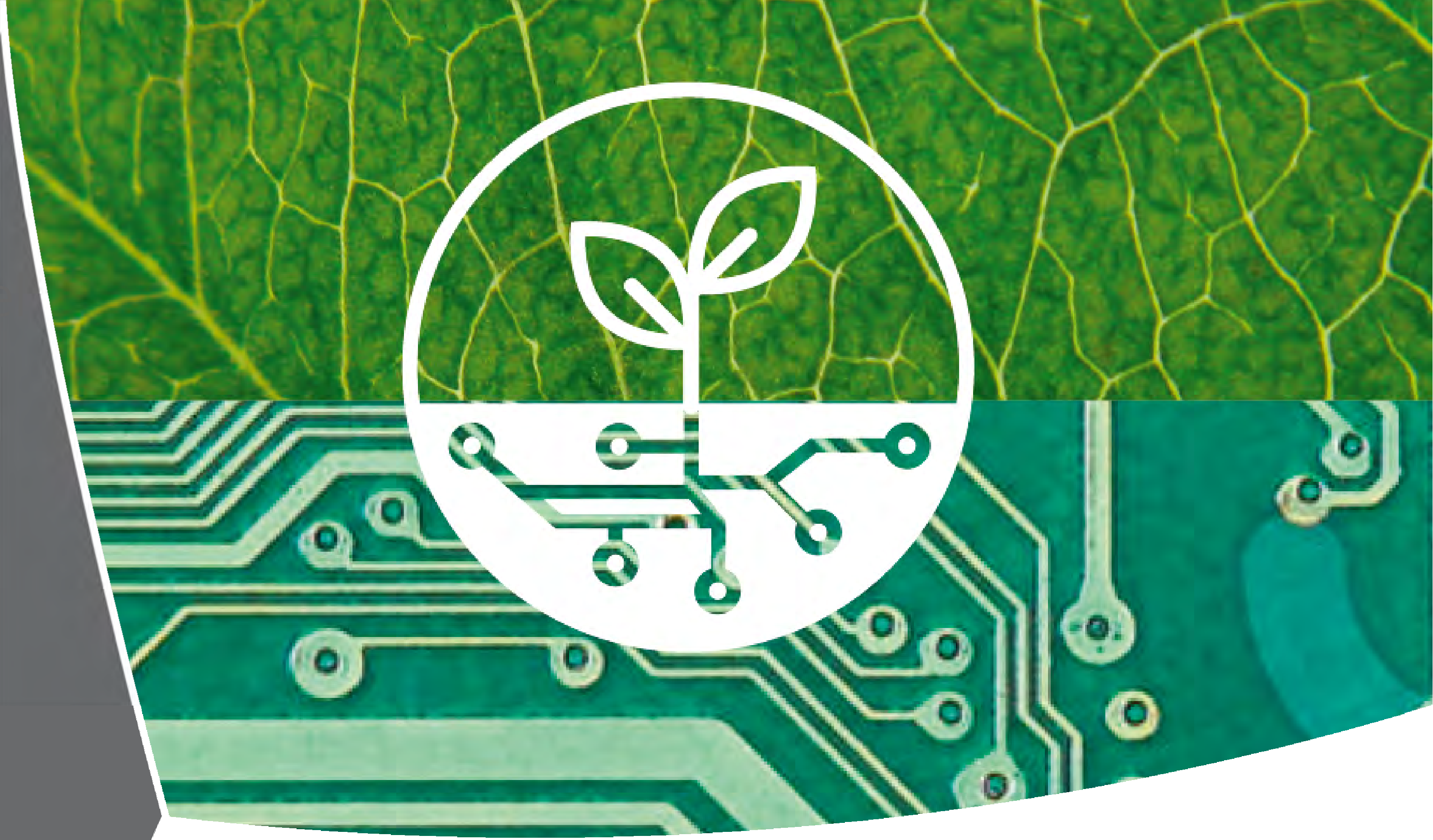

The EDEN Initiative

Portfolio and Strategy

Institute of Space Systems
Dept. of System Analysis Space Segment

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Institute of Space Systems
Department of System Analysis Space Segment (SARA)

Editors:
Daniel Schubert
Vincent Vrakking
Conrad Zeidler
Paul Zabel
Dr. Matthew Bamsey

Robert-Hooke-Str. 7
D-28359 Bremen
Telefon 0421 24420-1136
Telefax 0421 24420-1150
E-Mail: daniel.schubert@dlr.de
Internet: http://www.dlr.de/irs/en/desktopdefault.aspx/tabid-9327/14668_read-39524/

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1 Introduction

1.1 Background

The exploration of the solar system and in particular the Moon and Mars is one of the grandest endeavors of mankind. Sustained human presence in space requires the development of new technologies to maintain environment control, to provide water, oxygen, food and to keep the astronauts healthy and psychologically fit. The logistics of mission resupply is a major driver for how far humans can explore. Bio-regenerative Life Support Systems (BLSS) in conjunction with in-situ resource utilization will initially reduce and ultimately eliminate consumables from the logistics chain. Minimizing this need for resupply while ensuring human safety will allow astronauts to travel further and stay longer in space than ever before. While physical / chemical Life Support Systems (LSS) will form the back-bone (ensuring system reliability and a fallback strategy) of next generation life support systems, with time, BLSS will be expanded to become the prime system ensuring sustainable life support, in particular, for long-duration missions.

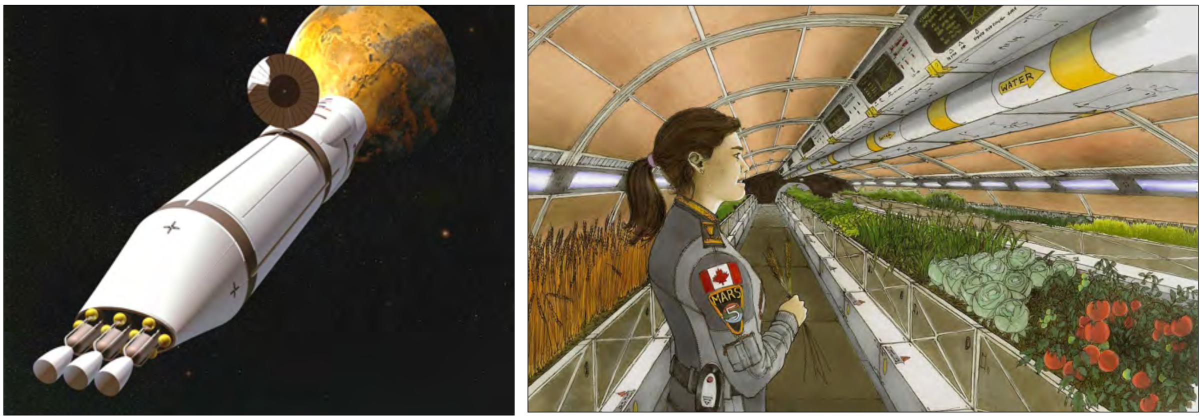


Figure 1: Artist impressions of a future mission to Mars including a surface greenhouse [Credits: Phil Smith, Mars Foundation]

The cultivation of higher plants takes a crucial role within BLSS as they can contribute to all major functional aspects within such systems. In this sense, the plants provide an all-in-one-approach, not possible with any single physical/chemical system:

Fresh Food

The most apparent function is the provision of food. The ability of current space food systems to provide fresh food over long-duration space missions is presently lacking. Leafy and high-water content crops generally only remain fresh for several weeks. After that time, the crew has to rely on dehydrated and pre-packed meals. Fresh food provides essential vitamins and other functional macromolecules, as well as useful bioactive compounds to support crew health, and function as countermeasures for the stresses of deep space exploration. In this way, fresh food supports the human metabolism and benefits the general physiological and psychological crew healthiness.

Atmosphere Revitalization

Since astronauts need oxygen for their metabolism and exhale carbon dioxide, this situation presents a perfect symbiotic relationship for their integration with plant based systems. Coupling a greenhouse or plant growth module with future habitats allows for the utilization of the astronauts' gaseous metabolic waste products (CO_2) as a feed source for the photosynthesis process of plants and the production of oxygen. Results from NASA's studies demonstrated that the O_2 needs of a single crew member could be met by approx. 10-20 m^2 plant area with high lighting. In addition to CO_2 reduction and oxygen generation, BLSS can degrade volatile organic compounds, an important aspect in closed systems, such as future space habitats.

Water Recycling

Through the exploitation of evapotranspiration, the plant's evaporated water can be collected from the greenhouse environment using dehumidification systems and contribute to system wastewater recycling. Recent research from the Lunar Greenhouse test stand at CEAC (University of Arizona) has shown that 12 m^2 of plant area could generate up to 21 L of potable water every day.

Psychological Well-being

Astronaut psychological well-being is of great importance and concern, especially during long duration missions. In addition to the already mentioned positive psychological benefit of eating fresh food, the presence and interaction with plants contributes to the overall well-being of the crew. Constant isolation and living in a highly-integrated technical environment, including the dependency on these machines/hardware systems, increases the desire to bond with 'natural' systems from Earth. Studies have shown that attending to plants (maintenance, harvest) can have a positive psychological effect on astronauts.

Consumables

When considering long-duration spaceflights with the possibility of only a few or even no resupply events, the creation of new consumables and/or the replacement of broken items and tools becomes more and more necessary. Bio-plastic, latex, or other high value compounds that can be generated from plants, can also help reduce consumables and increase mission autonomy. For example, transforming the bio-plastic into granulates and using them with the latest 3-d printing techniques, opens a wide variety of in situ production capabilities.

Adding up these features, higher plants represent a unique asset that makes the investigation of their cultivation in closed systems an essential endeavor for future space exploration.

1.2 The EDEN Initiative

In 2011, the DLR Institute of Space Systems launched its research initiative called EDEN - **E**volution & **D**esign of **E**nvironmentally-closed **N**utrition-Sources. The research initiative focuses on Bio-regenerative Life Support Systems (BLSS), especially greenhouse modules, and how these technologies can be integrated in future human-made space habitats.

EDEN was established within the DLR internal project CROP (Combined Regenerative Organic-Food Production) – a joint research endeavor between the *Institute of Aerospace Medicine* (ME) and the *Institute of Space Systems* (RY).

It is the goal of the EDEN team to further advance the latest cultivation technologies and to adjust these developments into space related applications. Even though, present scenarios for future human missions to Moon and Mars are still several years from coming to fruition, the time to develop these technologies needs to start today. Only this way, highly-reliable and resource-efficient BLSS will be ready for implementation into the mission architecture for humanity's journey to the Moon and Mars and - even more importantly – enable a sustainable and continuous presence there.

Figure 2: EDEN Initiative logo, designed by University of Arts, Bremen.

Organized by the Department of System Analysis Space Segment (SARA), the EDEN Initiative facilitates its own Space Habitation Plant Laboratory (EDEN Lab.), the institute's Concurrent Engineering Facility (CEF). Furthermore, the group receives support from the institute's Electronic Laboratory (E-Lab), and utilizes the institute's laboratory building (incl. integration hall) in order to foster the development of cutting-edge plant cultivation technologies.

Figure 3: DLR Institute of Space Systems (left) and its main laboratory (right).

The present document shall give an overview of the different achievements in recent years and layout the general strategy of the group with respect to their research focus for the next years.

2 EDEN Research Team

Daniel Schubert studied at the Technical University of Berlin and has an engineering diploma in industrial engineering with emphasis on aerospace and production techniques. In 2011, he initiated the EDEN group at the DLR Institute of Space Systems for technology investigations on Bio-regenerative Life Support Systems (BLSS) and is since then the team leader of this group. His research expertise is set on habitat interface analysis and plant accommodation and dynamic plant production planning.

Dr. Matthew Bamsey holds a M.Sc. in aerospace engineering (University of Colorado, USA) and conducted his Ph.D. in environmental biology with the University of Guelph (Canada). Matthew worked as a postdoctoral researcher at the University of Florida where he supported suborbital plant growth payload developments. He spent over ten years working as a student researcher at the Canadian Space Agency where he worked with the Arthur Clarke Mars Greenhouse project. Within EDEN, he conducts research related to Nutrient Delivery Systems.

Vincent Vrakking studied at the Technical University of Delft in the Netherlands and holds a M.Sc. in aerospace engineering. He has worked with the EDEN team on and off since 2012, before joining the team in 2015. Within the EDEN group he investigates the potential use of lightweight inflatable materials and structures that can house Bio-regenerative Life Support Systems (BLSS) and greenhouse systems in particular.

Paul Zabel studied aerospace engineering at the Technical University of Dresden. He joined the EDEN team in 2012. Mr. Zabel is the deputy manager of the EDEN Lab and is working on acquiring funding and projects for EDEN. His research expertise is hybrid Life Support Systems (LSS) containing greenhouse modules and physical/chemical LSS. Funded over NPI (ESA) he is doing his Ph.D. about the dynamic behavior of such hybrid systems.

Since January 2011 Conrad Zeidler is member of the EDEN research team. Within his Industrial engineering diploma at the Technical University of Braunschweig he specialized on aerospace engineering and has profound knowledge trade-off analysis techniques (e.g. AHP). He is an expert in simulation methods and control software. Within EDEN, he is responsible for monitoring and controlling the plant and environment parameters.

3 Research Domains & Focus

Controlled Environment Agriculture (CEA) is a combination of engineering, horticultural science and information technology to design highly-efficient plant growth systems. Through the implementation of CEA technologies the careful control of water and nutrient provision (e.g. H_2O, pH, EC, as well as soilless cultivation), the control of environmental conditions (e.g. temperature, RH, CO_2, O_2), and the provision of selective spectral light (e.g., red, blue, UV), it should be possible to achieve higher yields and shorter plant growth cycles than ever before. Through CEA, even the exact control of food quality (e.g. appearance, taste, enrichment of useful substances) is possible.

Since all grow parameters (compare Figure 4) are decoupled from the natural system (unlike open field cultivation), plant growth density can be increased (innovative grow accommodations).

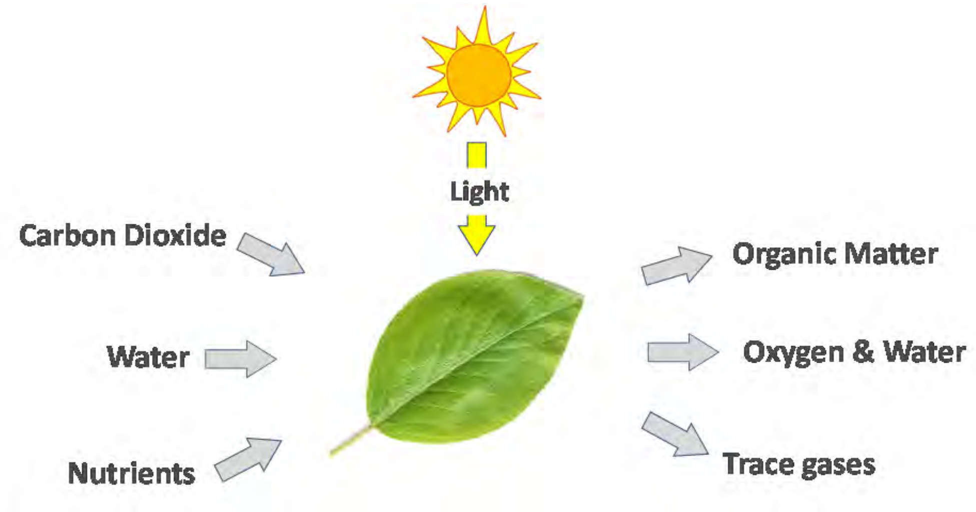


Figure 4: Basic principles of plant metabolism.

