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FROM DOWN UNDER TO THE MOON

Launching Australia's contribution to a sustainable lunar ecosystem.

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Introduction

The launch of the Artemis program clearly demonstrates humanity's resurging interest in the Moon and its exploration, and thus the importance of establishing an Australian foothold in the development of a sustainable lunar ecosystem. Utilising existing Australian expertise across industry and academia is vital for a significant and successful contribution to this complex geopolitical landscape. This will ensure Australia is able to competitively engage alongside existing space leaders.[1] The Australian space industry is likely to find its future dictated by its ability to successfully integrate itself in the advancement of current technological frontiers, opening the floodgates to funding, partnerships, and public approval, on the basis of contributing to the development of the Australian economy and humanity as a whole.

The following six recommendations outline how Australia can contribute to a sustainable lunar ecosystem. These recommendations are addressed to stakeholders including: the University of Adelaide, Australian Remote Operations in Space and on Earth Consortium (AROSE), Australian Space Agency (the Agency), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Space Industry Association of Australia (SIAA), Australian Centre for Advanced Photovoltaics (ACAP), and other industry and academic groups. The key topics addressed are: Lunar Sustainable Development Goals (LSDGs), legislation utilising ecological sustainable development (ESD), domestic policy, space medicine and psychology, lunar infrastructural development and engineering capabilities, and life-sustaining technologies.

Methodology

As an initial exercise, specific stakeholder profiles were assigned to team members, who then explored perspective-driven factors affecting their contribution to the lunar ecosystem. Following this, topic-centred research was conducted via consultation with Subject Matter Experts (SMEs), literature reviews, and collaborative discussion. Recommendations were then drafted and presented to SMEs for feedback. The final recommendations were thus refined and selected.

This White Paper was formulated by a dedicated team of individuals possessing diverse backgrounds and expertise, following a rigorous process. Nevertheless, the authors recognise the boundaries of their professional knowledge and experience. It was also necessary to operate within the fixed scope and timeframe of the Astra program, such that it was not always possible to consult across the entire breadth and diversity of the Australian space sector.

To ensure the feasibility of the recommendations, the following assumptions are made:

I. Stakeholders will operate on a suitable timescale and will be responsive to developments across the lunar ecosystem in different sectors.
II. Stakeholders possess sufficient influence and resources to work towards implementation.
III. Stakeholders will cooperate with each other where proposed.

Recommendation 1: Develop and promote the concept of Lunar Sustainable Development Goals (LSDGs).

Adopted in 2015, the United Nations Sustainable Development Goals (SDGs) revolve around human experiences on Earth. Extending the concept of sustainable development to the Moon would promote efforts to secure the longevity of humanity's activities on the Moon as well as its benefits to society on Earth. To this end, we recommend the development of the Lunar Sustainable Development Goals, which should be led by members of the Australian space sector. This includes the development and promotion of goals, targets and indicators that define quality of life for humans present on the Moon and sustainability of lunar operations. Additionally, the LSDGs should highlight the ability of space technologies and projects to have positive impacts on Earth, as recognised by the UN.[2]

It is in Australia's interest to develop well-defined and respected guidelines based on sustainable development. Reflecting the strategic space pillars set out in the *Australian Civil Space Strategy 2019-2028*, these guidelines may contribute to the 'Responsible' pillar, and assist Australia to maximise the opportunities arising from rapidly advancing space technology, such as areas aligned with autonomy, energy, communications, and health.[3]

The purpose of the LSDGs is to bring together a set of targets that guide the design and conduct of lunar operations and infrastructure to align with the values of equitable and long-term access to the benefits of space. Building on the SDGs and related concepts of planetary boundaries and ESD as a foundation,[4] a series of initial LSDG topics are proposed: quality of life, equitable access, preservation of resources, and preservation of environment. Topics like quality of life highlight the importance of interdisciplinary collaboration, such as the benefits of taking into account space psychology research when designing lunar habitats. The inclusion of commitments to sustainability-driven innovation,[5] technology transfer and democratising space technologies would follow in the footsteps of the UN's Space 4 SDGs initiative, with the aim of improving quality of life on Earth.[6]

The most prominent similarities between terrestrial and lunar goals include those aligned with basic human needs and resource utilisation. Access to consistent water, food, and comfort will all be key aspects of lunar development. Responsible resource use will also remain an important aspect of the LSDGs, so as to preserve prospects for future development.

Major differences in the lunar context revolve around the Moon's remoteness and lack of atmosphere, meaning SDGs concerning air pollution and greenhouse emissions have limited relevance. Environmental preservation will need to take into account geological/topographical alterations and orbital debris, which may affect access to certain areas and resources on the Moon.[7] The remoteness and hard vacuum of the Moon would raise concerns around the availability of oxygen, green spaces, social contact and 'free space', and these aspects will likely see representation in the goals.

