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Towards a Roadmap for Future UAE Deep Space Missions and the Sustainable Settlement of Humans on Mars

White Paper

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Executive Summary

The project led to the development of seven Opportunity Pathways (OPs), which, although specifically focused on space related developments, are relevant and can at the same time be used to address challenges that we face, or are yet to encounter, on planet Earth. With this in mind, the following opportunity pathways, as well as other outcomes of the project, will be used to further shape the UAE's Science, Technology and Innovation (ST&I) roadmap, development of future missions, criteria setting to ensure programmatic self-sufficiency, and positively influence relevant policies to create an enabling environment for investments and operations in space activities.

OP1: Mixed reality system for training operation

OP2: Earth/Mars-like virtual experience

OP3: Smart Mars sensing

OP4: Construction of airtight underground structures

OP5: Plant cellular agriculture for food production in space

OP6: Gut microbiome and virtual biosphere management

OP7: Self-growing biosensing material

The project also led to the identification of key technology areas that the UAE could be focusing on while leveraging existing stakeholders in relevant adjacent industries including Energy, Additive Manufacturing, Robotics and Remote Operations, and others. These are reflected in detail in the critical technology areas of the report. Six areas stood out as worthy of further exploration and consideration by experts from both the UAE and the rest of the world (RoW) are:

- Space Power and Energy Storage
- In-Space Propulsion Technologies
- Software and Applications
- Modelling, Simulation, Information Technology and Processing
- Thermal Management Systems
- Assembly, Integration and Testing facilities

Despite not being prioritised by UAE experts, the following areas were seen by international experts as particularly relevant for Deep Space programmes and the UAE space sector:

- Human Health, Life Support and Habitation Systems
- Robotics, Tele-Robotics and Autonomous Systems
- Life and Physical Sciences
- Human Exploration Destination Systems
- Space Entry, Descent and Landing Systems

Another important result is the identification of five technology areas where both UAE and RoW experts see high innovation potential by 2050. These are:

- Robotics, Tele-Robotics and Autonomous Systems
- Energy Production (solar and nuclear)
- Space Mining
- Space Food Technology
- Manufacturing in Space

The foresight study, on which this White Paper is based, is built on the continuous effort of the UAE to shape its space sector, through the identification of critical issues (barriers, drivers, opportunities and threats) enabling human settlement on Mars. The study contributed to a better understanding of the critical issues lying ahead of the Mars Missions and to a more-informed priority setting that allows the UAE to improve investment-related decision-making and acquire, over short-term, what is necessary to assist achieving the medium- and long-term goals.

The views on critical issues reveal that much of positive development in the space industry is laid on private sector. However, current pandemic has made this situation more uncertain and fragile thus emphasizing the need for stronger involvement of the government sector in helping private sector to overcome these uncertain times.

The implementation of most of the actions requires tight collaboration of different actors, in planning, designing, implementing and evaluating critical activities. To implement critical short-term actions, strong involvement of government actors is needed, namely space research centres UAESA, MBRSC and NSSTC. One of the central issues, which has also been emphasised in the National Space Strategy 2030, raised in developing the UAE's space sector is upgrading of national competences. Many actions initiating capacity building are in fact already launched in the education sector and society to raise public awareness of space sector. In this respect, government is expected to provide long-term support and invest in international collaboration together with Space Research Centres and business actors, to participate in space missions.

Critical mid-term actions to take in the UAE relate to improving the legislative framework, like founding an internal body within the UAE (similar to UN) that supervises the pathways and laws related to Mars missions and settlements. Legal framework requires multiple policy mix protocols and interdepartmental collaboration from the government institutions. Open method of coordination is one such approach to be implemented to engage collaboration. Furthermore, research and development activities in improving space health, which can at the same time improve health challenges on Earth were strongly emphasised.

The critical actions to be taken in long term relate mostly to getting to deep space because of long journey and living in deep space because of rough conditions. Many issues related to the challenges are prioritised by UAESA and other national space-related agencies.

A generally agreed concern related to United Nation's Sustainable Development Goals was that none of the current goals include outer space, therefore introduction of new goal, i.e. " Goal 18 on Responsible exploration and use of outer space" was greatly supported and welcomed by the stakeholders.

A noteworthy conclusion is the need for follow up foresight projects and 'deep dive' studies and assessments of the UAE space sector, which help to anticipate and recommend competencies and qualifications, capacities in space technologies and/or programmes, options for science and exploration missions, global collaboration and partnership opportunities, improvements in facilities and infrastructure, formulation and implementation of space relevant laws and regulations, and further development and coordination of the National Space Strategy 2030 with sector-specific priorities through evaluation supported by a National Committee for Oversight and Implementation.

Overall, the findings are strongly aligned with the UAE National Space Strategy 2030, as most of the prioritized short-term actions are relevant for developing advanced local capacities in space technology manufacturing and R&D, creating of space culture and expertise, promoting effective local and international partnerships and investments in the space industry, and ensuring a supporting legislative framework and infrastructure to match the future developments in the sector.

In general, the study helped to better understand the UAE long term vision to explore Mars and its ambitious goals, while creating strategic conversations among the UAE and international stakeholders on the need to develop future space exploration scenarios, strategic science and technology agendas across universities and research centers, as well as renewed debates on regulation and policy formulation.

The foresight study built on the continuous effort of the UAE to shape its space sector, technology areas, critical issues and critical actions contributing towards the goal of promoting sustainable human settlements on Mars. In so doing, the study helped to better understand those important areas and priorities that the UAE may want to invest in the short-medium-to-long-term. Other projects such as launching of the Hope Probe spacecraft in July 2020, and the conversation taking place on follow up initiatives will further contribute to achieving long term vision to explore Mars. Finally, the outcome of the study will further shape the UAE Science and Technology Roadmap, the National Space Strategy 2030, and other related space policy priorities in the UAE.

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Background

In 2017, Sheikh Mohammed bin Zayed Al Maktoum, launched the **UAE Space Exploration Vision** to build the first human settlement on Mars, in collaboration with major international space agencies and other key players from the space industry.

Interest in space has grown fast in recent years in many countries. One of the newcomer countries in the space sector is the United Arab Emirates who has set ambitious plans for Deep Space Missions to Moon, Mars and beyond. In 2016 the UAE formulated its National Space Policy to develop the country's space activities and achieve several long-term goals. In the core of UAE's Space Policy is:

> "To build a strong and sustainable UAE space sector that supports and protects national interests and vital industries, contributes to the diversification and growth of the economy, boosts UAE specialized competencies, develops scientific and technological capabilities, engrains the culture of in-novation and national pride, and strengthens UAE's status and role regionally and globally."
>
> National Space Policy of the United Arab Emirates, 2016, p.12.

In 2014, the UAE took a big step towards international space community when UAE Space Agency (UAESA was established. Opening of space specific a gency t o f oster r esearch and development (R&D and local space economy made the country a leading space nation in the region, and international collaborator, seeking to exploit the outer space together with other space-faring nations.

This White Paper has been commissioned by the UAESA to support and promote the open strategic conversations and systematic gathering of forward-looking insights **towards a roadmap for future UAE deep space missions and the sustainable settlement of humans on Mars**.

UAE Space Exploration Vision

The Mars human settlement was announced in 2017 by His Highness Shaikh Mohammad Bin Rashid Al Maktoum, Vice-President and Prime Minister of the UAE and Ruler of Dubai, and His Highness Shaikh Mohammad Bin Zayed Al Nahyan, Abu Dhabi Crown Prince and Deputy Supreme Commander of the UAE Armed Forces. As part of a 100-year national programme, the UAE will set a plan to prepare national cadres that can achieve scientific breakthroughs to facilitate the transport of people to the Red Planet over the next decades. The 100-year plan will involve scientific research programmes to nurture national cadres specialised in space sciences at universities in the UAE. It will also entrench a passion for space in younger generations. The project will inevitably lead to a myriad of research initiatives ranging from exploration and development to commercial services, including areas such as transportation means, energy generation and preservation, food production, and life support and habitation systems on Mars. Overall, the **UAE Space Exploration Vision is to develop scientific and innovative technical capabilities necessary to achieve a sustainable human settlement on Mars**. In line with this, a foresight exercise was carried out by UAESA and VTT to produce this White Paper supporting UAE efforts to achieve this visionary goal.

Global space industry

Over the last decade, the global space economy has consistently shown an annual growth that outpaces the growth of the global economy. From around 275B$ in 2010, the size of the space economy has grown to 414.75B$, according to the 2020 Space Report of the Space Foundation. This expansion has been led by technological and business model innovations that have reduced costs and broadened the existing customer base. Up until now the most important drivers of growth have been continuous increase in private investment, emergence of new companies, including start-ups and SMEs, as well as rising competition between China, India and other emerging players. The consolidation of the so called "New Space" phenomenon has been largely driven by commercial interests of innovation-oriented risk-taking players such as SpaceX, Blue Origin, OneWeb and Virgin Galactic, which, collectively raised over two-thirds of 2019 start-up investments. Notably, the Bryce's 2020 Start-Up Space report highlighted three major trends shaping the 2020s: first, rise in terms of investments, investors and recipients of start-ups funding which in 2019 reached 5.7B$; second, continuous need for ventures to deliver on their promises by showing profitability and sustainability; and third, growing number of start-ups looking at governments as prospective customers. While many would have seen these as the "New Normal" of the "New Space", the unexpectedly fast and multi-dimensional impacts of the coronavirus (Covid-19) pandemic have already created a potential "black hole" in the investment space, at least in the short-term.

Will Covid-19 become a "Black Hole" for space investments?

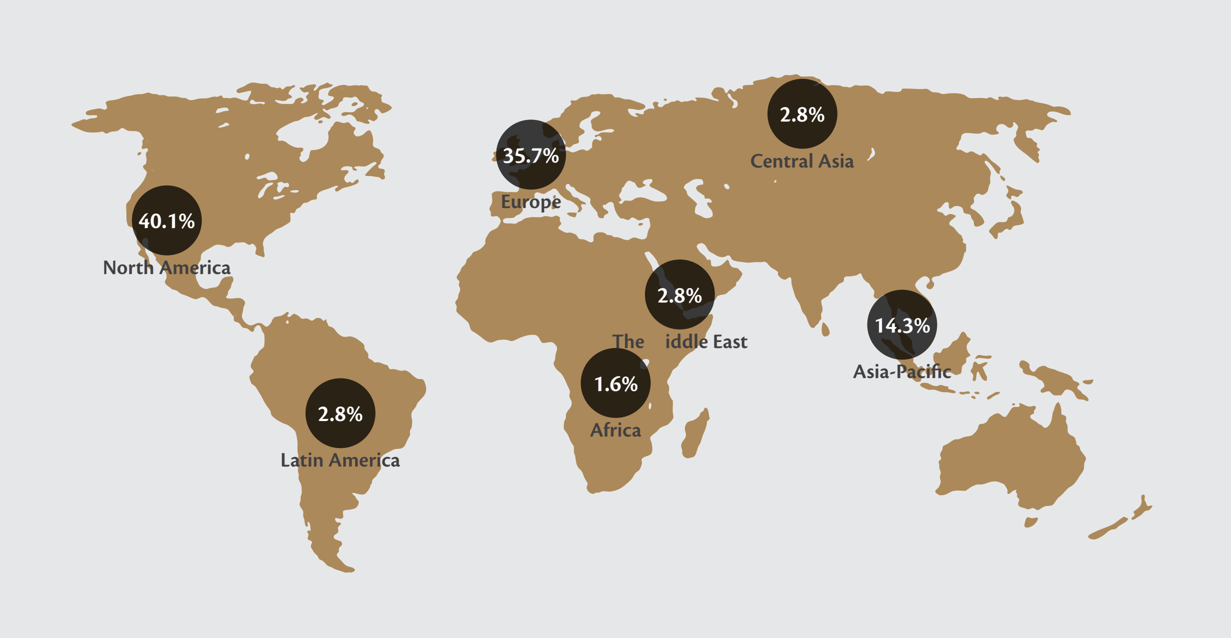
At the time of writing, early impacts of the Covid-19 outbreak have already shaken the space sector landscape. One of the first casualties of Covid-19 has been OneWeb which, in spite of attracting 1.25B$ in 2019, decided to file for bankruptcy on March 2020 after struggling to raise additional funding to complete the remaining 90% of their envisaged constellation of 650 low Earth orbit (LEO) satellites. Experts and specialised media such as SpaceNews have been monitoring the emergence of weak and strong signals indicating that, despite some ongoing government stimuli, an imminent investment vacuum is likely to result from the growing risk-averse atmosphere among banks, as well as angel and venture capital investors. Only in March 2020, SpaceNews reported that partly or fully due to the Covid-19 pandemic, more than 35 space events have been delayed or cancelled, entire workforces have been affected or laid off (for example at Bigelow Aerospace) and stock prices of important satellite operators have declined some 35-50%. These and other developments have positioned a black cloud of volatility, uncertainty, complexity and ambiguity (VUCA) over the "New Space" sector, which will not be weathered unless the unpredictable impacts of the Covid-19 are properly assessed and managed, in order for private and public players to resolve and evolve.

Towards a new Post-Covid-19 space landscape

In recent years, technological progress has revolutionised the space economy as additive manufacturing, artificial intelligence and nanotechnology have become mainstream in space value chain functions. This progress has in turn enabled development of several industries, technologies and services, such as global satellite connectivity solutions, agriculture planning, environmental monitoring, biodiversity protection and forest management, counterfeit or illegal drugs control, oil seeps mapping, CO_2 emission and pollution levels tracking, cybersecurity, autonomous mobility, weather forecasts, among many other application areas.

Increased investments and reduced entry barriers are driving the expansion of the space industry ecosystem, and new players are entering from Latin America, Africa and the Middle East, among these is the UAE (Figure 1).

Figure 1. Space industry value chain participants (%), 2018 (Source: Frost & Sullivan, 2018)



The largest country in space industry value chain is the USA, which has around 400 actors. The United Kingdom, Germany, France and the Netherlands have the largest space industries in Europe, whereas India, Australia and China dominate in the Asian Pacific region. The UAE has the second largest space industry in the Middle East after Israel.

Developments before the Covid-19 pandemic suggested that the space industry ecosystem would continue growing by 2025 as preparations for the next race to expand human presence into the Solar System are ongoing. This race of reaching Moon and Mars has been led by government space agencies and require extended allotted government budgets for building new capabilities across the globe. It remains to be seen whether the grow and investment rates will remain in the short-term. However, the Covid-19 crisis has pushed many space actors into what can be called the “New Normal” of turbulent times, which requires agile and strategic repurposing of certain company operations with two mutually reinforcing goals: firstly, to provide rapid and responsible high-tech responses to urgent societal needs on Earth (such as some companies’ efforts to manufacture critical medical equipment and ventilators, as well as personal protective supplies, for example face shields, medical masks, and gowns); and secondly, to create or strengthen strategic partnerships with government, business and research actors in order to generate new or more sustainable business models and services that would allow to secure the necessary resources to maintain critical operations and workforce until the space sector reaches a post-Covid-19 investment renaissance.