Starting from these facts, the research initiative will mainly focus on planetary scenarios, where the envisioned greenhouse modules will be integrated in general planetary habitat infrastructures. The necessary resources such as energy, thermal dissipation capabilities, water, and nutrients are considered to be provided by the outpost infrastructure.

For scenarios, where astronauts remain in a microgravity environment for a few days (Moon transfer) up to a period of 6-8 months (Mars transfer) a dehydrated food approach is more typical. Although possible, plant growth in microgravity is an extremely challenging endeavor and only with suboptimal grow results. Possible deployments e.g. on ISS are therefore only considered as validation campaigns – the final goal is to be seen in surface deployments.

With respect to the crop selection list, the EDEN Initiative will focus on vegetable- and fruit crops with high water content. These crops are mainly tomato, cucumber, radish, pepper, carrot, lettuce, strawberry, and dwarf trees for fruit provision such as apples, cherry and plum. These crops types typically only have short shelf lifetimes (several weeks), which makes their in-situ production a necessity. Starch- and grain crops like potato, wheat, and rice as well as oilproviding crops such as soybean and peanuts are not within EDEN's research focus. The products created from these plants are characterized by a long shelf lifetime, high packaging density, and easy processability.

Having set the global boundaries, the EDEN Initiative will further concentrate its research ambition on the integration of CEA technologies and the actual production process of crops, rather than the design of scientific plant growth chambers. It is the belief of the group that technology improvements of the last years have made it possible, to develop and deploy larger scaled CEA cultivation units to ultimately learn about the actual production process of higher quantities of crops (semi mass production principles).

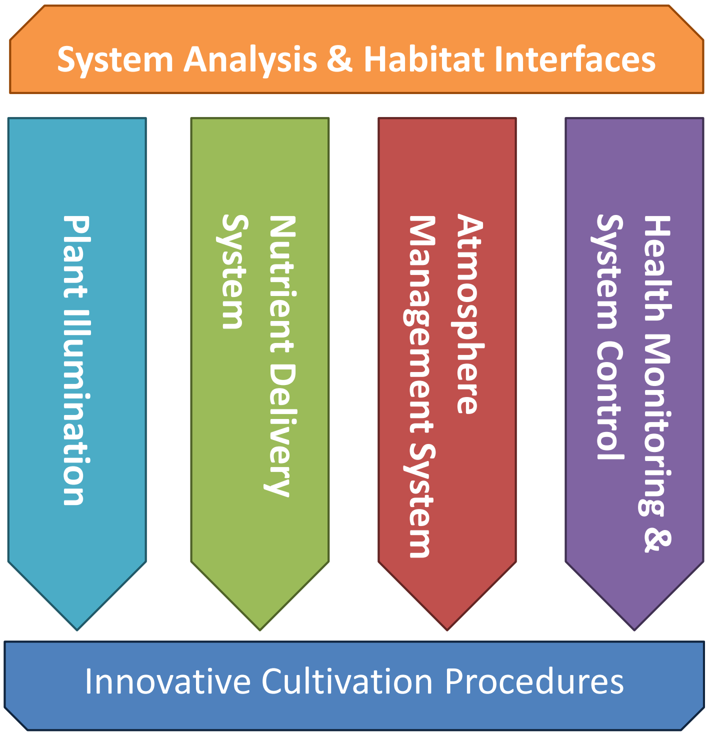


Figure 5: The six research domains of the EDEN Initiative.

Here, all necessary inherent technological-, cultivation-, handling-, and operation challenges shall be investigated by the initiative. These plant cultivation challenges shall be foregrounded, rather than the biological understanding of the *system plant*, which shall be the domain of plant biology.

As can be seen in Figure 5, the EDEN Initiative focuses its research on six main domains. Framed by the overall system analysis for greenhouse modules as an integrated part of habitats and planetary outposts, the four pillars of key CEA technologies, necessary for plant cultivation are foreseen. Results from these domains will be combined with innovative cultivation procedures creating an overall approach for the advanced production of plants in closed-loop environments.

Overall EDEN strategy:

Evaluation and design of **plant grow systems for planetary habitat integration** (Moon, Mars), where these systems work in close conjunction with physical/ chemical Life Support Systems. The required **Controlled Environment Agriculture technologies** and operation procedures shall be **developed and tested** within the EDEN Laboratory. The primary ambition is the achievement of **highly reliable** plant cultivation systems with **maximum biomass output** of high water-content crops, produced in a **resource-efficient** manner (power, water, nutrients) and with **high plant densities**.

3.1 System Analysis & Habitat Interfaces

Planetary greenhouse modules shall serve in the short-term as providers of supplemental food (=> high water-content vegetables and fruits) and in long-term as the main provider of healthy food for the crew (expansion of cultivation spectrum to starch crops and others). The additional benefits provided to the LSS by plants such as air purification (oxygen provision), water recycling, psychological well-being, and in the future provisions of raw materials are important aspects that also warrant investigation.

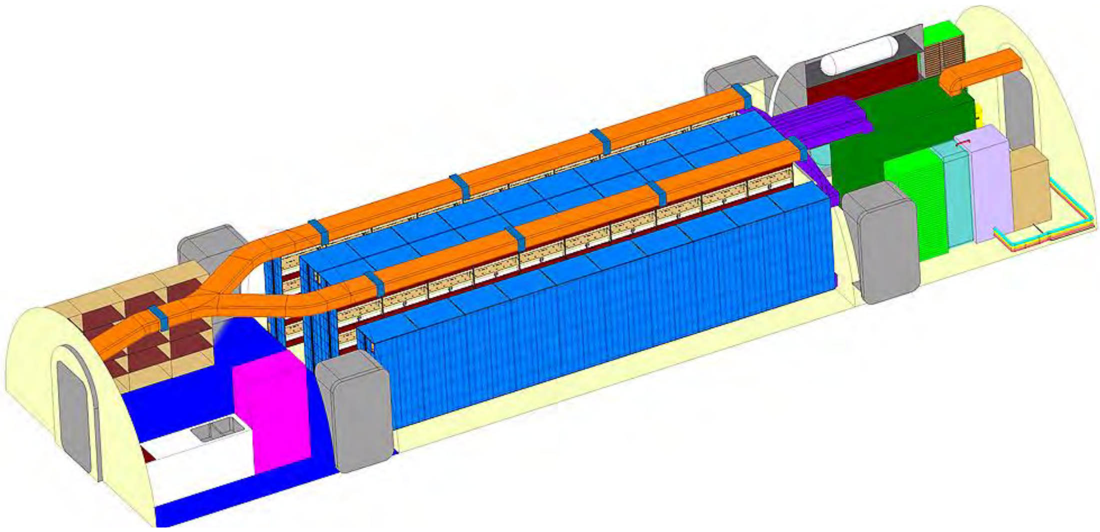


Figure 6: Example of a semi-deployable extra-terrestrial greenhouse module, designed by the EDEN Initiative.

Starting with general layout considerations of the greenhouse outer structure (e.g. spherical, dome-like, torsos shape) and environmental parameter analysis, the focus shall be set on systems engineering for these future greenhouse systems. The main research focus is the holistic evaluation of possible CEA technologies and their implementation in planetary surface greenhouses. Feasibility- and phase-A studies, technology evaluations, morphological boxes, and trade-offs are key instruments for this kind of investigation. Subsystem accommodation analysis as well as calculations of mass-, power-, and thermal budgets shall be performed to provide a considerable basis for the envisioned greenhouse module design.

Within the foreseeable future, it is unfeasible to completely replace physical/ chemical life support technologies by biological processes. Hybrid systems containing both types of systems are more realistic. Bio-regenerative processes will be complemented with a physical/ chemical backup for redundancy reasons, and vice versa. Hybrid LSS can also be seen as manmade closed ecosystems, which differ from their prototype biosphere (Earth), especially in the size. Sustainability of the biosphere is ensured by its biological diversity that creates an intricate network of metabolic paths with fail-safe redundant functions, by buffer stocks of inert biomass, and by the huge size of the planet and atmosphere itself. Such a system, produced by evolution is sustainable by stochastic control. In contrast, in a small manmade closed ecosystem, such as a planetary habitat, all these factors become more or less ineffective. In such a system, diversity and size are not sufficient for stochastic mechanisms to operate successfully. Manmade closed ecosystems require non-stochastic control and modelling to compensate the lack of buffer capacity for dampening the effects of periodic events and failures. The EDEN research group will therefore analyze the possibilities to interconnect physical/ chemical LSS with BLSS to form a highly-reliable hybrid Life Support System.

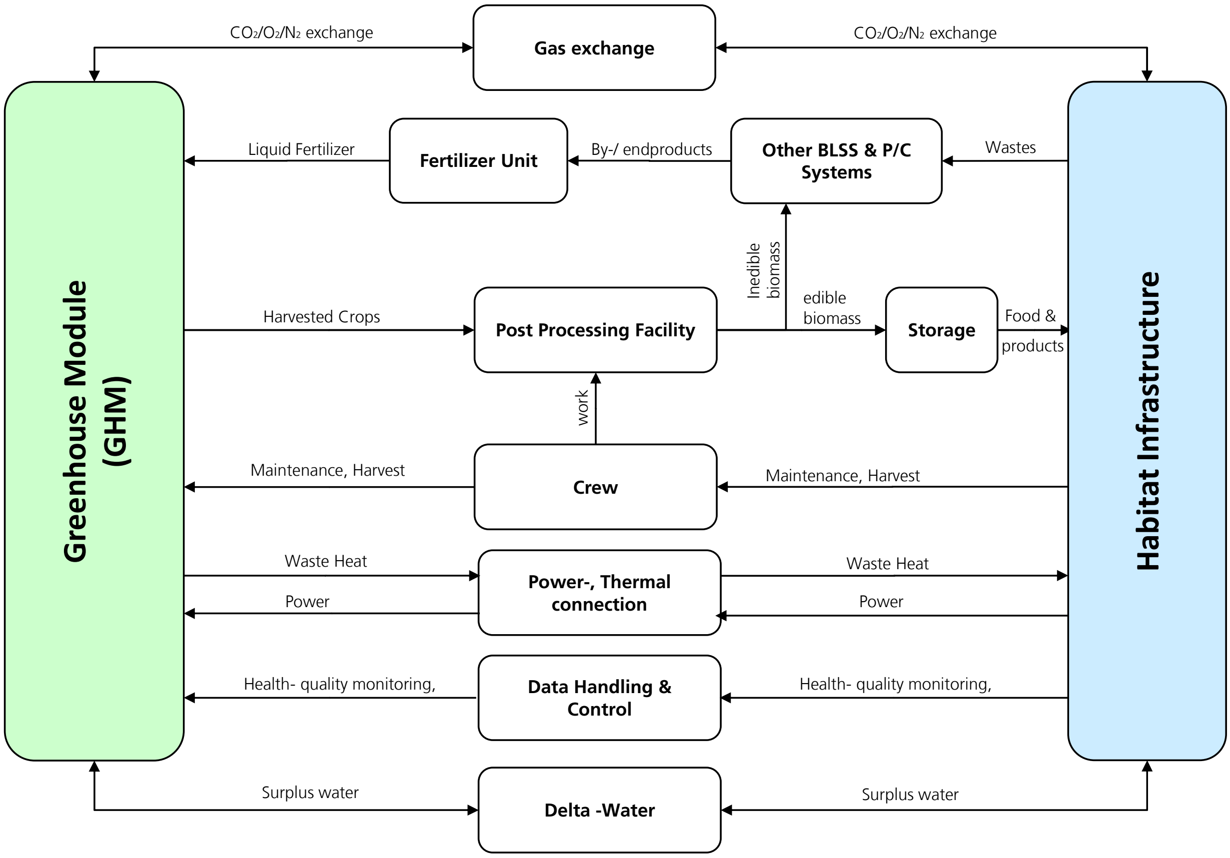


Figure 7: Overview of the Interface between Greenhouse Module (GHM) and the habitat.

The System Analysis approach, as a first step of understanding such complex systems and relationships shall be applied by the EDEN group. This way a solid understanding of the complex nature of biological systems and their technical (and organizational) support systems within close-loop environments like in Moon or Mars outposts can be generated. Therefore, the relationship between the greenhouse module and the habitat infrastructure shall be investigated (e.g. post-harvest procedures, food processing). See Figure 7.

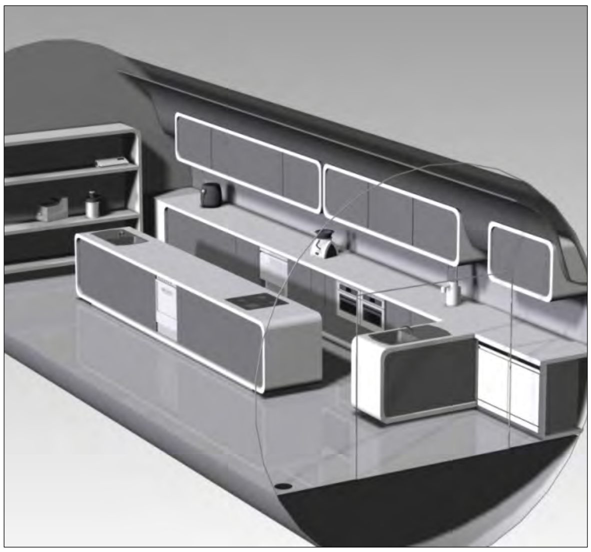


Figure 8: Post Processing Facility (PPF), elaborated by a combined student team of the Technical University of Berlin.

For design purposes, the Concurrent Engineering Facility (CEF) will mainly be utilized. This laboratory allows a team of space engineers and scientists from different disciplines to efficiently design space systems and missions on a Phase-A study level.

RESEARCH FOCUS:

The EDEN Initiative focuses on the following research topics within its *System Analysis and Habitat Interface* domain:

- Systems (and subsystem design respectively) design of greenhouse modules for planetary use as an integrated part of an outpost infrastructure.
- Subsystems accommodation analysis, mass-, power-, thermal budget estimates as well as crew time estimates.
- Investigation of the dynamic behavior of hybrid LSS consisting of a habitat, a greenhouse and physical/ chemical LSS.
- Evaluation, development and testing of post-harvest procedures in order to increase food shelf lifetime and to facilitate easy consumption by the crew.

3.2 Plant Illumination

Light is one of the most important parameters of plant growth. Photosynthesis mainly depends on the light spectrum, light intensity and illumination phases. Plant growth is significantly influenced by both the quantity and quality of light. The light that drives photosynthesis in plants is called Photosynthetic Active Radiation (PAR). The wavelength of PAR ranges from 400 to 700 nm. This implies that only a relatively small spectral bandwidth of visible light is used by plants (Compare Figure 9).

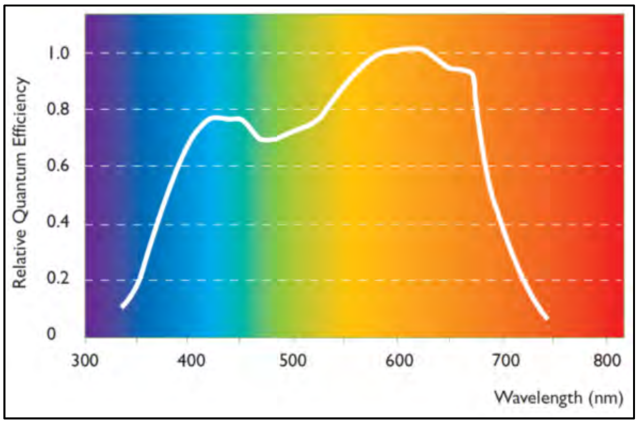


Figure 9: Quantum response – Relative photosynthetic response.