Stakeholders who are in a position to lead, develop and promote LSDGs for the benefit of all, include but are not limited to:

- AROSE, which promotes industry collaboration and technology transfer between the space sector and terrestrial industries.[8]
- The University of Adelaide's Andy Thomas Centre for Space Resources, which possesses the multidisciplinary expertise to investigate and assess the impact of various space operations.[9]
- SIAA, as advocates for businesses and individuals who play a key role in generating and reaping the benefits of the Australian and global space industries.[10]

Additionally, consultation with non-space industry organisations, dedicated to sustainable development, would provide valuable insights into the practical aspects of implementation.[11] Collaboration with international interest groups in the area of space sustainability would provide opportunities for the growth of these guidelines and ensure their relevance internationally given the importance of broad support for the LSDGs across the lunar ecosystem.[12]

Overall, we recommend that the Australian space industry begins working towards developing guidelines and example goals for LSDGs,[13] and ensures these are then adequately promoted on a domestic (including industry and academia partners) and international scale. While the aims of fostering sustainability will serve as a foundation, the LSDGs may be established as a 'living document' that evolves over time along with emerging research in areas such as lunar in situ resource utilisation, construction, agriculture and environmental monitoring, and will reflect the types of operations intended to be undertaken. Ideally, the LSDGs would be presented internationally to overseas space agencies, NGOs and multi-national governing bodies with the goal of expanding upon the guidelines and promoting them beyond Australia.

Recommendation 2: Develop domestic legislation for lunar activities with ecological sustainable development as its foundation.

The lunar ecosystem provides an opportunity to significantly advance the Australian economy.[14] However, despite potential gains, Australia must recognise their responsibility in participating ethically and sustainably to prevent long-lasting or irreversible damage to the lunar environment. Societal pressure emphasises this need, stemming from the understanding that abuse of natural resources results in detrimental, long-term consequences for resource availability. Therefore, we recommend that the Australian Space Agency encourage the Government to formulate a strong legislative framework that fosters sustainable space activity from public and private organisations.[15]

The concept of ESD,[16] and accompanying principles,[17] maintains prevalent national and international legislative backing.[18] Therefore, ESD poses as a viable legislative framework for balancing space innovation with lunar preservation. The precautionary principle will demand anticipatory action against potential environmental damage.[19] Given that restoration of the lunar environment is predicted to be difficult,[20] proactive risk mitigation undertaken by public and private organisations is crucial in promoting its long-term sustainability. As the principle maintains sufficient standing as customary international law,[21] its implementation would see Australia's space legislation aligning with internationally recognised environmental policies. As ordinary application of the precautionary principle would result in the unrealistic ban of all space activities due to the uncertain nature and inherent risks of future space activities,[22] recognition of threshold adjustments are proposed to mitigate this issue.

Intergenerational equity and integration stress the importance of nurturing both short-term and long-term interests.[23] With the lunar ecosystem predicted to be a long-term endeavour,[24] the guidance of both principles will safeguard the future of the lunar ecosystem from being depleted by organisations seeking to exploit the newfound opportunity. The value of the unique lunar landscape to ongoing research, and the wealth of its natural heritage, emphasises that the principle of conservation of biological diversity is fundamental to its ongoing preservation and continuation of these domains. Implementing the principle of improved valuation, pricing and incentive mechanisms would be highly influential in encouraging public and private organisations to conform with sustainable practices, avoiding significant environmental detriment. The 'polluter pays' principle, that an entity undertaking an environmentally hazardous activity should bear the risk of any accompanying damage,[25] is an example of an appropriate initiative. While this can be criticised as merely attaching a price-tag to inflicting environmental harm,[26] the principle can be shaped to invoke significant responsibility to those it applies to.

The adoption of ESD is ideal as the concept already exists within Australian legislation and predictably requires minimal amendments to apply to the lunar environment,[27] acting as a precedent to assist with integration into future legislation and reducing development time. The internationally-recognised status of ESD additionally increases the opportunity for diffusion of application to the international level.[28] However, challenges pertaining to ambiguity will need to be addressed through improved legislative drafting and formulation of clearer guidelines for practical application.[29]

In addition to the LSDGs detailed in Recommendation 1, the concept of ESD and its accompanying principles should be enshrined within all future legislation dealing with the lunar environment and associated activities. In doing so, public and private organisations will be encouraged to achieve ESD or face the possibility of legal challenge. Further, the implementation is both time and cost-effective given it will merely be an additional step within the legislative process and not a new legislation. Overall, ESD and its associated principles present a strong legislative framework to satisfactorily promote sustainability within the lunar ecosystem.

