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Sustainable Earth

GUIDELINES

From space back to Earth: supporting sustainable development with spaceflight technologies

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Abstract

For the past decades spaceflight has been a driver for technology development in various fields, e.g. generation of electrical power, and computers. Human spaceflight missions, require resources typically scarce (e.g. oxygen) and are usually transferred along with the crew to the respective mission target. Future long-term missions aim beyond Low Earth Orbit (i.e. Moon and Mars), necessitating advances especially in closed-loop life-support systems to guarantee mission autonomy. This requires careful handling of the resources, i.e. minimizing waste and where possible harvesting resources in situ. Similarly, on Earth a sustainable way of life requires careful handling of resources. This paper discusses how both pathways relate to each other and how "settling" Earth sustainably and settling in any space location do not differ in their basic paradigms. It is shown how spaceflight has had an impact on sustainability in the past, which technologies are developed for human spaceflight and how they can be applied on Earth to improve sustainability. Finally, a research infrastructure is presented, which can conduct research on closed-loop technologies, immediately benefiting space and terrestrial applications. This incubator is divided into separate functional modules, which allow testing of technology components. These components can be exchanged to test various permutations of technologies. It is recommended to exploit synergy effects between activities concerning human spaceflight and sustainability by intertwining and coordinating these actions. The technological improvement driven by spaceflight programs can be used to drive sustainability as well.

Keywords: Space exploration, Closed-loop technologies, Earth settlement, Sustainable development, Sustainability

Introduction

Many consider space the 'final frontier', the ultimate proving ground for humanity's will of expansion and endurance. After the Moon landings in the late 1960s and early 1970s, humanity has focused on human spaceflight in its immediate vicinity, i.e. Low Earth Orbit (LEO), e.g. by usage of several space stations such as Skylab, MIR and currently the International Space Station (ISS). All ISS partners (United States, Europe, Canada, Japan, Russia) and China plan to send humans to the lunar environment in the next decade, e.g. to the Lunar Orbital Platform Gateway (LOP-G) or also the lunar surface.

Others regard spaceflight, especially human spaceflight with criticism, often for the seemingly high costs involved and lack of immediate applicable, visible results for everyday life. Furthermore, one might argue that the current final frontier, at least the most important one, is making living on Earth sustainable.

Living on Earth and living in space have been generally regarded as two different challenges. On the former resources are abundant and readily available and for the latter, resources are scarce, need to be recycled and uprated to minimize the cost of space missions.

The connection between sustainability and a prosperous existence has been communicated in development strategies for several decades. Economic growth has been shown to be not a guarantee for societal improvement in

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developing countries, in fact causing new problems, e.g. due to environmental pollution. In the 1980s development programs have shown to be ineffective on a long-term and ideas of sustainability were discussed, defining sustainability as satisfying the needs of the current generation while keeping up a society's ability to meet needs of future generations [1]. This eventually led to the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, often referred to as Rio92, which agreed e.g. about the Agenda 21, setting a strategy for achieving sustainability in the twenty-first century. Follow-up conferences defined further steps, e.g. Rio + 20 in 2012, which eventually led to the official formulation and ratification of the United Nations Sustainable Development Goals (SDGs) [2] in 2017.

Awareness for the need of sustainable development resp. sustainability, although discussed for several decades, is spreading and thus now actions are taken with more urgency. Humanity is beginning to realize widely that Earth's resources are not limitless and that humanity's use of resources is endangering ecosystems worldwide and thus our own basis of living [3]. While Earth's "life support system" is by far more complex, robust and capable than any artificial life support system developed for e.g. space applications, it is strained and getting out of balance. Actions from multiple angles are necessary to keep Earth's "life support system" intact for our own well-being and that of future generations.

This paper explores the relation between technologies, processes and principles developed for and used in human spaceflight, and sustainability on Earth. Sustainability has ecological, economical and societal dimensions. With spaceflight technology especially the first two dimensions can be influenced and as the societal dimension is not independent of the former two, thus to some extent also the latter.

Requirements on a closed loop for human spaceflight are far more stringent compared to living on Earth. On the lunar surface the ecological footprint must be close to zero as there is no ecology, which can be exploited, except for water ice [4] and generally lunar regolith. Similarly, while there are resources on Earth, they have to be conserved and not exploited.

For instance, water, especially potable water, is limited in various regions on Earth. About 2 billion people do not have access to clean drinking water [5]. Technology can improve the sanitation situation as cleaning and saving water is an important part of a closed-loop system for e.g. long-term human spaceflight missions as well.

Paper outline

This guideline paper lines out, how human space exploration and sustainability on Earth are related in their challenges and thus also in their solutions concerning technology. We discuss the implications and recommend making use of synergy effects, by coordinating exchange of know-how between both fields.

In the remaining part of the introduction three concepts will be explained: that of lead users in technology development, which are drivers for new technologies, the meaning of closed loop as defined for human spaceflight systems and the idea of transferring technology from a spaceflight application to a terrestrial.

In the second section we will present the fundamental functions associated to human habitation on planetary bodies such as Moon or Mars and how they are also applicable for describing human life on Earth, underlining the similarity of the tasks of "settling" Earth and settling on Moon or Mars.

Afterwards examples for technology applications are given and how the respective space technologies can be beneficial for improving sustainability. This is done by presenting the general potential of the respective applications and at the same time show what current developments are in the sector of human spaceflight – pinpointing possible benefits from cooperation.

The fourth section then presents one possible approach of coordinating sustainability technology research within a research infrastructure designed by the authors. The infrastructure's purpose is closed-loop technology development and thus can act as furnace for technologies supporting long-term human spaceflight missions and sustainability on Earth. This chapter contains the approach, an overview of the purpose and design of the infrastructure, which includes lessons learned from prototype tests.

Before concluding the paper, the fifth section discusses the previously made statements, obstacles acting as barriers for technology adoption and proposes to coordinate space habitation research in closer alignment with sustainable development to improve the gain for both. A set of guidelines is presented as an outcome.

The space sector as lead user for technology development

To understand the role human spaceflight has in technology development in general, the following paragraphs will focus on the concept of lead users – a concept applicable to (human) spaceflight concerning many technological advances. This concept relates how human spaceflight can be a driver for development of technologies which are subsequently applied in other areas.

In management or economy theory, lead users are advanced users specialized in a certain area of application. They possess two characteristic properties [6, 7]:

- Lead Users are the first with certain needs or requirements, which other users, resp. market

participants, even early adopters, will only have some time later.
- Lead Users benefit significantly from innovation and are possibly even working on innovations themselves.

Lead Users can be individual experts, companies or organizations. They are participating in the innovation process earlier than other users and are contributing, e.g. by supporting innovation processes with scientists, manufacturers, and engineers or even conduct the innovation process wholly on their own.

A typical example for lead users is the Formula 1 racecar sector. It is a testbed and breeding ground for car technology later used by ordinary consumers of the car industry but advanced initially by the steep demands on racecars, e.g. concerning aerodynamics or engine technology.

Often lead users are active in a more extreme environment than ordinary users. Consequently, their needs surpass those of ordinary users and the solutions for their needs are often based on out-of-the-box thinking, pushing the limits of the state of the art further ahead. Therefore, innovations are tested and matured in the lead user sector, before being introduced into the general market for widespread use [6, 7].