The rapid progress in Light Emitting Diode (LED) technology enables the possibility to use purely electrical illumination for plant cultivation. The unique capability of LEDs lies within the combination of a variety of monochromatic lights to create a light source specifically tailored to plant photosynthetic and morphological requirements. The key strength of LED lighting in comparison to conventional light sources is reduced power (high efficiency w.r.t. electrical energy to light energy). By using LEDs (e.g. deep blue and red), only the needed light spectrum is provided to the plants thus resulting in additional energy savings and the exact control of crop quality. By, for example, verifying the light spectrum (e.g. adding UV-LEDs) and choosing a specific mix of time dependent illumination (the so called light recipes), the phenotype and the taste of the fruits can be manipulated. Even the enrichment of certain healthy substances (e.g. Vitamin C, B) can be fostered through this method (e.g. *functional food*). Furthermore, through maximizing the total light duration (e.g. 20h of illumination instead of 14h), the plant life-cycle can, in some instances, be shortened. This results in shorter production cycles and thus higher yields per time interval. Since LEDs are using less energy and have a higher power-to-light ratio, the thermal loads are considerably lower. With this new feature and the small design volume, so-called intra canopy lighting is made possible for the first time. This strategy enables the light system to be placed within the plant structure itself, thus allowing lower plant leafs to receive more light, which results in higher photosynthesis levels and higher overall yields. Target-lighting is another illumination strategy, where LEDs are arranged in that fashion that only the actual plant leaves are illuminated. In addition, LEDs are ideal for uses to frequent on-off cycling, unlike fluorescent lamps that fail faster when cycled often, or high-intensity discharge (HID) lamps that require a long time before restarting. Therefore, the possibility exists to shutter the LEDs in order to further decrease power consumption. These innovative light strategies are of high interest for the EDEN Initiative, since they help to decrease the power demand of artificial illumination, while potentially increasing the biomass yield.

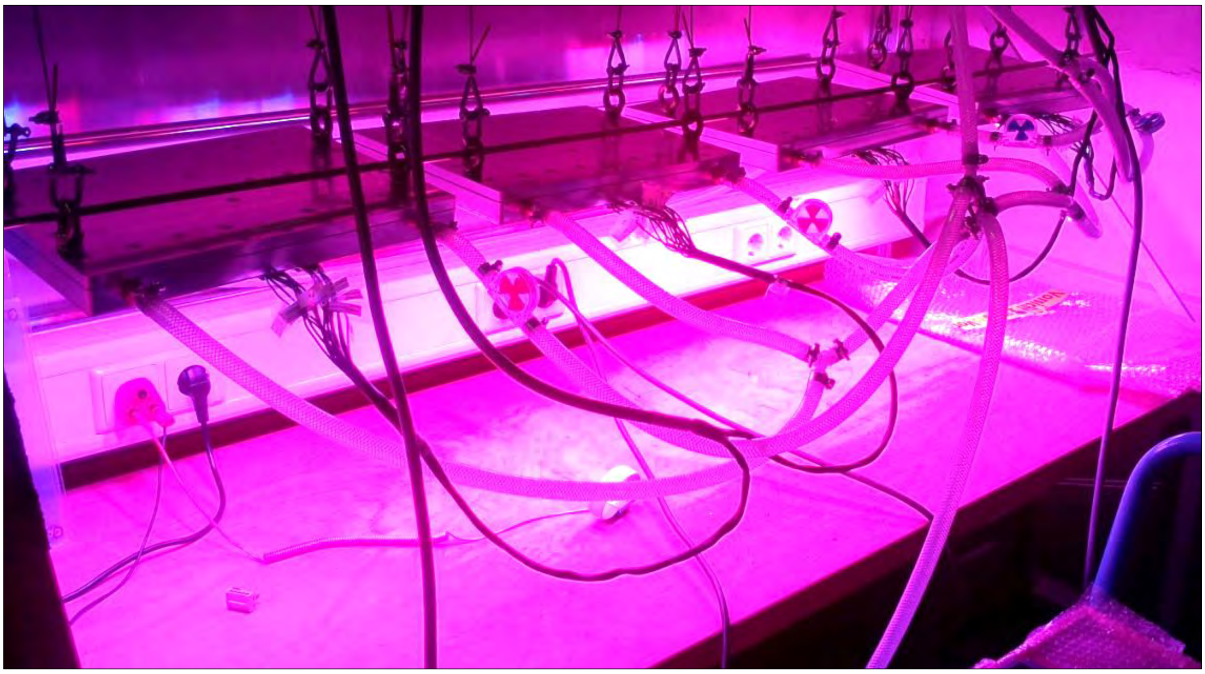


Figure 10: Experimental set-up of active water-cooled LED system provided by EDEN's research partner OSRAM.

In summary, the LED technology, as part of the CEA technology group, consumes less power, accelerates the natural plant life-cycle, can emit specific wavelengths, has less thermal loads so that intra-canopy lighting (as well as targeted lighting) is feasible, can be shuttered, is more shock resistant and has longer lifetimes than common technologies. Therefore, the EDEN research initiative will focus on this new plant illumination technology and will develop thin (~cm) actively-cooled LED panels that will facilitate the compact stacking of the plant grow levels, which will result in a high plant density in a given volume.

RESEARCH FOCUS:

The EDEN Initiative focuses on the following research topics within its *Plant Illumination* domain:

- Development of thin-, water-cooled LED systems as well as the control architecture.

- Analysis, development and testing of targeted lighting systems tailored for each relevant plant developmental stage, intra-canopy lighting strategies in order to increase biomass output for tall-growing plants, and LED-shutter principles to decrease power usage.
- Testing of light recipes in order to establish a fundamental component of the envisioned grow recipes.

3.3 Nutrient Delivery System

Nutrient delivery is the provision of water and nutrients in the amount necessary for optimal plant growth over all plant development stages. There are 17 currently known plant nutrients and typical nutrient solutions (e.g. Hoagland solution) are made up of various nutrient salts dissolved in water in varying concentrations. Each nutrient can itself directly influence plant growth. Nutrients must be carefully monitored and this is traditionally conducted through pH and electrical conductivity measurements.

Ion-selective sensors, an upcoming sensing technology can provide real-time measurements of these ion-selective nutrient concentrations. A nutrient deficiency or abundance can result in plant stress, limiting growth, resulting in any number of symptoms such as tipburn, chlorosis, localized tissue necrosis and potentially even plant death.

Figure 11: Aeroponic cultivation set-up inside the EDEN Laboratory. The roots are sprayed with a nutrient solution every five minutes for 20 seconds.

Nutrient solution sensor arrays with according mix control units are complex and require a certain mass (especially when considering an ion-selective approach). Combining this fact with the circumstance of a multi-compartment grow arrangement, where various plants in different grow development stages require all their own set of nutrient solution mixes, which need to be adjusted (e.g. every day), makes it a complex challenge. The EDEN Initiative will therefore focus on the development of a nutrient distribution system for several grow compartments, utilizing one central mix unit (and associated sensor array).

The method of delivery of the nutrient/water mix (hydroponic solution) can be conducted in various ways. These include soil-based, nutrient media based hydroponics systems as well as systems requiring no substrate, such as aeroponics. Each configuration can provide certain advantages, but for space-based BLSS, Aeroponics can provide the benefit that no soil or substrate is required (minimizing waste) while potentially producing higher plant yields.

The basic principle of Aeroponic systems is to grow plants suspended in a closed or semi-closed environment by spraying the plant's dangling roots with an atomized nutrient-rich water solution. Aeroponic equipment involves the use of sprayers, misters, foggers, or other devices to create a fine mist of solution to deliver nutrients to plant roots. No soil or grow media is needed for the whole life cycle. Furthermore, the plant's nutrient uptake can be improved by the exact control of plant root environment. Through this innovative irrigation principle a general reduction in nutrient solution throughput, decrease of water loss, higher plant density (than traditional grow procedures), limitation of disease transmission, and potentially higher plants yields can be achieved.

RESEARCH FOCUS:

The EDEN Initiative focuses on the following research topics within its *Nutrient Delivery Systems* domain:

- Development of highly reliable, low mass Nutrient Delivery Systems (NDS) e.g. Aeroponics and its integration in high-density plant production systems.
- Development and test of a centralized nutrient mix unit for a multi-chamber distribution approach.
- Incorporation and long-term test of ion-selective sensors in the relevant operational environment of functional plant growth systems.

3.4 Atmosphere Management System

Atmosphere management encompasses the monitoring and control of temperature, humidity and gas composition within the grow chambers. It accounts to one of the essential CEA technologies in order to assure optimal plant growth, since humidity and temperature influence the opening and closing of stomata and therefore the evapotranspiration process of plants. Furthermore, the Atmosphere Management System (AMS) is one of the most complex systems considering multi-chambered plant accommodations and shifted day/night cycles between the chambers.

By implementing recovery systems, the evapotranspired water of the plants can be used for irrigation purposes again (resource efficiency), or being fed-back towards the habitat for crew usage.

CO_2 is an essential element for plants and is metabolized with water, nutrients and light to oxygen, water and biomass (=> Calvin Cycle). In CEA systems, the air is enriched with CO_2 to increase the biomass generation and consequently the plant growth rates. Literature has shown that increasing the CO_2 level to 550 ppm will accelerate plant growth by 30 – 40%.

Since closed systems have no direct gas exchange with the external environment, volatile organic compounds (VOCs), emitted by system components and plants (e.g. ethylene), have to be filtered from the chamber air. Adequate air purification systems need to be developed in order to keep the greenhouse module environment in a healthy state. In the future a measuring, control and removal system for VOCs e.g. Ethylene will need to be integrated into the AMS.

Figure 12: Test set-up of the Atmosphere Management System (AMS) within the closed-loop test facility of the EDEN Lab.

The EDEN Initiative will develop and test these system components in order to develop a fully functional and highly reliable AMS. A first bread board has been built and tested within the closed-loop test facility of the EDEN Lab.

RESEARCH FOCUS:

The EDEN research initiative will focus on the following research topics within its *Atmosphere Management Systems* domain:

- Development of an atmosphere control system supplying precise humidity/ temperature environments within multi-chamber grow systems.
- Development of low energy consumption water recovery systems.

- Development of highly efficient regenerative trace gas separation (mainly Ethylene) and air purification (w.r.t. pathogens) systems.

3.5 Health Monitoring & System Control

Cultivation in closed environments is challenging especially when dealing with the different parameters for optimal plant growth, like temperature, relative humidity, gas composition, spectral light mix, and nutrient composition. The requirements are not only changing over the life-cycle of one single plant, but also differ between crop species. As space-based greenhouses will likely be multi-compartment systems consisting of numerous (e.g. 10-20) different crop types, they represent significantly complex small closed ecosystems. Considering closed-loop principles (e.g. water recovery), this control task has not been addressed by the scientific space community for the adequate implementation in space greenhouses.

Loss of control over a growth production chamber has negative effects on the food production, air revitalization and water recycling. Unlink terrestrial greenhouses, the loss of BLSS control may result in the loss of the mission. Therefore detection, diagnosis and failure tolerance become very important.

Figure 13: Main control station of the closed-loop test facility within the EDEN Laboratory. All sensors data and visual monitoring feeds are linked to this control station in order to monitor plant growth, but also to test remote control technologies.

In a small closed ecosystem damping-, buffer- and self-regulating factors become ineffective. Its diversity and size are not sufficient for stochastic mechanisms to operate successfully. A deterministic control system is therefore a prerequisite for the sustainable existence of a small closed ecosystem (compare chapter 2.1).

This includes at the basic level measurements by reliable sensors, scheme of control, and regulation. Furthermore, the control strategy of a closed ecosystem strictly depends on the system and control architecture, knowing that the highly branched and looped topology requires specific attention. Several measurement points are required to trace down the local climate parameters of a plant growth chamber and thus achieve a highly qualified control. Moving towards the use of new techniques and technologies is indispensable to facilitate the feasibility of the BLSS. Drastic reduction of mass, power and volume are inevitable to achieve a real possibility of long-duration missions.

Especially, the consideration of multi-chambered cultivation systems requires a new and optimized control architecture that provides adequate environmental settings in each chamber. The first objective is therefore stated in order to investigate a new architecture to create a resource efficient way of controlling this combined small ecosystem in a sustainable manner.

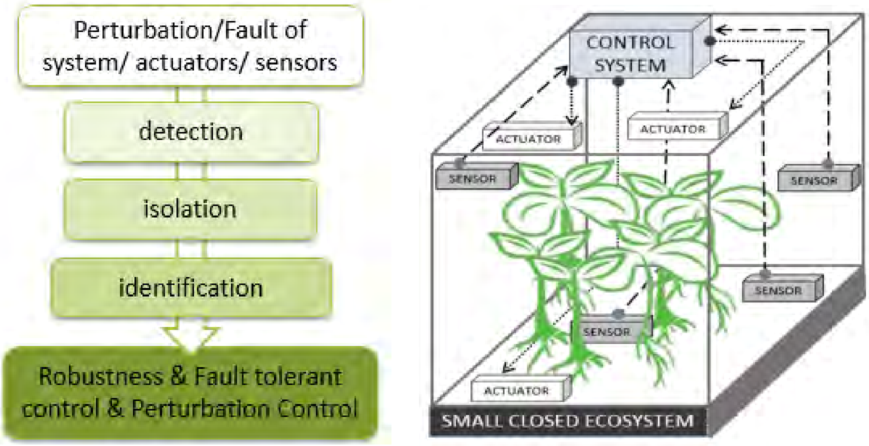


Figure 14: Optimization of Control Architecture & Optimization of Perturbation & Fault Response Actions.

The goal of a plant production chamber is to optimize the quality and quantity of produced biomass. Optimization is achieved using the control environment inside the chamber and achieving the optimal conditions for the specific cultivated plants.

As part of the fault avoidance activities the incorporation of an operational expert backroom will be considered as well. This backroom made up of experts from the disparate fields of horticulture, biology and aerospace engineering will be an essential part of future space-based BLSS. As available astronaut crew time will limit the possibility of significant human tending and inspection, the implemented sensor and actuator suite of future BLSS will feed essential data to the remote monitoring team, who will play an important role in ensuring BLSS system reliability.

RESEARCH FOCUS:

The EDEN Initiative focuses on the following research topics within its *Health Monitoring & System Control* domain:

- Testing and optimization of control architecture with respect to multi-compartment plant growth chambers (w.r.t. sensors, actuators).
- Testing and optimization of perturbation, fault, and malfunction response actions.
- Development and testing of remote control architectures (operational expert backroom) for greenhouse operations.

3.6 Innovative Cultivation Procedures

Within this research focus, new methods of plant accommodations shall be investigated. Since the environmental conditions (e.g. temperature, light, humidity, and gas composition) and the nutrient supply (e.g. water, fertilizer) are decoupled completely from the natural system, stacking of cultivation levels can be achieved. This dogma change in agricultural procedures enables a high density of plants in a relative small volume or footprint. Several plant accommodation approaches exist to increase the plant density in a given volume, such as cylindrical rotation-, parallel shelf-, angled shelf-, or spiral accommodation (compare Figure 15 for some examples). Trade-offs with respect to mass, plant density, handling, and achievable plant environment quality will be analyzed by the EDEN group. Furthermore, bread boards shall be built and tested within the EDEN Lab.

Figure 15: Different grow accommodations [Credits: Omega Farming & Valent].