Recommendation 3: Facilitate interdisciplinary initiatives to research and develop policies surrounding Australia's space activities.

Australia is still in the early stages of developing regulations and governance for space activities.[30] The future development of legislation and policies relating to Australian space activity will be imperative to responsibly foster the growth of the Australian space economy. As such, it is more important than ever to be conducting policy research related to Australia's future lunar activities that is responsive to the fast pace of technological developments. The research ecosystem outlined in this recommendation is intended to complement and potentially galvanise the ongoing processes of space law and policy development in Australia.

The proposed research network should facilitate formulation of future regulations and policies by engaging experts from a range of backgrounds, including government and commercial space. Collaboration with institutions from around Australia opens up dialogue that engages a diverse set of perspectives and helps raise the profile of different issues. Student participation should also be encouraged through research projects and scholarships. In this way, initiatives may be representative of present and future interests of every relevant stakeholder in the space industry.

Where this recommendation differs from existing initiatives is the bridging of the technology fields with policy research. While there are currently institutions that focus on developing policies or technologies for the space industry, there is an opportunity to bridge both sides of these developments at a national level.[31] In turn, this will create valuable opportunities to continuously foster and be at the forefront of ongoing policy discussions shaping the industry.

The University of Adelaide is in a prime position to promote cooperation to address existing gaps in legislation and policies relating to Australia's space activities. The University has played an important role in facilitating Australia's space endeavours, notably the Woomera Manual and Andy Thomas Centre for Space Resources.[32] The University's proximity to the Australian Space Agency also puts them at an advantage for being at the forefront of the space scene in Australia. Through leadership in this endeavour, participating institutions would be attractive recipients of funding and grants targeted to the space industry. Furthermore, it will enable the University to attract and provide opportunities for future students, academics, and collaborators interested in being part of Australia's rapidly growing space industry.

Some areas of interest which should be considered by this initiative include:

- Facilitating efforts to develop LSDGs, as suggested in Recommendation 1;
- Reviewing the application of ecologically sustainable development principles to the activities of space agencies and corporations, as well as possible processes for its implementation, as suggested in Recommendation 2;
- Regimes for natural and cultural heritage identification and protection in space;
- The role that legislation may play in encouraging and enabling the growth of Australia's commercial space sector;
- Corporate social responsibility (CSR) for commercial space companies, including the development of ways to measure the performance of corporations in space.[33]

The envisioned ecosystem of research institutes and space industry stakeholders would facilitate collaboration to identify priority areas for policies and reform. A challenge of space law and policy is that the policies and regulations, particularly with respect to the Moon, require long term commitment and striking a balance between current and future governance needs. This underscores the value of involving students in research activities to ensure that the future of the space industry is being represented and current discussions about space policies are carried over with the future generations of space professionals and policy makers.

Recommendation 4: Support and coordinate the development of research programs and training programs for space medicine and space psychology.

Increased participation in a lunar ecosystem implies increased long-term presence of humans in space.[34] As a result, it is necessary to develop an improved understanding of the physiological and psychological effects of spaceflight and lunar habitation on the human body. Health risks documented by NASA's Human Research Program include cancers, cardiovascular and neurodegenerative disorders resulting from space radiation; exacerbated bone and muscle loss in low gravity environments; and behavioural and cognitive health decrements due to isolation and confinement.[35] In addition, the Moon's inaccessibility indicates that many treatments for astronaut disorders will be reliant on remote health techniques.[36] The seriousness of these impacts necessitates developing the ability to understand, prevent and treat associated health risks as comprehensively as possible, in support of a sustainable lunar ecosystem.[37]

Notably, Australia possesses significant national research and development expertise in psychological, physical, and remote health which may be directed towards important space objectives.[38] This has already been demonstrated by stakeholders in academia including the Universities of Adelaide,[39] Wollongong,[40] and Tasmania.[41] More generally, facilities, centres and organisations such as the Centre of Antarctic, Remote and Maritime Medicine (CARMM),[42] the Australasian Society of Aerospace Medicine (ASAM), and the Australiasian College of Aerospace Medicince (ACAsM) demonstrate the breadth of national knowledge and interest in space health. By focusing the application of this expertise, Australia is presented with the opportunity to make a significant contribution to international space endeavours and ensure astronaut safety.