Against this background, the UAE has made significant investments to become an active player in the international space community with projects such as the Hope Probe 2020, also known as the Emirates Mars Mission, aimed to explore Mars and its atmosphere from 2021. **As a longer-term target, the Emirati government plans for human settlements on Mars** .

The UAE Space Agency overview

Vision

We proudly craft the future of the United Arab Emirates as a leader in Space and we inspire our future generations for the benefit of the nation and humankind.

Mission

We will proudly craft the future of the United Arab Emirates as a leader in Space by organizing and guiding the Space sector, by contributing to the national economy and sustainable development, by preparing generations of highly skilled professionals, and by developing Space research, Space programs, and strategic partnerships in the field of Space.

Objective [6]

Organise and develop the national space sector to support a sustainable national economy.

Develop the national cadres and support research, development, and innovation in space sector.

Enhance and highlight the role of the UAE both regionally and globally.

Ensure the provision of all administrative services in accordance with the standards of quality, efficiency, and transparency.

Establish a culture of innovation in the institutional work environment.

National Space Strategy 2030 [7]

Provision of competitive and leading space services.

Development of advanced local capacities in space technology manufacturing and R&D.

Launching inspiring space scientific and exploration missions.

Creating space culture and expertise.

Effective local and international partnerships and investments in the space industry.

Ensure a supporting legislative framework and infrastructure to match the future developments in the sector.

About the White Paper

Objective

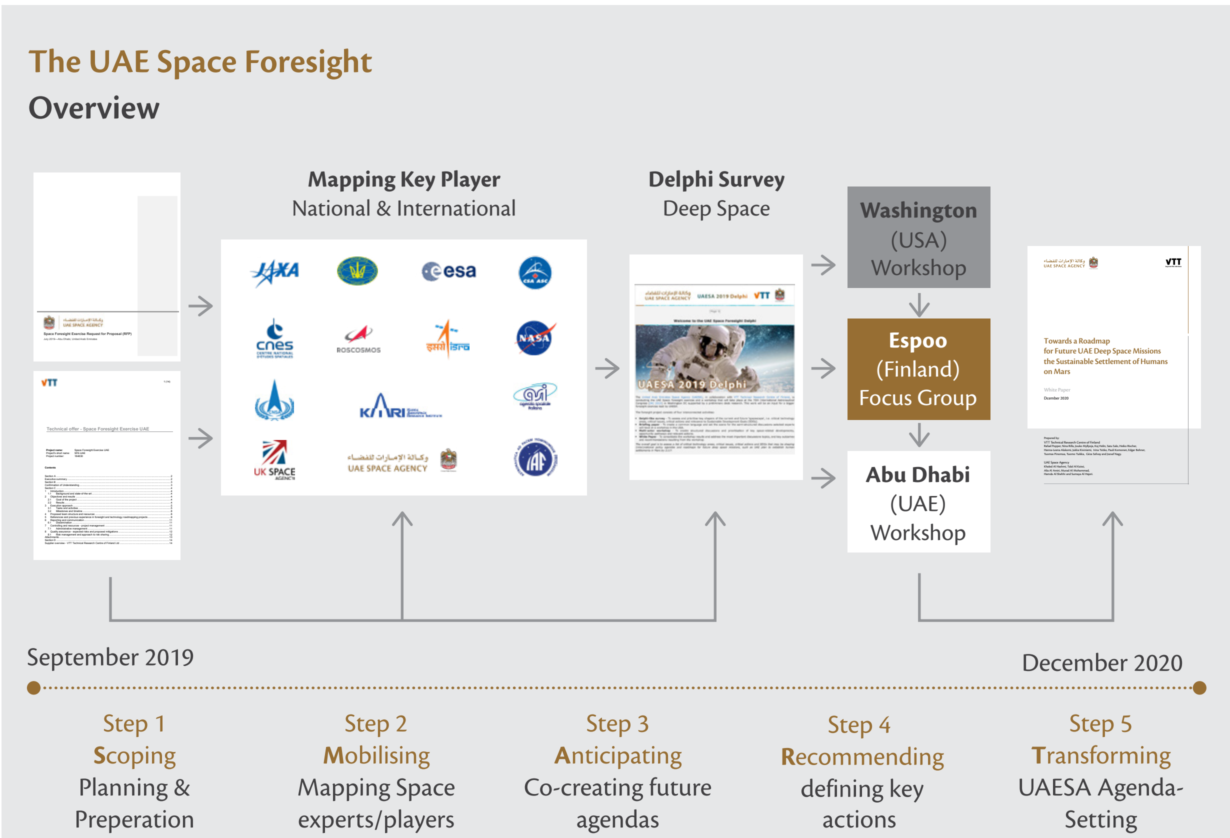
In 2018, the UAE Space Agency conducted an expert panel and a workshop on the prospects for the UAE Space Agency and its future space exploration plans and wanted to widen and reach out to international experts by adopting an open approach. To do so, UAESA commissioned VTT Technical Research Centre of Finland Ltd to conduct a short foresight exercise supported by an expert workshop at the 70th International Astronautical Congress (IAC 2019) in Washington DC and a wide range of activities, including a multi-stakeholder mobilisation and mutual learning workshop in Abu Dhabi (September 2019) and several focus groups with VTT space experts in Finland (see also methodology section below).

The main objective of the foresight exercise was to kick-off a national and international dialogue that would support the production of this White Paper and provide an agenda for future activities aligned with the National Space Strategy 2030. Overall, the main objective of the White Paper is **to serve as a stepping-stone and provide inputs for a bigger UAE Space Agency foresight exercise on the sustainable settlement of humans on Mars**.

Methodology

The White Paper methodology required a foresight process using a multi-stakeholder engagement approach, which enables and commits organisations to co-create the future through Action Roadmapping (Figure 2). The main components of the UAE space foresight process were the implementation of global Delphi survey, which offered inputs in workshops and focus

Figure 2. The VTT-UAESA White Paper methodology



groups organised in Washington DC, Espoo and Abu Dhabi (October-November 2019). This multidisciplinary foresight process mobilised expertise from various technical fields in the UAE, Finland, USA and over 20 other countries.

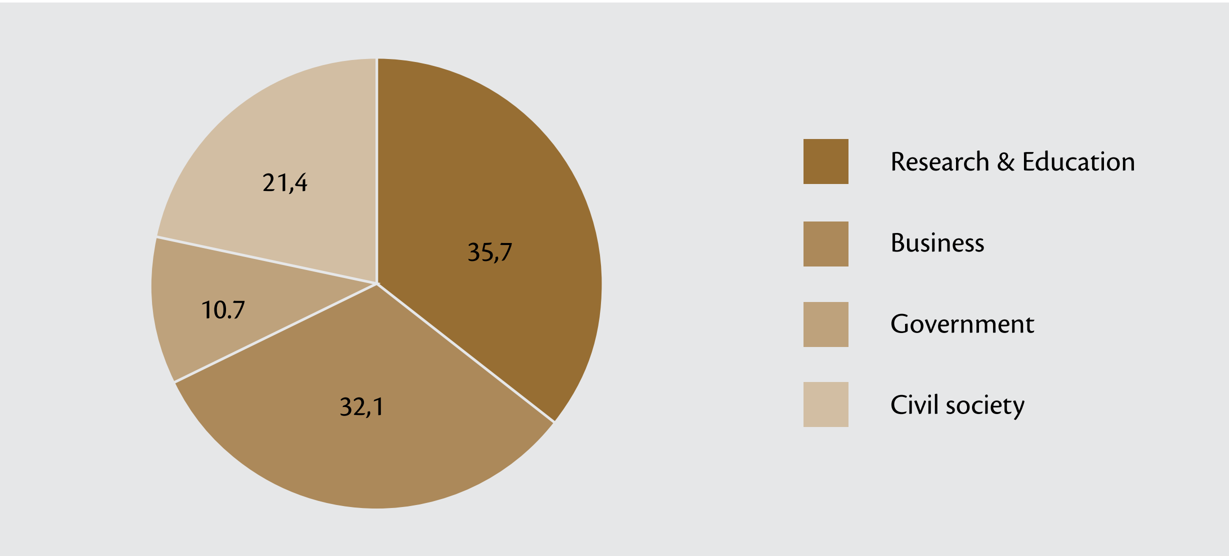
Step 1 – Scoping

The Scoping phase involved planning and preparation of a project proposal that responded to the UAESA needs of conducting a short foresight exercise in the area of "SpaceScape - the space landscape in 100 years". One important element of the requested methodology was to offer an opportunity for experts to attend discussions that converge space futurists with actual current technological advancements from a variety of sectors - conflating bold visions with achievable progress.

Step 2 – Mobilising

The Mobilising phase required the mapping of key space experts and players in the UAE and the world. The main purpose of this phase was twofold:

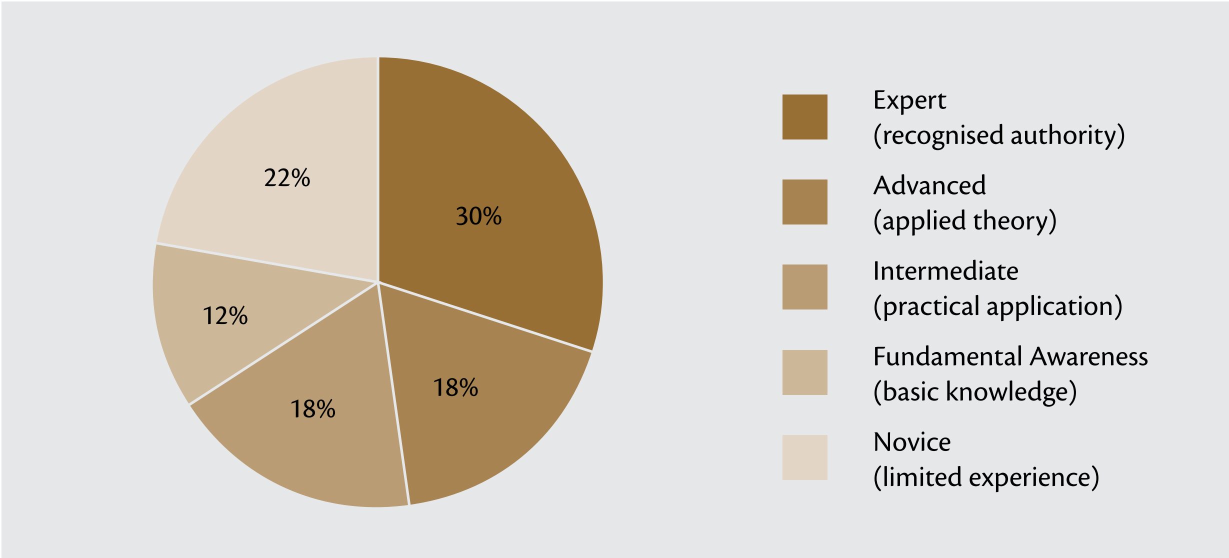
Figure 3. Washington DC workshop participants



- To conduct a rapid assessment of the state-of-the-art of deep space programmes in order to scan the environment and create a preliminary list of critical issues (barriers, drivers, opportunities and threats) and critical actions considered in ongoing and forward-looking strategies of leading and emerging agencies such as CSIRO (Australia), CSA (Canada), CNSA (China), ESA (Europe), CNES (France), ISRA (India), ASI (Italy), JAXA (Japan), KARI (Korea), Roscosmos (Russia), SSAU (Ukraine), UKSA (UK), NASA (USA) and UAESA (UAE).

- To identify a geographically diverse and multidisciplinary group of space actors to be invited to the project activities and the Delphi survey. The Washington DC workshop gathered the views from 28 research and education, business, government and civil society actors (Figure 3), the Delphi survey mobilised 175 actors from 26 countries (Figure 4), the focus group and internal meetings with 15 Finnish scientists from VTT supporting the identification of opportunity pathways for the UAE, while the Abu Dhabi workshop helped to assess and discuss preliminary results with around 25 UAE experts.

Figure 4. Delphi survey respondents



Step 3 – Anticipating

The Anticipating phase involved an online Delphi survey (Figure 5) providing a Big Picture panoramic overview of experts' opinions on the current and future "*SpaceScape*". The main purpose of the Delphi was to assess a list of critical technology areas, critical issues, critical actions and sustainable development goals (SDGs) that may be shaping (inter)national policy agendas and roadmaps for future deep space missions, such as the UAE's plan to establish human settlements on Mars.

Delphi surveys are commonly used as a mean to elicit views and knowledge through a well-structured questionnaire, which allows participants to provide feedback on previous responses. Although the Delphi technique traditionally involves two rounds of consultations, we see the emergence of Delphi-like surveys being implemented with one round, when participants use a system that allows them to revise their assessments with the help of real-time analytics.

Step 4 – Recommending

The recommending phase involved the organisation of two multi-stakeholder workshops and a focus group of space experts from the VTT Technical Research Centre of Finland.

- The workshop in Washington DC (USA) addressed questions to identify key technology areas, discuss about potential wild cards (planned and unplanned events), and weak signals (uncertainties) that could have an impact on the future of space technologies, the economy, society, the political aspects, ethical considerations, and the environment particularly with traditional and emerging space fairing nations.
- The focus groups in Espoo (Finland) were used to identify and assess space opportunity pathways. The main purpose of these events was to discuss preliminary Delphi results to co-create a set of thematic areas to become the main research foci of the Action Roadmap workshop in Abu Dhabi.

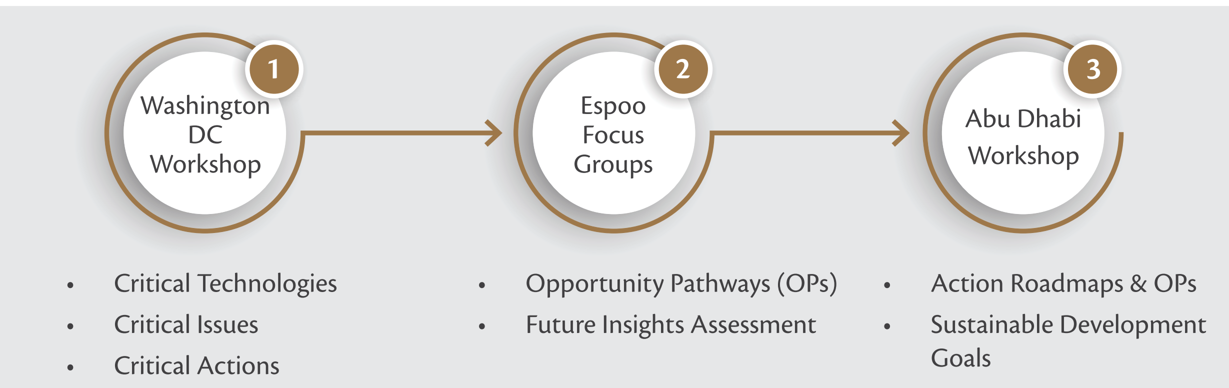
Figure 5. Delphi Survey welcome page

- The workshop in Abu Dhabi (UAE) engaged around 25 representatives from industry, research, university, government, and civil society organisations in a structured brainstorming session complemented with open discussions, which ultimately helped to define some top opportunity pathways (OPs) for the space sector in the UAE. The workshop was also used to go deeper into the research, education, innovation and regulation needs of prioritised OPs, taking into account future actions around some key aspects of the context, people, process and impact dimensions of future deep space missions, such as the UAE's plan to establish human settlements on Mars.