Spaceflight and human spaceflight especially represent a lead user situation. Requirements concerning e.g. robustness, performance, autonomy, reliability, and radiation hardness are usually exceeding those for terrestrial applications, due to the harsh space environment, the costs associated with space missions (and therefore the need for low risk operations) and the fact that often human life is relying on flawless operation of technical equipment.

One example for a lead user situation in the space sector, which led to terrestrial application, is solar cell technology. Solar cells are one major contributor to sustainable power generation on Earth. In the early 2000s solar power had not been a relevant contribution to world-wide power generation. In 2005 the actually installed total capacity of photovoltaic power had been 5 Gigawatts (GW) [8]. In just 10 years, this had increased by a factor of almost 50. In 2015 the total capacity was almost 230 GW, with the major shares associated to Europe (97 GW) and the Asia-Pacific area (96 GW) [8].

The first actual solar cell has been developed by Bell Labs in 1954 [9] – but lacked a practical application. This came in 1958 with Vanguard 1 [10], the second US satellite and fourth satellite altogether. Solar cell technology became more and more prominent for usage on satellites and remains a major element of today's spacecraft of various types, e.g. landers, interplanetary probes and Earth satellites. The major advantage of solar cells over the batteries used exclusively on early satellites has been their capability to harvest energy in space, allowing missions to last longer than with just primary batteries and to design lighter spacecraft, because rechargeable batteries meant they could be smaller than for previous missions, i.e. mass was saved.

At the same time, the new and expensive solar cell technology was affordable for the space budgets of the competing nations in the space race [10]. The space application boosted their development, despite the relatively large price (100$/ Watt compared to 0.5$/ Watt for typical terrestrial power sources), which was mostly associated to the high level of robustness and radiation hardness required for space missions [10]. This gradually reduced in the 1970s when terrestrial application began in a larger scale e.g. for navigation buoys and especially oil companies invested in this alternative power generation method after the oil crisis of 1973, e.g. Exxon [10]. Similarly, solar power generation became a major element in human spaceflight technology, e.g. for Skylab and even today's ISS.

Today solar cells are one important element for sustainable energy generation not just in space, but also on Earth – initially funded by the lead users of the space sector, requiring sustainable energy supply for their spacecraft. A similar approach can be adopted and should be facilitated e.g. for closed-loop technologies aiming at supporting humanity's sustainable living through development of sustainable technologies.

Definition of closed-loop technologies

But what exactly are closed-loop technologies? What is the closed loop regarding space habitation?

The closed loop concerns all resources and materials within the artificial habitat. Just like there is e.g. a carbon cycle on Earth, there is a loop of material fluxes in a habitat ensuring that all materials are present in their required amount for processing. This could e.g. be oxygen for breathing or water for drinking and watering plants. The closed loop should also include materials needed for building and construction, e.g. new parts for the habitat, equipment, furniture, clothing – otherwise these commodities would have to be regularly supplied from Earth.

The closed loop ensures that resources required by one element of it, are recycled from its output by other elements until the original resource is available again. Referring to human spaceflight systems the needs of different consumers (e.g. plants or humans), materials (e.g. CO_2 and O_2 & C) are exchanged and transformed (e.g. CO_2 and H_2O into O_2 and carbohydrates), e.g. by a bioregenerative life-support system based on edible plants. Such systems are currently being developed by e.g. the German Aerospace Center [11] and other space entities.

The concept of a closed loop is sketched in Fig. 1, showing three conditions for the materials oxygen, carbon and hydrogen, transformed between CO_2, H_2O, O_2, Carbohydrates and waste products. Transformation from the original condition could e.g. occur via plant growth. Out of H_20 and CO_2 are created, i.e. O_2 and carbohydrate production (via using light, i.e. energy which could be coming from outside via sunlight/ solar power generation). The plants' edible parts can be consumed by the human crew, again producing CO_2, H_2O and waste (e.g. feces and non-edible biomass), which has to be transformed into its original constituents as well to arrive at the original condition.

The actual loop is more complex than presented in Fig. 1 and includes further materials, e.g. nitrogen or other nutrients and energy, e.g. in the form of light for plant growth. Especially the latter is difficult to keep in a closed loop (unless using methods for energy harvesting, see Section 3), yet if sustainably used, e.g. by using solar power generation, there is no strain on the closed loop.

Closed-loop technologies are technologies, which are required to artificially create a closed loop and thus establish e.g. a planetary habitat, which is sustainable, i.e. it can operate without external input of resources, especially those transferred from Earth. Therefore, long-term human spaceflight missions have to achieve on their small scale, what Earth's population has to achieve on a large scale: sustainability. It is therefore prudent to assume that technologies developed for sustainable habitation in space can support sustainable development and sustainability on Earth.

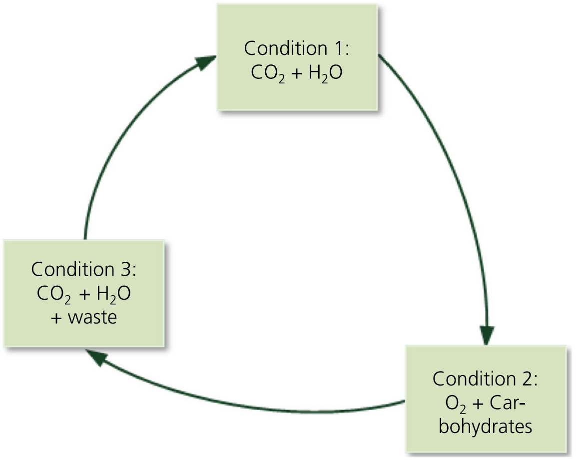

Fig. 1 An example for a closed loop. Beginning with CO_2 and H_2O, these can be transformed e.g. via plant growth to O_2 and Carbohydrates (i.e. edible bio mass). Consumption, e.g. by the human crew, transforms these via metabolism to CO_2 and H_2O again, yet also waste (either from the human metabolism or e.g. in the form of non-edible biomass). This waste has to be transformed into its constituents again, resulting in the initial condition. This is a simplified representation. Actual compositions of materials are more complex (e.g. including nitrogen)

Sustainability supported with spaceflight technology

Sustainable development is not possible with just a sustainable use of resources. Instead societal changes have to be initiated leading to more justice and equality, as defined by the United Nations Sustainable Development Goals (SDG) [2]. These goals even stand in a certain competition with each other – fighting poverty can include economic growth or lead to more consumption, which can contradict the idea of environmental sustainability [3]. In optimization theory, this is a typical case of a Pareto optimum, i.e. a complex system, to be optimized in several dimensions, has a state, where you cannot improve the system's value in one dimension, without reducing those values of other dimensions. Thus, there is a compromise where all values reach a maximum (or minimum, depending on the goal of the optimization) which cannot be further improved even in one dimension without deviating from the maxima of the other values.

The SDGs have a similar property, where once a relative maximum is reached in one goal, you cannot further improve one goal without degrading the others [12] in our current forms of society and economy. Concerning SDG 7, technical solutions for even cheaper energy supply might exist, but they could be less sustainable or e.g. polluting water and thus are not eligible selections for sustainability.

