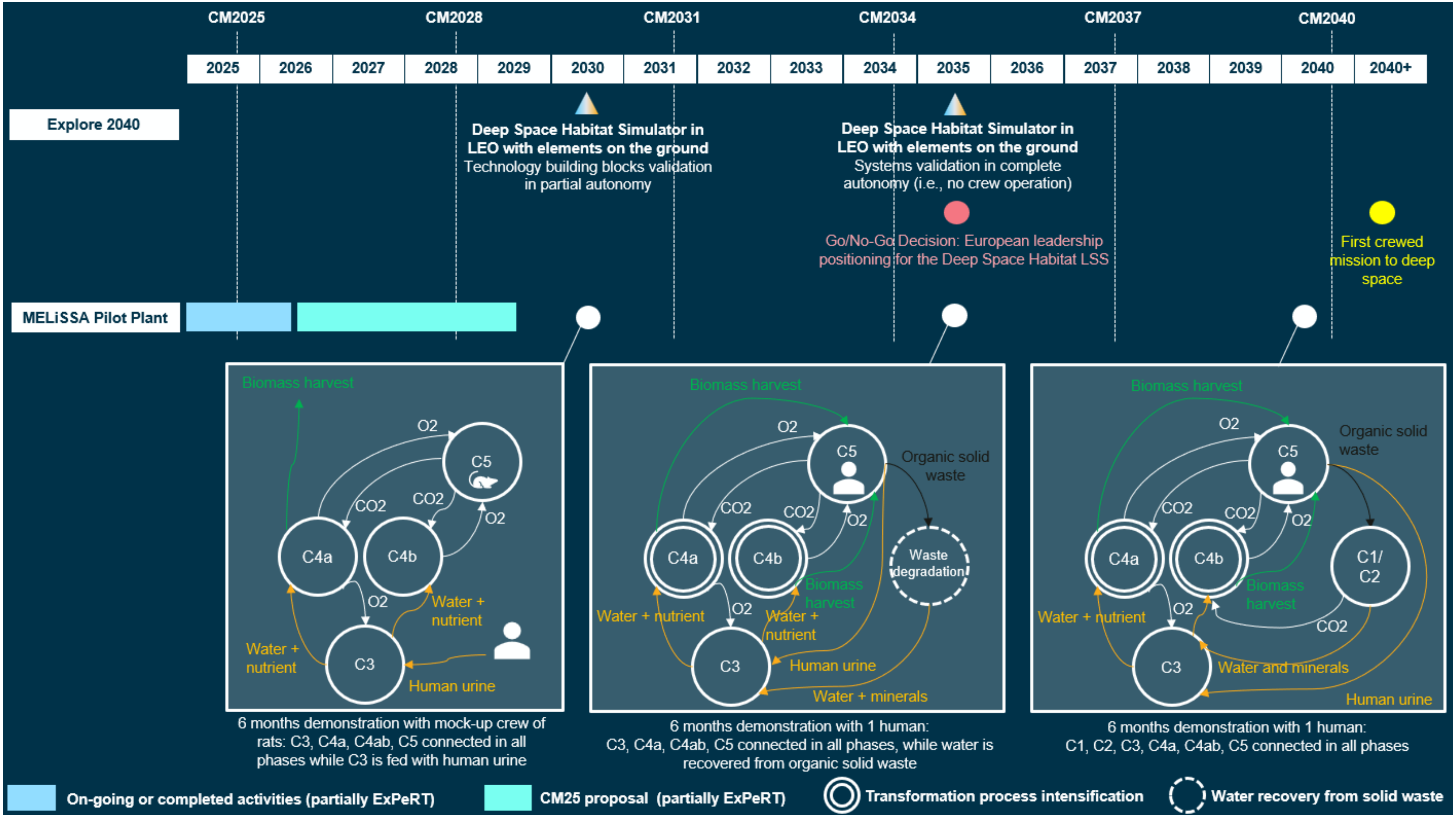
