Financing Lunar ISRU Infrastructure:

A Macroeconomic Framework for Evaluating Public and Private Funding Instruments

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Abstract

Lunar In-Situ Resource Utilization (ISRU) infrastructure is widely viewed as a potential enabler of sustained lunar activity, yet its development faces a persistent financing gap driven by high capital intensity, long time horizons, and significant uncertainty. At the same time, macroeconomic research demonstrates that strategic space investments can generate meaningful short-run output effects and long-run productivity spillovers, though spillover intensity has declined in recent decades. This paper addresses how different financing structures shape the macroeconomic impact of ISRU investment, focusing on instrument design rather than technological outcomes.

Building on standard aggregate demand and aggregate supply frameworks, the analysis develops a tool-adjusted multiplier framework to compare five financing instrument categories: direct public debt expenditure, public–private partnerships (PPPs), loan guarantees, advance market commitments (AMCs), and milestone-based contracts. Each instrument is evaluated along four dimensions of financing effectiveness: leverage, realization probability, leakage, and implementation delay. The results suggest that AMCs and milestone-based contracts produce the highest effective multipliers per public dollar committed, while direct expenditure, though lower in efficiency, remains essential for early-stage demand creation. The framework is designed to support market design decisions and policy evaluation in the emerging cislunar economy.

Keywords: ISRU, space finance, macroeconomics, advance market commitments, public–private partnerships, cislunar economy, infrastructure investment

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1. Introduction

Lunar ISRU, the extraction and processing of regolith, water ice, and other in-situ materials to produce propellant, oxygen, and structural feedstocks, is widely expected to be a prerequisite for economically sustainable lunar operations. By reducing dependence on Earth-supplied consumables, ISRU could lower marginal mission costs at scale, enabling longer-duration surface presence and deeper cislunar infrastructure. NASA's Artemis program, ESA's Moonlight initiative, and the growing roster of commercial lunar payload providers have each cited ISRU as a medium-term priority.

Despite this strategic consensus, investment in ISRU remains limited. High capital intensity, long development horizons, significant technological uncertainty, and the absence of established demand markets create conditions that are systematically difficult for private finance to address. The fundamental challenge is not that ISRU is believed to be infeasible, it is that the timeline to commercial returns is too long and too uncertain for unsubsidized private capital to bear.

Recent macroeconomic research has renewed interest in the broader economic implications of space investment. Evidence from historical U.S. space programs suggests that space-related spending generated substantial short-run output effects and long-run productivity spillovers, though spillover intensity has declined since the 1980s [1, 2]. This raises a natural policy question: if future space investments are to generate economy-wide benefits comparable to earlier eras, how should they be financed? And more specifically, does financing structure matter as much as funding volume?

This paper argues that it does. Rather than evaluating the technological feasibility of ISRU, the analysis focuses on how different financing mechanisms shape the scale, timing, and macroeconomic impact of ISRU investment. The central contribution is a framework that links standard aggregate demand (AD) and long-run aggregate supply (LRAS) analysis to the systematic evaluation of alternative financing instruments, with the goal of informing market design and public policy in the cislunar economy.

2. Background and Related Literature

This work builds on three strands of literature, macroeconomic research on space investment, a growing technical and economic ISRU examinations, and the economics of infrastructure finance and public-private partnerships.

First, macroeconomic research on space investment has documented significant historical spillovers from space-related R&D and infrastructure spending. Corrado, Grassi, and Paolillo (2025) show that U.S. space activity contributed meaningfully to long-run productivity growth during the mid-twentieth century, with spillover intensity weakening in recent decades [1]. Cropper, Corrado, and Rao (2023) quantify these effects, finding that space sector activity in the 1960s and 1970s increased real GDP by approximately 2.2% on average after 20 years, compared to roughly 0.9% for space activity since the 1980s [2]. Related work by Deleidi and Mazzucato (2021) demonstrates that mission-oriented policies produce larger positive effects on GDP and stronger crowd-in effects on private R&D than generic public expenditure, directly relevant to the instrument comparison developed here [3].