A further niche is the provision of trained healthcare professionals for space, either as astronauts or Earth-based telehealth practitioners; the importance of accessible health consultations has been underscored by the COVID-19 pandemic.[43] Australia is well-placed to contribute via the expansion and coordination of its space medicine and space psychology training programs, such as those administered by the University of Tasmania for remote health and aerospace health.[44] Resultant advances in research and training would also broadly benefit terrestrial health applications and accelerate the local biomedical industry.[45]

In support of the above outcomes, Australia should pursue two key avenues:

I. Prioritise research in Australian areas of expertise (including radiation and reduced gravity effects, astronaut psychology, telehealth, and space analogue research).
II. Coordinate the development of Australian space medicine and space psychology training programs, such that they are certified, globally competitive, and provide the necessary skills to enable consistent space healthcare.[46]

The first proposal is directed at the Australian Government, for administration of national focus and funding; and at research hubs, including the University of Adelaide and CARMM, to explore opportunities for growth and collaboration. This could be accomplished via applications for Australian Research Council (ARC) Centre of Excellence status or similar in the space medicine and space psychology fields. The second proposal is directed at the University of Tasmania and CARMM, for facilitation of training; and the Australian Health Practitioner Regulation Agency (AHPRA), ASAM and ACAsM, for regulation and consultation.

Recommendation 5: Apply Australian expertise in remote operations, autonomy, materials and manufacturing to provide key engineering capabilities within the lunar ecosystem.

A self-sufficient, sustainable, and scalable lunar ecosystem (as per the envisioned LSDGs of Recommendation 1) requires the adaptation of many terrestrial activities to the Moon.[47] Enabling these activities requires adapting critical terrestrial engineering capabilities to the lunar environment. Remote operations and autonomy are among the most vital technologies for conducting flexible,[48] long-term operations in the presence of hostile environmental factors and limited personnel.[49] In-situ resource utilisation (ISRU)[50] is also necessary to allow lunar production and habitation given high transport costs and sparse access to external resources.[51] Current research programs and roadmaps demonstrate significant interest in fulfilling these engineering needs,[52] and Australia is well-placed to contribute.[53]

Principles of remote operations and autonomy are already leveraged at large scales by the Australian agriculture, mining and telehealth sectors, resulting in foundational knowledge that can be usefully applied to space.[54] For example, best practices from the mining sector in autonomous asset management may be adapted to control complex activities on the lunar surface. Australia also possesses globally-recognised expertise in autonomy which has been turned towards enabling lunar technology platforms.[55] Industry strengths are further represented by new, collaborative initiatives and world-leading facilities such as the AROSE consortium and Space Automation AI Robotics Control Complex.[56] This suggests opportunities for cross-pollination: consider usage of local Internet of Things satellite expertise to facilitate communications during lunar remote operations.[57]

Similarly, major ISRU system components are incorporated by the Australian mining industry. National knowledge regarding resource exploration, extraction, transport and utilisation may assist the development and validation of equivalent architectures for space.[58] Broader ISRU research is supported by a variety of Australian stakeholders, such as the Andy Thomas Centre for Space Resources and the CSIRO.[59] Of added interest are the intersections between materials and manufacturing expertise within Australia and internationally,[60] such that research into advanced materials and lunar manufacturing can be conducted in tandem.

These examples suggest Australia is uniquely positioned to build upon its technical expertise to become a key enabler of a robust lunar ecosystem, while simultaneously growing the local engineering economy and knowledgebase. Given the range of topic areas and stakeholders involved, it is proposed to apply 'triple-helix' collaboration between industry, academia, and government.[61] This type of collaborative development may improve overall outcomes by taking full advantage of the strengths of different sectors; facilitating two-way technology transfer, such that lunar solutions for autonomy and manufacturing also benefit terrestrial industries;[62] and facilitating greater international influence and impact. Similar principles are demonstrated by the existing Australian Cooperative Research Centre (CRC) framework.[63]

To achieve these outcomes, new CRC (or similar) initiatives should be formed around the core areas of:

I. Autonomy and remote operations.
II. Materials, manufacturing and construction for space.

This recommendation is directed at the Australian government and Australian Space Agency for administration of funding and submissions; the AROSE consortium, as a focal point for the first CRC; and the University of Adelaide, as a focal point for the second CRC. A stated aim should be to demonstrate continuous deployment of resultant technologies on the Moon as part of commercial and/or Artemis missions in the short-to-medium term,[64] in support of measurable impacts and the LSDGs. The Australian Space Agency, AROSE, and representative organisations should also take an active role in promoting wider usage of resultant technologies to enable desirable lunar objectives (by other national and international stakeholders).

Recommendation 6: Apply Australian expertise in agriculture and energy generation to adapt existing and develop novel technologies to support a permanent human presence on the Moon.

Permanently sustaining human life on and around the Moon requires the development of a multitude of life supporting technologies. Similarly, minimising the critical risks and costs of space settlement requires improving the self-sufficiency of lunar habitats.[65] Australian expertise in energy production and agriculture provides a strong foundation for addressing these issues.

Prior plant growth experiments have been conducted in a microgravity environment and suggest that staple crops, such as potatoes, cannot grow normally in lunar gravity.[66] Additionally, these experiments were not designed to test the scalability of agricultural systems necessary to support permanent human habitation in a lunar environment.