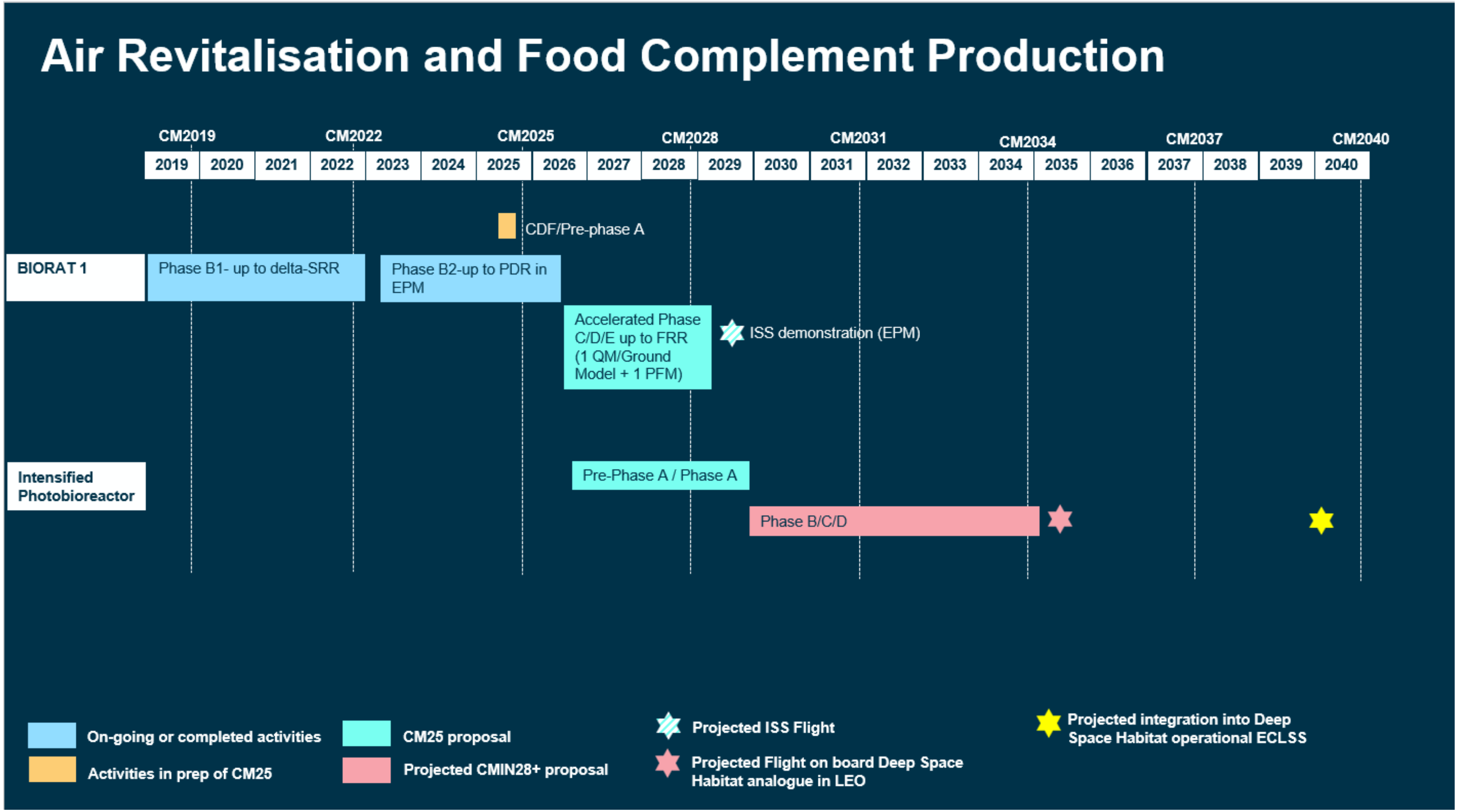
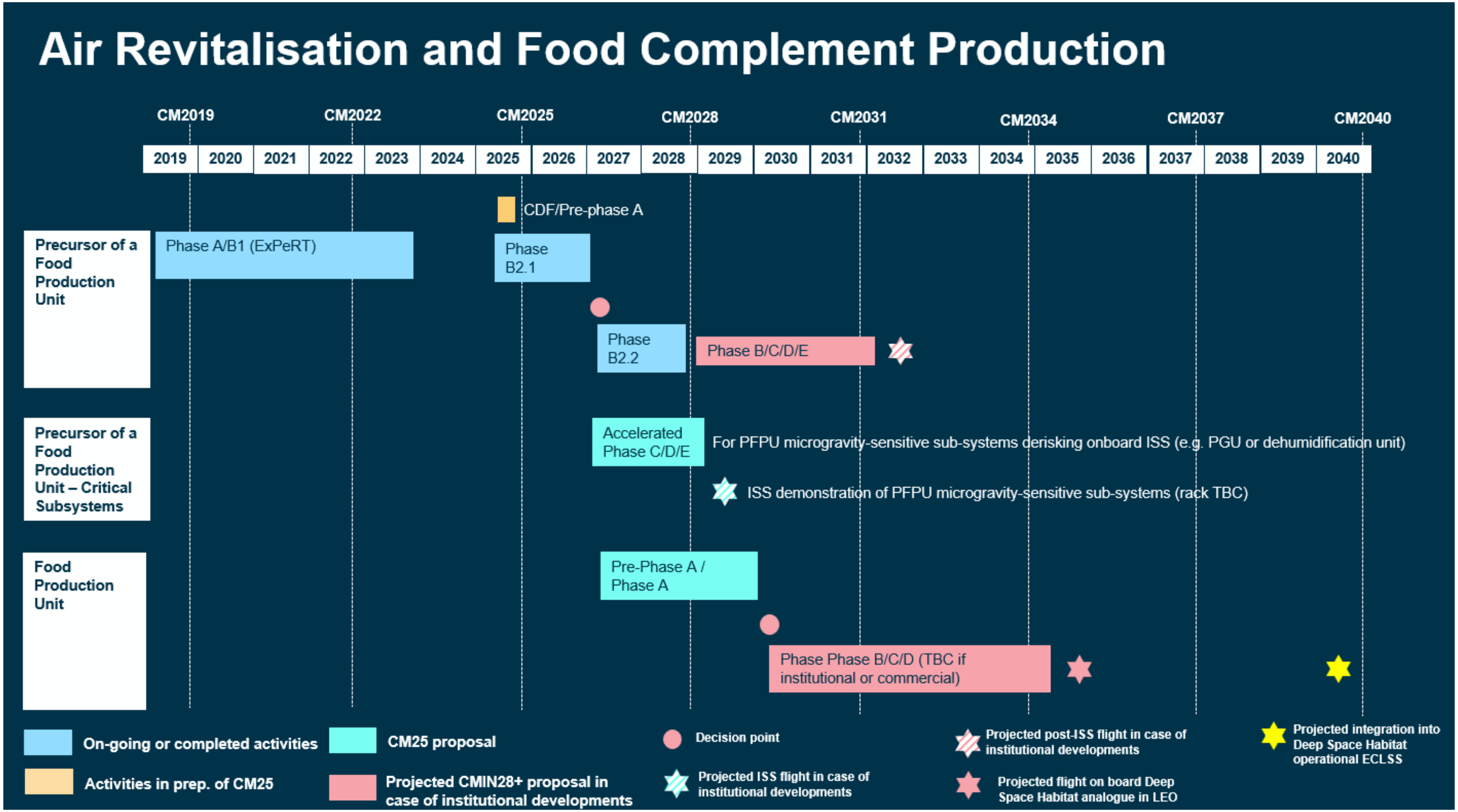