Step 5 – Transforming

Finally, the Transforming phase was about translating the results of the project into the set of recommendations and key messages presented in this White Paper. The first draft of the paper

Figure 6. Multi-stakeholder engagement



was submitted by VTT to UAESA in January 2020. Since then a VTT-UAESA task force engaged in a series of interactive co-creation meetings with several rounds of revisions and contributions from the UAESA Future Foresight team, in which UAESA incorporated inputs and supported the alignment of results with UAESA strategic objectives. The ultimate goal of this phase is to better inform future UAESA agenda-setting discussions by providing sound advice and a wide range of inputs on critical technology areas, critical issues, and critical actions that need to be considered in a follow up Deep Dive UAESA foresight project on the sustainable settlement of humans on Mars.

Key questions addressed in the White Paper

The White Paper addresses five key questions (Figure 7 from two perspectives, namely the views of UAE actors and the views of the Rest of the World (RoW actors including insights from 25 countries. However, for the comparative analysis of semi-quantitative assessments of the Delphi results, we have only used the opinions of respondents who indicated the following three levels of space expertise: Expert level (recognised authority, Advanced level (applied theory and Intermediate level (practical application. This basically resulted in RoW views from the following 15 countries: Austria, China, Finland, Germany, Great Britain, Greece, India, Italy, Luxembourg, Poland, Romania, Russia, Saudi Arabia, South Korea and the USA.

Figure 7. Key questions addressed in the White Paper

On Critical Technology Areas	What are the Critical Technology Areas for missions to establish human settlements in Mars? And what are the Top Areas where significant incremental or radical innovations are expected in the next 20 years?
On Critical Issues	What is the level of agreement regarding statements about critical issues (drivers, barriers, opportunities and threats) and the assessment of their importance for Moon and Mars Missions?
On Critical Actions	What is the responsibility of different stakeholder groups and expected implementation timeframe for selected Critical Actions for Moon and Mars Missions?
On Sustainable Development Goals (SDGs)	How important are Deep Space Missions (Moon & Mars) for the SDGs and how space initiatives could positively impact on them?
On Opportunity Pathways (OPs)	What important OPs can be identified for the development of necessary science, technology and innovation (STI) capabilities for Deep Space (Moon and Mars) missions?

On Critical Technology Areas

In the following section, Delphi survey responses are divided between experts coming from the UAE and the Rest of World (RoW) to show relative position of the UAE's perspectives, attitude and competences for Moon and Mars missions in the future.

Preliminary list of Technology Areas

Table 1. List of 18 Technology Areas

1. *Launch Propulsion Systems*
2. *In-Space Propulsion Technologies*
3. *Space Power and Energy Storage*
4. *Robotics, Tele-Robotics and Autonomous Systems*
5. *Communications, Navigation and Debris Tracking*
6. *Science Instrument, Observations and Sensor Systems*
7. *Nanotechnology*
8. *Modelling, Simulation, Information Technology and Processing*
9. *Materials, Structures, Mechanical Systems and Manufacturing*
10. *Software and Applications*
11. *Satellite Technologies and Techniques*
12. *Human Health, Life Support & Habitation Systems*
13. *Human Exploration Destination Systems*
14. *Space Entry, Descent and Landing Systems*
15. *Life and Physical Sciences*
16. *Ground and Launch Systems Processing*
17. *Thermal Management Systems*
18. *Ground Station Systems and Networks*

Top 10 Critical Technology Areas

The assessment of critical technology areas for Moon and Mars missions shows that technologies perceived critical for the UAE vary somewhat from the RoW views. The main difference is that the **RoW experts give much more importance to life and human-related technology areas (*e.g. Life and Physical Sciences; Human Health, Life Support & Habitation Systems; and Human Exploration Destination Systems*) than UEA experts**. In addition, the technology area on '*Robotics, Tele-Robotics and Autonomous Systems*' appears as the second most critical for RoW experts while it is absent from the Top 10 in the UAE.

The UAE is still a newcomer in the space sector where technological competences relate largely to building of space infrastructure than developing technologies related to living on Mars.

Figure 8. Top 10 Critical Technology Areas for Moon & Mars Missions

UAE Views

- Materials, Structures, Mechanical Systems and Manufacturing
- Space Power and Energy Storage
- Ground Station Systems and Networks
- In-Space Propulsion Technologies
- Software and Applications
- Ground and Launch Systems Processing
- Modelling, Simulation, Information Technology and Processing
- Satellite Technologies and Techniques
- Thermal Management Systems
- Communications, Navigation and Debris Tracking

RoW Views

- Life and Physical Sciences
- Robotics, Tele-Robotics and Autonomous Systems
- Space Power and Energy Storage
- Human Health, Life Support & Habitation Systems
- In-Space Propulsion Technologies
- Modelling, Simulation, Information Technology and Processing
- Thermal Management Systems
- Human Exploration Destination Systems
- Software and Applications
- Space Entry, Descent and Landing Systems

Top 5 Additional Technology Areas

In addition to 18 pre-defined technology areas provided in the Delphi, respondents were able to suggest and assess new areas. UAE and RoW views on the criticality for Moon and Mars missions strongly deviated from each other regarding additional technology areas. In fact, both groups saw only one of the technologies equally critical, namely Assembly, Integration and Testing facilities. Again, ROW views concentrated more on human-related technologies, such as oxygen or food production, while monitoring and sensing of space were seen more critical for the UAE.

For an emerging space country such as the UAE, the short-term focus is on building up local technological capabilities, while the RoW (especially pioneering spacefairing countries) prioritised more specific areas, such oxygen/energy production, water/food systems, etc. (Figure 9).

Figure 9. Top 5 Additional Technology Areas for Moon & Mars Missions

UAE Views	RoW Views
• Satellite	• Oxygen Production
• Space Weather	• Energy Production; Solar and Nuclear
• Assembly, Integration and Testing Facilities	• Water Processing Systems
• Manufacturing in Space	• Assembly, Integration and Testing Facilities
• Pointing Accuracy	• Space Food Technology

Top 5 Critical Technology Areas by innovation potential

Assessment of UAE's technological position by 2050 for Moon and Mars Missions reveals that UAE is expected to have average competences in the most technologies, but at the same time Ground Station Systems and Networks is seen to develop more positive for UAE. In this area, UAE could develop leading expertise. UAE and the RoW perceive technological development for Moon and Mars missions slightly different in the assessment of innovation potential of different

Figure 10. Ranking of Top 5 Technology Areas by Innovation Potential in 2040

UAE Views	RoW Views
• Robotics, Tele-Robotics and Autonomous Systems	• Robotics, Tele-Robotics and Autonomous Systems
• Life and Physical Sciences	• Modelling, Simulation, Information Technology and Processing
• Space Power and Energy Storage	• In-Space Propulsion Technologies
• Space Entry, Descent and Landing Systems	• Space Power and Energy Storage
• Software and Applications	• Human Health, Life Support & Habitation Systems

technology areas. Although human-related technological areas were not seen critical by UAE, Life and Physical Sciences contain innovation potential in the future according to the UAE respondents. Both groups agree that Robotics, Tele-Robotics and Autonomous Systems and Space Power and Energy Storage have the potential for novel developments when it comes to reaching Moon and Mars in future.

Top 5 Additional Technology Areas by innovation potential

Given the additional technology areas' innovation potential, the UAE and the RoW views are quite aligned, with energy productions being the most important area to solve in the next 20 years.

Figure 11. Ranking of Top 5 Additional Technology Areas by Innovation Potential in 2040

UAE Views

- Energy Production; Solar and Nuclear
- Space Mining
- Space Food Technology
- Wireless Power Transmission
- Manufacturing in Space

RoW Views

- Energy Production; Solar and Nuclear
- Space Mining
- Space Food Technology
- Manufacturing in Space
- Human Conditions (Noise, Vibration, Heat, Breathing Air Quality)

On Critical Issues

This section presents critical issues (i.e. drivers, barriers, opportunities and threats) that have been assessed as critical for reaching Moon and Mars.

Top Drivers

The following drivers were considered critical for future Deep Space agendas, and have reached at least 60 percent criticality in the survey, or reached high agreement among respondents but not reached 60% criticality for Moon and Mars mission.

Table 2. Top Drivers expected to shape future Deep Space missions

Top Drivers	UAE	RoW
1. Space agriculture will greatly impact agriculture on earth and in space.	✓	✓
2. In addition to technical expertise, great teamwork abilities and leadership skills, the mental aspect of "emotional intelligence" will be among the most important skill sets for future astronauts.	✓	✓
3. Private sector will take the lead in running space developments through more efficient use of resources.	✓	✓
4. Space science continues to be performed mainly by robotic spacecraft.	✓	✓
5. The Outer Space Treaty stating space is "the common heritage of mankind" will continue to remain as one core principle forbidding claims of sovereignty.	✓	✓
6. Timeframe for having human settlements in Mars is feasible.	✓	✓
7. Developing services to Earth establishes most stable research base for advancing space technologies.	✓	✓
8. Development of affordable and safe space solar power will be a major new space industry benefiting Earth.	✓	
9. Making observations from space will improve significantly our capabilities to understand and model the causes, processes, and effects of global climate change.	✓	✓
10. Sustainable development agenda in space should be built in way that that it places people and the planet Earth at the center.		✓

Top Barriers

The following barriers were considered critical for future Deep Space agendas, and have reached at least 60 percent criticality in the survey, or reached high agreement among respondents but not reached 60% criticality for Moon and Mars mission.

Table 3. Top Barriers expected to shape future Deep Space missions

Top Barriers	UAE	RoW
1. The development of space as an arena for multiple government and private activities will pose significant policy and legal challenges.	✓	✓
2. International consensus on the issue of debris management cannot be reached.	✓	
3. Developing space activities in a multi-professional and interdisciplinary manner is a crucial aspect for space sector to support the development of long-term space missions.	✓	✓
4. Intense competition between governments, ideologies and commercial profit is going to get increasingly harsh.	✓	
5. Sustainability debate regarding space should go beyond LEO (Low Earth Orbit).	✓	✓
6. Sustainable Development Goals (SDGs) cannot be applied as such in space, consequently, a fully new sustainable agenda should be built for space exploration and usage.	✓	
7. Funding issues will remain as the largest limiting factor for sending humans to Mars.		✓
8. Our understanding on human mental capabilities is not on a level that would enable us to understand profoundly what will happen psychologically during long-term space missions.		✓
9. Making giant advances in human-robot interaction (HRI) is crucial for enabling long-term space exploration such as travelling to Mars.		✓
10. Development of the Moon will take lead in developing space technologies.		✓

Top Opportunities

The following opportunities were considered critical for future Deep Space agendas, and have reached at least 60 percent criticality in the survey, or reached high agreement among respondents but not reached 60% criticality for Moon and Mars mission.

Table 4. Top Opportunities expected to shape future Deep Space missions

Top Opportunities	UAE	RoW
1. Private sector investments to space developments will go on more than 15% of annual increase. Space industry as a whole will double to $800bn by 2030.	✓	✓
2. Space Food production systems, using minimal inputs, will develop methods necessary also for the growing Earth population.	✓	✓
3. 3. In the future, the space will be working as an increasingly attractive platform for education in all levels of an education system.	✓	
4. Increased multidisciplinarity of the space sector and being open to non-technical or scientific contributions as valid insight resources, e.g. art, philosophy, sociology of space, psychology, creativity research.	✓	✓
5. International space station (ISS) will remain as a primary space laboratory until 2030.	✓	✓
6. Mega-constellations of satellites would increase the number of satellites in Low Earth Orbit by a factor of 10 by 2025.		✓
7. Comparative studies on the evolution of Venus, Mars, and Earth will take significant leaps by 2030 providing important insights about Earth's future.		✓

Top Threats

The following threats were considered critical for future Deep Space agendas, and have reached at least 60 percent criticality in the survey, or reached high agreement among respondents but not reached 60% criticality for Moon and Mars mission.

Table 5. Top Threats expected to shape future Deep Space missions

Top Threats	UAE	RoW
1. Human capabilities to work in improvising manner should and can be improved to work under challenging and emerging circumstances in space.	✓	✓
2. The problem of debris, "over 500,000 individual pieces of debris hurtling at velocities of over 27,000km an hour", will increase.	✓	✓

Both of the groups see critical issues for future Deep Space agendas similarly; only the ranking of issues varies slightly. The international space community sees the development of sustainable development agenda in space as a more critical driver than the UAE, whereas for example barriers are observed very differently by the groups. Due to newness of space-related issues in the UAE, the role of space education as opportunity is stronger in the UAE than in the assessment of the RoW. However, it is notable that neither of the communities perceives many threats critical for future missions. The only concerns refer to the adaptability of human capabilities to work in space in future and the diminishing of debris.

On Critical Actions

This section describes the most critical actions, which the UAE should take to reach Moon and Mars. Actions are introduced in order of urgency, i.e. starting from actions which require immediate attention in short-term (by 2030) and move to medium- (by 2070) and longer-term actions. Given that survey responses focused on shorter-term actions, the more far-reaching actions were co-created in workshops. Actions relate to four types of management dimensions, namely context, people, process and impact, together with an indication of the expected responsible actors. In this section, views are incorporated as one coherent action roadmap that flavours insights from both the UAE and the RoW actors.

Overview of the Action Roadmap for future Deep Space agendas

Out of 92 actions, the majority of actions related to the impact, i.e. transformation and sustainability-oriented actions (32%), and the process dimensions, i.e. how to catalyse and foster actions (31%). Like anticipated, most of the actions were assessed to be urgent to act upon within the next ten years (51%), while the longer the time horizon, the less actions were identified in the roadmap. The main stakeholder group is clearly government. In 75% of actions, the government is mentioned as one of the main responsible actor groups or as a single actor. In turn, engagement of civil society was seen important in only few cases. Only the distribution of actions by implementation timeframe, management dimension and responsible actors is presented in Figures 12 and 13 below.