Current Australian research and industry leaders are already working to overcome knowledge gaps by leveraging existing technologies and expertise. For example, Australian growers commonly suffer from unreliable rainfall and water resistant soils and are thus highly invested in efficient water usage. This knowledge can aid space-based systems in becoming more resource efficient.[67] Relevant techniques developed by Australia's agriculture research industry, particularly the CSIRO, could be transferred to solve similar issues that will be faced on and around the Moon. Additionally, the Plants4Space ARC Centre of Excellence, led by the University of Adelaide, is currently working on plant production systems for use in space.[68]

The Plants4Space research centre and CSIRO should form, and increase, cooperative partnerships with domestic growers, agricultural companies, universities and agricultural research groups to adapt existing ground-based technologies for use in microgravity and low gravity environments. Specific examples include the CSIRO's Water Use Efficiency initiative and research into water repellent soils.[69] Australian industry and partners should also aim to launch a resulting technology demonstrator mission to NASA's Lunar Gateway station or subsequent lunar base camp as soon as it is feasible to do so.

A sustainable and permanent human presence on the Moon also requires further research into and development of energy generation technologies. As fossil fuels are not available in a lunar environment, renewable sources (such as solar and hydrogen from water/electrolysis) will be essential to power production on the Moon. This is critical to life sustainment and, in the case of hydrogen generation through electrolysis, will also produce vital oxygen. Notably, the Australian energy industry is a net exporter of energy produced and a global leader in renewable source production and development.[70]

Hydrogen investment in Australia has reached $133-$185 billion as of 2022.[71] With this expenditure for development and a successful pipeline and fuel-adjacent industry already present, the logical next step is towards space utilisation. The Australian Centre for Advanced Photovoltaics (ACAP), has received $45 million for its "cutting-edge solar photovoltaic" research, with partnerships in the Australian Renewable Energy Agency (ARENA) and universities across Australia.[72] Australian research and industry have made extensive advancements in renewable energy sectors, furthering the ability and feasibility for meaningful contribution in this sector.[73]

ARENA, ACAP and Australian universities should seek further funding and pivot the application of their research to space (approaching both industry and government for usage and funding). The Australian hydrogen industry should also expand operations to the space sector, as a joint effort with advanced research conducted in academia (particularly the University of Adelaide's Institute for Sustainability, Energy and Resources). Improvements in solar and hydrogen technology that result should additionally be applied to the domestic market where possible, and publicised to promote continued investment in space sector development.

Recommendations

Recommendation 1: Develop and promote the concept of Lunar Sustainable Development Goals (LSDGs). This recommendation is directed to the University of Adelaide, AROSE, SIAA and the Australian space community more broadly.

Recommendation 2: Develop domestic legislation for lunar activities with ecological sustainable development as its foundation. This recommendation is directed to the Australian Government and Australian Space Agency.

Recommendation 3: Facilitate interdisciplinary initiatives to research and develop policies relating to Australia's space activities. This recommendation is directed to the University of Adelaide in collaboration with universities and research institutes around Australia.

Recommendation 4: Support and coordinate the development of existing research programs and novel training programs for space medicine and space psychology. This recommendation is directed to CARMM, the University of Adelaide, the University of Tasmania, ASAM, ACAsM, and the AHPRA.

Recommendation 5: Apply Australian expertise in remote operations, autonomy, materials and manufacturing to provide key engineering capabilities within the lunar ecosystem. This recommendation is directed to the Australian Government, Australian Space Agency, AROSE, and the University of Adelaide.

Recommendation 6: Apply Australian expertise in agriculture and energy generation to adapt and develop existing technologies to support a permanent human presence on the Moon. This recommendation is directed to the University of Adelaide, Plants4Space, the CSIRO, ARENA, and ACAP.

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Endnotes

[1] Such as NASA, ESA, SpaceX, JAXA, etc

[2] André Baumgart et al., 'Space for the Sustainable Development Goals: Mapping the Contributions of Space-Based Projects and Technologies to the Achievement of the 2030 Agenda for Sustainable Development', *Sustainable Earth* 4, no. 1 (2021): 6, https://doi.org/10.1186/s42055-021-00045-6.

[3] Australian Space Agency, 'Advancing Space: Australian Civil Space Strategy 2019–2028' (Canberra: Commonwealth of Australia, April 2019), https://www.industry.gov.au/publications/australian-civil-space-strategy-2019-2028.

[4] Sarah Cornell, 'Planetary Boundaries', Stockholm Resilience Centre, accessed 13 March 2023, https://www.stockholmresilience.org/research/planetary-boundaries.html.