All CEA technologies are linked with this research domain. The growth chamber, housing the plants, is interconnected with all CEA subsystems (NDS=> root compartment; LEDs=> shoot zone illumination; AMS => environmental condition of the chamber; health monitoring and control => plant health status). In this sense, one can consider the plant growth chamber as a biological reactor with complex input- and output relationships. To control this overall task and to mitigate possible system disturbances, this research focus will evaluate, design and test possible strategies for optimal high-density plant growth.

Furthermore, new cultivation methods and plant maintenance procedures shall be investigated, like spiral stem-folding, cut & grow strategies, and scrogging with respect to tall-growing plants (e.g. cucumber, tomato). Here planting-, maintenance- , harvest-, and post-harvest procedures will be tested within the EDEN Lab. Special plant support structures will help to cultivate healthy plants and minimize crew time where possible.

All these investigations will help to build up complete growth recipes including all environmental-, metabolic-, morphological-, and treatment factors necessary for optimized plant growth within closed-loop environments like in Moon and Mars habitats. This will form a holistic approach of a high-efficient plant production and will also create a solid ground for future crew time estimates.

Finally, the EDEN Initiative foresees the active transfer of knowledge, gained from the above mentioned research domains, into terrestrial applications. Therefore, several feasibility studies, market surveys and analysis were performed and patents were established in the past years. Vertical Farming, desert greenhouse modules, home farming, and Molecular Farming (or Pharming) are only some examples of the investigated spin-offs. For further information, please refer to Chapter 6 (Terrestrial Spin-offs).

RESEARCH FOCUS:

The EDEN Initiative focuses on the following research topics within its *Innovative Cultivation Procedures* domain:

- Development of new stacking methods for plant cultivation in order to achieve maximum of plant density in a given volume.
- Creation and test of specific growth recipes (light mix, air, and nutrient composition) for specific fruits and vegetables with high-water content.
- Evaluation and testing of new handling- and cultivation procedure (incl. innovative plant support structures) for advanced plant cultivation under CEA regimes in order to create a solid knowledge basis for crew time estimates.
- Combining the research results from all domains and actively transforming them into terrestrial applications.

3.7 Overview

The table gives an overview of the full research scope within the EDEN Initiative:

Evaluation and design of **plant grow systems for planetary habitat integration** (Moon, Mars), where these systems work in close conjunction with physical/ chemical Life Support Systems. The required **Controlled Environment Agriculture technologies** and operation procedures shall be **developed and tested** within the EDEN Laboratory. The primary ambition is the achievement of **highly reliable** plant cultivation systems with **maximum biomass output** of high water-content crops, produced in a **resource-efficient** manner (power, water, nutrients) and with **high plant densities**.

Domain	Research Focus
System Analysis & Habitat Interfaces	• Systems (and subsystem design respectively) design of greenhouse modules for planetary use as an integrated part of an outpost infrastructure. • Subsystems accommodation analysis, mass-, power-, thermal budget estimates as well as crew time estimates. • Investigation of the dynamic behavior of hybrid LSS consisting of a habitat, a greenhouse and physical/ chemical LSS.

Domain	Research Focus
	• Evaluation, development and testing of post-harvest procedures in order to increase food shelf lifetime and to facilitate easy consumption by the crew.
Plant Illumination	• Development of thin-, water-cooled LED systems as well as the control architecture. • Analysis, development and testing of targeted lighting systems tailored for each relevant plant developmental stage, intra-canopy lighting strategies in order to increase biomass output for tall-growing plants, and LED-shutter principles to decrease power usage. • Testing of light recipes in order to establish a fundamental component of the envisioned grow recipes.
Nutrient Delivery System	• Development of highly reliable, low mass Nutrient Delivery Systems (NDS) e.g. Aeroponics and its integration in high-density plant production systems. • Development and test of a centralized nutrient mix unit for a multi-chamber distribution approach. • Incorporation and long-term test of ion-selective sensors in the relevant operational environment of functional plant growth systems.
Atmosphere Management System	• Development of an atmosphere control system supplying precise humidity/ temperature environments within multi-chamber grow systems. • Development of low energy consumption water recovery systems. • Development of highly efficient regenerative trace gas separation (mainly Ethylene) and air purification (w.r.t. pathogens) systems.
Health Monitoring & System Control	• Testing and optimization of control architecture with respect to multi-compartment plant growth chambers (w.r.t. sensors, actuators). • Testing and optimization of perturbation, fault, and malfunction response actions. • Development and testing of remote control architectures (operational expert backroom) for greenhouse operations.
Innovative Cultivation Procedures	• Development of new stacking methods for plant cultivation in order to achieve maximum of plant density in a given volume. • Creation and test of specific growth recipes (light mix, air, and nutrient composition) for specific fruits and vegetables with high-water content. • Evaluation and testing of new handling- and cultivation procedure (incl. innovative plant support structures) for advanced plant cultivation under CEA regimes in order to create a solid knowledge basis for crew time estimates. • Combining the research results from all domains and actively transforming them into terrestrial applications.

4 Space Habitation Plant Laboratory (EDEN Lab)

In 2014, the Space Habitation Plant Laboratory (EDEN Lab.) was opened. The main driver for the establishment of this research laboratory was the necessity to gather hands-on experience with the cultivation of higher plants in (semi) closed-loop environments. The laboratory offers a unique set of cultivation chambers for the conduct of plant growth studies and the development of the necessary supporting technologies. In particular, Controlled Environment Agriculture (CEA) technologies will be developed and tested within the EDEN Laboratory.

Figure 16: View from the workshop area into the biological clean room (Closed-loop Test Facility) of the EDEN Laboratory.

The EDEN Lab. is organized in three segments (compare Figure 17). The first segment – the work area - is foreseen to set up the different experiments, modify existing experiments and to prepare for upcoming integrated test campaigns. The work area offers space for a work bench, including tools for the mechanical machining of components, 1-2 variable workstations for precision mechanical work such as electrical soldering, 1-2 multifunctional tables for different assembly, integration and test activities, and two desks for data analysis and completing lab documents/reporting. The main observation deck is also located within this area, where six screens visualize the grow parameters and give visual video feeds of plant health status.

The core of the EDEN Lab is the closed-loop test facility (experiment area). The work area and the closed-loop test facility are separated by an air-tight PET wall. This provides an environmental barrier between experiment development and implementation. A sliding door allows for access between the two sections. The closed-loop facility is considered as a biological clean room, preventing pathogen establishment, such as bacteria or fungi. Adequate precaution procedures need to be applied before entering this room (e.g. disinfection of hands, clean room suits, and overshoes).

Several plant growth chambers of different types are located within the experiment area. In particular, five single growth chambers (fabric tents) are established for parallel plant growth experiments, LED testing, plant accommodation-, and irrigation tests (e.g. Aeroponic). Furthermore, the closed-loop facility offers four high-precision, multivariable plant growth systems, including support cabinet in order to study comparative experiments on illumination and gas exchange research questions.

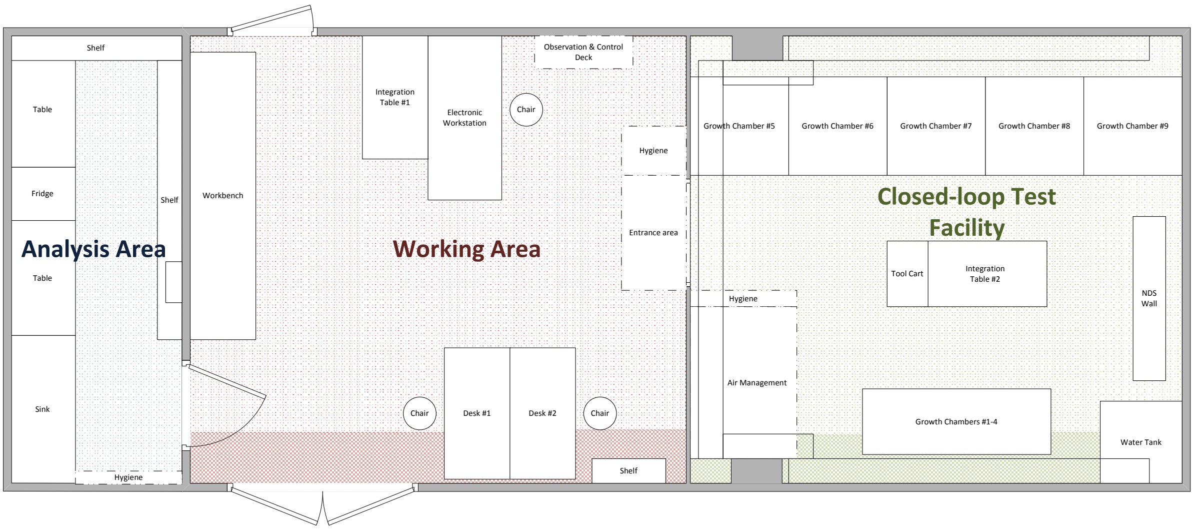
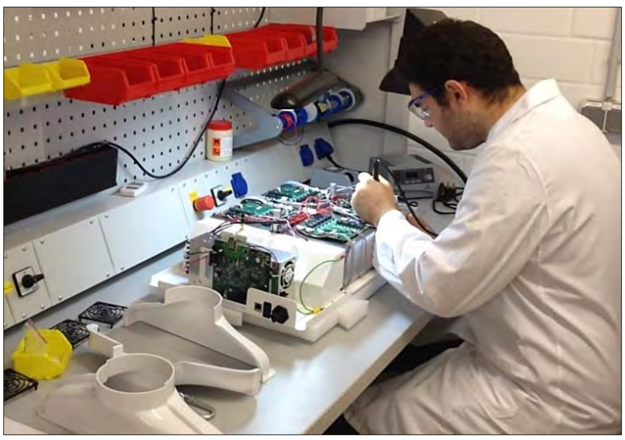


Figure 17: Schematics of the EDEN Laboratory (Space Habitation Plant Laboratory).

A dedicated Nutrient Delivery System (NDS) bread board allows the testing of an automated system for multi-compartment growth arrangements (LabVIEW controlled mix computer, reverse osmosis system, nutrient supply and measuring equipment). The environmental conditions within the test facility are managed by the Atmosphere Management System (AMS), which is also located within the room. The AMS bread board comprises a water recovery subsystem, a CO_2 injection subsystem, a Trace Gas Separation Unit (TGSU), sensor arrays, and several circulation fans. All sensor data is transferred to the central observation deck within the work area.



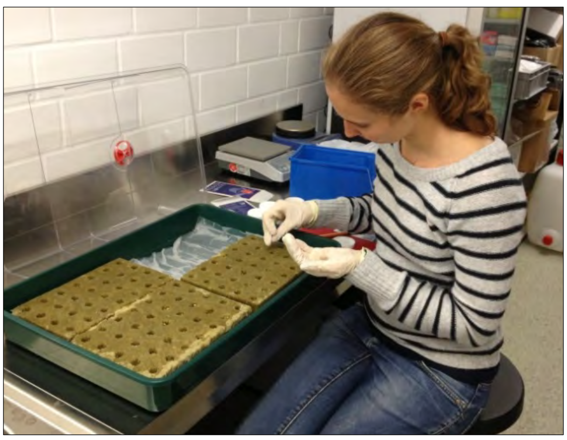


Figure 18: Left: Electronic work bench within the work area; Right: Analysis room for pre-cultivation and post-harvest procedures.

Within the analysis area (compare Figure 18, right), the pre-cultivation procedures as well as post-harvest analysis are performed. The room offers two work tables, a fridge for sample storage, and two wash basins. The room is equipped with analytical test tools and test stands (e.g. dry oven, precision scales, and microscope). In addition, the room offers space for the storage of spare parts and components for the different CEA technologies. Fertilizers and nutrient salts are stored here as well so that the stock solutions can be mixed. A special seed archive allows the EDEN team to choose between various crop cultivars.

Figure 19: Test plant cultivations under CEA regimes within the Closed-loop Test Facility of the EDEN Laboratory.

5 Analogue Testing Expertise

It is essential to test and validate plant cultivation technologies in an environment similar to space and with relevant mass flows to increase their Technology Readiness Level (TRL). Testing individual subsystems to investigate performance requirements in clean rooms are typically insufficient to address the complex system interactions. Furthermore, integrated system tests in realistic operational environments are difficult, often not planned nor budgeted, resulting in on-orbit surprises. Given the risks, costs and complexities associated with human missions to Moon and Mars, space-analogue research on Earth can be a powerful tool to explore the challenges associated with working and living upon another planet. Here, on ground space-analogue simulations of planetary surface operations that test the technologies and exploration strategies, will provide valuable data and represents an essential method in pushing the TRL and to gain solid knowledge and experiences for mission planners, engineers and planetary scientists.

Figure 20: Mars Desert Research Station (MDRS) in Utah (USA), managed by the Mars Society. The EDEN group participated in two missions in 2013 and 2014 at this analogue test site, conducting plant cultivation experiments [Credits: Jim Urquhart].

Having conducted several design studies about greenhouse systems, the EDEN Initiative in collaboration with Volker Maiwald of the Department of System Analysis Space Segment had the opportunity to participate in the International Lunar Exploration Working Group's EuroMoonMars B mission (Crew 125) at the Mars Society's Mars Desert Research Station (MDRS) in early 2013. This participation took place mainly under the auspice of relating the analogue test site with the habitat design studies of the department and to prepare future missions with the perspective of greenhouse system tests.

One year later in 2014 Lucie Poulet (former member of the EDEN Initiative) participated in the Reliability and Redundancy of Extreme Environment Habitat Structures and Power Systems mission (RAR Mission) within Crew 135. The main focus of the mission was structural and power assessments to improve habitat performance, efficiency, reliability and redundancy. Lucie Poulet conducted a study on illumination and Nutrient Delivery Systems of the GreenHab (see Figure 20, right), which was performed to make it more efficient in terms of plant production and crew time use.

Figure 21: HI-SEAS habitat on the Mauna Loa volcano in Hawaii (USA) [Credits: Ross Lockwood]

In 2014, Lucie Poulet was selected among several hundred candidates to participate in the HI-SEAS (Hawaii Space Exploration Analog and Simulation) Mission II in Hawaii, USA (Figure 21). HI-SEAS missions are conducted by the University of Hawaii and are funded by the NASA Human Research Program. The first mission was conducted in 2013, lasted four months, and focused on a food study. Mission II was the first of three psychological studies, whose durations respectively are four, eight, and twelve months, focusing on crew behavior and performance. During four months, Lucie lived together with five other crew members without direct communication with the outside world, in a dome-shaped habitat on the slopes of the volcano Mauna Loa on the Big Island of Hawaii. The area has Mars-like features and is in a remote area at an elevation of approximately 8200 feet above sea level.