Technology cannot be the ultimate solution for overall sustainable development, as it only addresses certain SDGs. It can improve living conditions (e.g. via telemedicine for remote areas), ease e.g. working situations or education, but its function per se, does not promote the non-environmental related SDGs. While the SDGs are interlinked and depend on each other, certain SDGs are more susceptive for approaches of problem solving with technologies from human spaceflight programs, e.g.:

- Goal 2: Zero Hunger: Improving crop yield through artificial means while at the same time reducing the induced environmental impact can be achieved by adopting human spaceflight technologies for planetary greenhouse food production (e.g. reducing water consumption and pollution).
- Goal 6: Clean water and sanitation: Both are also a major concern for human spaceflight missions and thus recycling technology, often associated with food production, or water are a major development branch.
- Goal 7: Affordable and clean energy: Human spaceflight has a high need for energy due to the life

support systems involved, but in general spaceflight missions rely on regenerative power sources as resources are scarce. Developments, e.g. more efficient solar cells, directly benefit similar energy generation strategies on Earth.

- Goal 11: Sustainable cities and communities: This goal is a general link to human spaceflight, as any human spaceflight mission aiming at a long-term presence, has to be a sustainable community.
- Goal 12: Responsible consumption and production: This goal can benefit from recycling technologies and processes as well as overall production strategies benefiting recycling and resource efficiency developed from human spaceflight missions, e.g. additive manufacturing using recycled material.
- Goal 17: Partnerships for the goals: Facilitating cooperation between human spaceflight and sustainable development would be directly addressing this goal. Furthermore, spaceflight activities themselves already involve international partnerships, partnerships between public and industry, science and engineering.

Other goals, e.g. Goal 1: No poverty, can be addressed indirectly e.g. by improving access to food and water. Less effort and resources spent on food and water supply allows more resources to be spend on e.g. education to reduce poverty.

In general, technology – and especially human spaceflight technology – can improve the ability to attain a Circular Economy, if defined as “realization of (a) closed loop material flow in the whole economic system” [13]. The closed-loop material flow is the paradigm for a long-term human spaceflight mission to Moon or Mars. Thus, closed-loop technologies are developed for the lead-user application of human spaceflight, but can be adapted for terrestrial use, promoting sustainable development as part of science and technology for sustainability (STS).

The subsystems of the aforementioned greenhouses (Section 1.3) are resource efficient, e.g. using aeroponic nutrition with little water loss. The used water is also recycled. These technologies are not only applicable to food production for a human space exploration mission, but can be adapted to terrestrial application, e.g. in vertical farms located in urban areas. This would improve food security, lessen stress on existing agriculture areas and lessen the demand in agriculture resources such as water. Furthermore, local food production would reduce CO_2 emissions associated with food transport from rural areas to urban. To close the loop of bio-regenerative life-support systems, non-edible plant products are reused and recycled.

At the same time, energy is a precious commodity in a closed habitat, especially for a lunar base, where e.g. the lunar night can last up to 14 days, due to the Moon’s slow rotation. Thus, solar power generation is not sufficient for power supply and efficient energy storage is needed to provide electrical power during lunar night. Elaborating energy-efficient habitat technology, e.g. by energy harvesting of radiated heat, can in the long run be used for terrestrial housing as well, reducing energy consumption.

As usable resources are scarce on Moon and Mars, especially those needed for human habitation, waste is a non-affordable loss. Any used materials and resources have to be treated to allow them to be reused, recycled or up-cycled. Similarly, reduction of using primary resources on Earth will benefit from such technology developed for human spaceflight.

While development of technologies aiding in sustainability is not unique to human spaceflight programs, they can nonetheless contribute to sustainable development on Earth. If humanity masters closed-loop technologies for living on other planetary bodies in the solar system, it can use the same techniques on Earth.

Especially in the area of fighting climate change and adapting human settlement towards the aggravated environmental challenges, the space community is already contributing towards solutions on Earth. Generally, the data used for evaluating climate change and its impacts are often gathered by space based systems. Furthermore, the research of space actors is also focusing on this current challenge, e.g. NASA’s Goddard Institute for Space Science has a program investigating impacts of the climate change on human life and the environment and contributed to the *Climate Change and Cities* report of the Urban Climate Change Research Network [14]. This also stresses the already existing link between research concerning human settlement on Earth and space, highlighting the potential to learn also from Earth settlement for settlements on other bodies such as Moon or Mars. Challenges, faced by Earth communities, e.g. waste management, water security [14] are similar in nature to those of a sustainable space community.

Human habitation in space

An artificial habitat as e.g. used for long-term lunar or Martian missions has five main functions, when securing a crew’s survival and comfort. These are:

Cultivation: generate

Harvesting resources on-site, reduces the dependency on supply from Earth. Harvesting ice from the lunar soil [4] would be one example. This water can be used for water supply, oxygen production or to generate e.g. fuel. Similarly, lunar or martian soil can be used to create building blocks for habitat structures.

This function is usually associated with In-Situ Resource Utilization (ISRU). The more extensive this function is used, the less material and support is required from Earth. Usually, the footprint on the respective other planet is less severe, due to the very limited amount of humans involved and thus resources used. Theoretically however, the usage of resources can occur too extensively just as it can on Earth, exploiting the extraterrestrial location. While this endangers the long-term feasibility of a mission, it also raises ethical questions aiming at conservation, as explored by e.g. Alan Marshall [15], who explains the importance of preventing pollution and exploitation of a possibly existing Mars ecosystem.

The most typical generation process for space missions is using solar power generation to supply electrical energy to the system.

Recycling: close the loop

All material flows should be based on recycling of used materials opposite to wasting resources, without reuse and having a material flow leading out of the system (and thus interrupting the closed loop). This would require continuously replacing the resources, which is difficult when those are scarce on the respective mission site and the effort to transfer them from Earth to the mission site is large. Increasing consumption above the limits of the resources within the loop would lead to causing an impact, which per definition cannot exceed the resources present on site plus those supplied from outside (which for a long-term mission should be as close to 0 as possible, to make the mission affordable), otherwise the habitat cannot operate successfully.

This relates to the Commoner-Ehrlich equation [3]:

$$I = P \cdot C \cdot T \tag{1}$$

where I is the impact, P the population, C the consumption of goods per capita and T the throughput per unit of consumption in terms of natural resources (*Note:* C is also labeled as A for affluence, but in the context used here, this is less intuitive. The A also coins the term $IPAT$ equation, often used for Eq. (1)).

The population for a space mission is usually set – unless considering permanent settlement, where off-spring would also need to be accounted for. Typical crew sizes are 6 persons. Their consumption cannot be 0 – they need e.g. food, oxygen, heat, or water to flourish.

In a closed loop per definition, no resources are used on site; only resources originally brought along are used. Therefore, T is 0, i.e. the impact becomes 0 as well. While this should be strived for, it is physically not possible – the second law of thermodynamics, i.e. fact that no process can be conducted without losses means that T cannot be 0. If possible however, the resources can be gained sustainably. For instance if the only required outside resource is energy, this can be accumulated with solar power generation and thus not reduce the locally available resources, i.e. the throughput would still be 0.

For any loop, which is not leading to a throughput of 0, i.e. which is not fully closed, consumption cannot grow without increasing the impact. As a completely closed-loop is realistically not possible, consumption growth cannot be indefinite in a realistic habitat.