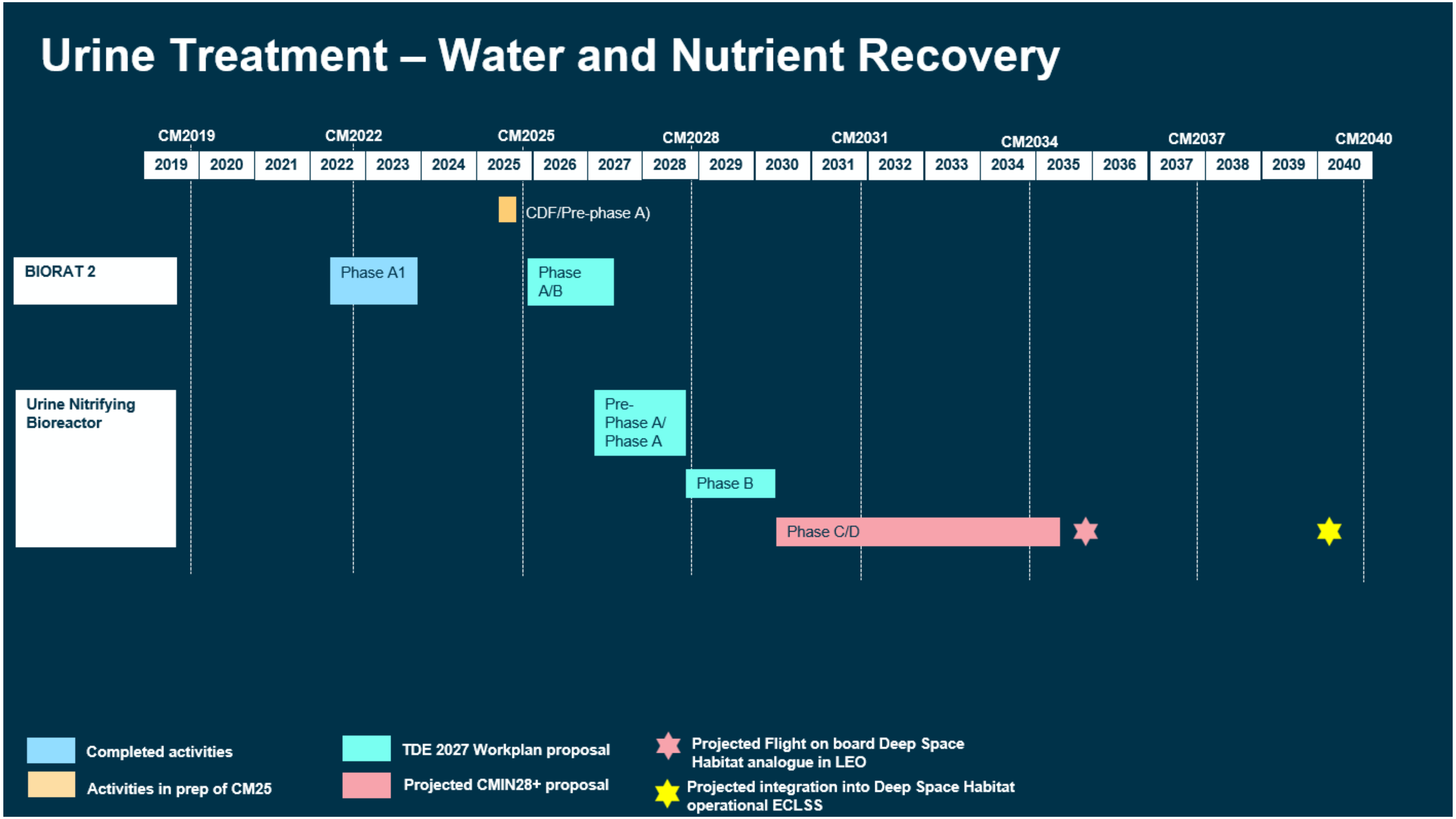
10.3.2. MELiSSA Pilot Plant Integration and Testing Roadmap