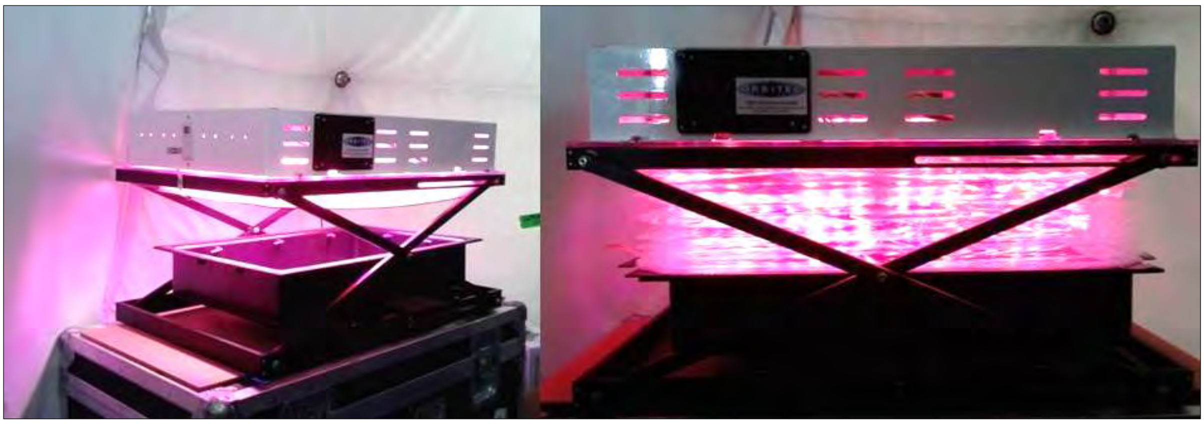


Figure 22: Biomass Production System for education (BPSe) within the HI-SEAS Habitat in Hawaii.

Although, Lucie Poulet participated in this mission out of her private interest (she was on unpaid leaves from DLR for the time of the study), she performed some plant cultivation experiments, supported by the EDEN team, the Kennedy Space Center, and EDEN's partners Heliospectra and ORBITEC. The prime focus of these experiments was to investigate the effect of different lighting wavelengths on plant growth and to assess the effects of having plants in the habitat on the crew during long-duration isolation periods. In close collaboration with ORBITEC, she deployed the BPSe (Biomass Production System for Education) - the educational unit of the plant cultivation system VEGGIE. The VEGGIE system is momentarily being tested on the ISS in order to eventually provide fresh lettuce to the crew. After successful completion of the isolation mission, the BPSe has been transferred to Bremen, Germany in order to conduct further plant experiments in the EDEN Lab.

In addition to the BPSe tests, Lucie Poulet investigated plant growth under different illumination systems, which were provided by Heliospectra and NASA. She also performed a plant cultivation outreach activity together with the DLR School_lab, involving school classes in Germany, USA, and France. See chapter 8 for more details.

These initial analogue missions have already shown how analogue test site utilization can enhance EDEN's research and expertise in the field of habitat and Life Support System (LSS) design and in general the preparation of human missions to the Moon and Mars.

Figure 23: Neumayer Station III in Antarctica [Credits: AWI].

The main goal of the EDEN Initiative within the analogue testing domain is the design and development of a mobile greenhouse system incorporating all necessary CEA technologies to be deployed at the Antarctic Neumayer Station III of the Alfred Wegener Institute (see Figure 23). Crews working in this Antarctic station, operate under constraints analogous to those faced by astronauts operating on-orbit or on other planetary surfaces. The constraints include extreme environments, challenging resupply logistics, similar crew size and psychological isolation. In-situ plant production often represents the only solution remote station crews have for fresh produce.

In 2012, the EDEN team submitted a proposal to the 6th Space Call within FP-7 under the acronym EDEN-ATS. The project was aimed to activity *2.1-01-02_SSF Exploitation/ Earth-analogue*. The proposal passed the threshold and received a total score of 14.00 points out of 15.00. Despite the very good result, EDEN-ATS was not funded due to the high amount of competitors in this activity. In 2014, a similar proposal was submitted (called EDEN-ISS) within the Horizon2020 under *COMPET 7 - 2014: Space exploration – Life support*. The proposal scored 14.50 points out of 15.00 and is now been funded by the European Commission.

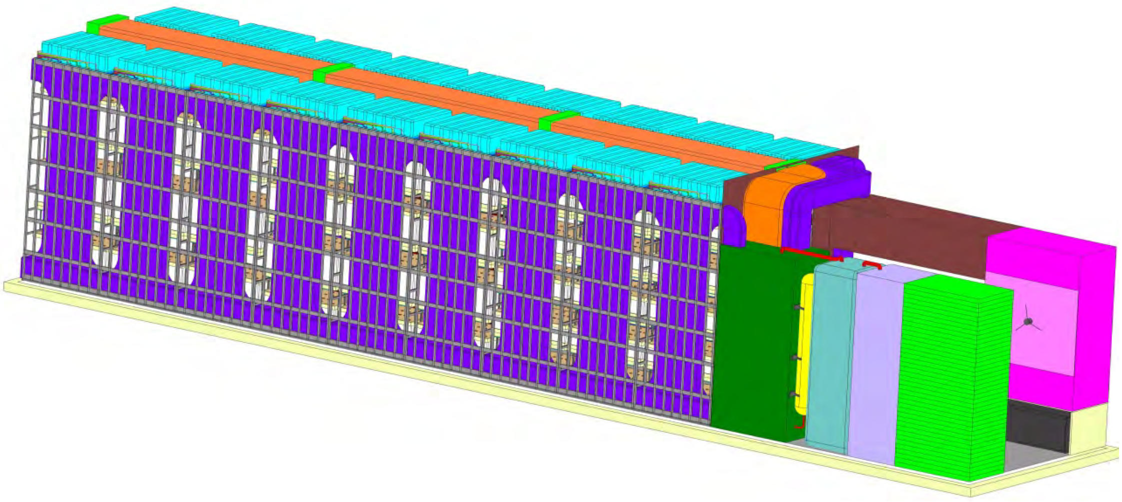


Figure 24: Initial design of the Antarctic greenhouse system for the Neumayer Station III designed by the EDEN team.

The project has a total budget of 4.5 M€ and is planned for four years (beginning early 2015) of intensive research and development of plant cultivation technologies and -procedures. Together with the EDEN team, the EDEN-ISS consortium consists of the top international scientists in the area of Controlled Environment Agriculture (CEA) technologies from Europe and Canada (and furthermore USA, Russia and Japan with respect to the Scientific Advisory Board – SAB). The project reflects a multidisciplinary group of experts representing aerospace engineering, medicine, agriculture, horticulture, microbiology, polar and marine research, food science, and psychology.

The research objectives relate to the operation of each of the respective CEA technologies within this relevant operational environment. Based upon successful demonstration, this analogue mission will enhance their respective Technology Readiness Levels (TRL) for future utilization in space-based systems.

In addition the project will further enhance the knowledge about crew time assessments. The quantification of realistic crew time requirements over the long-term operation of this greenhouse within this mission relevant environment will have considerable benefit over laboratory extrapolations.

Last but not least, remote operational experiences will be gathered. The incorporation of a remote backroom operations team that can collaboratively interact to monitor and control aspects of the locally tended greenhouse will contribute new knowledge about requirements and potential efficiency improvements from this regard (tele-operation).

6 Terrestrial Spin-offs

EDEN's research results will extend the knowledge of plant cultivation procedures in closed or semi-closed environments, an area with increasing terrestrial market potential. Closed or nearly closed-loop plant cultivation systems can enable terrestrial agriculture to be conducted in areas currently unsuitable for agriculture.

A detailed market analysis was performed in collaboration with the DLR-Technology Marketing (DLR-TM) department. The focal point was set on terrestrial applications, resulting from the research findings of the EDEN Initiative with respect to greenhouse modules utilizing CEA technologies.

The EDEN team identified and analyzed five terrestrial spin-off markets (compare Figure 26) and created a roadmap for a successful market entry strategy. The five segments were analyzed with respect to general applicability of the idea, risks and market barriers, consumer preferences and pyschograms, existing market participants (competitors) and projects, as well as potential market volume and potential sales volume estimates.

Figure 25: Market analysis conducted in 2012, 180 pages.

Due to global warming, desertification is becoming an increasing problem, transforming once fertile lands into inhospitable deserts. Modified greenhouse modules, which can be located in desert regions, can act as an opportunity to utilize these areas for agriculture. Greenhouses optimized with closed-loop habitat technology excel in this purpose due to their low water requirements compared to traditional agriculture due to e.g. aeroponic irrigation systems, ion-selective sensors. Additionally, the abundance of solar power, ability to grow crops throughout the whole year, and the decrease of crop losses due to drought, insects and diseases, make closed-loop greenhouse modules a potential solution for producing crops in desert climates.

Furthermore, modified greenhouse modules can contribute to the food independency in the area of remote locations. Here, fresh food can be produced as supplement to the people working on offshore facilities, remote villages, high-mountain regions, islands and remote work sites. Even the deployment as mobile greenhouses in refugee camps, embedded in the general international emergency aid campaigns, can become feasible.

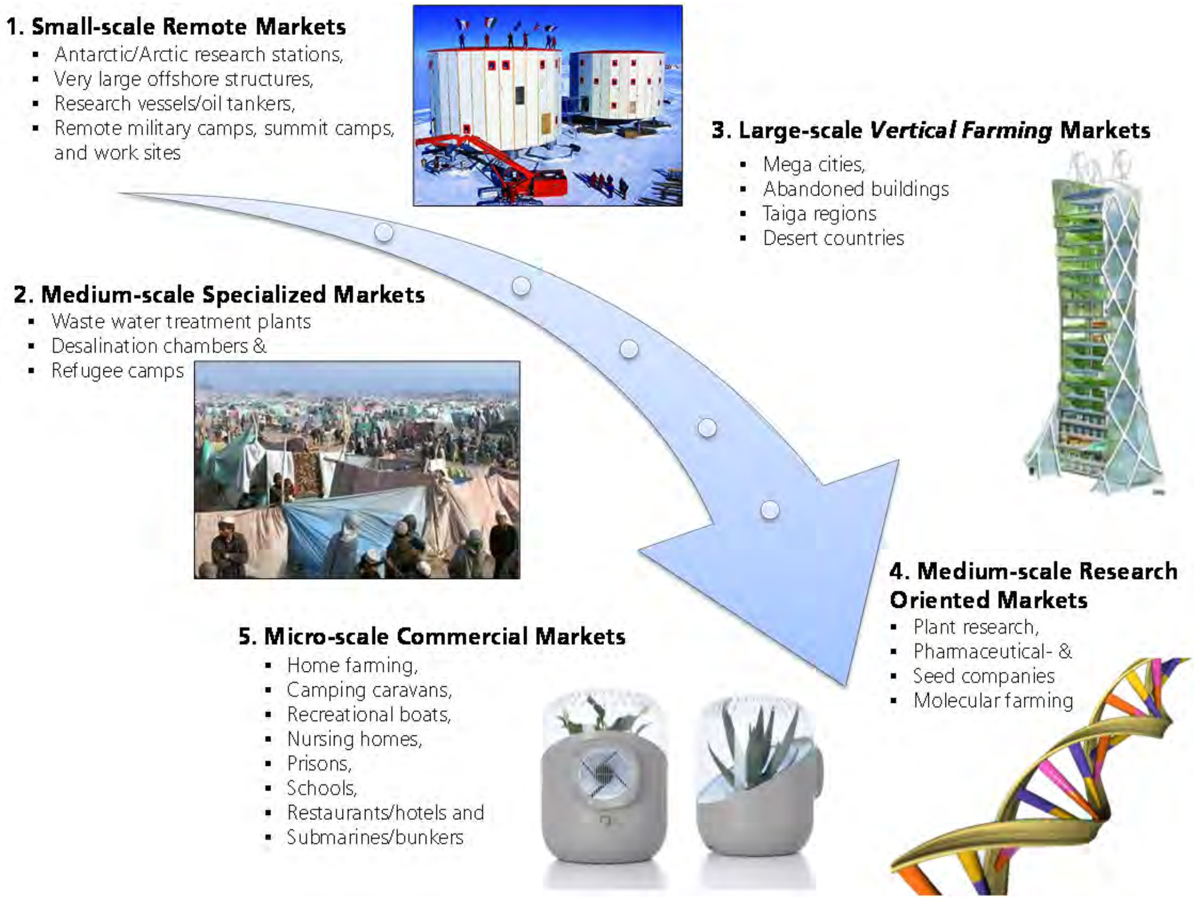


Figure 26: Market strategies (road map), derived from EDEN Market analysis conducted in 2012 for the deployment of CEA Technologies.

Molecular farming (also known as molecular pharming or bio-pharming) is the use of genetically engineered crops to produce compounds with therapeutic value. These crops will become biological factories, used to generate drugs, vaccines and other expensive plant products. The envisioned greenhouse modules can be transformed into small production units and can provide a highly adjustable growth environment for small- and medium-scale tests (and even production cycles) by completely controlling the input and output parameters of the production process. Furthermore, from a pure research perspective, this could be important for a wide range of medical plant investigations. Additionally, experimentation with genetically modified plant species could be conducted risk free utilizing the envisioned greenhouse modules, by avoiding the possibility of external contamination or outbreak.

One of the newest research topics is called Vertical Farming (VF), which is steadily becoming a subject discussed broadly in political and scientific communities. Vertical Farming is a proposed agricultural technique involving large-scale agriculture in urban high-rises or "farmscrapers". Using cutting-edge greenhouse methods and CEA technologies, these buildings would be able to produce fruits, vegetables and other consumables (e.g. herbs, pharmaceutical plants) throughout the entire year. The concept foresees the growing and harvesting of a wide range of plants in high density urban areas (mega cities) and the sale of these crops directly within the city, reducing the required transportation efforts as opposed to the standard rural farming model. First pilot production building are already established in Asia, Europe, and North America. The advantages of this method are:

- The high accommodation of agriculturally productive area (growing in vertically mounted floors)
- The increase in crop yields (by using optimized production methods, such as light exposure variations, or additional CO_2 supply)
- The protection of the crops from weather-related problems (with respect to outdoor farming); no requirement for pesticides
- The minimization of water requirements (through water recycling methods)

The EDEN Initiative conducted a CE-study for a conceptual Vertical Farm in 2012 within its spin-off ambition (see Figure 27). The conceptualized Vertical Farm is a building with 37 floors, a square footprint of 44 x 44 m² (0,19 ha) and a total height of 168 m. There are 25 plant cultivation floors in the building with multiple stacked plant growth layers on every floor. A total edible biomass output of approximately 13,3 metric tons/day can be achieved with a total grow area of ca. 93.000 m². The analysis comprised layout planning for each floor, plant production analysis, and a detailed cost analysis.

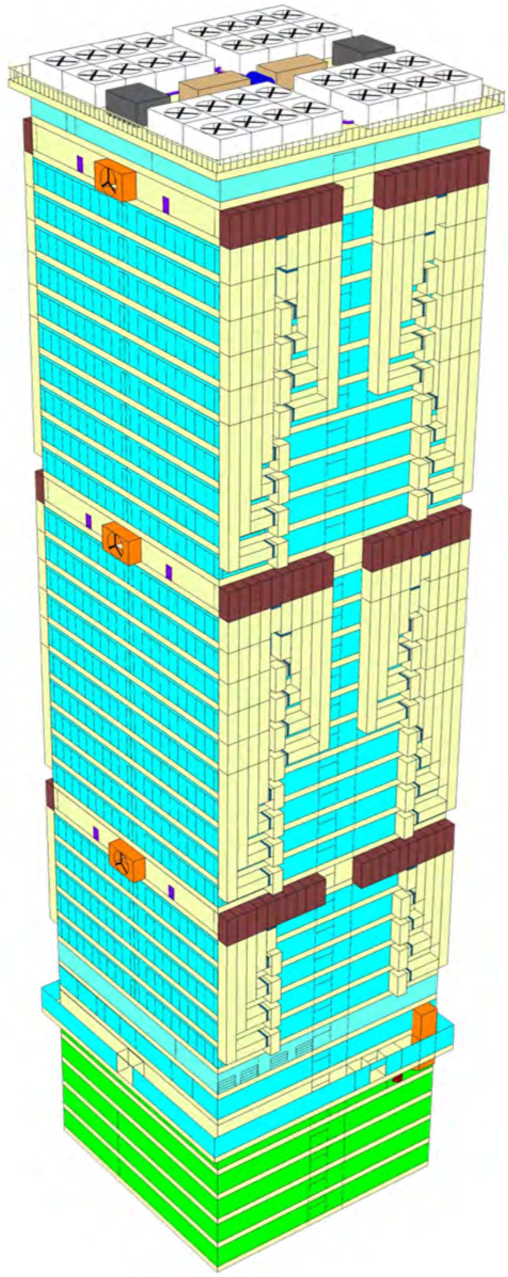


Figure 27: Vertical Farm design which was elaborated during a CE study at the DLR Institute of Space Systems.