Figure 12. Critical Actions by implementation timeframe and management dimension

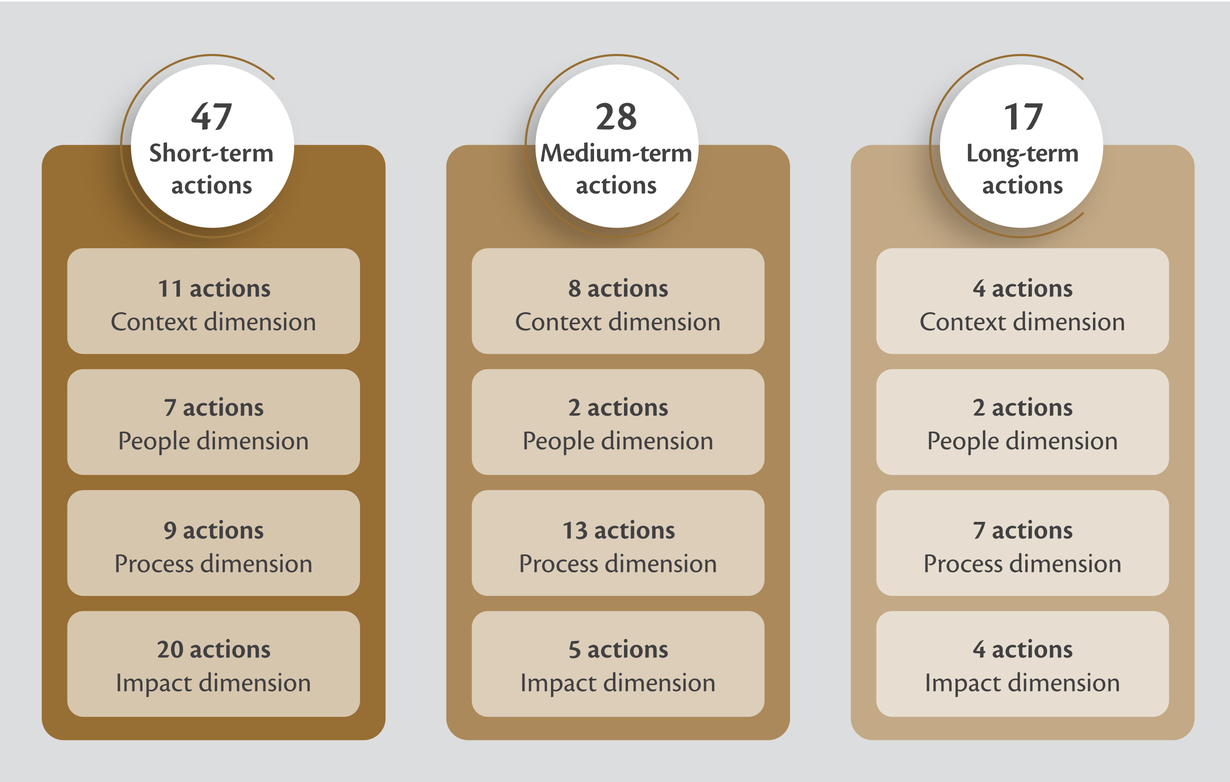
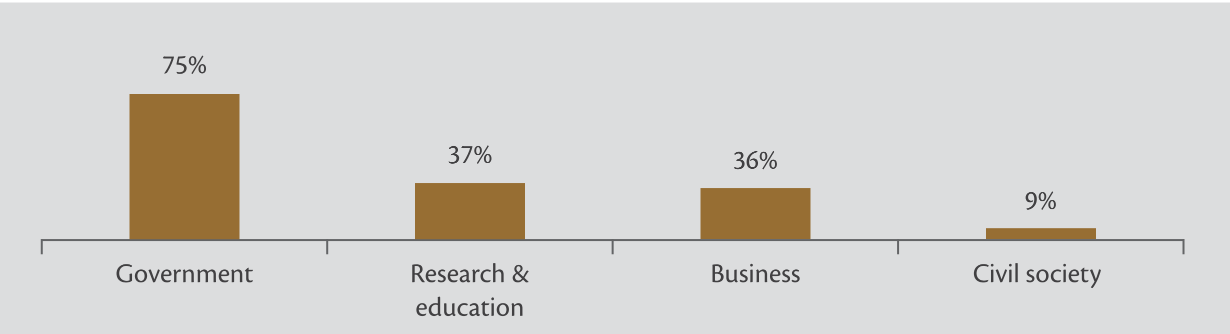


Figure 13. Critical Actions by responsible actor(s)



Understanding the typology of critical actions

The following four innovation management dimensions (Table 6) were used to cluster the prioritised critical actions.[9]

Table 6. Key Innovation Management Dimensions

*The **Context dimension** consists of four key aspects: 'Momentum', reflecting the potential space for innovation, i.e. expectations of entrepreneurs, political drive from regulators or procurement, exemplars from other technological or social enterprises, and the perception of problems that call for solutions; 'Foresight', showing the capacity to anticipate, strategise and overcome gaps in the innovation curve; 'Resources', emphasising the need for healthy combinations of skills, finance, location, markets, etc.; and 'Mobilisation', including champions and facilitators, civil society engagement, government engagement, research and education engagement, business engagement and proactive participation.*

*The **People dimension** consists of two key aspects (i.e. aptitude and attitude) shaping the activities of government, research and education, business and civil society actors. Many objectives remain unfulfilled when innovations fail to mobilise the right people, or do not provide the right incentives or skills for key people. 'Aptitude', refers to the actual skill set or competences of people involved in the design, development, implementation and diffusion of a sustainable innovation; 'attitude', means the type of behaviour of the same people.*

*The **Process dimension** consists of two key aspects: 'Catalysts', contributing to initiate, develop and implement the innovation; and 'Fosterers', including factors that further consolidate and diffuse the innovation. Some examples of critical factors that can be considered 'Catalysts' include: compressibility (to offer user-friendly solutions); crowd-sourcing (to achieve truly bottom-up financial support); learning-by-doing (to promote more assertive evolution and incremental innovation); supportive services (to deal with specific bottlenecks in the innovation process); absorptive capacity (to generate and act upon valuable information or intelligence); ex-ante impact evaluation (to recognise and measure important benefits and possible risks); and piloting and experimenting (to avoid disappointments and manage expectations). Similarly, the following factors can be considered 'Fosterers': incentives (to further position the innovation); coordination (to manage the relationship between the innovation team, sponsors, supporters and beneficiaries); networking and synergy (to better capitalise momentum-related critical factors); knowledge management (to reinforce the innovation capacity of the team); intellectual property management (to improve the competitive advantage); ex-post impact evaluation (to promote improvements through learning and demonstrate the positive environmental, social and economic impacts); and communication and dissemination (to increase the sectoral and geographical transferability).*

*The **Impact dimension** consists of two key aspects: 'Transformation', meaning the capacity to make positive changes in the quadruple helix of SI and knowledge production; and 'Sustainability', referring to changes in the socio-technical system where the SI operates that lead to positive environmental, social, economic, government and infrastructure transformations without compromising the needs and welfare of future generations.*

Critical Actions for the Short-term

In total, 47 critical actions with a short-term timeframe were identified by international stakeholders participating in the Delphi survey and organised workshops.

12 actions supported the 'context' dimension. The most important and immediate action concerning the **UAESA**, in collaboration with other **government** agencies, is the establishment of a Fully-fledged Mars Policy Roadmap (Long-term Policy) to create future-proof cross-sectoral policies and promote foresight-driven research, technology development and innovation initiatives for space missions. Other actions where UAESA's involvement, together with **government, academia** and other **Space Research Centres** – such as the Mohammed Bin Rashid Space Centre (MBRSC, and the National Space Science and Technology Centre (NSSTC – would be significant, include: (1 engaging different stakeholders to establish programs to encourage and conduct basic and applied research in the field of space science and technology, for scientific and commercial purposes. So far, the UAESA has established a Science, Technology and Innovation Roadmap supported by an implementation plan inclusive of programs and initiatives funded by the agency and aimed to engage local universities and research centre in basic and applied research related to space science and technologies; and (2 utilizing space technology to improve the quality of life of people by continuously improving the level of security, safety and protection of the environment and public health.

Other actions for the consideration of **government** actors include: (1 working to promote internal and external coordination of UAE position on international space-related issues; (2 developing space industry to be a source of national pride and happiness for the people; (3 helping companies operating in the domestic space sector — especially national companies; (4 addressing issues that affect the sustainability of space activities; (5 encouraging and supporting private sector to advance space exploration; and (6 exploiting political initiative for developing space mission for space mining and in-situ resource utilisation. Actions that would require collaborative efforts between the **government** and **Space Research Centres** (UAESA, MBRSC, NSSTC and others should focus on: (1 conducting outreach campaigns to raise awareness of space activities, developments and science, and promote international collaboration for instilling national pride; (2 coordinating the various national efforts and fostering effective collaboration and communication among all stakeholders (e.g. public, private, academic and educational sectors; and (3 extending citizen science initiatives to involve the public in research related to Mars (e.g. Galaxy zoo, BOINC.

Regarding the 'people' dimension, **UAESA** would be focusing on developing and encouraging, in collaboration with research centres and academia, the scientific and aerospace engineering professionals in the country, for example, through a MSc in Space Science. The UAESA is already coordinating with local universities to enhance the academic offering. A BSc in aerospace engineering is being offered at Khalifa University and since 2020 the same will be available at UAE University. A MSc in space science will be introduced in UAE University to bridge existing gap on availability of space scientists. The NSSTC is working with UAEU to introduce In-Situ Resource Utilization topics in the program. Every space project should engage students at all levels (undergraduate and postgraduate in capacity building activities. Annually there are over 10,000 students involved in awareness raising events.

Another critical action includes organising, with **government, academia** and **Space Research Centres** (UAESA, MBRSC, NSSTC), mandatory educational awareness workshops for other governmental bodies to educate the employees about Mars and Mars mission. Both MBRSC and UAESA will continue organizing education awareness workshops targeting the youth and professional bodies to get them engaged in strategic conversation on articulating the Mars vision into short- and long-term plans and encourage professional bodies to have their own plans contributing to the vision in a collaborative and coordinated manner. UAESA could also consider forming partnerships in the outer space domain that serve its goals, realize mutual benefits with its allies, and achieve global recognition for the UAE. Furthermore, **government** actors could think of including a ‘space discovery course’ in the curriculum (secondary level. **Space Research Centres** (SCASS and NSSTC should increase space situational awareness operations and capabilities. **Government** entities, together with **Space Research Centres** (UAESA, MBRSC and NSSTC and **business** actors should obtain and develop capabilities for space exploration and Earth observation, while scientific capabilities should also be developed, by Space Research Centres (MBRSC, NSSTC, SCASS and academia, by training national space professionals as part of the Emirates Mars Missions (EMM in collaboration with international universities.

In the short-term the **UAESA** is planning to implement the following actions supporting the ‘process’ dimension. The Agency would focus on developing, together with **Space Research Centres** and **business** actors, advanced autonomous robotic missions: robust and durable mechanics and self-mending techniques (e.g. 3D printing of broken parts and means to replace them. To do so, the UAESA is currently working with Khalifa University to attract students from Middle East countries to enrol into its master program with minor in space engineering. For two consecutive years, the university attracted students from Bahrain and engaged in agency’s CubeSat projects. The UAE University is planning to leverage on the ‘813’ satellite project (inspired by the Arab World's golden era, which is designed and build by NSSTC to attract students from Arabic countries to enrol into the MSc in Space Science and provide with an opportunity to engage in the real satellite project. The NSSTC is planning to organize program based on the 813, which includes workshops, seminars and conferences over the life cycle of the 813 Project attended by Arabic scientists and engineers. Simultaneously, the UAESA aims to elevate, in collaboration with other governmental bodies, the country’s status in order to become a centre of excellence for educating and developing professionals in the fields of astronomy, space science technology and engineering.

The ST&I roadmap identified and prioritized autonomous technologies as a topic in which the UAE needs to develop capabilities to support its future deep space missions. The UAESA is working with both Khalifa and UAE Universities in this field and it is expected that other stakeholders such as KU, Dubai Future Foundation R-Labs will be developing local research capabilities in autonomous technologies and additive manufacturing. It is essential that **government** agencies focus their efforts on improving the planning, access to and efficient use of radiofrequency spectrum and orbital slots; support transparency, openness, coordination and information sharing regarding space operations and activities; mitigating (in collaboration with SCASS space debris; while enforcing sustainability principles across countries in order to maintain resources and life on Earth 50-100 years from now. In turn, **business** actors should create and commercialise a ‘survive on Mars’ video game to benefit stakeholders and the communities (money + knowledge, while **business, research** and **civil society** actors could be creating simulators to mimic Mars experience that would encourage people to move to Mars.

In terms of ‘impact’ dimension, 20 short-term actions have been identified. Amongst these, the **UAESA** is strongly committed to connect national space sector to the development of other sectors, like national security, disaster and crisis management, healthcare, public health, telecommunications and broadcasting, and transportation and logistics. The UAESA is pushing an agenda with other industry sectors such as Oil and Gas on dual usage technologies and trying to benefit from existing know how in oil reservoir exploration, while assessing potential common interest to extend this work to Moon and Mars. As part of the United Nations Platform for Space-based Information for Disaster Management and Emergency Response UN-SPIDER, the UAE supports countries in disaster monitoring. The UAE enrolled into the SPIDER programme with MBRSC as an operator. In addition, the NSSTC is establishing an Earth and Planetary Science unit and working closely with environmental agencies and relevant government entities to develop land cover and use while trying to provide solutions that could be applicable to public health and crisis management.

The **UAESA** is also dedicated to develop, in collaboration with other **government** agencies, business and **research** actors, a globally coordinated and uniform space exploration capacity building program for education and research; to ensure adequate investment and financial support with appropriate facilities and infrastructure for space industry; and to enhance scientific studies and research in space technologies for the transfer of knowledge and technical skills, by establishing labs and collaborative projects. Other critical actions for national **government** entities include developing standards and regulations that enhance the security and stability of the space environment (including debris mitigation); ensuring active management of radiofrequency and satellite orbital resources and effective science, technology and innovation programs; aligning space industry development with important national interests that include safety, security and stability; recognizing the right of all nations to explore and use space for peaceful purposes and for the benefit of humanity; working on creating emergency plans to deal with environmental hazards (e.g. storms); improving safety and security of space activities and the space environment, including cyber and terrestrial infrastructure security; and creating an attractive regulatory environment to invite global companies and investments to the space sector, as well as entrepreneurship and innovation.