[5] Sustainability driven innovation may draw on the concept of Corporate Social Innovation (CSI). CSI is a strategy aimed at encouraging a culture of social innovation, to be achieved by firms individually and in collaboration with each other, and the integration of socially responsible policies into business plans:

Ian A. Christiensen, 'Applying Corporate Social Responsibility Principles in the Space Sector', in *14th Reinventing Space Conference* (London, 2016), https://swfound.org/media/205652/rispace_applying_csr_principles_in_the_space_sector.pdf.

[6] UNOOSA, 'Space4SDGs: How Space Can Be Used in Support of the 2030 Agenda for Sustainable Development', United Nations Office for Outer Space Affairs, 19 December 2022, https://www.unoosa.org/oosa/en/ourwork/space4sdgs/index.html.

[7] Eric Dahlstrom and Maria A. Pozza, 'New Risks of Future Lunar Landings', in *Risk Management in Outer Space Activities*, ed. Maria A. Pozza and Joel A. Dennerley (Singapore: Springer Nature Singapore, 2022), 221–39, https://doi.org/10.1007/978-981-16-4756-7_8.

[8] Stefano Ferretti et al., 'ESPI Report 59 - Space for Sustainable Development' (ESPI, 1 June 2016), https://www.espi.or.at/wp-content/uploads/espidocs/Public%20ESPI%20Reports/Rep59_online_1600617-1243.pdf.

[9] Andy Thomas Centre for Space Resources, 'About Us', University of Adelaide, 1 December 2021, https://set.adelaide.edu.au/atcsr/about-us.

[10] SIAA, 'About the SIAA', Space Industry Association of Australia, 28 November 2022, https://www.spaceindustry.com.au/about/.

[11] Organisations with experience and expertise regarding the business cases for sustainable development and the implementation of initiatives include the Global Compact Network Australia, and the Sustainable Development Solutions Network:

UN Global Compact Network Australia, 'What We Do', UN Global Compact Network Australia, 2 May 2022, https://unglobalcompact.org.au/un-global-compact/;

DFAT, 'Global Compact Network Australia Business Development Partnership', accessed 14 March 2023, https://www.dfat.gov.au/aid/who-we-work-with/private-sector-partnerships/opportunities/Pages/global-compact-network-australia-business-development-partnership.;

SDSN Australia, New Zealand and Pacific, 'About Us', 25 June 2019, https://ap-unsdsn.org/about/.

[12] For instance, the Secure World Foundation is an international group whose aim is to collaborate with governments, industry, international organisations and civil society to promote sustainable and peaceful uses of outer space:

SWF, 'Who We Are', About Us, Secure World Foundation, 29 November 2022, https://swfound.org/about-us/who-we-are/.

[13] Stakeholders from industry, academia and government, including those identified in this section.

[14] Andreas K. E. Sherborne, 'The Commercialisation of Space: An Overview of Legal Risks and Considerations', in *Risk Management in Outer Space Activities*, ed. Maria A. Pozza and Joel A. Dennerley (Singapore: Springer Nature Singapore, 2022), 19-46, 28, https://doi.org/10.1007/978-981-16-4756-7_2.

[15] Sherborne, "Commercialisation of space," 29.

[16] Australia's National Strategy for Ecologically Sustainable Development 1992 defines ESD as "using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased.": See note 74 below.

[17] Australia's National Strategy for Ecologically Sustainable Development, 1992 (see note 74 below) incorporates the principles of:

- Precautionary principle
- Intergenerational equity
- Integration
- Conservation of biological diversity
- Improved valuation, pricing and incentive mechanisms.

[18] In 1987, The Report of the World Commission on Environment and Development, *Our Common Future* ('Brundtland Report') coined the term 'sustainable development.':

World Commission on Environment and Development, *Our Common Future* (Oxford ; New York: Oxford University Press, 1987), https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

Report of the World Commission on Environment and Development: Our Common Future. Oxford: Oxford University Press: 1987. The 1992 *Rio Declaration on Environment and Development* ('Rio Declaration') followed suit, introducing the principles deemed fundamental for effective environmental governance, including those listed above:

United Nations Conference on Environment and Development, *Report of the United Nations Conference on Environment and Development: Rio de Janeiro, 3-14 June 1992; Official Records* (New York: United Nations, 1993).

Within the same year, Australia developed the *National Strategy for Ecological Sustainable Development,* adding the 'ecological' precursor and evidencing their commitment to environmental sustainability via these means: See note 74 below.

ESD and the fundamental principles were enshrined within the Environment Protection and Biodiversity Conservation Act 1999 (Cth) ('EPBC Act') s 3A: See note 75 below.

[19] The precautionary principle is defined in s 3A EPBC Act as where "there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.": See note 75 below.