Self-sufficiency: produce & repair

To be self-sufficient and thus cost effective on a long term, the habitat also needs the capability to produce and repair its own constituents.

This can mean producing clothes, furniture, tools or food. The latter – if part of a bio-regenerative life-support system – might be an especially relevant part of the closed loop.

One possibility of producing structural parts is 3D-printing of regolith (soil, which would mean a $T > 0$) [16], others might be using plant bio-fibres from the food produce to create clothes, which are bio-degenerable and thus do not violate the closed loop. Once worn out the clothes can return to the loop of materials and be recycled.

This not only requires technology to produce and repair, but also the design has to reflect that function. Self-sufficiency has to be part of the design process, ensuring that e.g. building materials are selected, which can be either gained on site (via e.g. soil) or are easy to use in a closed-loop manner vs. materials, which can hardly be transformed between the different conditions (see Fig. 1).

Resilience: establish well-being

The habitat has to support human (possibly even animal) life for a prolonged period of time. This includes e.g. protection from radiation and the usually hostile environment as well as e.g. medical care and comforts required for mental health.

The before mentioned functions are applicable for infrastructure and communities on Earth as well, if a sustainable way of life is to be attained. Cultivation, i.e. using resources is part of economy – it should occur in a sustainable way, i.e. not more resources should be used than can be replaced. Recycling should occur to reduce the amount of resources needed. Self-sufficiency ensures production and repair capabilities. If guaranteed locally, the costs for transportation can be kept low. Resilience is also a major function on Earth, as the homes need to be a shelter for inhabitants.

In difference to a space habitat, which is a relatively small system, the system on Earth can be larger, e.g. whole communities, cities, nations.

While more usable resources and a natural life-support system are existent on Earth, the basic premise is the same as for other bodies in the solar system.

Space technology applied for sustainable habitation on Earth

Considering that Earth is just one of several planetary locations to "settle", there are several advantages that space technology can bring as spin-offs [17]. As explained in Section 1.2, spaceflight has been a driver for technologies facilitating sustainable development before, i.e. for solar cells now enabling among other technologies sustainable power generation.

This section describes two major fields, which are shared research interests for terrestrial application and application for human spaceflight. It is further shown what current potentials are and which technologies in the spaceflight sector are developed and thus could be available as solutions for analogous applications on Earth.

Energy technologies

Generally, energy harvesting, e.g. collecting (waste) energy in the form of heat, for further use, can reduce primary power consumption. There are also natural sources for energy harvesting, e.g. geothermal heat or principally solar radiation as exploited via solar cells.

Energy harvesting is a potential source of energy for devices not suitable for e.g. batteries or other power sources, which require a certain space [18].

For instance, harvesting energy from artificial light sources provides $100\,\mu\mathrm{W/cm}^2$, about factor 1000 less than natural sunlight [19]. Yet, even with this low number, it can still contribute to energy savings, which is explained in the following.

Energy consumption is expected to increase by a factor of about 1.5 until 2050, from about 420 million Terajoule to about 630 million Terajoule, with the industrial sector being the major contributor at currently about 250 million Terajoule and projected about 340 million Terajoule [20]. In comparison, residential energy consumption is about 53 million Terajoule and is projected to be about 100 million Terajoule in 2050 [20]. Renewables are expected to provide about 250 million Terajoule of energy [20].

At the same time, the industrial, but also residential sector are expected to be the prime areas for introducing energy harvesting on a large scale, mainly due to smart homes, internet of things and automation processes [21].

The U.S. Energy Information Administration (EIA) estimates about 10% of commercial energy consumption are used for lighting [22]. Assuming a similar rate for the worldwide energy consumption for lighting means that up to 34 million Terrajoule can be gained by energy harvesting from lighting in industrial sectors alone, resp. be saved. Assuming 95 $\mathrm{kgCo_2/GJ}$ for coal [23], harvesting the energy consumed by lighting could potentially save 3.2 billion metric tons of CO_2 emissions per year comparing it to power production via burning coal.

Energy harvesting technologies are developed and used for powering sensors on the ISS, showing the potential of reducing the power demand for closed systems [24]. More exotic sources for energy harvesting are investigated for long-term missions to Mars [25]. Mechanical jitter onboard satellites, due to their operation, can also be harvested for energy [26], reducing power consumption.

Using budgets from space programs for developing energy harvesting technologies can thus aid in sustainable development and at the same time advance humanity's ability in spaceflight. For instance, energy harvesting methods used for exploiting vibrations of satellites [26] could be used to harvest vibrations of machinery, ship engines, airplanes and other sources for energy. While development for terrestrial application could fail due to the so-called Valley of Death [27] of technology development – lacking funding and immediate usage – the steep and special needs of human spaceflight missions can lead to funding of technology development which otherwise would not occur, similarly to the previous adoption of solar cell technology.

Energy harvesting is only a small part of a closed loop, when concerning human spaceflight systems. The majority of the closed-loop is concerning material exchanges as described in Section 1.3.

Food production and bio-regenerative technologies

Another example for future technologies improving sustainability are the food production technologies associated with planetary greenhouses. Relevant for human spaceflight for food production and as bio-regenerative life-support system, these technologies of e.g. growing food locally, recycling bio-mass effectively can also be applied on an urban or home scale and thus reduce transportation effort, i.e. CO_2 emissions due to traffic. Effects do not just concern the local availability of the produce, but also yield size and efficiency of agriculture, e.g. concerning water and land usage [28].

Water usage can be reduced to 5% of traditional agriculture [29], which is especially relevant for regions where water is scarce. Therefore, developing technologies for e.g. water reduction in vertical or generally controlled urban agriculture can improve the situation in areas suffering from water shortage, potentially improving the living conditions of 2 billion people [5]. Water shortages are a world-wide threat [30]. Areas threatened by droughts due to climate change are Africa, North America, South America and Oceania [31].

Water shortages are a threat because of agriculture, which is using 70% of the world's available fresh water of which 60% are wasted on ineffective agriculture [30].

Reduction of water usage would mean a reduction of T in Eq. (1), thus lowering the impact I or allowing an increase of either consumption C (i.e. here food produce, allowing safer food availability) or population P.

Similarly as in certain regions of Earth, water is scarce on Moon and Mars, requiring efficient usage and recycling of water for long-duration human spaceflight missions. Additionally, food production has to occur not only efficiently, but also reliably.

For instance, space greenhouse technologies necessitate development of plant health systems [32], which allow precise monitoring of plant health to act quickly should the need arise. These technologies can be applied on Earth just as well, to improve plant health and thus crop yield and reliability. They are developed to be operated remotely allowing a team of experts to assess the data and when necessary implement countermeasures to plant stress or diseases [32].

For application on Earth it is also relevant to incorporate the closed-loop aspect. Recycling human waste products, e.g. urine, for plant growth would be one way of achieving this - regaining nutrients and at the same time achieve sanitation. Obviously, these techniques require close health monitoring to prevent the spreading of diseases, but the general feasibility has been proven by experiments conducted in a space analogue environment in Antarctica [33].

Case study: incubator for habitation

The degree of self-reliance and sustainability required for long-duration human missions in outer space cannot be reached incrementally by individual technologies. As any complex system, an artificial ecosystem capable of supporting human life for a considerate amount of time (several years at least) has to be matured and all relevant technologies have to be tested in unison with humans-in-the-loop. Aiming at a sustainable long-duration habitat, recycling- and adjoining habitat technologies are used to achieve a (nearly) fully closed-loop infrastructure.