Comparing Figure 28, one can see that there is an increase in yield of all crops in the VF compared with traditional cultivation techniques. To produce an equal amount of edible output as that produced in a VF with a footprint of 0,19 ha, an area of 216 ha of field cultivation is needed. This is a required agricultural land increase factor of 1.115. The increases in yield of the VF is the result of the protected environment (optimized growth conditions), shortened growth periods, additional numbers of grow cycles and harvests per year (no seasonal restrictions) as well as area utilization optimization (vertical stacking).

The EDEN Initiative, which targets the investigation and design of high yield plant production systems plans to contribute significantly to this upcoming field of technology and strengthens this way Germany's and European competitiveness within it.

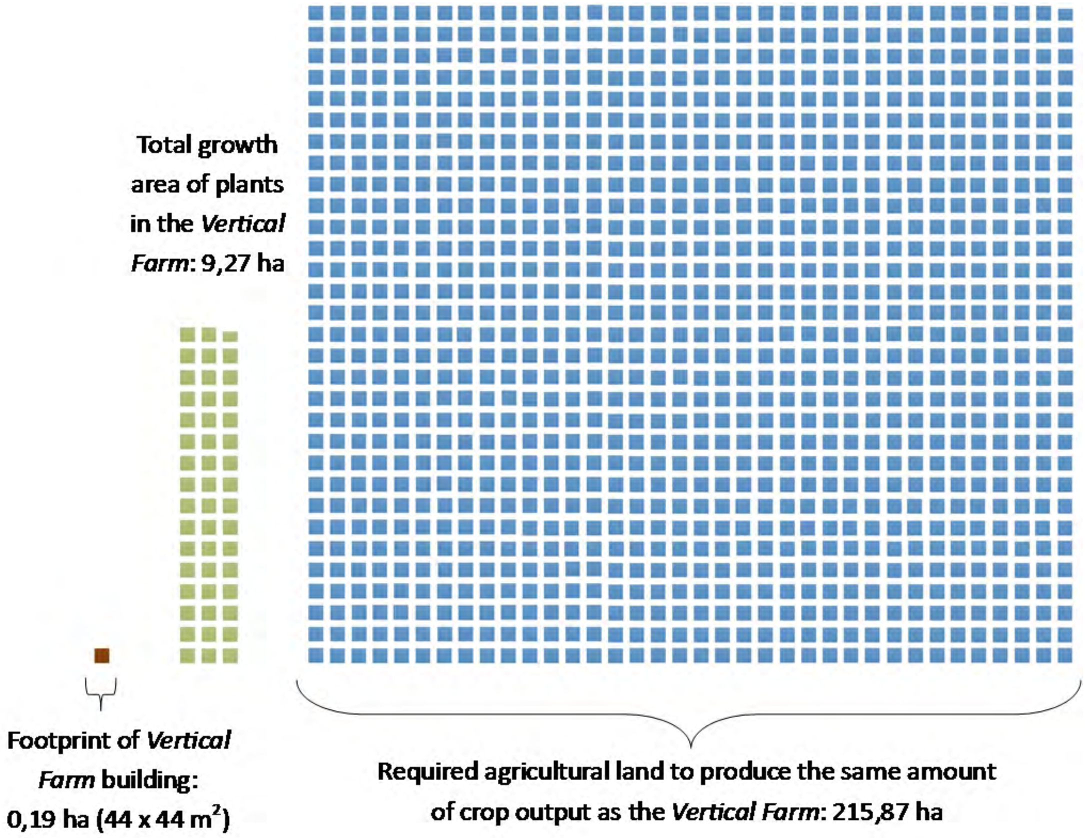


Figure 28: Comparison of production footprint of the Vertical Farm to traditional agriculture.

In order to push the technological- and economic feasibility of Vertical Farming, the EDEN Initiative has become an active member of the newly founded *Association for Vertical Farming*. Located in Munich (Germany), the association is an internationally active non-profit organization, focusing on advancing Vertical Farming technologies, designs and businesses. The EDEN team supports this association with technical expertise and economic analysis and supports the organization of combined conferences and workshops on this subject.

Figure 29: Logo of the international operating *Association for Vertical Farming*

By investing in this research, new cultivation approaches in producing food and other useful elements can be achieved in a resource-efficient manner. This way the aspect of sustainability shall be highlighted, which is also confirmed by the European Union within their EUROPE 2020 Initiative (Innovation Union) to refocus on R&D and innovation policy on major challenges for the European society like climate change, energy and resource efficiency, health and demographic change.

7 Projects & Grants

This chapter gives an overview of all projects and grants related to the EDEN Initiative.

7.1 GHM System for Space System

Greenhouse Module (GHM) for Space System is an ESA funded project within ESA's MELiSSA activities (GSTP). The goal of the ESA GHM for Space System project is to design an automated production facility for higher plants, utilizing mass production principles while minimizing mass, volume, and power demands. Within the project the EDEN team studies and designs multiple greenhouse module concepts for a crewed base on the lunar surface.

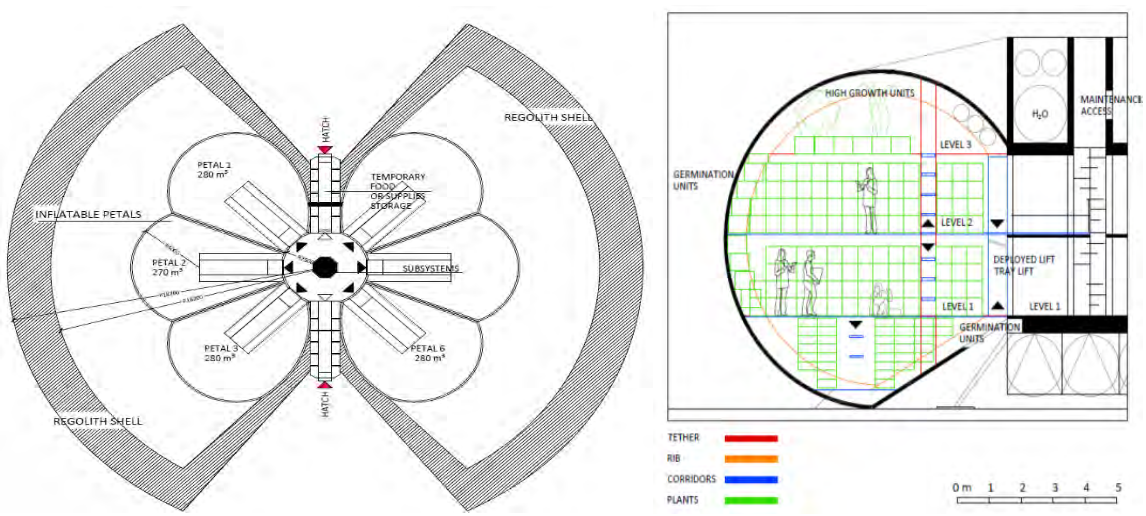


Figure 30: One concept of a Lunar greenhouse module.

The project combines the disciplines, associated with higher plant cultivation, into a solid space-proven concept taking all systems engineering aspects into account. During a Concurrent Engineering (CE-study), a phase-A design is elaborated.

Project Partners: DLR-RY (Project lead), Airbus Defence & Space, Märka Design, HTWD Horticulture Department, Enginsoft, and DLR-ME.

Time Frame: 11/2012 - 12/2014

Total Budget: 150 k€

7.2 EDEN-ISS

The EDEN-ISS project foresees the development and demonstration of higher plant cultivation technologies, suitable for future deployment on the International Space Station (ISS) and from a long-term perspective, within Moon and Mars habitats. The EDEN ISS consortium is comprised of the leading European experts in the domain of human spaceflight and Controlled Environment Agriculture (CEA). Starting in 2015, the consortium will design and test essential CEA technologies using an International Standard Payload Rack (ISPR) cultivation system for potential testing on-board the ISS. The technologies will be tested in a laboratory environment as well as at the highly-isolated Antarctic Neumayer Station III, operated by the Alfred Wegener Institute. EDEN-ISS was submitted within the Horizon2020 under COMPET 7 - 2014: Space exploration - Life support.

Project Partners: DLR-RY (Project-Lead), DLR-ME, LIQUIFER Systems Group, CNR, University of Guelph, AWI, Enginsoft, Airbus Defence & Space, TAS-I, Aerosekur, Heliospectra, Limerick Institute of Technology, Wageningen UR, Telespazio

Time Frame: 04/2015-12/2018

Total Budget: 4,5 M€ (1,04 M€ for DLR-RY)

7.3 :envihab Lebenserhaltungssysteme (C.R.O.P.-1)

:envihab Lebenserhaltungssysteme or C.R.O.P.-1 (Combined Regenerative Organic-Food Production) is a DLR internal project of the Institute of Aerospace Medicine (DLR-ME) and the Institute of Space Systems (DLR-RY). The project timeline is foreseen for three years (2012-2014). The team investigates a combined regenerative Life Support System (LSS) consisting of a urine and bio-waste recycler based on microorganisms, a greenhouse module and a fish farm. The C.R.O.P project investigates areas such as nitrification (the conversion of ammonia from urine to a more manageable nitrate solution), detoxification of hormones, anti-bodies and other harmful degradation products as well as the cultivation of beneficial microorganisms to improve plant growth.

Figure 31: Dr. Hauslage examining the bio-filtration tubes at the CROP Laboratory at the Institute of Aerospace Medicine (DLR).

The EDEN team investigates the necessary CEA technologies for plant cultivation. The nitrification process results are tested within the EDEN Lab for plant cultivation. Furthermore, phase-A design studies are organized for the development of complete and mobile C.R.O.P. test containers.

Project Partners: DLR-ME (Project Lead), DLR-RY, Agrohort

Time Frame: 01/2012 - 12/2014

Total Budget: 435 k€[1] (for RY only)

7.4 :envihab Lebenserhaltungssysteme (C.R.O.P.-2)

The second phase of the DLR internal project :envihab Lebenserhaltungssysteme is called C.R.O.P.-2 and is foreseen for a duration from 2015 to 2017. Planned project highlights are the full linkage of the two single processes (nitrification tubes at ME) with the higher plant cultivation (EDEN Lab at RY). Furthermore, a mobile test facility for the overall C.R.O.P. process is planned to be developed and built.

Project Partners: DLR-ME (Project lead), DLR-RY

Time Frame: 01/2015 - 12/2017

Total Budget: 435[1] k€ (for RY only)

7.5 HB-RY EDEN Lab Grant

In 2013 as well as in 2014, the leadership of the DLR Institute of Space Systems dedicated a budget to further build up the EDEN Laboratory. The amount of 50 k€ were allocated for each year. With this budget the necessary infrastructure construction work could be conducted within the laboratory.

Project Partners: DLR-RY

Time Frame: 2013 & 2014

Total Budget: 100 k€

7.6 Controlled Environment Agriculture Development for Space and Earth (CEADSE)

The Controlled Environment Agriculture Development for Space and Earth (CEADSE) project intends to utilize the pull of space technology by advancing the readiness of CEA technologies within Greenhouse Modules (GHM). CEADSE is funded by an International Incoming Fellowship

[1] Total cost basis (Vollkostenrechnung)

as part of the Marie-Curie Actions of the European Commission. Within this grant, Dr. Bamsey conducts his postdoctoral research within the EDEN group.

Project Partners: DLR-RY (Project Lead), EU (grant provider)

Time Frame: 09/2013 - 08/2015

Total Budget: 170 k€ (for RY only)

7.7 Fonds de recherche nature et technologies (FRQNT)

Additional support for the research stay of an EDEN postdoctoral researcher (Dr. Bamsey) is provided by the Province of Québec (Canada). This funding supports Canadian researcher while they conduct research associated with the development of BLSS, while also conducting educational outreach activities with Canadian students of all ages (primary to university level).

Project Partners: FRQNT (grant provider), DLR EDEN postdoctoral researcher (Dr. Bamsey)

Time Frame: 09/2013 - 08/2015

Total Budget: 60k CAD (~40 k€)

7.8 Networking/Partnering Initiative (NPI)

ESA NPI (Networking/Partnering Initiative) supports work carried out by universities and research institutes on advanced technologies with potential space applications. A DLR affiliated topic for the ESA NPI is the "Combination of Physical-Chemical Life Support Systems with Space greenhouse modules for higher loop closure at different internal pressure levels". This project supports a PhD position in close collaboration with the Technical University of Dresden (Germany). Focus is set on the improvement of the readiness levels of greenhouse modules as part of LSS by taking advantage of the experience and reliability of current physical-chemical LSS. Furthermore, proper interface and buffer methodology analysis between the greenhouse module and other habitat systems will be investigated.

Project Partners: DLR-RY (Project Lead), European Space Agency (ESA), Technical University of Dresden

Time Frame: 09/2013 - 08/2015

Total Budget: 90 k€

7.9 Market Analysis: CEA-Technologies (DLR-TM)

In 2012, the EDEN team conducted a market analysis in close collaboration with DLR's internal Technology Marketing department (DLR-TM). The goal was to identify and analyze potential market areas for greenhouse modules utilizing CEA technologies. In addition to market segmentations, the team analyzed potential CEA applications, estimated the potential market volumes, identified associated risks and created a roadmap for a successful market strategy. Refer to chapter 7 for more details.

Project Partners: DLR-RY (Project Lead), DLR - Technology Marketing (DLR-TM)

Time Frame: 2012

Total Budget: 20 k€ (fixed price condition)

7.10 Scaling of Life Support Systems (SCALISS)

The SCALISS (Scaling of Life Support Systems) project is an ESA (MELiSSA Group) project (GSTP). TAS-Italy is the project lead on this project. The project shall address human missions (e.g. planetary/low orbit base, transit mission) to all destinations of interest including LEO, CIS-Lunar space and interplanetary space (e.g. Mars, asteroid). The project goal is to develop a dynamic model, related to functions and technologies to scale BLSS regarding crew number and mission duration. This model shall allow a phase-A assessment for BLSS in the context of a future mission design. Scalability concepts for BLSS technology will be investigated and a model including boundary conditions as well as describing the BLSS for a given mission duration and crew number will be elaborated.

Project Partners: TAS-Italy (Project Lead), DLR-RY, Enginsoft, Technical University of Munich

Time Frame: 2015

Total Budget: 15 k€ (for EDEN group)

7.11 German Trainee Programme (GTP)

In 2009, DLR and the European Space Agency (ESA) signed an agreement for the 'Training of German Young Graduates on Space Technology – the German Trainee Programme (GTP). Since then, young German engineers and scientists have been sent to ESA on a DLR grant for a period of 1-2 years. To the participating German graduates, the scheme offers working skills, and opens up job entrance and career opportunities.

Since 2012, the EDEN Initiative is involved in this program and has evaluated young bio engineers for the Advanced Life Support group MELiSSA (Micro-Ecological Life Support System Alternative). This collaboration is planned to be continued for upcoming years and will further strengthen the relationship EDEN has with ESA and MELiSSA in particular.