For competence building, **government** and **research** actors should develop education initiatives related to space science and astronomy; participate in collaborative projects (national, regional and global) related to space (e.g. exploring of outer space); develop advanced planetary protection strategies for protection of Earth as well as Mars; and ensure that national space program will enrich knowledge about the universe and to continuously improve the lives of citizens. In addition, **government** and **business actors** should together invest in innovative and lucrative commercial space projects that strive to position the UAE as a regional hub for space business and activities and promote space-related scientific programs and projects that enhance implementing space missions. **Business actors** are suggested to invest in establishing a robust, sustainable, diversified and innovative commercial space sector that contributes to the continued growth and diversification of the economy, and to facilitate doing business, such as buying assets from Mars to Earth (block chain that is secured by quantum computer). Finally, **government**, in collaboration with **Space Research Centres** and business actors, should participate in space missions of other nations with continuous and increasing government support. In addition, the Covid-19 pandemic shows the need for collaboration with national and international health authorities on healthcare technologies, life support systems and remote healthcare provision for astronauts and future space settlers.

Critical Actions for the Medium-term

Altogether 28 critical actions for the medium-term were identified as important for the attention of relevant actors. Addressing the ‘context’ dimension, the **UAESA** is committed to collaborate with other **government** bodies, in order to facilitate competition between all space agencies to fast-tract settlement on Mars by e.g. launching a shared challenge to conduct feasibility studies or engage in ex-ante impact assessment of Mars relevant initiatives, such as the Mohamed Space Settlement Challenge; and, with **business** actors, in order to improve commercial space travel and lower the price of getting to space (e.g. MOUs with airports to be operated as space ports for suborbital tourism and science), as well as to produce Mars movies and TV series related to Mars test facilities for enhancing the reality factor, including cartoons, documentaries, school plays, and programmes similar to The Astronauts in Dubai TV. The **government** should in turn explore possibilities of: establishing an orbital space station around Mars (for staying, training, remote observation, assembly of launching craft); exploiting long-term Mars governmental goals fostering the activities towards space settlements; and founding an internal body (similar to UN) that supervises the pathways and laws related to Mars missions and settlements. Furthermore, the **government** could team up with **business** actors to stock on Mars mineral resources, which can facilitate settlements and are locally unavailable, using asteroid mining.

While successful examples of interdepartmental collaboration and regulation initiatives are expected in the short-term, it is foreseen that by 2070 the **government** would have established coherent policy mix protocols in a variety of areas. Initial efforts to intertwine policy interventions in the UAE would require some kind of open method of coordination (OMD) between several UAE government departments. In the space sector, some OMC-like initiatives are deemed necessary between the Department of Economic Development (DED), the Department of Health (DoH) and the Department of Education and Knowledge (DEK). Some cross-departmental policy areas for OMC and strategic foresight projects on the Space Economy include big data, robotics, artificial intelligence, circular economy, internet of everything and the post-Covid-19 space economy. Future initiatives on Space Health require 'deep dive' foresight studies on artificial intelligence (AI) applications in healthcare, mental health, automated health monitoring systems and agile personalised medicine. In terms of Space Education and Knowledge needs, virtual and augmented reality, as well as remote and personalised space education in virtual learning environments (VLE) would require programmes, procedures and protocols with far less safety and ethical considerations than physical learning environments (PLE).

Two critical actions relying on the 'people' dimension were identified. Here, the **government** and **education** actors could play a role by setting up a space programme for school students to go into space for a short trip, in order to make spaceflight a common learning experience, while the **civil society** could act by engaging with religious and other community leaders to foster public discussion about the ethical and societal challenges of inhabiting other planets. **Government** actors could also improve the attitudes by providing clear career path for space-related fields based on deliverables, motivation and money. Primary school courses in space travel and Mars missions could be explored and introduced by **education** actors.

In terms of 'process' dimension, stakeholders identified 13 critical actions. Even though the actions were given a medium-term timeframe, however, some of them might require short-term implementation in the UAE. There are four actions to which the UAESA is strongly committed. These include: (1) identifying, in collaboration with the **government**, parallel strategic goals that can support Mars mission and enable advancing space habitats anywhere in space; (2) developing, in collaboration with **business** and **research** actors, food production, safe buildings, and reliable connectivity in space; (3) engaging, together with **business** actors, in space mining and mining of asteroids for human settlements in Mars; and (4) establishing, with the support of business and research actors, manufacturing location at Earth orbit for human settlements in Mars. Critical actions for the attention of business actors include: (1) developing robotic missions that can be more practical and economic than sending humans to space or other planets; (2) developing dedicated repairing robots aiming for self-sustained team of robots and drones; (3) advancing efficient space mining technologies and use of materials both in space and in the Earth; and (4) building deep space transportation as commodity (like airline) to develop deep space tourism business. **Business** actors could collaborate with **research** actors to develop in-situ resource (water) extraction and utilisation, as well as Mars ice mining, water harvesting and splitting with solar energy.

Five critical actions related to 'impact' dimension were identified, three of which are most important for the **UAESA**, and include: (1) designing, together with **business** actors, home structures that would sustain the storms on Mars (to be piloted in the Mars Science City); (2) creating, together with other **government** agencies, governance policies for future Mars inhabitants; and (3) developing, in collaboration with **government, research** and **business** actors, advanced techniques to manage space waste and debris in a most sustainable manner. **Government** actors could lead the establishment of 'natural parks' on Mars to preserve regions of particular importance (e.g. places where there may be liquid water). **Government** and **research** actors should work together on raising the level of robotic and autonomous environmental monitoring of Mars to similar level that exists now on Earth (networks of ground-based weather stations and seismic stations, constellations of orbital satellites for atmosphere and surface remote sensing).

Critical Actions for the Long-term

The survey and workshop results revealed 17 critical actions to be considered by leading actors in the long-term.

Considering the 'context' dimension, two critical actions are most important for the attention of **UAESA**, in collaboration with **government and business** actors. These include establishing a well-defined system to select, train and prepare large population of future settlers on Mars, and founding inter-planetary stations infrastructure that will help in facilitating transport for deep space mission. Critical actions for **business** and **research** actors include developing communication infrastructure for Mars and from Mars to Earth, while **business** actors are to focus on developing Space Tourism consumer services (e.g. wedding parties on the Moon; 50th anniversary on Mars.

With regards to 'people' dimension it was considered important for the **government**, within the Mars mission, to send frozen embryos to Mars and develop artificial incubators. **Education** actors could explore the possibilities of organising 'space camps' for children during summer holidays, if space journey's duration was to reduce considerably.

Seven critical actions were mapped against the 'process' dimension. Developing a chain of space stations (providing possibilities of refuelling, repairing, restocking or U-turning between Earth and Mars was believed to be a long-term priority for the UAESA, in collaboration with **research, business**, and **government** actors. Critical actions concerning **government's** contribution include establishing higher education in Mars, and setting up a security team for Moon and Mars Missions, given that any issue could be a threat to human lives. **Research** should focus on developing a human-transportation system with minimum space requirement and resources e.g. hyper sleep. Furthermore, **research** actors, in collaboration with **government**, should be developing an electromagnetic railgun technology for launching material into earth orbit, thus dramatically reducing the cost of sending the vast amount of materials to Mars, while **research** and **civil society** actors continuously investigate scenarios of the sun becoming a real giant, making Earth non-inhabitable. **Intergovernmental** organisations might evaluate the use of Artificial Intelligence in potential military conflict resolutions on Mars.

Within the 'impact' dimension, **UAESA** together with relevant **government** agencies, **business, research** and **civil society** actors, should aim at identifying the top 5 socio-economic sectors that are to provide multi-systemic sustainability to Mars related activities. **Government** actors are to develop a code of conduct for the habitants, in order to define the roles/duties and relationships style between people living on Mars. In collaboration with the United Nations, **government agencies** should invest in Mars summit that generates knowledge of, and promotes, Mars economy ("Department of Mars"). Meanwhile, **research** actors should explore ways of improving in-situ resource recycling, such as new in-space materials and energy, as well as their utilisation.

On Sustainable Development Goals

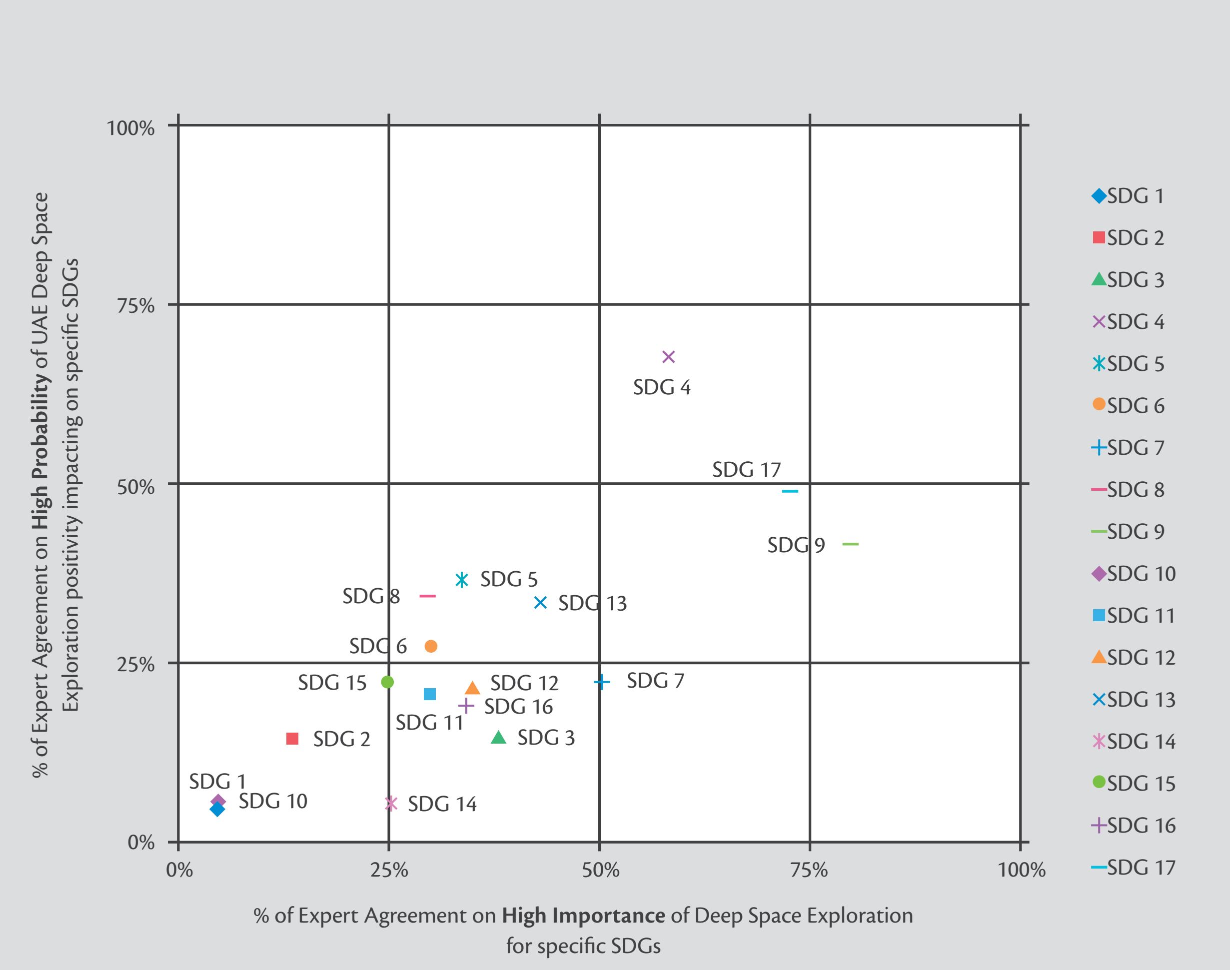
In addition to developing strategic actions for the roadmap to reach Moon and Mars, space experts were asked their opinion about suitability of Sustainable Development Goals to space industry. The experts also evaluated the importance and probability of deep space exploration contributing to specific SDGs.

The UAE and international respondents agreed that Quality Education (SDG 4, Industry, Innovation and Infrastructure (SDG 9 and Partnerships for the Goals (SDG 17) are amongst the most important SDGs in the space context. The only difference was that the UAE experts believe that the deep space exploration has very positive impact on the following three SDGs (Figure 14), while the experts from the RoW were more conservative in their impact assessment (Figure 15):

Figure 14. UAE views about Deep Space Missions and the UN SDGs

- **SDG 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all**
- **SDG9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation**
- **SDG 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development**

Figure 15. RoW views about Deep Space Missions and the UN SDGs



Interestingly, one of the strongly agreed issues was that Deep Space missions to the Moon and Mars should be better integrated into the Sustainable Development Goals (67 % of respondents) as the current SDGs do not sufficiently integrate outer space but concentrate on Planet Earth only. Experts agree that 3 current SDG's (SDG 17 - Partnerships for the Goals, SDG 4 - Quality Education, and SDG 9 - Industry, Innovation and Infrastructure) can all be reinforced with space exploration and thus it may be useful to have a new SDG which encompasses that value and helps shed light on the benefits of space exploration in this regard. Therefore, it was suggested that United Nations should introduce a new sustainable development goal specifically focused on space-relevant issues, potentially called '**SDG 18 on Responsible exploration and use of space**.' An idea which may be worth exploring is if the UAE leads an effort within the UN to have an 18th Sustainable Development Goal (SDG 18).

Opportunity Pathways (OPs) for the UAE

Based on the workshop results, 6 technology areas were selected and 7 opportunity pathways (Figure 16) proposed for the UAE. Most of these opportunities relate to Human Health, Life Support & Habitation Systems which is important but less emphasised technology area in the Delphi survey by UAE experts, while in international experts' views human-related technologies were seen more critical for Moon and Mars missions. Each of the opportunity pathways was designed for attaining Mars, listing key drivers and main deliverables.

The OPs could be integrated within the implementation plan of the Space Science, Technology and Innovation (ST&I)Roadmap for the UAE and further scope the proposal in partnerships with relevant space research centres and businesses.

Figure 16. Opportunity Pathways for UAE

OPI 1	Mixed reality system for training and operation
OPI 2	Earth/Mars-like virtual experience
OPI 3	Smart Mars sensing
OPI 4	Construction of airtight underground structures
OPI 5	Plant cellular agriculture for food production in space
OPI 6	Gut microbiome management
OPI 7	Self-growing biosensing material

OP1: Mixed reality system for training and operation

ISS expedition/mission duration is normally about six months and training for the mission takes about two years. For the Mars mission this means about 4-5 years, which is not feasible. With mixed reality (MR) the crew could do training during flight to Mars and get support to critical operation in space craft or on Mars. These methods reduce possibilities of human errors especially in critical tasks. Training and operation support are not only limited to the journey, but the same tools and methods could be used before mission training and on Mars soil. Augmented reality (AR) also allows better remote support for crew in short transmission delay area e.g. supporting centre could give near real-time support to crews by adding relevant information to 3D space via AR. Also, robots' and rovers' remote operations could be more effective with MR. Operator could jump into operational environment and get the feeling of being there. This will make remote operation more effective and reduce errors.