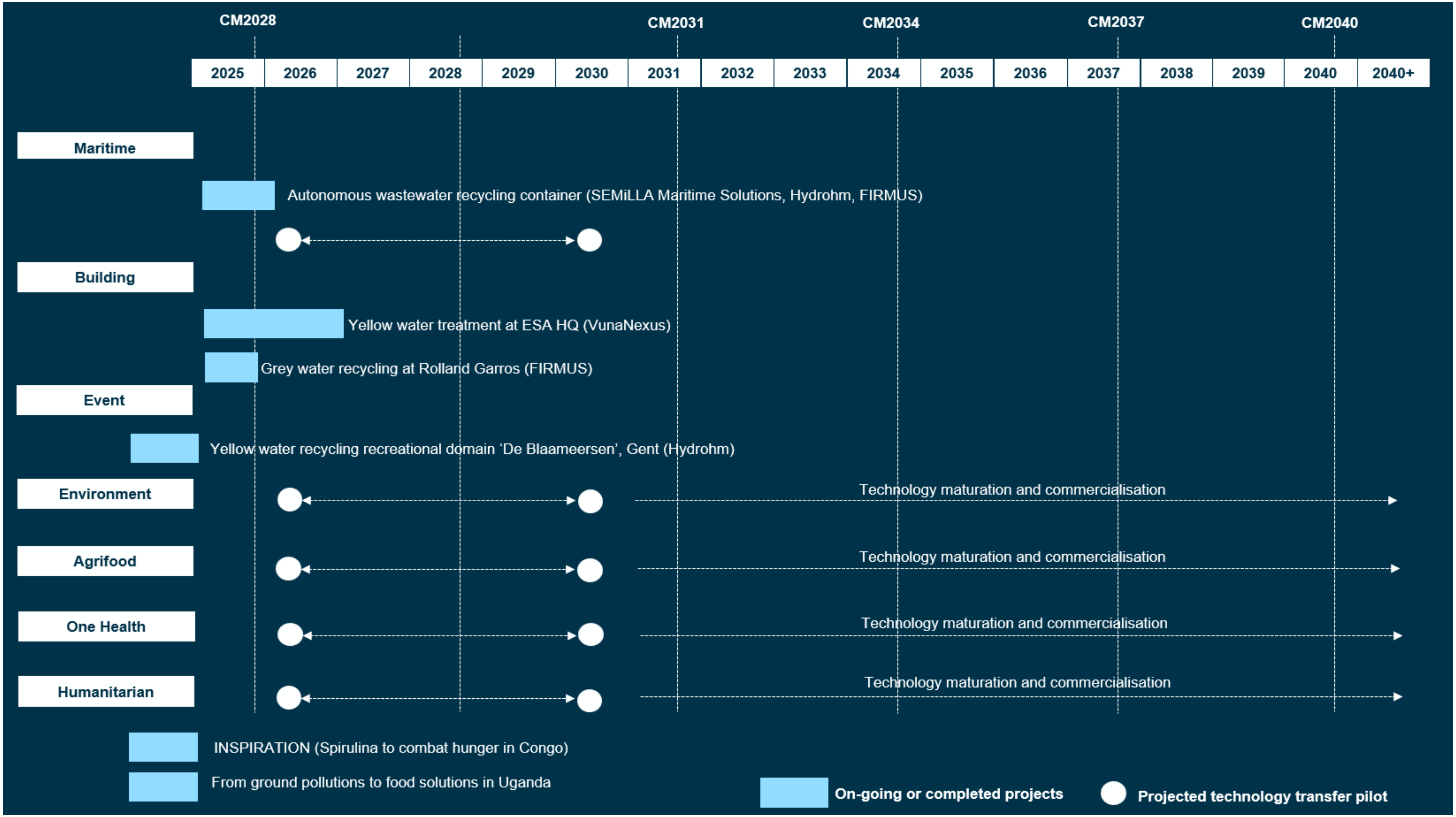
10.3.3. MELiSSA Flight Hardware Development Roadmap