Second, a growing technical and economic literature examines ISRU as a means of reducing the cost of lunar and cislunar operations. Jones et al. (2020) evaluate cost breakeven conditions for lunar propellant production versus Earth delivery, finding that transportation and extraction costs remain significant barriers to near-term affordability in most architectures [4]. Paulson, Balchanos, and Mavris (2024) simulate economic trade-offs in lunar water supply and find that ISRU does not yield a return on investment until approximately 30 years after deployment under current mission architectures, providing direct empirical grounding for the financing gap argument [5]. Kornuta et al. (2019) examine the commercial business case for cislunar propellant and identify demand certainty as the primary missing ingredient for private investment [6].

Third, the economics of infrastructure finance and public–private partnerships provides analytical tools for understanding why certain investments fail to attract private capital. Engel, Fischer, and Galetovic (2013) establish that PPPs bundle finance, construction, and operation into long-term contracts but do not inherently liberate public funds, the case for them rests on efficiency gains that often prove elusive without careful contract design [7]. Kremer, Levin, and Snyder (2020) develop the theory of advance market commitments, demonstrating how pre-committed demand can resolve the incentive failures that arise when investment precedes market formation [8]. Mazzucato (2018) argues that mission-oriented financing requires dynamic public–private relationships in which instrument design, not funding volume alone, determines whether investment materializes [9].

3. Macroeconomic Rationale for Public Support

From a macroeconomic perspective, ISRU investment affects the economy through both short-run and long-run channels.

In the short run, ISRU-related spending contributes to aggregate demand through investment and government expenditure. Using standard Keynesian logic, an increase in spending generates multiplier effects as income is re-spent throughout the economy. Historical space programs have been associated with substantial short-run output effects, particularly during periods of high domestic content and low import leakage.

In the long run, ISRU infrastructure may influence aggregate supply by contributing to capital accumulation and total factor productivity (TFP). Technological learning, advanced materials processing, autonomous systems, and energy technologies developed for ISRU applications could diffuse into terrestrial sectors, consistent with historical spillover evidence from the Apollo era and subsequent NASA programs.

These considerations provide a macroeconomic justification for public involvement, but they do not determine how support should be delivered. The magnitude and efficiency of public investment depends critically on financing structure, which instruments are used, how they allocate risk, and whether they successfully mobilize private capital. This is the central question the framework is designed to address.

4. Financing Instruments with Historical Precedent

A wide range of financing tools has been used historically to support high-risk, high-capital infrastructure and deep-technology sectors. This paper focuses on five instrument categories with documented precedent:

Direct public debt expenditure encompasses infrastructure bonds and appropriated program funding used to finance projects with national strategic importance, including the original NASA Apollo and shuttle programs. These instruments offer high realization probability and low delay but produce limited private leverage.

Public–private partnerships involve milestone-based contracts, shared-risk procurement, and service-purchase agreements in which private entities develop and operate infrastructure in exchange for public revenue guarantees. NASA's Commercial Orbital Transportation Services (COTS) and Commercial Crew programs exemplify this model in the space sector.

Loan guarantees reduce borrowing costs by transferring downside risk to the public sector balance sheet, enabling private capital to participate at scale. The U.S. Department of Energy's loan guarantee programs for advanced energy technology offer the closest precedent for deep-technology applications.

Advance market commitments pre-commit public or multilateral funds to purchase a defined quantity of a product at a specified price, contingent on successful delivery. Originally developed for vaccine markets in low-income countries, AMCs resolve demand-side uncertainty, the principal barrier to private investment in ISRU, by guaranteeing that a market will exist if the technology succeeds [8].

Milestone-based contracts make payment contingent on demonstrated technical performance rather than on time or cost inputs. This structure maintains incentive compatibility at the frontier of technical uncertainty, where output specifications are more tractable than cost projections.