Box 1. Mixed reality system for training and operation

Mixed reality system for training and operation: Robots, rovers and manual support work

Key Technology Areas

- Robotics, Tele-Robotics and Autonomous Systems
- Software and Applications
- Modelling, Simulation, Information Technology and Processing

Key Drivers

- Operator / User could jump in to remote operated environment by using MR system. Environment can be built real-time with 360° video feed and other censoring.
- More effective knowledge transfer and/or critical manual work execution during the mission.
- Less errors in critical tasks.
- External human reach as humans will use AR to control robotics in an environment that is not for human.
- Effective training: on Earth, during "flying", and on Mars.
- Protecting HR and human expertise by isolating from operational environment.

Expected Outcomes

- MR visualization module
- Teleoperation module
- Diagnostics module

OP2: Earth/Mars-like virtual experience

Missions to Mars are mentally and psychologically demanding for astronauts and settlers. Earth-like virtual experiences would allow them to recover from demanding work and stress, and it would support astronauts/settlers' relaxation. In the future the system could be a Holodeck-like environment that allows also telepresence. With telepresence astronauts/settlers could meet their families and friends in a virtual environment and have a social gathering or celebration together. The system could be also used on Earth. Settling candidates could feel conditions of future Mars mission, which will help them in decision making and lower the mental burden of settlers. Also, Mars-like virtual experiences would support the candidate's selection process from the space programme side. Mars-like virtual experience systems could also be used for designing the settling process and missions on Mars surface as mission specialists would have better understanding of the conditions on Mars.

Box 2. Earth/Mars-like virtual experience

Earth/Mars-like virtual experience (relaxing, re-covery, exploration)

Key Technology Areas

- Human Health, Life Support & Habitation Systems.
- Software and Applications.

Key Drivers

- Making possible for people on Earth to visit people on Mars as if they were there in person (and vice versa).
- Improving mental health of astronauts and other settlers.
- Helping decision making for candidates.
- Planning for future surface activities.
- Scarcity of Earth resources.
- Minimising unforeseen circumstances and reducing risks of Mars missions.
- Training, exploration and amusement.
- Lower mental burden in settling on Mars.
- Building a Holodeck-like environment to relax and recover.

Expected Outcomes

- Virtual environment with visual and sound.
- Authoring system to create environments.

OP3: Smart Mars sensing

Assessing environmental conditions on Mars is vital for the survival of future Mars settlements. Smart sensing technologies - with applications in human health, life support and habitation systems, modelling, simulation, information technology and processing - can contribute to safer living conditions and the overall success of Mars missions. Cooperation between governments and private sector stakeholders is required in order to increase awareness of relevant opportunities and to boost capacity and technological advances in space sensing, which would be enabled by testing facilities on Earth and a network of seismic sensors. An important target is to develop effective dust sensors for mission-critical environments, with possible application to solar panels, ventilation, external doors/airlocks, etc. (also linked to OP4 below). Furthermore, networks of surface weather stations will allow testing smart sensing in Mars' analogue environment on Earth and lead to new developments in monitoring networks for air quality and radiation, while advanced computing capabilities can support the progress of sensors for monitoring conditions related to energy production in UV, thus achieving better energy efficiency. In order to ensure smoother application of smart sensing, especially as underground sensors and personal/implanted sensors (e.g. to deal with health issues in Martian environment) are offered, plans for upgraded big data processing technology and infrastructure should be made and implemented. This, in turn, would lead to increased life expectancy, as well as better possibilities for local production on Mars, since environmental conditions become more observable and manageable.

Box 3. Smart Mars sensing

Smart Mars sensing for assessing environmental conditions

Key Technology Areas

- Human Health, Life Support & Habitation Systems.
- Modelling, Simulation, Information Technology and Processing.

Key Drivers

- Maintaing health of first settlers.
- Enabling future settlements on Mars.
- Building comparative knowledge of environmental similarity/dissimilarity between Earth and Mars.
- Developing future space mining and in-situ resource utilisation.
- Increasing planetary protection, e.g. reduce pressure on natural resources (water).
- Improving healthy and productive living on Mars, e.g. Smart cities.

Expected Outcomes

- Capacity building and technological advances in space sensing.
- Testing smart sensing in Mars with an analogous environment on Earth.
- Develop sensors for conditions for energy production (solar panel optimisation) in UV.
- Improve big data processing technology and infrastructure.

OP4: Construction of airtight underground structures

Due to the hostile conditions on the surface of Mars, life of humans could take place in underground spaces, sheltered from sandstorms and the high radiation in Mars atmosphere. For best quality of life underground, an artificial space containing compressed air could be created, to allow the freedom of movement for people without wearing a space suit similar to terrestrial atmosphere. Such underground spaces could be mined caverns, drifts and tunnels. The surfaces of these tunnels need to meet high requirements on leak tightness, so that the pressurized air can be kept in the tunnels. This requires engineered barriers to seal the underground space against leaks, blow outs, and even geotechnical events. VTT has long experience in design, manufacturing and monitoring of engineered barriers. This experience was gained in the design and construction of geological repositories for the storage of nuclear waste in Finland. As a first step, the geological conditions on Mars need to be studied in order to select the right sites and locations for such underground facilities. The next step focuses on the tailored development of the barriers.

For sealing of the underground spaces, large amounts of materials are needed. Such materials could be cementitious composites, or geopolymers, building the basis for injection grouts, shotcretes or normally casted concretes. The manufacturing of these materials requires an environment next to water, mineral raw materials that should be mined on Mars from near surface quarries or explorations. The development and manufacturing of such materials under Mars conditions are in the focus of another major step in this project.

Finally, the technical feasibility could be demonstrated in a mock-up environment with a comparable terrestrial geology. Such a demonstrator requires next to the technical solutions, a safety case and an extensive risk analysis. The performance of the demonstrator could be monitored by means of sensors, non-destructive technology and related data acquisition systems.

Box 4. Construction of airtight underground structures

Construction of airtight underground structures for realistic testing of Mars environment

Key Technology Areas

- Human Health, Life Support & Habita-tion Systems.

Key Drivers

- Novel testing and training facilities.
- Multidisciplinary approach, including sociological and psychological studies.

Expected Outcomes

- Assessment of Mars near surface geology and permeability of the host rock.
- Development barrier materials and designs.
- Demonstrator built in a comparable terrestrial geology.

OP5: Plant cellular agriculture for food production in space

Cellular agriculture is a relatively new term for the utilization of cell cultures of the whole variety of host organisms for the production of agricultural commodities rather than production by farmed animals or crops. As such, the fully contained approach bears the potential to provide humanity with nutritious, safe and healthy food while minimizing resource inputs such as energy, land and water. The latter is especially important for space operations, while seasonal and geographical independence is also important on Earth. Products can be either acellular e.g. proteins, chemicals, pharmaceuticals and materials, or cellular e.g. food, cosmetics and materials. Cellular products have a clear cost advantage because of less downstream processing and less waste creation. Cellular products from plant cell cultures have shown particularly outstanding nutritional profiles (high protein, beneficial lipids, dietary fibres, health-promoting compounds etc.) and could be suitable as main food source according to nutritional recommendations regarding the increase of dietary intake of plant-based food. In the context of astronaut food, it will be important to investigate gut microbiome based on plant cell culture-derived food (link to OP 6). Besides food, plant cell cultures can be used for the production of pharmaceuticals and it will be worthwhile to test a broad variety of species for certain applications. Another big advantage of plant cell cultures is the simplicity of the required growth medium, which is chemically fully defined and consists of inorganic ingredients i.e. salts, sugar as carbon source and some low concentration vitamins and phytohormones dissolved in water. In order to achieve the expected outcomes, it is suggested to perform a whole cycle of plant cell biomass generation and prepare plant cell culture-based food demos from a variety of cell lines. The whole process will be critically examined to pinpoint critical parameters from the perspective of utilization in space missions. Additionally, the generated demo food will be analysed to certify its nutritional suitability as astronaut food.

Box 5. Plant cellular agriculture for food production in space

Plant cellular agriculture for food production in space

Key Technology Areas

- Human Health, Life Support & Habita-tion Systems

Key Drivers

- Efficient and modular plant-based food production for physical and mental health of astronauts.
- Solving Earth problems: population, agriculture, energy; More space for agriculture productions, less land consumption on Earth; Improving water productivity efficiency.
- Planting on Mars for O_2 production.
- Increasing research about biodiversity, plants and micro-organisms.
- Agriculture production for pharmaceutical research on Mars.
- Study of the mitigation of greenhouse gases.
- Study of insect die off on Mars.
- Applying different agriculture techniques on Mars.

Expected Outcomes

- Report detailing composition of diverse plant cell cultures and defining benefits and deficits as space food; plant cell demo material.
- Report revealing critical parameters and their optimisation.
- Report summarising process options; plant cell-based demo food.

OP6: Gut microbiome and virtual biosphere management

There is strong evidence on the connection of gut microbiome and overall human health, including stress and mental status. In a situation when the diet of the travellers is limited and most probably poor in dietary fibres, misbalance of the gut microbiota may have devastating effect on the health of humans. Some large research and technology organisations (RTOs), such as VTT in Finland, have well-established dietary digestion models which can be used in examination of digestibility of the developed new food ingredients (e.g. plant cells). With metagenomic and metabolomics approaches VTT can examine the effects of different dietary additives to improve stability of microbiome. Consequently, new potential foods and ingredients can be developed. In addition, the influence of recycled water on stability and functionality of gut microbiome needs to be examined. Clinical trials need to be done in co-operation with clinical partners.

A long-term habitation of planets or other interstellar objects will create new evolution in the local biosphere. Micro-organisms, bacteria, viruses, everything that humans contain and bring to extraterrestrial circumstances will continue their evolution and eventually diverse from the evolution occurring on planet Earth. Meanwhile, the Earth's biosphere with its diversities will evolve in its own way. This evolution will introduce severe challenges in interplanetary travel. First, as human beings are biospheres of their own, they may contaminate Earth with their micro-organisms of 'extraterrestrial' origin. Second, return to Earth may be impossible due to lack of resistance to micro-organism evolution on Earth. A virtual biosphere is a computational simulation of micro-organisms and their evolution based on real digital twin style of data replication. All the data gathered from Earth micro-organisms can be simulated in real-time and risk for disease calculated based on genome evaluation. Virtual biosphere would replicate both Earth and planetary evolution of micro-organisms. A process to build up resistance for viruses could be created so that simulation and data-driven vaccination development could happen to keep the real biospheres in synchronization.

Box 6. Gut microbiome and virtual biosphere management

Gut microbiome and virtual biosphere management

Key Technology Areas

- Human Health, Life Support & Habita-tion Systems.

Key Drivers

- For survival and good life, gut microbiome plays an important role. One-sided diet (on Mars) causes extreme demands on gut microbes. Hence, management of gut microbiome is crucial.
- Healthy life.
- Sustainability: reduce medication.
- Genome data comparison.

Expected Outcomes

- Technology for monitoring and development of balanced gut microbiome.
- Demonstration of response of gut microbiome to stress factors.
- Demonstration of functionality of various gut microbiomes.
- Response to viruses via supercomputer and AI algorithms.

OP7: Self-growing biosensing material

Biological materials in nature outperform synthetic materials in many ways. Materials produced by biology have remarkably sophisticated functions and are for example able to self-repair and regenerate. The production of these smart materials is guided merely by genetic information and driven by dissipation of chemical or light energy. This biological growth process can be harnessed for the production of biosynthetic living materials, i.e. biofabricated materials. In contrast to conventional manufacturing, where synthetic or biobased components are processed into materials, biofabricated materials grow and regenerate nutrients into materials in a bottom-up process. Production of these materials is typically simple and low cost as the material produces itself and little processing is required. If needed, the materials may be structured using additive manufacturing. Moreover, often the materials can be often produced using organic waste as nutrients. The materials are biobased, biodegradable, and applicable to closed-loop production. Taken together, these features make self-growing biofabricated materials interesting for agile, on-demand and distributed production in resource scarce or self-sustained closed environments such as space operations. Researchers have already learned to control microbial growth to produce, for example, concrete, packaging foams and fabrics. To demonstrate the possibilities of biofabrication, VTT have used microbial growth to produce materials for headphones.

Importantly, material biofabrication enables the engineering of completely new functions into materials. Here the incorporation of new biosensing functions and mimicking active sensing of natural organism should be explored. These new sensing materials could be produced on site and on demand using simple resources. The first target is to construct a living biosensing material prototype. The paths to engineer relevant air or water quality sensing self-growing materials need to be identified. Notably, the synthetic biology tools for engineering biosensing materials are already existing. The most interesting biosensing targets will be factors that are important for the well-being of humans in space, such as air-impurities, air-borne pathogens, or chemical water contaminants. In the long term, the interfacing of the living materials with electronic systems as well as CO2 and/or O2 neutral material production will be important.

Box 7. Self-growing biosensing materials

Self-growing biosensing materials

Key Technology Areas

- Human Health, Life Support & Habitation Systems.

Key Drivers

- To consider the health of the astronaut.
- Self-sustained closed environments need agile production of smart materials.
- Developing such materials using platform of bioengineered living materials.

Expected Outcomes

- Technology for production of living biosensing materials
- Demonstration of sensing impurities using living biosensing materials, and biosensor characterization
- Demonstration of growing biosensing materials in self-sustained environment

Strategic Goals and recommendations

We would like to conclude by looking at how the identified critical issues relate to the six main pillars of the UAE's National Space Strategy 2030. With regards to the first pillar - *'Provision of competitive and leading space services'* - the most important opportunity is notably in mega-constellations of satellites increasing the number of satellites in Low Earth Orbit (LEO) by a factor of 10 by 2025 (also critical to pillars two and three). The most significant drivers strengthening the first pillar include: Space science continues to be performed mainly by robotic spacecraft; Developing services to Earth establishes most stable research base for advancing space technologies; and Making observations from space will improve significantly our capabilities to understand and model the causes, processes, and effects of global climate change.

The second pillar focuses on the *'development of advanced local capacities in Space technology manufacturing and R&D'*. Besides the above-mentioned opportunity, prospects are expected to emerge as space food production systems will develop necessary methods, also for the growing Earth population, using minimal inputs. The main driver supporting this pillar refers to the development of an affordable and safe space solar power, which will become a major new space industry benefiting Earth. However, there are also critical issues to be wary of. Given that space activities develop in a multi-professional and interdisciplinary manner, it is crucial for space sector to support the development of long-term space missions. Another challenge to be considered is the need to make giant advances in human-robot interaction (HRI, which will enable long-term space exploration, such as travelling to Mars.