As a consequence the German Aerospace Center has worked on a concept for a research infrastructure called Incubator for Habitation (I4H), designed for developing habitation technologies for deployment on Earth or in space.

The I4H research infrastructure can be seen as a lead user environment, where technologies are developed and tested for an extreme deployment such as Moon and Mars habitats and then been adapted towards terrestrial scenarios. It is a sort of "Petri dish" for a circular economy on a small scale, where technologies and their application can be "cultured" and investigated in test cases.

The main concept of the envisioned research infrastructure is a holistic approach by interlinking all major habitat functions into one test habitat, allowing a simultaneous interplay of all habitat elements. In particular, the investigation into the following areas shall foster future habitat technologies:

- Water recycling methods
- Air revitalization technologies
- Waste recycling (liquid & solid)
- Food production and processing
- Material utilization and advanced manu-facturing

Yet, this is to be achieves in a modular system, where individual technology components can be exchanged. In comparison to previous attempts of closed-loop habitation, the INCUBATOR's strength lies in technology and (sub-)system replacement, which allows it to be operated with system variations. This adaptability enables transfer of these technologies to other applications. If a closed-loop habitat is designed only in one specific way, with one specific combination of systems and technology options, it is hard to adapt these to applications outside this specific habitat and therefore e.g. use them for terrestrial applications.

The facility shall serve the following purposes:

- Act as proof of concept of a fully self-reliant, closed-loop human habitat (i.e. a human crew should be included),
- facilitate simulation of human planetary exploration missions (e.g. to Mars),
- enable testing and maturing of all necessary technologies (systems and modules) for sustainable space and terrestrial application,
- enable common and strategically coordinated research activities of all stakeholders within the habitat community, and
- public engagement for both space and terrestrial ecological application.

The authors have been working on the overall concept of space habitation in several projects both theoretical and practical.

Approach

The design of the INCUBATOR has been evolved in the past 7 years, incorporating information of various studies and tests into the design, serving as one cornerstone of research in the field of sustainability technologies for the department.

Concurrent engineering study: I4H's initial design

The first step in the evolution of I4H has been a concurrent engineering (CE) study, conducted in the Concurrent Engineering Facility of DLR [34].

Typical for CE studies, the study team involved all relevant domains, e.g. human factors, food production and waste management, into the study, which occurred within the study location.

Answering the respective requirements, design iterations have been set up by the team iteratively, analyzing each iteration on its performance and gaps concerning requirements, e.g. about the closed loop, before further adaptations have been undertaken. Using a common data model, the study team established a draft design with a – theoretically – closed loop of all involved materials, detailing all relevant components for the system design and the accommodation. Details about the study results can be found in [35].

The design comprised of 12 modules, containing all relevant subsystems, human crew equipment and a central dome structure for training of human spaceflight missions on planetary bodies (i.e. Moon or Mars). A material matrix consisting of balances for all involved materials, e.g. water or carbon, allowed modelling the closed loop.

Space greenhouse design: initial design

As one focal point of further research, greenhouses for space have been selected, resulting in several designs. Due to their potential as bio-regenerative life-support system in combination with food-production, greenhouse technology is not just a contributor and enabler for long-term space exploration but also a contributor in the field of STS, furthering sustainability on Earth via technology.

To further Space greenhouse studies, as one focal point of the research for human space exploration, design studies have been undertaken, e.g. in [11]. These initial designs were studies that paved the way for developing a prototype, but also for applying the respective agriculture technology on Earth.

Contributions to vertical farming

Based on the technology paradigms for the space greenhouses, design studies for Earth applications in the form of vertical farms have been conducted in a similar manner as the original I4H design, i.e. via concurrent engineering.

The result has been a tall building, containing 25 cultivation floors, incorporating aeroponic watering systems, capable of producing an estimated 13 metric tons of fresh food per day. Details about the design can be found in [36].

Space greenhouse prototype in Antarctica

Based on previous studies, DLR developed and operated a prototype space greenhouse in Antarctica as an analogue test for future missions in space. The technology, e.g. the aeroponic nutrient delivery system, as well as processes in operation have been analyzed and tested.

Analogue test missions have been one part of DLR research in the area of human space exploration [17], the EDEN ISS mission, as this greenhouse mission was dubbed, was however by far the most advanced, containing a prototype greenhouse system module – similar to what has been envisioned for the I4H test lab.

The system was successfully deployed and operated in Antarctica and within the project further designed into a space capable system [37].

Refinement of I4H

As a further step and with lessons learned concerning operations, based on analogue tests, and new designs ideas, the I4H design has been refined. Its components and operation have been drafted more thoroughly. The results are given in the following paragraphs.

Incubator description

The research infrastructure, the INCUBATOR, will comprise four main elements, which can be seen in Fig. 2.

Habitat simulator

The Habitation Simulator comprises a number of modules that house the actual habitat technologies to be tested. The modules consist of an outer shell, insulating the interior from the exterior for maintaining the closed loop. Within the shell there is the actual functional module, linked to one or more habitat tasks (e.g. waste management). The important part is that all functional modules are interlinked, exchanging materials with each other such as gases (e.g. oxygen, carbon dioxide, Methane), fluids (e.g. potable-, grey-, black-, and process water), and solid materials (e.g. edible and inedible biomass, solid wastes, but also raw materials, products, and tools). The output of one module can be regarded as the input for another or several other modules. By linking all modules with their specific material flows, one large artificial ecosystem is created. This way, all modules stand in a complex demand and supply relationship. Over demand or under supply of a certain material or compound need to be balanced in order for achieving an overall sustainable equilibrium.

The internal structure of each functional module can be extended into maintenance halls (pre-installed or mobile). These maintenance halls are also air-tight and provide work space to exchange and maintain equipment components of the functional modules. This way a certain system or unit can easily be exchanged or repaired,

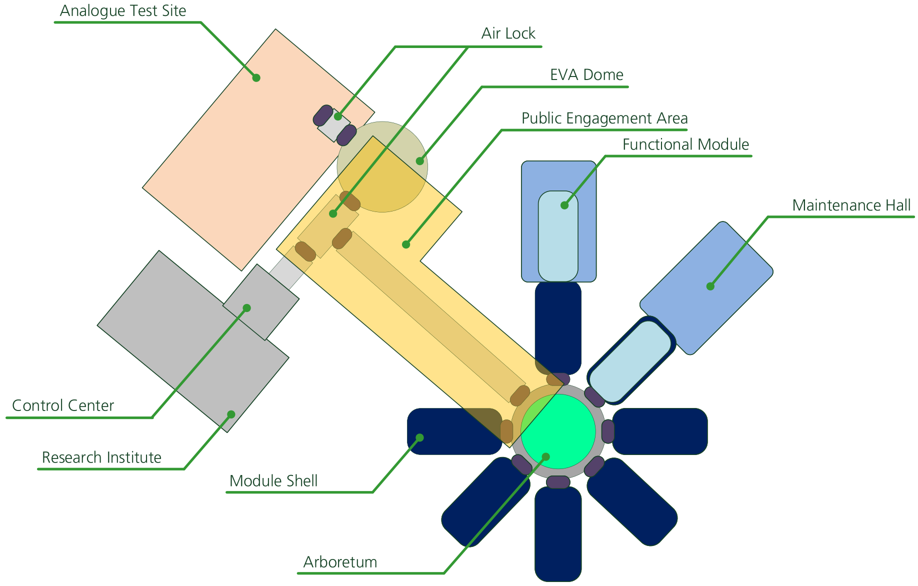

Fig. 2 Schematic view of the Incubator with all relevant elements. Functional modules (e.g. for air management) are contained (air-tight) within module shells. For exchange of equipment they can be extended into maintenance halls. An overarching public engagement area allows view of major operations, e.g. in the dome. The outside is connected via air-locks to maintain a closed-loop. An EVA dome allows simulation of "on surface" operations, an analogue test site links the operation to e.g. robotic experiments

before the functional modules is moved back into the closed-loop system of the habitat.