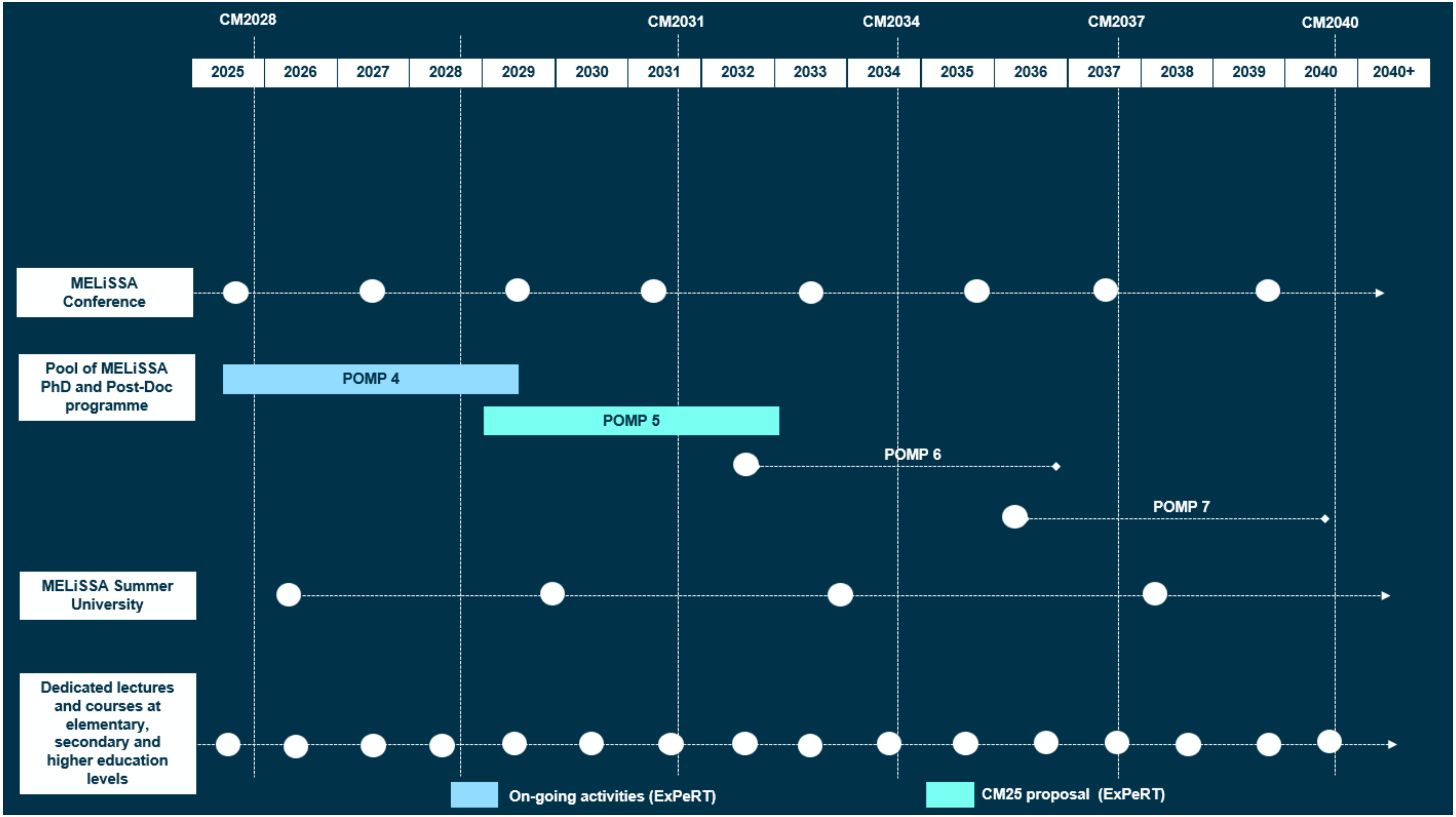

Air Revitalisation and Food Complement Production
CM2019
CM2022
CM2025
CM2028
CM2031
CM2034
CM2037
CM2040
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040
CDF/Pre-phase A
Precursor of a Food Production Unit
Phase A/B1 (ExPeRT)
Phase B2.1
Phase B2.2
Phase B/C/D/E
Precursor of a Food Production Unit – Critical Subsystems
Accelerated Phase C/D/E
For PFPU microgravity-sensitive sub-systems derisking onboard ISS (e.g. PGU or dehumidification unit)
ISS demonstration of PFPU microgravity-sensitive sub-systems (rack TBC)
Food Production Unit
Pre-Phase A / Phase A
Phase Phase B/C/D (TBC if institutional or commercial)
On-going or completed activities
CM25 proposal
Decision point
Projected post-ISS flight in case of institutional developments
Projected integration into Deep Space Habitat operational ECLSS
Activities in prep. of CM25
Projected CMIN28+ proposal in case of institutional developments
Projected ISS flight in case of institutional developments
Projected flight on board Deep Space Habitat analogue in LEO


Urine Treatment – Water and Nutrient Recovery
CM2019
CM2022
CM2025
CM2028
CM2031
CM2034
CM2037
CM2040
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
CDF/Pre-phase A)
BIORAT 2
Phase A1
Phase A/B
Urine Nitrifying Bioreactor
Pre-Phase A/ Phase A
Phase B
Phase C/D
Completed activities
Activities in prep of CM25
TDE 2027 Workplan proposal
Projected CMIN28+ proposal
Projected Flight on board Deep Space Habitat analogue in LEO
Projected integration into Deep Space Habitat operational ECLSS

10.3.4. MELiSSA Technology Transfer and Commercialisation Roadmap



10.3.5. MELiSSA Education and Outreach Activities Roadmap



10.3.6. MELiSSA Project Governance

DRAFT

MELiSSA Steering Committee

Role

The MELiSSA Steering Committee is a sub-group of appointed MELiSSA Partners who provide rapid support the MELiSSA Project Manager for the project's day-to-day matters.

Responsibilities

The members of the Steering Committee shall take on the following responsibilities:

- In their area of expertise, provide recommendations to the MELiSSA Project Manager to help with the project's day-to-day decision-making process.
- Support the MELiSSA Project Manager in the preparation of the MELiSSA Coordination Meetings (held online, at MELiSSA board level, every two months) and the MELiSSA Board Meetings (held face-to-face, at MELiSSA Board level, every six months).
- Meet-up with the MELiSSA External Board of Advisors on an ad-hoc basis.