The third pillar, concerned with *'Launching Inspiring Space Scientific and Exploration Missions',* could be driven by the fact that the timeframe for having human settlements on Mars is feasible. Opportunities are seen in the International Space Station (ISS) remaining the primary space laboratory until 2030, as well as in the growing number of satellites in LEO. Relevant challenges, apart from those linked to the second pillar, include also the uncertainty about psychological impact of long-term space missions, and Moon developments taking lead in developing space technologies.

The most important drivers to take into account regarding pillar four on *'Creating space culture and expertise'* include, in addition to technical expertise, great teamwork abilities and leadership skills, as the mental aspect of "emotional intelligence" will be among the key skills-sets for future astronauts. Sustainable development agenda in space, placing people and the planet Earth at the center, can further strengthen this pillar. Identified opportunities in this area are plentiful, with the following being most projecting: In the future, the space will be working as an increasingly attractive platform for education in all level of an education system; Increased multidisciplinarity of the space sector and being open to non-technical or scientific contributions as valid insight resources, e.g. art, philosophy, sociology of space, psychology, creativity research; and Comparative studies on the evolution of Venus, Mars, and Earth will take significant leaps by 2030 providing important insights about Earth's future. Several challenges have also been recognised. Here attention should be paid to the intensifying competition between governments, ideologies and commercial profit; improving human capacity to work under challenging and emerging circumstances; taking the space sustainability debate beyond LEO; and designing a new sustainability agenda for the purpose of space exploration and usage, since the Sustainable Development Goals (SDGs) cannot be applied.

With regards to the fifth pillar of *'Effective Local and International Partnerships and Investments in the Space Industry'* three drivers reinforcing the agenda have been identified and include: space agriculture greatly impacting agriculture in space and on Earth; private sector taking the lead in running space development through more efficient use of resources; and affordable and safe space solar power developing as a major new space industry, with benefits to Earth. Major opportunity is represented by private sector investments to space development increasing more than 15% annually. Space industry is expected to reach $800bn by 2030. Other relevant opportunities relate to the development of novel food production systems, and increased multidisciplinarity of the space sector. Expected challenges associated with this agenda include, similarly as in pillar four above, growing competition between governments and planning the sustainable development beyond LEO, but also issues related to not reaching an international consensus on the concern of debris management, as well as funding issues remaining the largest limiting factor for sending humans to Mars.

The fi al sixth pillar aims at *'Ensuring a supporting legislative framework and infrastructure to match the future developments in the sector'*. Important drivers to take into consideration include discussions on legislation and regulation regarding exploration, settlement and exploitation of space since the Outer Space Treaty stating space is "the common heritage of mankind" will continue to remain a core principle forbidding claims of sovereignty. Negotiations of sustainable development in space should place people and planet Earth at the centre. The challenges to this agenda include taking the sustainability debate beyond the LEO; designing a new sustainable agenda; reaching international consensus on debris management as the issue of "over 500,000 individual pieces of debris hurtling at velocities of over 27,000km an hour" will only worsen; and policy and legal challenges are anticipated whilst space develops as an arena for multiple government and private activities.

Table 7. Critical actions relevant to the National Space Strategy 2030.

National Space Strategy	Short-term actions	Medium-term actions	Long-term actions
Provision of Competitive and Leading Space Services	29%	36%	36%
Development of advanced local capacities in Space technology manufacturing and R&D	40%	47%	13%
Launching Inspiring Space Scientific and Exploration Missions	31%	58%	12%
Creating Space Culture and Expertise	51%	29%	20%
and Investments in the Space Industry	63%	31%	6%
Ensure a supporting legislative framework and infrastructure to match the future developments in the sector	40%	20%	40%
Total	**46%**	**35%**	**19%**

Annex 1: Critical Actions by timeframe

Table 8. Short-term actions

47 Critical Actions for the short-term

Context dimension	Leading Actor(s)
Establish a Fully-fledged Mars Policy Roadmap (Long-term Policy) to create future-proof cross-sectoral policies and promote foresight-driven research, technology development and innovation initiatives for space missions.	Government (UAE SA)
Conduct outreach campaigns to raise awareness of space activities, developments and science, and promote international collaboration for instilling national pride.	Government & Space Research Centres (UAESA, MBRSC, NSSTC and others)
Coordinate the various national efforts and foster effective collaboration and communication among all stakeholders (e.g. public, private, academic and educational sectors).	Government & Space Research Centres (UAESA, MBRSC, NSSTC and others)
Work to promote internal and external coordination of UAE's position on international space-related issues.	Government (UAE SA)
Engage different stakeholders to establish programs to encourage and conduct basic and applied research in the field of space science and technology for scientific and commercial purposes.	Government & Space Research Centres (UAESA, MBRSC, and NSSTC) and Academia
Develop space industry to be a source of national pride and happiness for the people.	Government (UAE SA)
Help companies operating in the domestic space sector — especially national companies.	Government (UAE SA)
Address issues that affect the sustainability of space activities.	Government (UAE SA)
Utilize space technology to improve the quality of life of people by continuously improving the level of security, safety and protection of the environment and public health.	Government & Space Research Centres (UAESA, MBRSC, NSSTC and others) and Business
Encourage and support private sector for advancing space exploration.	Government (UAE SA)
Exploit political initiative for developing space mission for space mining and in-situ resource utilisation.	Government (UAE SA)
Extend citizen science initiatives to involve the public in research related to Mars (e.g. Galaxy zoo, BOINC).	Government & Space Research Centres (UAESA, MBRSC, and NSSTC) and Academia

People dimension	Leading Actor(s)
Train national space professionals as part of the Emirates Mars Missions (EMM) in collaboration with international universities to develop scientific capabilities.	Space Research Centres (MBRSC, NSSTC, SCASS and Academia)
Develop and encourage scientific and aerospace engineering professionals in the country, for example, through a MSC in Space Science.	Research Centres and Academia
Increase space situational awareness operations and capabilities.	Space Research Centres (SCASS and NSSTC)
Obtain and develop capabilities for space exploration and Earth observation.	Government & Space Research Centres (UAESA, MBRSC, and NSSTC) and Business
Form partnerships in the outer space domain that serve its goals, realize mutual benefits with its allies, and achieve global recognition for the UAE.	Government (UAE SA)
Organise mandatory educational awareness workshops at the governmental bodies to educate the employees about Mars and Mars missions.	Government & Space Research Centres (UAESA, MBRSC, NSSTC and Academia)
Include a 'space discovery course' in the curriculum (secondary level).	Academia

Process dimension	Leading Actor(s)
Improve the planning, access to and efficient use of radiofrequency spectrum and orbital slots.	Government (UAE SA and TRA)
Support transparency, openness, coordination and information sharing regarding space operations and activities.	Government (UAE SA)
Elevate the country's status in order to become a centre of excellence for educating and developing professionals in the fields of astronomy, space science technology and engineering.	Government (UAESA)
Mitigate space debris.	Government (UAESA) and SCASS
Support initiatives in peaceful use of space (e.g. developing space capabilities, especially in disaster management and relief; telecommunications, navigation, land observation).	Government (UAESA)
Develop advanced autonomous robotic missions: robust and durable mechanics, and self-mending techniques (e.g. 3D printing of broken parts and means to replace them).	Space Research Centers and Business
Enforce sustainability principles across countries in order to maintain resources and life on Earth 100-500 years from now.	Government (UAE SA)
Create and commercialise a 'survive on Mars' video game to benefit stakeholders and the communities (money + knowledge).	Business
Create simulators to mimic Mars experience for public to encourage people in moving to Mars.	Business, Research, Civil society

Impact dimension	Leading Actor(s)
Participate in space missions of other nations with continuous and increasing government support.	Government (UAESA), Space Research Centres and Business
Develop education initiatives related to space science and astronomy.	Government (UAESA), Space Research Centres
Ensure that national space program will enrich knowledge about the Universe and to continuously improve the lives of citizens.	Government (UAESA), Space Research Centres
Develop standards and regulations that enhance the security and stability of the space environment, including debris mitigation.	Government (UAESA)
Ensure active management of radiofrequency and satellite orbital resources and effective science, technology and innovation programs.	Government (UAESA)
Align space industry development with important national interests that include safety, security and stability.	Government (UAESA)
Recognize the right of all nations to explore and use space for peaceful purposes and for the benefit of humanity.	Government (UAE SA)
Enhance scientific studies and research in space technologies to transfer knowledge and technical skills, by establishing labs and collaborative projects.	Research (with help of Government, Business and Civil society)
Improve safety and security of space activities and the space environment, including cyber and terrestrial infrastructure security.	Government (UAESA)
Participate in collaborative projects (national, regional and global) related to space (e.g. exploring of outer space).	Government (UAESA) and Space Research Centres
Connect national space sector to the development of other sectors, like national security; disaster and crisis management; healthcare, public health; telecommunications and broadcasting; transportation and logistics.	Government & Research Government, Business, Research
Create an attractive regulatory environment to invite global companies and investments to the space sector, as well as entrepreneurship and innovation.	Government
Promote space-related scientific programs and projects that enhance sending space missions.	Government & Business
Invest in innovative and lucrative commercial space projects that strive to position your country as a regional hub for space business and activities.	Business & Government

Impact dimension	Leading Actor(s)
Ensure adequate investment and financial support with appropriate facilities and infrastructure for space industry.	Government (with Business & Research)
Establish a robust, sustainable, diversified and innovative commercial space sector that contributes to the continued growth and diversification of the economy.	Business
Facilitate doing business, buying and assets from Mars to Earth - block chain secured by quantum computer.	Business
Develop advanced planetary protection strategies for protection of Earth as well as Mars.	Government, Research
Work on creating emergency plans to deal with environmental hazards (e.g. storms).	Government

Table 9. Medium-term actions

28 Critical Actions for the medium-term

Context dimension	Leading Actor(s)
Establish an internal body (similar to UN) that supervises Mars missions and settlements, goals, pathways and laws.	Government
Generate competition between all space agencies to settle on Mars, e.g. Shared challenge to conduct feasibility studies or engage in ex-ante impact assessment of Mars relevant initiatives, such as the Mohamed Space Settlement Challenge.	Government (UAESA)
Enhance space travel business to lower price of getting to space, such as MOUs with airports to be operated as space ports for suborbital tourism and science.	Business
Establish an orbital space station around Mars (for staying, training, remote observation, assembly of launching craft).	Government
Stock mineral resources on Mars which are locally unavailable using asteroid mining to facilitate settlements.	Government, Business
Produce Mars movies and TV series, related Mars test facilities for enhancing the reality factor, such as cartoons and documentaries and school plays and programmes similar to The astronauts in Dubai TV.	Business
Exploit Mars governmental goal fostering the activities towards space settlements.	Government

People dimension	Leading Actor(s)
Set up a space programme for school students to go into space for a short trip (days) to make spaceflight an ordinary thing.	Government, Education
Engage with religious and other community leaders to foster public discussion about the ethical and societal challenges of inhabiting other planets.	Civil society
Explore and introduce courses in primary schools of space travel and Mars missions.	Education
Improve attitude by providing clear career path for space-related fi lds based on deliverables, motivation and money.	Government

Process dimension	Leading Actor(s)
Apply open book scientific approach to prevent Mars missions aborted or frozen for several years or decades.	Government & Research
Identify parallel strategic goals that can support Mars mission and enable advancing space habitats anywhere in space.	Business, Research & Government
Develop robotic missions that can be more practical and economic than sending humans to space or other planets.	Research, Business, Government
Develop food production, safe buildings, and reliable connectivity in space.	Business & Research
Develop dedicated repairing robots aiming for self-sustained team of robots and drones.	Business & Research
Advance efficient space mining technologies and use of materials both in space and on Earth.	Government & Business
Engage in space mining and mining of asteroids for human settlements on Mars.	Government & Business
Establish manufacturing location at Earth orbit for human settlements on Mars.	Business, Research & Government
Develop Mars ice mining, water harvesting and splitting with solar energy.	Research & Business
Develop in-situ resource (water) extraction and utilisation.	Research & Business
Build deep space transportation as commodity (like airline) to develop deep space tourism business.	Business

Impact dimension	Leading Actor(s)
Design home structures that sustain the storms on Mars to be piloted in the Mars Science City.	Business
Raise the level of robotic, autonomous environmental monitoring of Mars to similar level that exists now on Earth (networks of ground-based weather stations and seismic stations, constellations of orbital satellites for atmosphere and surface remote sensing.	Research, Government
Create governance policies for future Mars inhabitants.	Government
Establish 'natural parks' on Mars to preserve regions of particular importance (e.g. places where there may be liquid water).	Government
Develop advanced techniques to manage space waste and debris in a sustainable manner.	Government, Research, Business

Table 10. Long-term actions

17 Critical Actions for the Long-term

Context dimension	Leading Actor(s)
Establish a well-defined system to select, train and prepare large population of future settlers on Mars.	Government
Develop Space tourism consumer services (e.g. a wedding party on the Moon; 50th anniversary on Mars).	Business
Establish inter-planetary stations infrastructure that will help in facilitating transport for deep space mission.	Government, Business
Develop communication infrastructure for Mars and from Mars to Earth.	Business, Research
People dimension	**Leading Actor(s)**
Send frozen embryos to Mars and develop artificial incubators.	Mars Government
Organise 'space camps' during holidays for children.	Education
Process dimension	**Leading Actor(s)**
Develop a human-transportation system with minimum space requirement and resources, e.g. hyper sleep.	Research
Launch a super AI-army that stops a war happening in Mars between two countries.	Intergovernmental bodies
Set up a security team for Moon and Mars Missions to reduce potential threats to human life.	Government

Process dimension	Leading Actor(s)
Develop an electromagnetic railgun technology for launching material into earth orbit; dramatically reducing the cost of sending the vast amount of materials to Mars.	Research, Government
Investigate scenarios of the sun becoming a real giant and making Earth non-inhabitable.	Research, Civil society
Develop a chain of space stations between Earth and Mars, refuel, repair, supply chain, U-turn.	Research, Business, Government
Establish higher education in Mars (university, etc.).	Government
Recognise what kind of businesses would be suitable for Mars settlers (jobs on Mars), by identifying the top 5 socioeconomic sectors that would be providing multi systemic sustainability to Mars related activities.	Government, Business, Research, Civil society
Develop a code of conduct for Mars habitants, which will define the roles/duties and relationships style between settlers.	Government
Invest in Mars summit that generates knowledge of, and promotes, Mars economy, i.e. "Department of Mars".	Government, United Nations
Improve in-situ resource recycling, e.g. new in-space materials and energy, and their utilisation.	Research

Annex 2: List of authors

Authors from VTT team

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Nina Rilla (PhD) is a Senior Scientist in Ethics and Responsibility of innovations at VTT Ltd. She has received a Doctoral degree in international business. She has over twelve years of experience in the field of science, technology and innovation studies, and she has participated in various national and international projects of innovation policy, for example dealing with social enterprises, skilled talent and regional innovation ecosystems. Her expertise areas are (eco) systemic innovation, R&D&I collaboration, socio-technical change, responsible innovation and impact assessment. Her interest in foresight studies, technological development and innovation has involved her in international roadmap and foresight studies.