[20] Lotta Viikari, 'Chapter Four. International Environmental Law In The Space Sector', in *The Environmental Element in Space Law: Assessing the Present and Charting the Future*, ed. Frans G. von der Dunk, vol. 3 (Leiden, The Netherlands: Brill | Nijhoff, 2008), 119-206, 173, https://doi.org/10.1163/ej.9789004167445.i-396.

[21] Rutwik Navalgund, 'Reduce, Reuse and Recycle: An Environmental Law Approach to Long-Term Sustainability of Outer Space', *Air and Space Law* 45, no. Issue 3 (1 June 2020): 285–308, 302, https://doi.org/10.54648/AILA2020040.

[22] Viikari, "International Environmental Law in Space," 174.

[23] Intergenerational equity is defined in s 3A EPBC Act as "requiring the present generation to preserve the health, diversity and productivity of the environment for the benefit of future generations." Integration is defined in s 3A EPBC Act as "decision-making processes should effectively integrate both long-term and short-term economic, environmental, social and equitable considerations.": See note 75 below.

[24] Navalgund, "Reduce, Reuse and Recycle," 287.

[25] Viikari, "International Environmental Law in Space," 190.

[26] Viikari, "International Environmental Law in Space," 195.

[27] Claudia Cinelli and Katarzyna Pogorzelska, 'The Current International Legal Setting for the Protection of the Outer Space Environment: The Precautionary Principle *Avant La Lettre*', *Review of European, Comparative & International Environmental Law* 22, no. 2 (2013): 186–201, 201, https://doi.org/10.1111/reel.12026.

[28] Cinelli and Porgorzelska, "Protection of Outer Space," 200.

[29] Sara Dalledonne, 'International Environmental Law and Environmentally Harmful Space Activities: Learning from the Past for a More Sustainable Future', *Journal of Property, Planning and Environmental Law* 13, no. 2 (17 August 2021): 139–51, 146, https://doi.org/10.1108/JPPEL-09-2020-0040.

[30] Current domestic legislation governing space activities in Australia concerns launch and return activities, addressing matters including insurance and management of risks to public health and safety as part of the licensing requirement:

Australian Space Agency, 'Conducting Australian Space Activities', Department of Industry, Science and Resources, 7 February 2022, https://www.industry.gov.au/australian-space-agency/regulating-australian-space-activities/conducting-australian-space-activities.

[31] Notably, the Australian National University hosts the Australian Centre for Space Governance (of which University of Adelaide is a part): "ACSG brings together national expertise in space law, governance, policy, security, property, history, philosophy and social sciences, to answer these

needs. There are six nodes of the ACSG led by experts across six universities…" Institutions that conduct space research and industry collaboration in the fields of science and engineering include but are not limited to: University of Queensland, University of Wollongong, University of New South Wales (Australian Centre for Space Engineering Research), Australian National University (Institute for Space), University of Western Australia (International Space Centre), and Queensland University of Technology (Planetary Surface Exploration):

ANU InSpace, 'Australian Centre for Space Governance', Australian National University Institute for Space, 18 November 2022, https://inspace.anu.edu.au/activity/missions/australian-centre-space-governance.

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Andrew W Kirkpatrick et al., 'Severe Traumatic Injury during Long Duration Spaceflight: Light Years beyond ATLS', *Journal of Trauma Management & Outcomes* 3, no. 1 (25 March 2009): 4, https://doi.org/10.1186/1752-2897-3-4.

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[39] The University of Adelaide is investigating guidelines for lunar architecture and habitat design to support psychological well-being during extreme isolation, in addition to stable medicine formulations for space:

Andy Thomas Centre for Space Resources, 'Deep Space Habitation', University of Adelaide, 19 April 2022, https://set.adelaide.edu.au/atcsr/space-research/deep-space-habitation;

Quy Don Tran et al., 'Space Medicines for Space Health', *ACS Medicinal Chemistry Letters* 13, no. 8 (28 April 2022): 1231–47, https://doi.org/10.1021/acsmedchemlett.1c00681.

[40] The University of Wollongong is developing and deploying radiation dosimeters for astronauts:

National Committee for Space and Radio Science, "Australia in Space."

[41] The University of Tasmania has developed world-leading remote health training programs for Antarctic and other remote environments (of particular relevance as 'space analogues'):

University of Tasmania, 'Healthcare in Remote and Extreme Environments', University of Tasmania, 13 January 2023, https://www.utas.edu.au/study/healthcare-in-remote-and-extreme-environments.

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Austrade, 'Space in Tasmania', Global Australia, accessed 5 March 2023, https://www.globalaustralia.gov.au/industries/space/state-ecosystem/tasmania.