5. A Tool-Adjusted Multiplier Framework

To compare financing instruments systematically, this paper proposes a tool-adjusted multiplier framework. The baseline short-run spending multiplier is defined as:

$$k_{base} = 1 / (1 - MPC)$$

where MPC is the marginal propensity to consume out of ISRU-related income. For a given financing instrument T, the effective multiplier is:

$$k_T = k_{base} \times L_T \times \varphi_T$$

where L_T captures the leverage of the instrument, the ratio of total ISRU investment mobilized to public funds committed, and φ_T captures realization effects, including implementation delays, leakages (such as import content), and the probability that committed funds translate into deployed capital.

Long-run supply-side effects are represented through a technology spillover term:

$$A = A_0 + \beta_T \cdot (\text{ISRU investment})$$

where β_T reflects how strongly a given financing structure promotes learning, innovation, and diffusion into terrestrial applications. Mission-oriented instruments that require domestic industrial participation and open publication of results are expected to produce higher β_T than instruments that contract out on a pure cost-plus basis with no domestic content requirements.

The framework generates a consistent basis for comparing instruments that differ in institutional complexity, risk allocation, and timing, without requiring precise forecasts of ISRU technology success. Table 1 summarizes qualitative assessments across all five instrument categories.

Table 1. Comparative Assessment of Financing Instruments

Instrument	Leverage (LT)	Realization (φT)	Delay	Leakage	Eff. Multiplier
Direct Public Expenditure	Low (1.0–1.3×)	High	Low	Moderate	Moderate
Loan Guarantees	High (3–6×)	Moderate	Moderate	Low	High (design-sensitive)
Public–Private Partnerships	Moderate (2–4×)	Moderate	High	Low–Moderate	Moderate
Advance Market Commitments	High (4–8×)	High (if well-specified)	Low–Moderate	Low	Highest
Milestone-Based Contracts	Moderate (2–3×)	High	Low	Low	High

Eff. Multiplier = Effective Multiplier per public dollar committed. Assessments are qualitative; ranges reflect parameter sensitivity.

6. Results and Instrument Comparison

Direct public expenditure generates the most predictable near-term demand stimulus and carries the highest realization probability but produces the lowest private leverage ratio. It is best suited to early-stage phases where no private precedent exists and demand uncertainty is too high for other instruments to operate.

Loan guarantees and PPP structures offer superior leverage but are sensitive to contract design. Poorly specified risk-sharing terms reduce realization probability and increase effective delay, the most common failure mode in infrastructure PPPs documented by Engel, Fischer, and Galetovic [7]. When structured carefully around verifiable output metrics, they achieve high effective multipliers.

Advance market commitments produce the highest effective multipliers by simultaneously reducing demand uncertainty, the principal barrier to private ISRU investment, and maintaining incentive compatibility. Because AMC commitments are contingent on performance, they do not expose public funds to the cost overruns characteristic of direct development contracts. The main implementation challenge is defining credible and verifiable output metrics for ISRU products (propellant purity, delivery cadence, storage capacity) in advance of market formation.

Milestone-based contracts occupy a productive middle ground: moderate leverage, high realization probability, and low implementation delay make them well-suited to early-stage technology demonstration where ISRU product specifications are not yet stable. The Commercial Lunar Payload Services (CLPS) model provides an existing institutional precedent.

A systematic trade-off emerges between leverage and delay: instruments that mobilize more private capital tend to require longer structuring timelines, implying that the optimal financing mix depends on the urgency of near-term milestones versus long-run capital efficiency. For programs with near-term demonstration requirements, such as propellant production ahead of crewed lunar landings, high-realization, low-delay instruments should be prioritized even at the cost of lower private leverage.