Project Partners: DLR-RY (evaluation committee), DLR-VO-LT (Project Lead), ESA-MELiSSA (GTP Tutor)

Time Frame: Yearly

Total Budget: not applicable

7.12 DFG-1 (proposal status)

This proposal was submitted to the Deutsche Forschungsgemeinschaft (DFG) in late July 2014. The proposal was worked out in close collaboration with the Technical University of Dresden (Prof. Dr. Tajmar, Institute of Aerospace Engineering). The proposal topic "Optimization of Control Mechanisms for Small Closed Ecosystems" shall facilitate the development pathway to high-reliable control architectures for multi-chambered greenhouse systems and a better understanding to maintain an optimal growth environment within.

Project Partners: TU-Dresden (Project Lead), DLR-RY

Time Frame: 01/2015-12/2017

Total Budget: 252 k€

7.13 Moon Analogue Path - MAP (proposal status)

The project scope (ESA GSTP proposal) foresees research in analogue test sites in order to provide affordable simulation opportunities for missions in extreme environments that are characterised by high risk, high costs and high level of uncertainties often due to unknown context of the missions.

Project Partners: Technical University of Crete (Project Lead), DLR-RY, SPIN, SOBRIETY

Time Frame: 2015

Total Budget: 30 k€ (for DLR-RY)

8 Outreach Activities & Press

The fascination of space agriculture is something that the spectrum from young students to grandmothers can relate to. Plants are something in which all people can associate, whether it is from a direct green thumb association or simply as a consumer of fruits and vegetables, the importance is obvious. Combining plant growth with space exploration further adds to this fascination and this has been used by a number of countries and leaders in educational curriculum development as a tool to motivate learning across any number of the associated subjects (e.g. math, biology, physics, sustainability).

Figure 32: One of EDEN outreach activities was conducted within the DLR School_Lab.

This has been explicitly demonstrated through highly successful space learning program within the DLR School_Lab in collaboration with the EDEN team. Several plant biology aspects, regarding the CEA cultivation of plants in future greenhouses on Moon and Mars, were worked into a pupil's education plan.

One outreach highlight was the Bottle Crop Campaign, conducted by Lucie Poulet during her stay in the HI-SEAS isolation study in Hawaii in 2014. School classes from Germany, USA and France participated in this event. The Bottle Crop is a single bottle filled with a specific amount of nutrients, dissolved in water. Once filled, a planted lettuce seed located in the neck of the bottle germinates. No water needs to be refilled. When the lettuce has consumed all its water the salad head is ready to be harvested. The school classes started this soilless growth experiment at the same time as Lucie in her habitat in Hawaii. The school children could observe the developmental stages of the lettuce and could exchange their grow results with Lucie and the other school classes. Through several Q&A sessions (via video messages/ blog), Lucie reached out to the school children and taught them about the challenges of human

Figure 33: Lucie Poulet in a video message to school children in France, Germany, USA, and Canada.

missions to Mars and the tasks of Bio-regenerative Life Support Systems (BLSS). With this relatively simple set-up, many children were reached and became fascinated with space exploration.

More outreach activities are planned over the next years. One goal will be the development of a dedicated educational research kit for CEA cultivation procedures. It addresses the challenges of a long-duration human mission to Moon and Mars. The tool kit will most likely be comprised of a plant cultivator, several CEA technologies (e.g. LED light system, aeroponic diffusors, fertilizer mixer, and various sensors), a control unit (for e.g. light, air, and temperature) and a plant/ root compartment. Additional to this plant cultivator, the kit comprises several seeds, developed by NASA for their International Space Station (ISS) microgravity plant experiments (e.g. tomatoes, wheat, and peppers). Also an experimental analysis kit will be developed, helping pupils to analyze e.g. the water/ fertilizer content, the LED radiation levels, humidity. A handbook for teachers will outline background knowledge about human spaceflight, closed-loop LSS, extraterrestrial greenhouse modules and habitats as well as sustainability related to growing plants under a CEA regime. The educational kits will be lent out to several school classes (in parallel) in order to perform these relatively extended experiments (e.g. three months). The school classes can verify the growth- and environmental parameters (e.g. adjustment of the spectral light, nutrient solution concentration, day/night light periods). The school classes need to document their experiments in a growth handbook. Specially developed homework tasks complete the experiment and convey background knowledge. After experiment completion, the classes come together at the School_Lab to present their results.

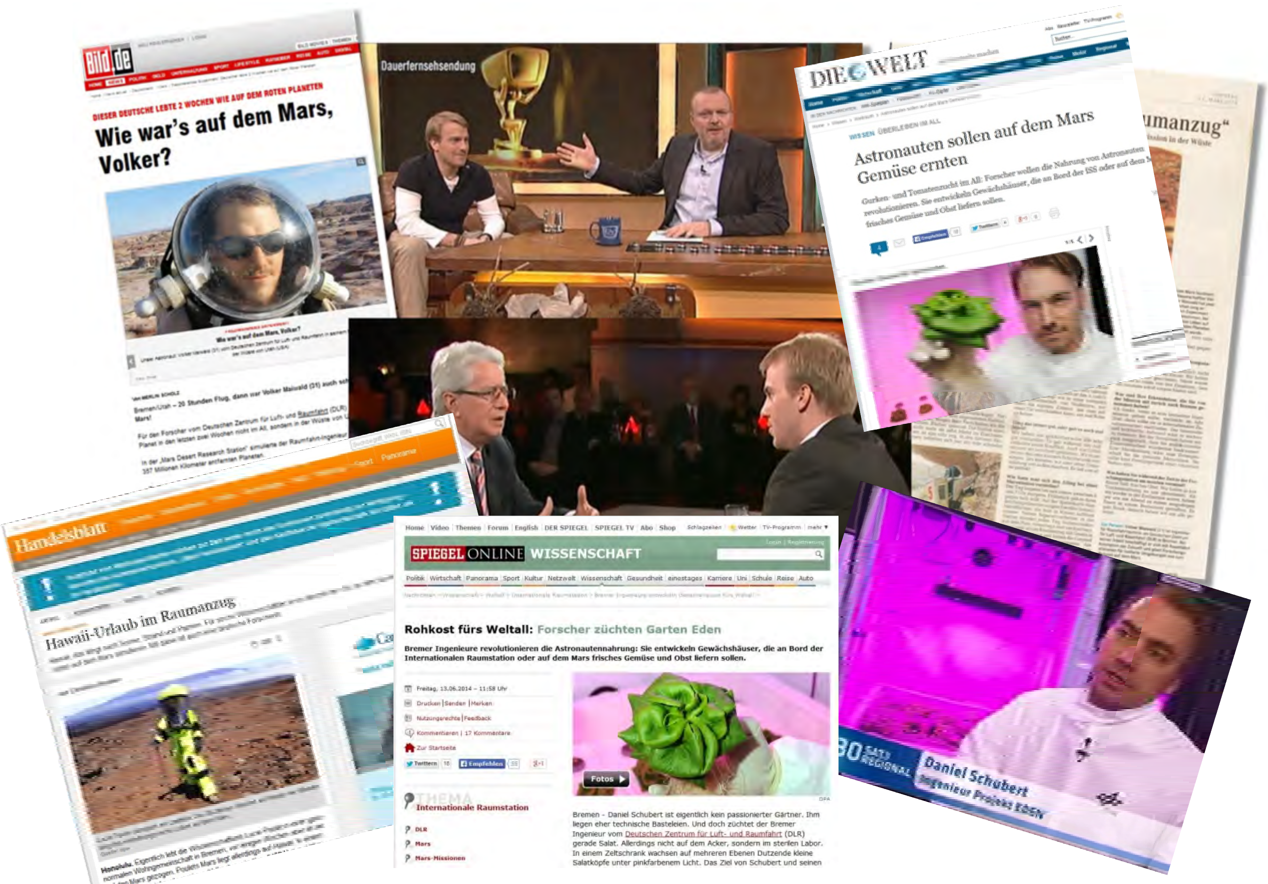


Figure 34: Examples from media responses to EDEN projects.

While planning more educational materials, the press on national and international level is recognizing the EDEN research efforts as well. The analogue mission, conducted in 2013 by Volker Maiwald resulted into approx. 80 print-, TV-, radio-, and internet contributions. Highlights were the invitations to TV shows with Frank Elstner (Menschen der Woche) and *TV Total*, where a broad public could be reached.

The same media interest can be observed for Lucie Poulet's analogue mission in Hawaii. For the rest of the 2014 and most likely beginning 2015, more media interest can be anticipated, when she returns home from Hawaii.

In addition several TV contributions were made of the EDEN Laboratory in general such as ARTE, SAT-1, RTL, Buten & Binnen (Radio Bremen), as well as contribution in high level newspapers (e.g. Süddeutsche Zeitung, Spiegel).

From 2013 to August 2014, more than 160 media articles were written or TV/ Radio contributions produced about the EDEN Initiative, the expertise of its members and its adjoining projects and research campaigns and analogue project contributions. An overview of all media related key figures can be found in chapter 10.

9 Research Partners

Since 2011, the EDEN Initiative has established a research network, consisting of seven universities, 7 non-profit research organizations (incl. space agencies like NASA, ESA), and 14 industry partners. In total, 28 partners are actively involved in the EDEN research initiative, where mostly NDAs, MoUs, LoIs or complete collaboration contracts have been established.

No	Logo	Name	Country	Type	Role within EDEN
1		Institute for Aerospace Medicine	Germany	Research Institute (Non-profit)	• Combined project C.R.O.P. • Microbiological sampling for the EDEN Lab • Proposal member for Antarctic Greenhouse (DLR-TM) • Publication of combined research papers • EDEN-ISS project partner
2		Institute for Horticulture - University of Applied Sciences, Dresden	Germany	Academic	• Consulting on horticulture issues • Combined students & master thesis • Proposal member for Antarctic Greenhouse (DLR-TM) • Publication of combined research papers
3		Alfred Wegener Institute	Germany	Research Institute (Non-profit)	• Runs the Neumayer Station-III in Antarctica • Test site for envisioned greenhouse module • EDEN-ISS project partner • Publication of combined research papers • Proposal member for Antarctic Greenhouse (DLR-TM)
4		Heliospectra	Sweden	Non-Space Industry (SME)	• Manufacturer of high performance LED research panels for plant cultivation • EDEN-ISS project partner
5		Rijk Zwaan	Nether-lands	Non-Space Industry	• Supplier of seeds specifically designed for cultivation under CEA regimes • Main supplier for EDEN experiments • Combined Vertical Farming research
6		European Space Agency (ESA) – ESTEC – MELiSSA group	Nether-lands	Space Agency	• GSTP projects (GHM for Space Systems) • NPI grant provider • Mutual collaboration on the field of higher plant cultivation in closed systems • Publication of combined research papers
7		Technical University of Dresden	Germany	Academic	• NPI project partner • Supervision of PhD candidates • Publication of combined research papers
8		NASA – Kennedy Space Center (KSC)	USA	Space Agency	• Consultancy on horticulture aspects • EDEN-ISS: Scientific Advisory Board Member • Publication of combined research papers

No	Logo	Name	Country	Type	Role within EDEN
9		Controlled Environment Agriculture Center, University of Arizona	USA	Academic	• Consulting on horticulture issues • Collaboration on organizing the AGROSPACE conference, Italy • EDEN-ISS: Scientific Advisory Board Member
10		Airbus Defence & Space	Germany	Space Industry	• ESA project partners on "GHM for Space Systems" • Combined industry project proposals • Pathogen detection (e-nose) and decontamination experts (Transportable Modular Aerosol-based Decontamination and Disinfection System - TransMADD) • Proposal member for Antarctic Greenhouse (DLR-TM) • EDEN-ISS project partner
11		Enginsoft	Italy	Non-Space Industry (SME)	• ESA project partners on "GHM for Space Systems" • Thermal and environmental analysis & simulations • EDEN-ISS project partner
12		OHB System	Germany	Space Industry	• CE-study support on biological aspects and human factors/ operations • Combined proposal on parabolic flight experiment on aeroponic diffusion systems
13		Thales Alenia Space	Italy	Space-Industry	• Experts for space-borne greenhouse systems • Expertise in on-orbit Life Support Systems • Consulting on space system related issues • EDEN-ISS project partner
14		Liquifer Systems Group	Austria	Space Industry (SME)	• Consulting on human factors within space systems • EDEN-ISS project partner • Combined CE study on habitation test facility (FLAsH) • Publication of combined research papers
15		OSRAM	Germany	Non-Space Industry	• Consulting on illumination systems • Provider of first water cooled LED systems for the EDEN Lab. • Proposal member for Antarctic Greenhouse (DLR-TM)
16		Controlled Environment Systems Research Facility – University of	Canada	Academic	• Consulting on horticulture issues • EDEN-ISS project partner • Publication of combined research papers • Exchange of experts

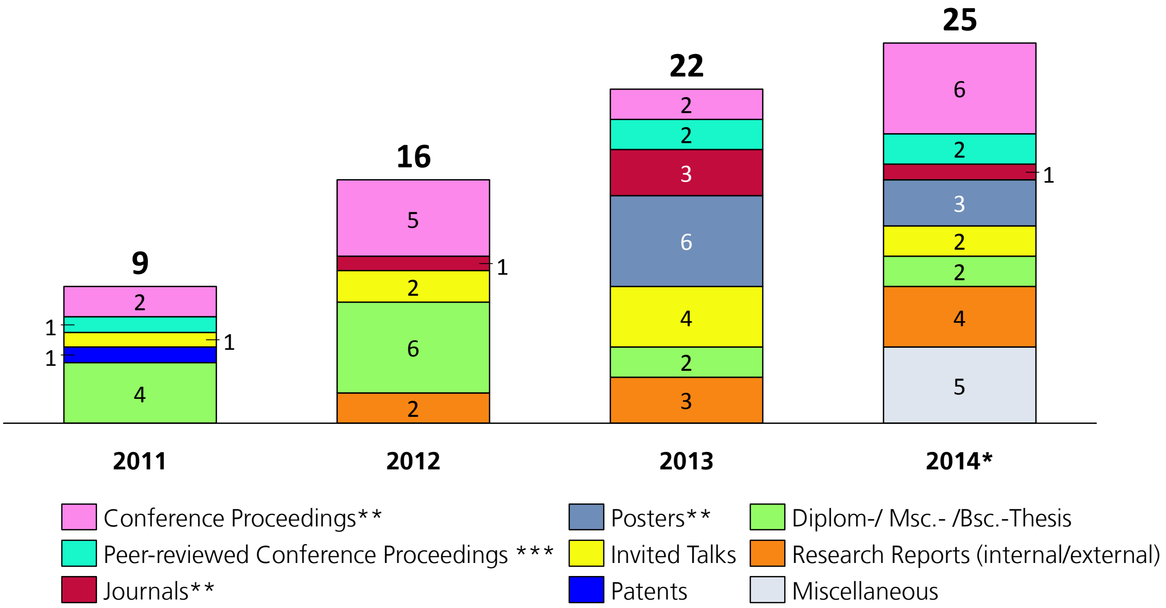
No	Logo	Name	Country	Type	Role within EDEN
		Guelph			
17		Aerosekur	Italy	Space Industry (SME)	• Specialist for deployable structures • Main organization of AGROSPACE conference in Sperlonga, Italy • EDEN-ISS project partner • Exchange of experts
18		Wageningen UR Greenhouse Horticulture of the Dutch Foundation for Agricultural Research	Nether-lands	Research Institute (Non-profit)	• Commercial greenhouse research institute • Soilless cultivation experts • Consulting on horticulture issues and led illumination systems • EDEN-ISS project partner
19		ORBITEC	USA	Space Industry (SME)	• Developer of VEGGIE unit onboard ISS • Combined research during analogue test studies • Provision of VEGGIE ground unit to EDEN Lab • Associated research partner for EDEN-ISS
20		Technical University of Vienna	Austria	Academic	• Consulting on lunar greenhouse system design • Publication of combined research papers
21		Limerick Institute of Technology	Ireland	Research Institute (Non-profit)	• Experts ISS plant grow chambers • Production of plant bioactive compounds • EDEN-ISS project partner
22		University of Arts - Bremen	Germany	Academic	• Designers for the EDEN logo • Consultancy on Corporate Design
23		National Research Council	Italy	Research Institute (Non-profit)	• Consulting on horticulture issues • Food safety experts • EDEN-ISS project partner
24		Artec ContainerWerk	Germany	Non-Space Industry (SME)	• Specialized on container based constructions • Production line for outfitting & refurbishment of used 40' containers • Combined industry proposal for commercial exploitation of mobile greenhouse systems
25		Technical University of Berlin, Mensch-Maschine Systeme	Germany	Academic	• Consultancy on human factors • Combined design study on Post Processing Facility (PPF) as interface towards habitats