By sealing off the test facility, a closed-loop situation can be generated. Human crews can test the living and working situation in this environmentally-closed facility.

Space simulation areas

The habitat simulator is optionally supplemented by areas for space simulations. There could be a dome containing a simulated extra-vehicular activity (EVA) area in meaningful environments (e.g. a simulated martian surface) with conditions dissimilar to the outside. An airlock would connect the habitat and the outside, possibly a test area for terrain tests not requiring a closed loop.

Impact from research in these areas concerning terrestrial sustainability will likely be low, but not zero. Robotic-human interaction could occur also in terrestrial applications, e.g. a vertical farm.

Research Institute & Control Center

The adjoining research institute offers space for the multiple research groups, conducting their specific field of research. The building will house various laboratory areas for initial bread-board developments and single technology testbeds, prior integrating them into the habitat simulator.

Besides offices for the scientists and engineers, the institute will house a dedicated business incubator, facilitating the stringent technology transfer capability (lab-to-market) of the research infrastructure towards terrestrial sustainability applications and processes.

A control center is the nucleus for monitoring and controlling the complex system of the habitat simulator. Artificial intelligence and Big Data approaches will be implemented in order to optimize the multi-facet flow relationships between the functional modules. Further, the overall control of the habitat simulator and the communication with the enclosed crew will be organized via this control center.

Public engagement area

Finally, the element of public engagement shall be closely interlinked with the INCUBATOR. The engagement area shall allow visitors to observe the crew and scientists during their work – following ethical principles to ensure crew safety and well-being – allowing them to connect to the work and results. At the same time an exhibition shall inform the visitors about the research background (space related and terrestrial) and sustainability.

Incubator in operation

The INCUBATOR designed during I4H will allow - for the first time – testing of a real closed-loop situation, including the dynamic interplay of bio-regenerative Life Support Systems with their physical/chemical counterpart systems. Although, theoretically proven, a stable near-to-100% closed-loop environment has never been generated in the previous facilities and tested over a longer period of time (months to years). The capability to exchange system components will allow incremental improvement of the system into a stable and reliable configuration.

As all functional modules within the INCUBATOR operate in a supply and demand relationship to each other with respect to the exchange of their input/output materials, the complex behavior of this unique closed-loop system can be studied for the first time in detail in a controlled condition. This accounts for short duration tests, but even more for long-duration tests of several months up to years.

A dedicated science board will issue calls for experiments, possibly with a certain focus (e.g. water recycling systems, air purification and revitalization methods, high-density food production, advanced decentralized manufacturing) depending on previously identified research needs. After a selection of experiments and contributors, campaign planning will accommodate the individual experiments into a schedule.

The facility allows the accommodation of a test crew (between 4 and 12 people). Especially, process- and method testing can be conducted within multiple test campaigns. In particular, the presence of humans, who work and live in the habitat, enables the science community to investigate new handling procedures related to the life on Moon and Mars (e.g. Microbial spread patterns, human factors, and psychology). New and innovative approaches for handling the daily living, such as preparation of food, laundry, personal hygiene, dish washing, and producing & repairing clothes are only some examples that need to be faced with new and out-of-the box approaches.

Discussion

Sustainability requires the impact of humans on their environment to be as low as possible, resp. at a level, which can be compensated by renewing resources (e.g. wood, solar light, wind), which is especially true for extraterrestrial environments. If the throughput T in Eq. (1) is not reduced and assuming a constant population P, the consumption C cannot grow without also increasing the impact I. This is essentially a no-growth economy, which is not in opposition to societal prosperity (see [3], p. 19). Since the world-wide population is in fact growing, there has to be either a decrease in T or in C to achieve a stable impact.

Reducing T can be supported with technologies, processes and mind sets associated to human spaceflight. More efficient resource usage, smart recycling and renewable production can all contribute.

Similarly as before concerning solar cell technology, it is prudent to assume that space technology can have a benefit for sustainability. This is especially true given the examples of how e.g. energy harvesting has still potential for improvement and thus reduction of CO_2 emissions (see Chapter 3.1).

Exploiting results from human spaceflight technology development for sustainable development on Earth effectively adds funding to efforts of achieving the SDGs. In general, one can say due to the lead user role of human spaceflight, it is a funding source for certain technology developments, which would otherwise not be further developed, being stuck in the "Valley of Death" of technology development [37]. This means only when a certain technology is the key solution to a given problem (here associated to human spaceflight), will it receive funding for further development. Thus, from a general point of view funding will be added to development if there is a certain need, which can only or most efficiently be addressed by that specific technology.

For example, if there are four technologies identified to be beneficial for water purification, funding from sources associated with sustainable development might e.g. fund two for further development. If for certain reasons, e.g. concerning light-weight, one of these four technologies is suitable for human spaceflight applications, it might receive funding from this budget, e.g. national space budgets. In the end three out of four technologies will be available, one of which funded by sources not directly aligned with sustainable development.

Funding for human spaceflight development and sustainability goals

Civil space programs had a volume of 44.5 billion US Dollars (USD) in 2018, of which 11.6 billion were spent in human spaceflight activities [38]. That money is spent on operating, maintaining and supplying human spaceflight activities, yet a proportion is also related to development of new technology for e.g. the Lunar Orbital Platform Gateway. The NASA budget request for exploration systems in 2019 has been in total 4.558 billion USD for 2019 [39]. Of these 1.16 billion USD have been associated to the Orion program and 0.89 billion USD to advanced exploration systems, which includes, e.g. habitat components of a future lunar base.

For human spaceflight activities, there is an additional budget for ISS (1.46 billion USD), the Commercial Crew Program and Crew and Cargo Program (2.11 billion USD) as well as Human Spaceflight Operations (0.14 billion USD), amounting to a total budget of 5.76 billion USD for human spaceflight activities, i.e. current and those in development.

Of NASA's 21.5 billion USD budget for 2019, the development budget for human spaceflight technologies is approximately 9.5%, roughly 10%. For the 11.6 billion USD related to human spaceflight activities the ratio is 35.6%. Not all of this money is related to closed-loop technologies. For instance, development within the Orion program also involves testing of the capsule, development of heat shields and computer systems.

Assuming if at all only moderate rates of increase between years, one can deduct that approximately one third of the money associated to human spaceflight is dedicated to the development of technologies in the coming years. Given the above 11.6 billion USD for human spaceflight activities in total, about 3.9 to 4 billion can be assumed for the development of new technologies.