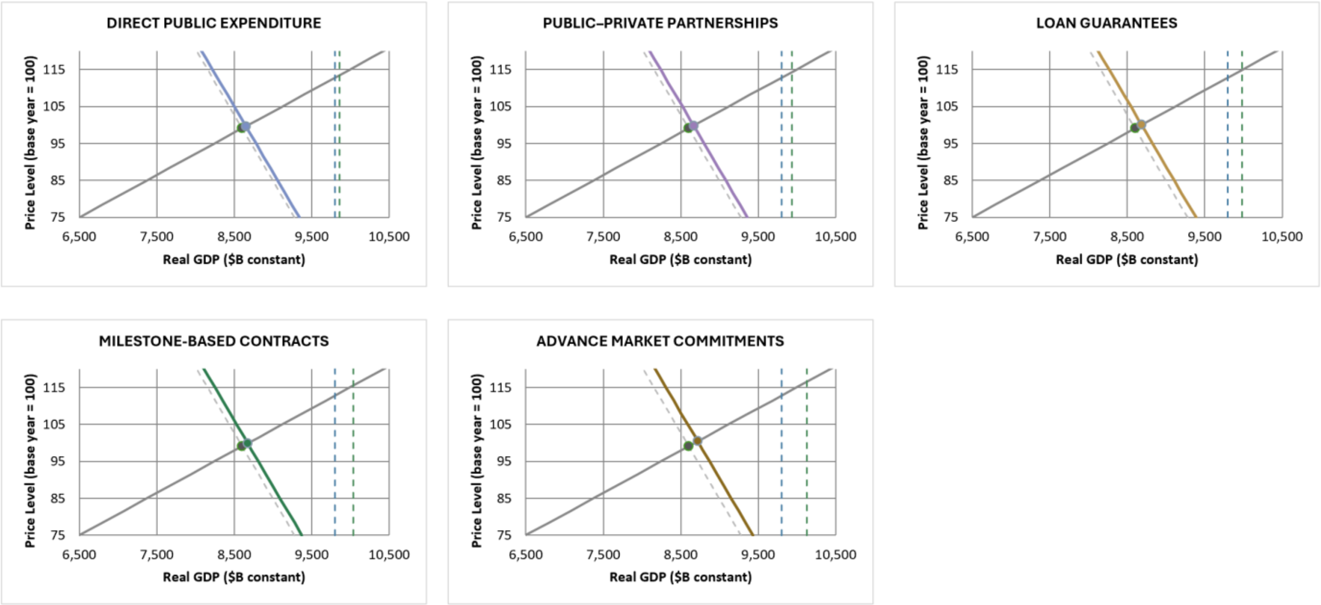
Table 2 presents quantitative baseline estimates for k_T and β_T at baseline parameter values (MPC = 0.75, L_T and φ_T at historical midpoints). These values make explicit the quantitative claims embedded in the qualitative rankings of Table 1. The k_T column gives the effective multiplier per public dollar committed; β_T gives long-run spillover intensity. Section 8 reports robustness of these results across the full parameter space.

Table 2. Quantitative Baseline Results (MPC = 0.75)

Instrument	L_T	φ_T	k_T (baseline)	k_T rank	β_T (baseline)	β_T rank
Advance Market Commitments	6.0×	0.82	**19.68**	**#1**	**0.080**	**#1**
Loan Guarantees	4.0×	0.62	9.92	#2	0.035	#3
Milestone-Based Contracts	2.5×	0.84	8.40	#3	0.055	#2
Public–Private Partnerships	2.5×	0.70	7.00	#4	0.030	#4
Direct Public Expenditure	1.15×	0.92	4.23	#5	0.018	#5

$k_T = k_{base} \times L_T \times \varphi_T$; $k_{base} = 4.0$ at MPC = 0.75. Loan guarantees rank #2 on k_T at baseline but #3 on β_T, reflecting lower innovation incentive content. Parameter ranges and robustness checks reported in Section 8.

Figure 1. Short-Run AD Shift and Long-Run LRAS Spillover by Financing Instrument



7. Policy Implications

These results have direct relevance for the design of public programs supporting lunar ISRU development.