Jouko Myllyoja (M. Sc. Marketing, M. Sc. Environmental engineering, BA) works as a senior scientist in the research area of business, innovation and foresight. He shares particular interest towards methodological development of foresight. His tasks has covered designing and managing foresight projects, including roadmaps and scenarios in various substance areas. His thematic fields of interests concern e.g. innovation ecosystems, sustainable development and future of work. His managerial assignments cover projects such as Cybersecurity Awareness and Knowledge Systemic High-level Application (Horizon 2020) and ICT for Health in South Africa (Ministry for Foreign Affairs of Finland).

Kaj Helin is a Principal scientist in virtual engineering area. He is a Certified Project Manager IPMA level C. Helin manages the mixed reality facilities in VTT Tampere. Helin has participated and managed several ESA, EU and national projects. Kaj Helin joined VTT in 1998 and has gained 21 years of experience in virtual/augmented reality, simulation, safety analysis, ergonomics and usability. Helin is a member of the following committees: Executive Committee of European Association for Virtual Reality and Augmented Reality, and IEA-Technical Committee on Human Simulation and Virtual Environments. Helin has coordinated following ESA projects: EdcAR - Augmented Reality for AIT, AIV and Orbit Operations; MobiPV4Hololens - ISS procedure viewer to Hololens; AROGAN - Augmented reality-based ISS and ground applications: and VirWAIT - Virtual workplace for AIT & PA training and operations support.

Satu Salo (PhD), Senior Scientist at VTT Technical Research Centre of Finland Ltd, has 20 years of theoretical knowledge and hands-on practical skills in process microbiology, including case studies in food and paper industry and in hospitals, performance of hygiene surveys, process hygiene studies with emphasis on biofilms, microbiological detection methods in hygiene monitoring, cleaning and disinfection of process surfaces, hygienic engineering and design, and microbiological risk analysis and management. She has been a project leader of a project strategy nd recommendations for microbiological cleanliness of futurecargo integration, which was funded by ESA and participated in project BioSafety In Space; and Automated biomonitoring of air and water quality in human spacecraft (in the frame of ESA's GSP programme).

Hanna-Leena Alakomi (PhD in microbiology) Research Team Leader in the Process Microbiology and Food Safety team at VTT Ltd. In addition, she is a IPMA C certified project manager. She has 25 years of experience in studies related to microbial ecology, probiotics, control of harmful microbes, food safety and quality. She has participated in several EU projects and coordinated several nationally funded and contract based confidential R&D projects. She has 52 publications in peer-reviewed journals and 3 patents.

Irina Tsitko (PhD in microbiology) is a Senior Scientist in the process microbiology and food safety team at VTT Technical Research Centre of Finland Ltd. She has over 20 years' experience (in academia and industrial research) in environmental and industrial microbiology, including drinking water system biofouling and human gut microbiome. She has a strong background in molecular biology methods and various microscopy techniques for microbial community characterization. She is also acting as a curator at VTT Culture Collection, the collection with IDA status.

Pauli Komonen (M. Soc. Sc) is a Research Scientist at VTT specialized in corporate foresight and human insight with 10 years of experience. Komonen has worked with major domestic and international organizations, including clients in industries like telecom, FMCG, finance, energy, technology, media, travel, and engineering. Komonen's research interests cover leading- edge consumer behavior, foresight-driven business strategies, systemic changes and human-centric futures. Komonen has provided expert commentary on the leading Finnish television channels, newspapers and radio channels. Komonen is also an experienced speaker and facilitator, with appointments ranging from keynote speeches to co-creation sessions

Edgar Bohner (Dr.-Ing., Principal Scientist, Research Team Leader at VTT) has earned two master degrees in Civil Engineering from the University of Karlsruhe in Germany and the Royal Institute of Technology in Stockholm, Sweden. He holds a doctoral degree in the field of concrete cracking due to reinforcement corrosion from the Karlsruhe Institute of Technology in Germany. He works as Principle Scientist and Research Team Leader in the field of structural materials and built infrastructure at VTT. He has authored more than 80 scientific publications in peer-reviewed journals, books and conference proceedings. His fields of expertise are durability of concrete structures, deterioration and corrosion processes, life cycle assessment and material testing. He has further experiences in the areas of nuclear waste management and monitoring of structures. He has recently participated in the EU FP7 projects DOPAS with the task of instrumentation and monitoring of a concrete tunnel end plug, and MODERN2020, where his expertise contribution was related to the development and design of monitoring systems for EBS.

Géza Szilvay (PhD), Senior Scientist at VTT Technical Research Centre of Finland Ltd, is a project manager and expert in fungal biotechnology, genetic engineering, biosynthetic materials, and biointerface research. Before joining VTT in 2010 he worked as a post-doctoral fellow at Columbia University (NY, USA). He has 19 years of experience working in the fields of biomolecular and biomaterial research. To date he has published 39 peer-reviewed papers and has 6 patent applications.

Tuomo Tuikka (PhD) is a Research Manager at VTT Technical Research Centre of Finland. He has had a long career both in ICT research and in software industry. Tuomo has a PhD on Computer System Support on Design using Virtual Prototyping from 2002. He has both academic and software industry background with experience from various parts of the world.

After University of Oulu, he went to software industry, being responsible on R&D of a software product line. His current duties include responsibility on data-driven solutions research encompassing e.g. health and industrial domains. Dr. Tuikka is involved in many European and national research and innovation activities including big data, artificial intelligence, and software and services. He is a member of the board of software and services initiative NESSI European Technology Platform, participates in the International Data Space Association (IDSA) activities, and European Research Consortium for Informatics and Mathematics (ERCIM). Furthermore, at Big Data Value Association he is currently participating in Data Sharing working group of BDVA as a co-lead of the group.

Heiko Rischer (PhD), Principal Scientist, is Research Team Leader of Plant Biotechnology at VTT where he is leading innovative applied research covering chemicals, health, personal care, cosmetics and food, among other areas. At the University of Helsinki, he is appointed Adjunct Professor in Pharmaceutical Biology and he fulfils teaching duties there and at other Universities. He is a Biologist with PhD in natural product chemistry building on more than 25 years of experience in the biosynthesis of plant secondary metabolites. He is an expert in plant cell and tissue culture techniques, analytics of secondary metabolites including metabolic profiling and the biotechnological production, up to industrial scales, of phytopharmaceuticals and other plant-derived compounds. Besides customer projects he has been involved in interdisciplinary EU-projects as either scientist or manager.

Tuomas Pinomaa is a manager at VTT. He has graduated in Materials Science. (M.Sc. Helsinki University of Technology, 1992). His responsibilities are related to management and coordination of customer relations and sales of direct customer projects. Pinomaa has been working at VTT since 2011 in different roles in customer relations management. His previous work include several projects where complex and diverse research topics have been productized to service packages that are easier to explain, and thus, sell to customers. The best examples of those productization projects are VTT ProperTune®, is VTT's integrated computational materials engineering (ICME) concept and VTT ProperScan®, which is a holistic approach for Overall Equipment Efficiency (OEE). Before joining VTT Pinomaa was serving Finnish metal industry for two decades (Outokumpu Group 1991–2002, Mint of Finland 2002-2010). His job was related to customer centric product development, process development and international investment projects.

Jukka Kiviniemi is Customer Account Lead at VTT Technical Research Centre of Finland. He has over 20 years of experience in mobile and computing industry, from the perspectives of key account management, solution sales, business development, project management and computing system development. He also has over 10 years of experience in space industry. His current responsibilities involve key account management for global mobile and space industry customers, marketing and sales planning, coordinating marketing activities, and keeping track on the sales funnel. His work also includes new customer openings, pricing, legal aspects, tenders, contract negotiations and contract closures.

Jozsef Nagy (subcontractor) is Founder and CEO of Calibrum, a US-based company providing online software products for real-time decision making. Jozsef received his Bachelor of Science degree in Hungary and his Microsoft Certified Solution Developer certification in New York. He has over three decades of experience in designing, developing and implementing complex, large-scale, custom enterprise solutions and commercial software products for mission-critical applications. Jozsef has extensive expertise in Cloud Data Warehousing and Big Data advanced analytics and reporting.

Authors from UAESA team

Khaled Al Hashmi (PhD) is Director of the National Space Science and Technology Centre (NSSTC) and Advisor to Director General - National Space Programs (UAE Space Agency). Dr. Al Hashimi is seconded to lead the National Space Science and Technology Centre to support the development of manufacturing facilities and capabilities in design and build of small satellites and R&D related to space science and technologies. Spearheading national space program for the UAE Space Agency inclusive of the program management of the UAE Mars Mission “The Hope” project, the 813 Arabic Satellite, and other small satellite projects, directing the development and implementation of the Space Science & Technology and Innovation roadmap. He held several roles in senior executive management positions that demanding critical business transformation as Chief Operating Officer, Executive Director, and Director at various Space, Aerospace, Oil & Gas industries, government administration and state-owned enterprises in areas of Strategy, Business Planning, Organization Development, and Operations. Earned a Doctorate in Business Administration and an MSc in Th rmal Power & Fluids Engineering from the University of Manchester from University of Manchester, graduated from Harvard Business School–General Management, earned a Diploma in Public Sector Innovation from University of Cambridge. His first Degree was a BSc in Aerospace Engineering from Saint Louise University

Talal Al Kaissi is Advisor of Strategic Projects at the UAE Space Agency. He joined the UAE Space Agency in September 2018 as an Advisor to the Director General on Strategic Projects. Among several duties one of his core focus functions is supporting the activation of the UAE Space Agency Investment Promotion Plan and the development of a holistic national Space Economy with an emphasis on attracting space startups and investments to the UAE. Prior to his role at the Agency, Talal served at the UAE Embassy in Washington DC for 9 years as a Sr. Advisor for Commercial Affairs at the UAE Trade & Commercial Office and also led US / UAE Space Affairs. Talal graduated from California State University in Long Beach with a BS in International Business in 2006. Talal serves on the World Economic Forum Space Tech Council.

Alia Al Amiri is Head of Strategy and Future at the UAE Space Agency. Alia joined the UAE Space Agency at the early stages of establishment. She has more than 18 years of experience in UAE government sector. Her multidiscipline duties include developing corporate strategies, managing strategic performance, managing policies and procedures, building excellence practices, overseeing future foresight activities. Alia graduated from University of Wollongong in Dubai with MBA degree in 2005.

Murad Al Mohammad is Institutional Excellence Specialist at the UAE Space Agency. Murad joined the UAE Space Agency in August 2017 as an Institutional Excellence Specialist. Building excellence practice and improving performance all over UAE Space Agency functions are his main roles. He has over twelve years of experience in building and implementing excellence models, building management system, improving performance and processes and building policies and procedures in UAE government sector, including Dubai Municipality, Ministry of Economy, Dubai Roads & Transport Authority (RTA), and many more. Murad holds a bachelor degree in Industrial Engineering from Hashemite University in Jordan. He is also Norton Caplan BSC Certified.

Hamda Al Shehhi is a Space Technology Senior Researcher at the Space Missions Department of the UAE Space Agency. Since she joined the Agency in 2017, she has focused on providing support and performing scientific research in the investigation and application of space science to Agency missions and projects. Further on she had successfully developed technical and administrative skills while supporting space-related research and development (R&D) projects hat aid the advancement of space science and technology in the UAE. Hamda is a graduate of University of Sharjah with a BS in Nuclear Engineering. She is also a graduate of the Space Studies Program from the International Space University 2019

Sumaya Al Hajeri is Head of Space Policy and Regulation at the UAE Space Agency. She is professional in the field of Space and Telecommunication policies and regulations with a 13 years of experience. She has contributed towards achieving several projects such as: the draft federal law on regulating space activities, the space regulations and the regulatory procedures. Sumaya worked at the Telecommunication Regulatory Authority since 2007 as a Radio Planning Engineer where she developed the National Spectrum Plan as per the outcomes of the World Radiocommunication Conferences by the International Telecommunication Union. In 2012, she was involved in the Telecommunication Competition Regulations and Licensing and contributed towards: licensing major space telecom operators in the UAE and development of the Universal Service Obligation Policy. She graduated from the Future Foresight Program in 2018, and developed a future foresight scenarios of Space Accessibility based on international legislations and R&D uncertainties. Sumaya is a holder of a bachelor in Communication and Electronics Engineering 2007 from the UAE University, and Master of International Law, Diplomacy and International Relations 2011 from Paris Sorbonne University, and currently a student at Mohamed Bin Rashed School of Governance studying Master in Public Policy. Sumaya has a number of contributions in the field of women in ICT as part of the ITU agenda, Research policy proposal on increasing Emirati women participation in the workforce, and a study on history of Emirati women empowerment in the UAE.

Fatima Al Shamsi is Space Policies Specialist at the UAE Space Agency. She Joined the Agency in 2018 where her core duties includes supporting the development and governance of the National Space Strategy 2030, and the development of reports related to space economy and sustainability, in addition to active participation in the work related to United Nations Committee on the Peaceful Uses of Outer Space. Prior to her role in the agency, Fatima worked as a strategist and a research engineer in Abu Dhabi Digital Authority, Khalifa University, and the Agency for Science, Technology, and Research (A*Star) in Singapore. Fatima Holds a Master Degree in Computing and Information Science from Khalifa University. She is also a Bachelor Degree in Security and Network Technologies from Zayed University.

Endnotes and references

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8 The following documents were reviewed for building Delphi statements:

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10 Although the open method of coordination (OMC) emerged as a framework for cooperation between European Union Member States, the underlying principles are valid to promote cooperation between departments, autonomous regions or emirates in a single country. The OMC could be seen as a 'soft' law in the sense that it promotes a form of policy-making that does not result in binding legislative measures and it does not require the introduction or amendment of existing laws. The OMC involves the identification and definition of common objectives; the establishment of measuring instruments (statistics, indicators, guidelines); and the benchmarking or comparison of performance and best practices of OMC interventions. Read more at https://ec.europa.eu/culture/policy/strategic-framework/european-coop_en

11 https://en.wikipedia.org/wiki/International_Space_Station

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13 Kelly, J.R., Kennedy, P.J., Cryan, J.F., Dinan, T.G., Clarke, G. and Hyland, N.P. (2015) Breaking down the barriers: the gut microbiome, intestinal permeability and stress-related psychiatric disorders. Front Cell Neurosci 9:392.

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