The Steering Committee meetings shall be organised and chaired by the MELiSSA Project Manager. Additionally, the members of the Steering Committee might be called upon the MELiSSA Project Manager on an ad-hoc basis to support urgent matters. The Steering Committee members are not allowed to make financial or programmatic decisions on behalf of the MELiSSA project.

MELiSSA External Board of Advisors

Role

The External Board of Advisors to the MELiSSA Project shall be a collection of individuals who bring a unique set of knowledge, skills, expertise, and networking contacts which augment the ones of the formal MELiSSA Board. The External Board of Advisors shall support the MELiSSA Board to guide the Project in the most effective and successful manner.

Responsibilities

The members of the External Board of Advisors shall take on the following responsibilities:

- Be available to serve as consultants by:
  - Educating and sharing their unique knowledge, skills, and expertise with the MELiSSA Project.
  - In their area of expertise, providing advice and guidance to the MELiSSA Project to help the MELiSSA Board make decisions that are in the Project's best interest and that are in line with the Project's objectives and vision.
- Expand the MELiSSA Project's network.
- Promote the MELiSSA Project in their own network.
- Abide by the confidentiality rules set in the MELiSSA Non-Disclosure Agreement for External Advisors

The primary interface of the External Board of Advisors with the MELiSSA project shall be the MELiSSA Project Manager. The External Board of Advisors may attend the MELiSSA Board meetings or the MELiSSA Steering Committee meetings on an ad-hoc basis and upon invitation from the MELiSSA Project Manager. Members of the External Board of Advisors are encouraged to attend the MELiSSA Project's public events on a voluntary basis (e.g., MELiSSA conferences). The members of the External Board of Advisors are not allowed to make decisions on behalf of the MELiSSA project.

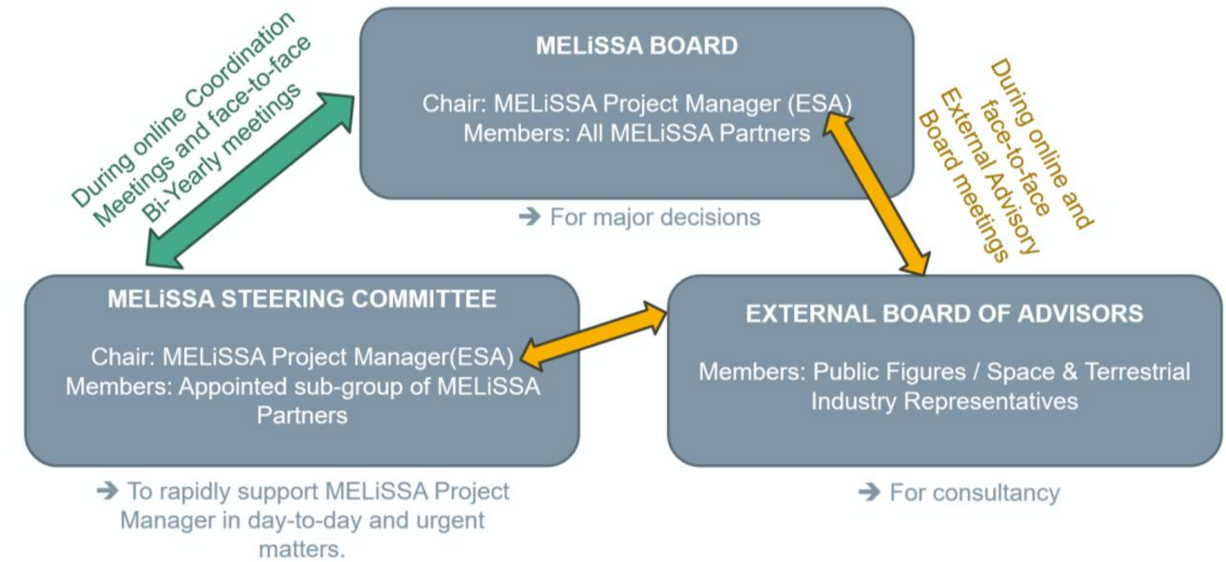


Figure 9 MELiSSA Governance

10.3.7. Applicable and Reference Documents

10.3.7.1. Applicable Documents

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10.3.7.2. Reference Documents

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