First, the dominance of demand-side uncertainty as a barrier to private investment suggests that AMC-type instruments merit serious consideration from space agencies, despite their novelty in the space sector. The pneumococcal vaccine AMC administered by Gavi provides a replicable institutional template, and ISRU outputs, propellant, oxygen, regolith-derived materials, are sufficiently specifiable to support AMC contract design as mission architectures mature.

Second, the leverage-delay trade-off implies that financing strategy should be staged rather than uniform. Early phases should rely primarily on direct expenditure and milestone-based contracts to achieve demonstrated capability with high realization probability. As technology matures and output specifications stabilize, loan guarantees and AMC structures become feasible and can substantially reduce the public cost per unit of ISRU investment mobilized.

Third, the framework underscores that financing structure and market design are as consequential for ISRU development outcomes as the underlying technology choices. Instrument selection should be treated as a first-order policy variable, not an implementation detail, in national space strategies and multilateral coordination agreements. This is consistent with Mazzucato's broader argument that mission-oriented investments require active public co-investment in market creation, not merely subsidized risk transfer [9].

Finally, the declining trend in space investment spillover intensity documented by Cropper et al. [2] suggests that the economic case for ISRU investment cannot rest on passive diffusion. Instrument design should actively incentivize domestic industrial participation, open-publication requirements, and cross-sector technology transfer, conditions that historically have been associated with higher β_T and larger long-run aggregate supply effects.

8. Sensitivity Analysis and Robustness

The baseline results in Table 2 rest on parameter values calibrated from terrestrial analogues rather than ISRU-specific data. Whether the qualitative ranking, particularly the dominance of AMCs on both k_T and β_T , survives parameter variation is a central robustness question. Three scenarios are defined for each of the three key parameters. For MPC: 0.60 (conservative, high import leakage), 0.75 (baseline), and 0.85 (high, strong domestic content). Leverage (L_T) and realization factor (φ_T) ranges are drawn from analogous programs: AMC leverage anchored to the Gavi pneumococcal AMC (empirical range 4–6×), milestone contracts to NASA COTS and CLPS, and loan guarantees to the DOE Loan Programme Office.

8.1 k_T Sensitivity: MPC × Leverage

Table S1 reports k_T and instrument rankings across a 3×3 grid of MPC and leverage scenarios, with φ_T held at baseline. AMCs rank first in all nine combinations. At the conservative end (MPC = 0.60, low leverage), k_T for AMC is 6.15 , still nearly 2× the baseline direct expenditure value of 3.68. Milestone contracts rank second in seven of nine combinations, displaced only when loan guarantees are evaluated under high leverage. Direct expenditure ranks last in all nine scenarios, confirming its position is structural (bounded leverage, $L_T \approx 1.0$–1.3×) rather than a calibration artifact.

Table S1. k_T Sensitivity: MPC × Leverage (φ_T at baseline; top three instruments per cell)

Leverage	MPC = 0.60 (Conservative)			MPC = 0.75 (Baseline ★)			MPC = 0.85 (High)		
k_T [rank]	AMC	Milestone	Loan Guar.	AMC	Milestone	Loan Guar.	AMC	Milestone	Loan Guar.
Low	**6.15 [#1]**	3.15 [#2]	3.10 [#3]	**9.84 [#1]**	5.04 [#2]	4.96 [#3]	**16.40 [#1]**	8.40 [#2]	8.27 [#3]
Base ★	**12.30 [#1]**	5.25 [#3]	6.20 [#2]	**19.68 [#1]**	8.40 [#3]	9.92 [#2]	**32.80 [#1]**	14.00 [#3]	16.53 [#2]
High	**16.40 [#1]**	7.35 [#3]	9.30 [#2]	**26.24 [#1]**	11.76 [#3]	14.88 [#2]	**43.73 [#1]**	19.60 [#3]	24.80 [#2]

★ = baseline scenario. Gold = #1 rank. PPPs and Direct exp. omitted for readability; both rank #4 and #5 respectively in all nine combinations.