The UN estimates that currently 2.5 to 3 trillion USD are missing in developing countries for achieving the SDGs each year [40]. At the same time, sustainable development has a potential volume of market opportunities of 12 trillion USD [40]. Thus, organizations involved in human spaceflight technology development can reduce the funding gap – not just by investing in the required technologies, but also by making sustainability more affordable through new technologies, which are e.g. more efficient. If cleaning water can be achieved with less financial effort than before, achieving access to water as one SDG becomes more affordable.

Similarly, space technology companies investing in such technologies can also be part of the before mentioned market opportunities, ensuring additional funding. This is attractive as space funding is highly subjected to political decisions concerning space programs and thus can be insecure during times of political change.

Research fields

The scale of applications of space technology differs and can encompass:

- Households (e.g. with a combination of water and waste treatment systems with energy and food supply sized to standard house installations),
- Small communities (e.g. sharing of technical infrastructure in the close neighbourhood/ districts; hospitals; holiday resorts; (refugee) camps),
- Urban areas (synergies between centralized systems to make mega cities cleaner and more independent from external supply),
- Nations (higher efficiency of resource utilisation by interaction of the national resource management depending on their abilities, e.g. geographical advantages such as regions rich of water or sunshine as resource),
- Developing countries (robust low-tech solutions for a sustainable public health including water, sanitation and hygiene).

Research fields that are associated to habitat technology are shown in Fig. 3 in the form of a shell model. The inner shell (light green) are the basic habitat functions as previously explained. Main contributions can be made in relation to closed-loop applications, which are benefiting not only the space sector (human spaceflight & habitats), but can directly be translated to terrestrial applications, e.g. decentralized systems within small communities (e.g. hospitals, schools). The second shell (green) displays possible applications, products, and new methods that can be developed by habitat research.

Further, the outer layer (blue) outlines an abstract of basic research domains. It inhabits a multiple translation potential (e.g. cradle to cradle approaches) towards basic questions not only for space habitats, but also for terrestrial small communities (e.g. remote villages, small islands) or inner-city communities (e.g. districts), e.g. concerning:

- Reuse of biowaste for heating/ energy generation (by using waste heat) and where possible usage for fertilization of on-site food production, increasing the closed-loop ratio and decreasing need for energy,
- More efficient bio-food production and including the food-production into the closed-loop life-support system reduces the required resources and increases efficiency, e.g. via usage of LEDs. Improving compactness allows on-site food production, combined with using resources from the loop, e.g. waste products for fertilization. Such compact systems can also be used for households or in urban areas to allow local food production. Following this, transportation costs and effort can be reduced and thus greenhouse-gas emissions.
- Waste water (i.e. non-drinkable but otherwise not polluted water) can be recycled by using it for plant/ food production, which can reduce the amount of required water. This approach is also useful for households or larger communities, e.g. refugee camps, and can lessen the demand for water. Methods for increasing agriculture efficiency and effectivity would help alleviating this problem.

Sustainable development does not just require technologies, but also processes, governance principles, generally mind sets that support sustainability (e.g. a non-growth economy), just like a space habitat needs them. These need to be developed just as well, in addition to the technology.

Obstacles to technology adoption

The previous sections describe and discuss the potential of technology adaptation for terrestrial application.

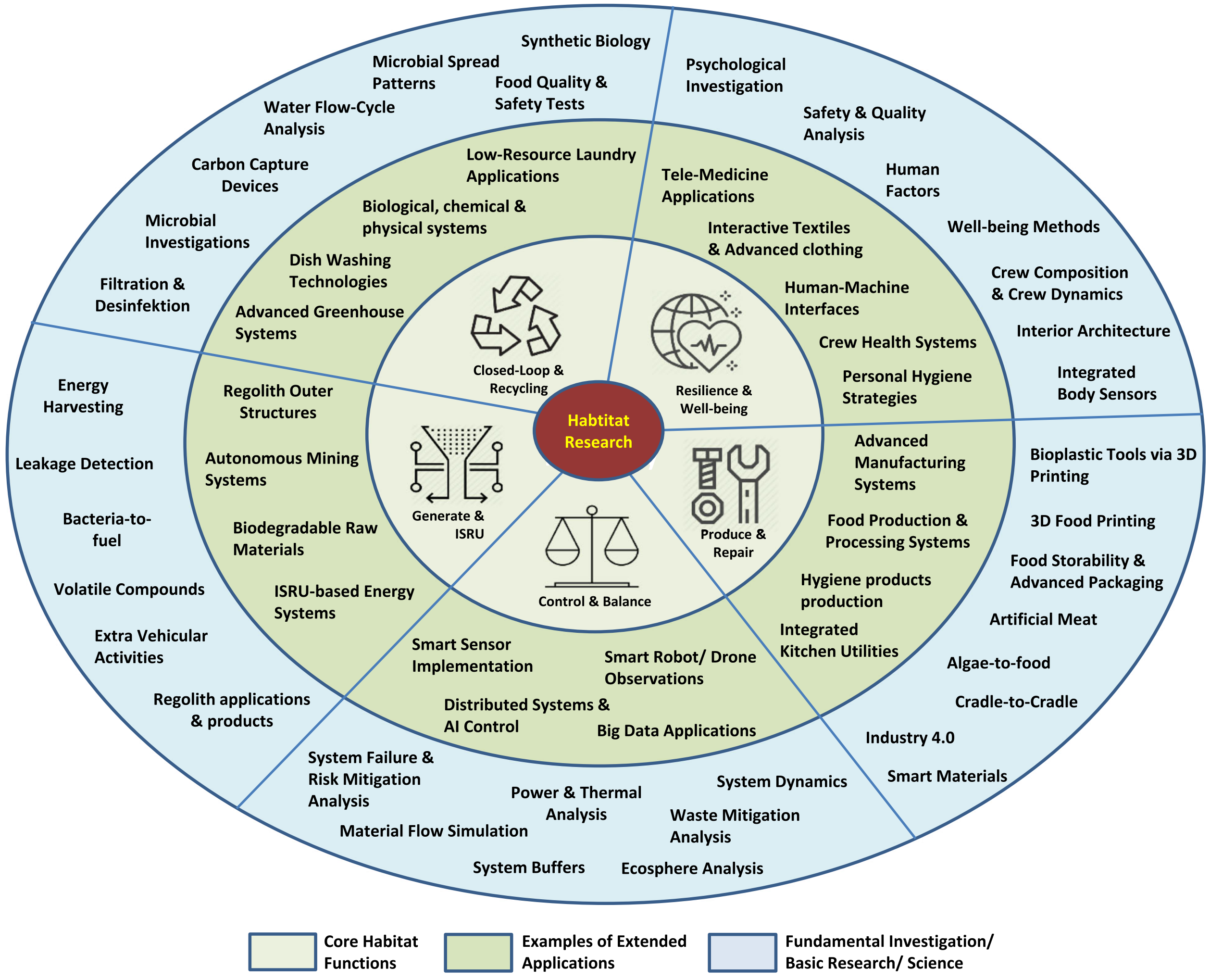

Fig. 3 Domains in habitat research bases on basic functions (light green), examples of adjoining products and methods (green), and fundamental research (blue)

However, a mere similarity in technological resp. functional needs, is not a sufficient condition for successful adoption of a technology. The transfer of the technology has to be carefully planned and coordinated to ensure success. Otherwise benefiting from human spaceflight spin-offs cannot happen.