No	Logo	Name	Country	Type	Role within EDEN
26	BrickBorn Farming	Brickborn Farming: INTEGAR – Institut für Technologien im Gartenbau GmbH	Germany	Non-Space Industry (SME)	• Combined Proposal on Vertical Farming in 2013 • Planned CE-study on Vertical Farming concept in 2014/15 • *Bottle Corp* Campaign with DLR School_lab in 2014
27	Telespazio A Finmeccanica/Thales Company	Telespazio	Italy	Space Industry	• EDEN-ISS project partner • Remote operation expert
28	Sadler Machine Company	Sadler Machine Company	USA	Space Industry (SME)	• Expert in Antarctic greenhouse systems • Manufacturer of the *Lunar Greenhouse* test stand of CEAC • FP7 proposal partner
29	Association for Vertical Farming	Association for Vertcial Farming	Germany	Non-profit Organization	• Lobby association for Vertical Farming • Combined organization of conferences and workshops of the subject of Vertical Farming • Combined publications and White Papers

10 Key Figures

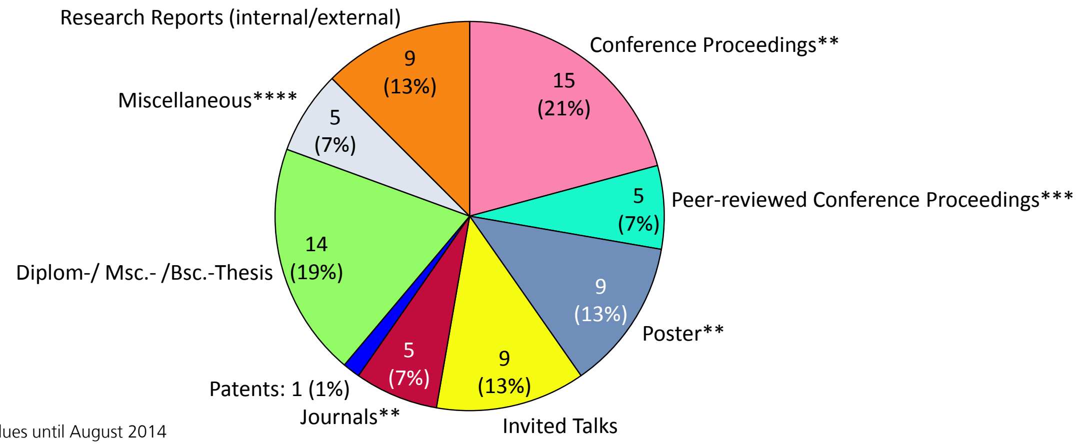
This chapter gives an overview of EDEN's key figures such as publications, budgets, media releases, and research partners.

10.1 Publications & Key Figures 2011 – 2014*



* Values until August 2014; ** Main and coauthor ship; ***only main author

10.2 Total Publications & Key Figures 2011 – 2014*



* Values until August 2014

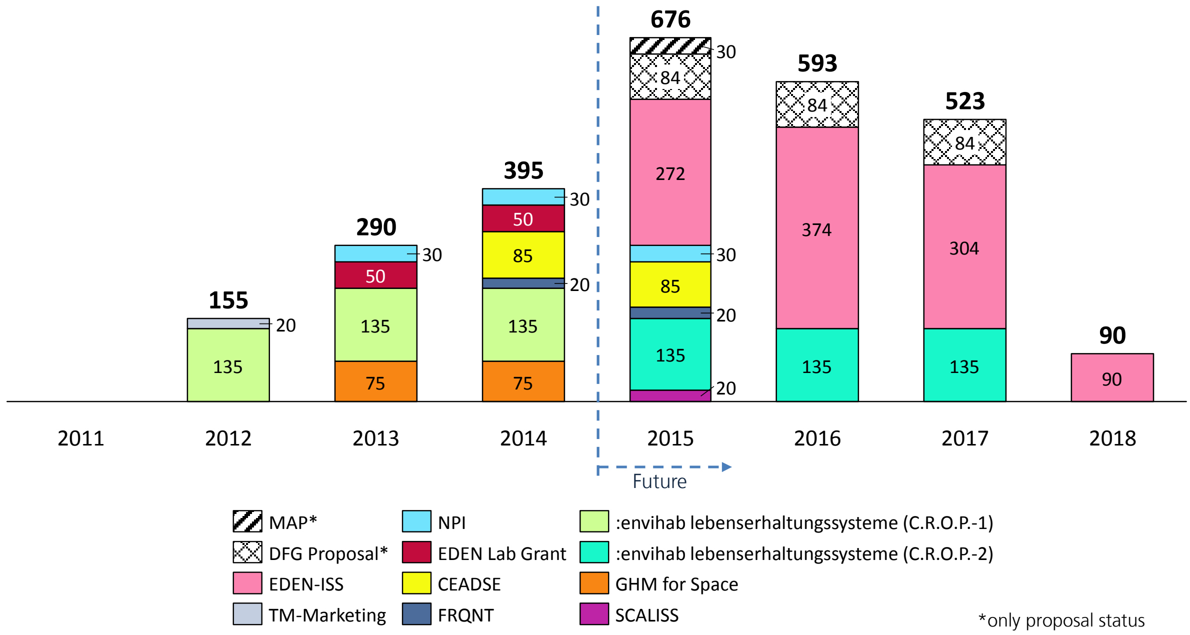
**Main and coauthor ship

*** Only main author ship

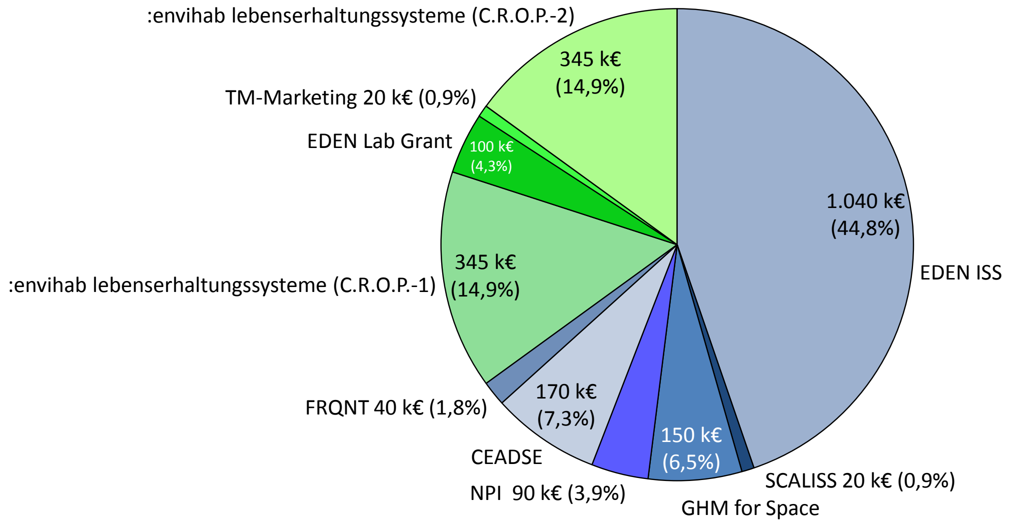
**** Miscellaneous:

- Organisation of AGROSPACE Conference 2014 & White Paper Workshop, Sperlonga (Italy)
- Head of Technical Commitee of AGROSPACE Conference 2014, Sperlonga (Italy)
- Session Chair for Session 5: "Analouge Testing", Agrospace Conference 2014, Sperlonga (Italy)
- Co-Chair for Session F4.2 - Advanced Life Support Testbeds and Facilities, COSPAR 2014, Moscow (Russia)
- Dr. Bamsey was nominated for membership on the AIAA Life Sciences and Systems Technical Committee

10.3 Budgets Overview & Forecast 2011 – 2018 [in k€]

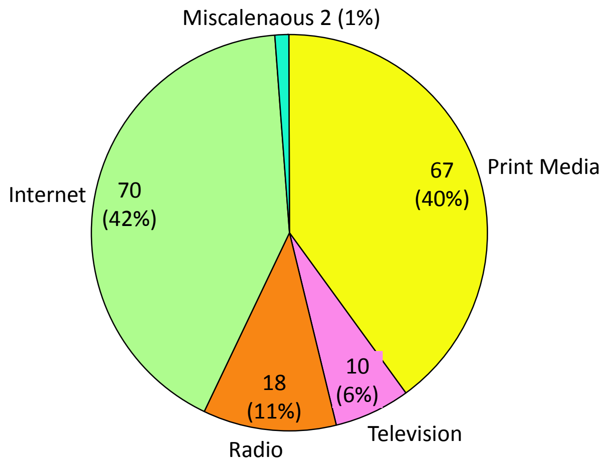


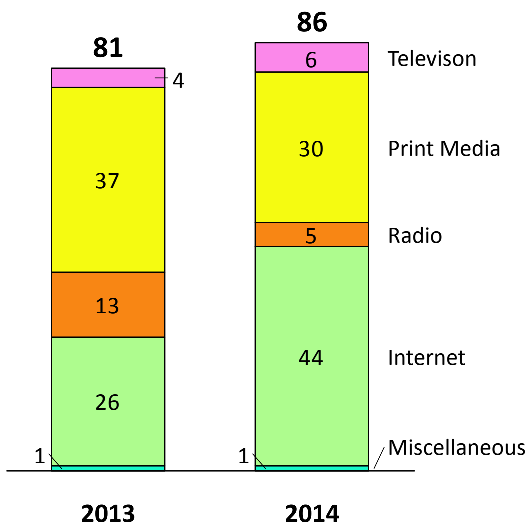
10.4 Total Budget Distribution 2011 – 2018 [in k€]



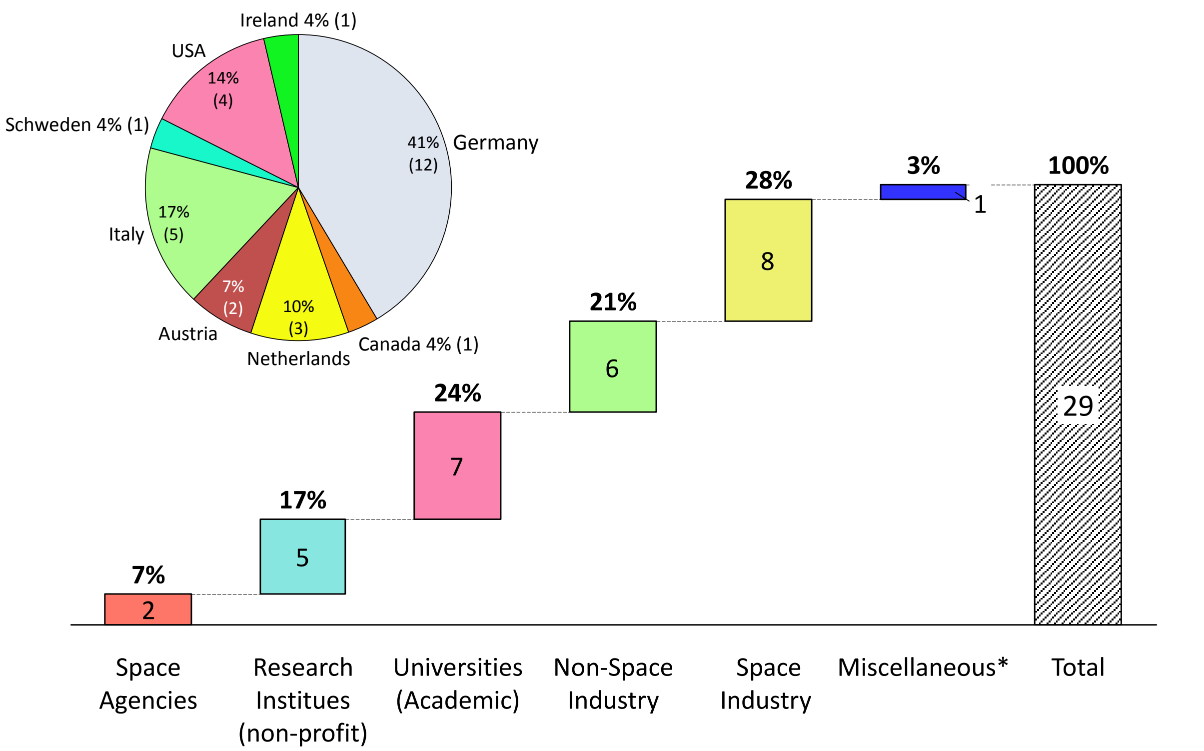
Note: Blue pies represent third-party money (total 65%; 1,51 M€); Green pies represent DLR internal budgets (total 35%; 0,81 M€); Budgets of proposals are not included in this pie chart.

10.5 Media Activities 2013 – 2014 (Total and yearly distribution)





10.6 Research & Network Partners



*Association for Vertical Farming

11 Final Statement

Bio-regenerative air revitalization, water recycling, waste management systems and the sustainable production of nutritious food for human survival in space is a challenge that needs to be overcome, not only for space applications, but also for terrestrial applications.

The EDEN research direction can lead to new resource-efficient, sustainable living and strengthen the global food, energy and resource recovery industries. The imperatives for this research endeavor are high and challenging, and the requirement to adapt CEA technologies for the space sector adds even further challenges. Nevertheless, by investing in this research, new cultivation approaches in producing food and other useful elements can be achieved in a resource-efficient manner. Out of necessity, these actions have to be initially performed on the ground, both in laboratory environments, as well as in mission relevant extreme environments, such as highly-isolated Antarctic research stations.

Within only four years (2011-2014), the EDEN group was able to output a total of 73 key figures (e.g. journal contributions, peer-reviewed proceedings, invited talks, patents, and Diplom/ Msc/ Bsc thesis). Also with a third-party money ratio of over 63% (~1.4 M€ in total), the research group displays a solid funding situation among DLR research entities. Furthermore, the EDEN group established a research network of 29 partners from academia to industry. The public awareness of the EDEN Initiative can be proven by it's over 160 contributions in print, TV, radio and internet in 2013-2014 alone.

The EDEN Initiative dedicates its research effort to the development of Bio-regenerative Life Support Systems (BLSS) and hopes to continue to receive and further advance the support it receives from higher management within DLR, but also within the political and scientific communities and public in general.

12 Yearly Budget Request

(Confidential - only included as insert)