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Patricia Downing, Mark Baxter, and Edward McCullough, 'Developing a Sustainable Lunar Economy: Expanding the Moon Base Beyond Exploration', in *1st Space Exploration Conference: Continuing the Voyage of Discovery* (Orlando, Florida: American Institute of Aeronautics and Astronautics, 2005), https://doi.org/10.2514/6.2005-2551;

Allison Zuniga et al., 'Building an Economical and Sustainable Lunar Infrastructure to Enable Human Missions', in *70th International Astronautical Congress* (Washington, DC, 2019), https://ntrs.nasa.gov/api/citations/20190032258/downloads/20190032258.pdf;

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AROSE, 'Australian Remote Operations Capability Review' (Perth WA: AROSE, November 2021), https://www.arose.org.au/wp-content/uploads/2021/11/AROSE-Remote-Operations-Capability_Review_Nov2021.pdf.

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Rob Ambrose et al., 'NASA Technology Roadmaps TA-4: Robotics and Autonomous Systems' (NASA, July 2015), https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_4_robotics_and_autonomous_systems_final.pdf.

[50] ISRU involves "transforming raw resources in planetary environments into materials and products" and has been identified by the CSIRO as "an essential capability to support […] more sustainable space activity.":

Mark Dunn, 'In-Situ Resource Utilisation (ISRU): Taking Mining out of This World' (CSIRO, 2020), https://mininginnovationnetwork.com/wp-content/uploads/2020/12/Mark-Dunn.pdf:

Typical lunar applications may include habitat construction using regolith, manufacturing of solar panels, and extraction of water and oxygen.

[51] Viorel Badescu, ed., *Moon*: *Prospective Energy and Material Resources* (Berlin, Heidelberg: Springer, 2012), https://doi.org/10.1007/978-3-642-27969-0;

ISRU Gap Assessment Team, 'In-Situ Resource Utilisation Gap Assessment Report' (ISECG, 21 April 2021), https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2021/04/ISECG-ISRU-Technology-Gap-Assessment-Report-Apr-2021.pdf.

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ISRU Gap Assessment Team. "In-Situ Resource Utilization Gap Report.";

Space Technology Mission Directorate, 'Space Technology Research Grants Program, Lunar Surface Technology Research Opportunities Appendix', Appendix (Washington, DC: NASA, 15 July 2020), https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=765891/solicitationId=%7B0BA38320-8F63-2EAF-D97B-0AB42AF17C35%7D/viewSolicitationDocument=1/ST-REDDI-2020-Appendix-B5-LuSTR-2020.pdf.

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Australian Government Space Coordination Committee, 'State of Space Report 2020-2021' (Canberra: Australian Space Agency, April 2022), https://www.industry.gov.au/sites/default/files/2022-10/state-of-space-report-2021.pdf.

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Low Luisa, 'Lift off! Space Projects Soar with New Funding', The University of Sydney, 22 July 2022, https://www.sydney.edu.au/news-opinion/news/2021/07/22/lift-off--space-projects-soar-with-new-funding.html.

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Ragav Sachdeva et al., 'Autonomy and Perception for Space Mining', in *2022 International Conference on Robotics and Automation (ICRA)* (2022 IEEE International Conference on Robotics and Automation (ICRA), Philadelphia, PA, USA: IEEE, 2022), 4087–93, https://doi.org/10.1109/ICRA46639.2022.9811661.

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Thierry Peynot, "Lunar rover being designed in Australia," interview by Robin Williams and David Fisher, *The Science Show*, ABC, September 10, 2022;

Stuart Layt, 'QUT Rover Gets Its Eyes for Being Part of NASA Moon Mission', *Brisbane Times*, 2 December 2021, https://www.brisbanetimes.com.au/national/queensland/qut-rover-gets-its-eyes-for-being-part-of-nasa-moon-mission-20211202-p59e7y.html.

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Kevin W. Farries et al., 'Sintered or Melted Regolith for Lunar Construction: State-of-the-Art Review and Future Research Directions', *Construction and Building Materials* 296 (16 August 2021): 123627, https://doi.org/10.1016/j.conbuildmat.2021.123627;

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The CSIRO is involved through the development of national state-of-the-art lunar analogue test facilities:

Fran Molloy, 'Moon-in-a-Room: CSIRO's New Facility to Advance off-Planet Science Exploration', *Resourceful by CSIRO*, 12 December 2021, https://www.csiro.au/en/work-with-us/industries/mining-resources/resourceful-magazine/issue-25/moon-in-a-room.

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NASA Technology Transfer Program, 'NASA Spinoff', accessed 13 March 2023, https://spinoff.nasa.gov/.

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CSIRO, 'Researching Water Use Efficiency for Increased Grain Yield', 21 May 2021, https://www.csiro.au/en/research/plants/crops/farming-systems/wue-initiative.

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