One obstacle for adaption can be different environmental conditions. Applying e.g. agriculture technologies on Moon or Mars will be different than in an Earth environment, even if they are similar. Often this will lead to relaxation, e.g. the thermal or radiation loads on Earth will be less stringent, but in any case, a redesign can be required.

Access to a certain apparatus applying the technology, e.g. a greenhouse will be different, thus changing the respective processes needed to operate it. Maintenance cannot require specialized knowledge if the technology is to see widespread use. Personnel has to be trained in the usage of the technology and all this has to be achievd in coordination with the stakeholders. Ownership of the process has to lie with the stakeholders on Earth, to ensure success.

The capability of facilitating a certain goal via the technology can be different as well, even though the overall functionality is the same. Eveland [41] describes that a technology has to facilitate achieving a certain goal, if technology transfer is going to be successful. Specifically, this can lead to different details in technological application, which have to be coordinated with the stakeholders. One example would be to not just use similar crops in a greenhouse as for a space mission, but adapt the crop selection to that required on ground by the stakeholders. This has to be an iterative process, as a change in this operational detail might require design and process adaptations.

Technology transfer essentially boils down to communication [41], therefore it is important to communicate similarities and differences between stakeholder needs on Earth and for space application, e.g. concerning:

- Goal specifics (e.g. crop selection)
- Environmental differences (e.g. temperature regimes)
- Operational differences (level of training of personnel)

As Eveland states: "Technology is information, and exists only to the degree that people can put it into practice and use it to achieve values" [41].

Thus, the stakeholders have to be able to achieve their goals with the respective technology – communicating these and the repercussions this has on e.g. design, operation, further development of the technology is mandatory for success. Efficient communication requires dialogue with the users of a technology, NGOs, politics to ensure that all aspects are considered.

Technology development can be described via so called S-curves, when depicting performance over time [42] as given in Fig. 4. An initial fluid phase shows slow progress – the principle of the technology is known, but application has not yet a better performance than incumbent technologies. This phase is also the location of the before mentioned "Valley of Death". If not enough funding is received, a technology cannot progress beyond this point. Afterwards, once the technology has matured somewhat, the performance increases and application also facilitates progress, which leads to a steeper gradient in the transitional phase. Only after the technology has matured significantly, progress begins to slow down, while only specific attributes are further improved. At this point in time, often other technologies emerge with a better performance, usually in the fluid or transitional phase.

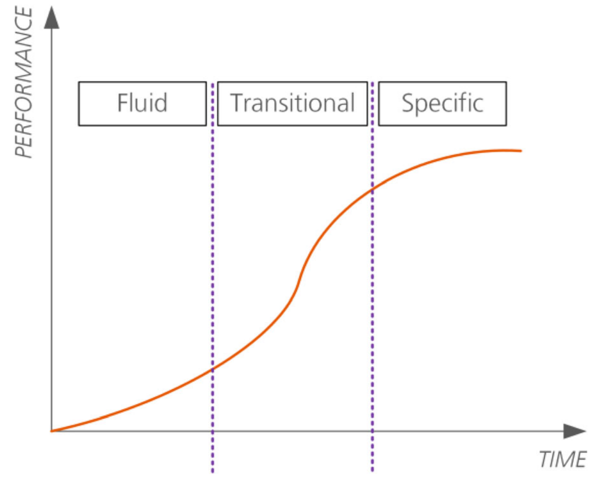

Fig. 4 Typical progress in technology development measured in performance over time. There will be a fluid phase, where performance increases slightly over time, a technology emerges. The transitional phase sees significant increases in performance, before the curve flattens and finally the specific phase, where only specific parameters are improved, maturation of the technology is high. Based on [41]

The benefit of technology transfer as described here is that the fluid phase has been overcome by investment of the original application, here spaceflight. Yet, the introduction of this technology has to occur in a way that the performance is outweighing that of the incumbent technology, i.e. the output over input (e.g. personnel hours for operating the technology) is better compared to the incumbent. The incumbent at the same time, will usually be in the specific phase, nearing or at the end of further improvement.

A further obstacle for successful improvement of sustainability with human spaceflight technology are rebound effects, resp. the need to be aware of such effects and how to prevent them. Rebound effects occur, when measures to achieve a certain goal, in the long run result in the opposite. One example would be, e.g. reducing water usage in agriculture, which in the long run resulted in larger areas being used and while the amount of water used for irrigation per area was reduced, the increase in area resulted in more total water usage [43].

Careful planning and communication with the stakeholders have to be applied to prevent rebound effects and thus lower the risk for an unforeseen negative outcome.

Recommendation for action

The previous chapters have established that human spaceflight missions and sustainable human presence on Earth face similar challenges and therefore can benefit from similar solutions. To improve the synergy between closed-loop technology development for human spaceflight and achieving sustainability on Earth we make the following recommendations to administrations, agencies and politics:

1. Increase awareness in both communities, i.e. human spaceflight and sustainable development, for common research areas and efforts (e.g. identifying technologies in the "Valley of Death"),
2. create common research programs to improve synergy effects by targeting both research communities (space exploration and STS),
3. create a common forum (e.g. by establishing conferences or workshops) to facilitate exchange of ideas, challenges and solutions, and
4. communicate the similarity of challenges and especially derivation of solutions for sustainability challenges from space technology to make use of human spaceflight popularity for acceptance of sustainability measures,
5. facilitate technology adaption to developing countries by including them via programs and

networks in the development and adaptation process of these technologies.

Funding and expertise from human spaceflight programs can also benefit sustainable development and thus create a double use, increasing the research effectiveness. In addition, bringing scientists and engineers from the respective other field into the research can also improve innovation by out-of-the-box solutions.

On the other hand, expertise for sustainable living on Earth, e.g. from urban planning and development, can benefit future settlements on other planetary bodies. A strong link between development of sustainability technologies for Earth and habitation technologies for space can be very beneficial.

Conclusion

This paper discusses the contribution human spaceflight technology development can have to sustainable development. The closed-loop paradigm associated with long-term missions is similar to the sustainability paradigm. Technology driven reduction of ecological footprint is one path to sustainability.

Furthermore, it has been shown where human spaceflight can contribute technology to terrestrial applications, e.g. in the area of energy harvesting or food production.

A research infrastructure, the Incubator for Habitation, has been proposed based on a case study, which can be used to develop closed-loop technologies and should bring together actors from the terrestrial and spaceflight area. These can benefit both with the Incubator serving as a nucleus for research.

Finally, recommendations have been made on how to integrate the two research communities with each other to maximize the results of the respective technology developments, i.e. those of the space community and of the science and technology for sustainability community.

Authors' contributions

DS provided the description of the lead user concept and the five functions of human habitation. PZ provided the description of the space greenhouse prototype in Antarctica. DS, DQ, PZ an VM worked on the description of the Incubator. VM provided the remaining parts, especially the overal structure, introduction, the chapter about space technology on Earth and discussion. The authors read and approved the final mansucript.

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Competing interests

The authors declare that they have no competing interests.

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