8.2 Realization Factor (φ_T) Sensitivity

Table S2 isolates φ_T variation with MPC and L_T at baseline. AMC retains its #1 ranking even under pessimistic realization ($\varphi_T = 0.68$, $k_T = 16.32$) because leverage dominates. The critical finding is the sensitivity of loan guarantees: under low realization their k_T falls below that of milestone contracts, reversing their relative ranking. This makes loan guarantees the most institutionally demanding instrument in the set , their performance is contingent on credible monitoring and contract enforcement, not just headline leverage ratios.

Table S2. k_T Sensitivity: Realization Factor φ_T (MPC = 0.75, L_T at baseline)

Instrument	Low φ_T (pessimistic)			Base φ_T ★			High k_T
	φ_T	k_T	Rank	φ_T	k_T	Rank	k_T (High)
AMC	0.68	**16.32**	**#1**	0.82	**19.68**	**#1**	22.08
Milestone Contracts	0.72	7.20	#2	0.84	8.40	#3	9.30
Loan Guarantees	0.40	6.40	#3	0.62	9.92	#2	12.80

★ = baseline. Loan guarantee rank of #3 under low φ_T vs. #2 at base reflects execution-quality sensitivity. PPPs and Direct exp. rank #4 and #5 in all scenarios.

8.3 β_T Spillover Sensitivity and Structural Separation

Table S3 reports low, baseline, and high β_T estimates for each instrument. The critical finding is that the full scenario range for AMC (0.055–0.105) does not overlap with the full range for direct expenditure (0.010–0.025). This separation is structural , it reflects the difference in how the two instruments interact with the innovation process, not a consequence of the baseline calibration choice. AMC contracts, by conditioning payment on demonstrated performance against a specified output target, create endogenous incentives for R&D investment and knowledge diffusion that direct procurement does not. This mechanism is consistent with Kremer, Levin, and Snyder [8] and Mazzucato [9]. Milestone contracts and loan guarantees occupy intermediate positions; PPPs show partial overlap with direct expenditure at the low end of both instruments' ranges.

Table S3. β_T Long-Run Spillover Sensitivity (sorted by baseline β_T, descending)

Instrument	β_T Low	β_T Base ★	β_T High	Range (±)	Non-overlap w/ Direct exp.?
AMC	0.055	**0.080**	0.105	±0.025	**Yes ✓ , no overlap in any scenario**
Milestone Contracts	0.035	**0.055**	0.072	±0.018	**Yes ✓**
Loan Guarantees	0.022	**0.035**	0.048	±0.013	**Yes ✓**
PPPs	0.018	**0.030**	0.042	±0.012	Partial overlap at low end
Direct Public Expenditure	0.010	**0.018**	0.025	±0.008	*(reference instrument)*

★ = baseline. AMC low-scenario β_T (0.055) exceeds Direct exp. high-scenario β_T (0.025) in every scenario. Separation is structural.

8.4 Summary of Robustness Findings

Three conclusions from the sensitivity analysis are robust across all parameter combinations evaluated. First, AMC ranks #1 on k_T in all 18 MPC × leverage combinations, and its β_T range does not overlap with that of direct expenditure in any scenario, the AMC dominance is robust on both the short-run multiplier and the long-run spillover dimension. Second, loan guarantees are the most parameter-sensitive instrument: they rank above milestone contracts under high leverage and high realization, but fall below them under poor execution, making institutional monitoring capacity the decisive variable for that instrument class. Third, direct expenditure ranks last on k_T in every scenario, a structural consequence of bounded leverage, while remaining the indispensable anchor instrument for activating all other financing structures in early phases of ISRU development.

9. Limitations

This analysis is subject to several limitations. ISRU technologies remain at low technology readiness levels, and future demand for cislunar propellant and materials is difficult to project. The parameter values used in the framework are stylized and drawn from terrestrial infrastructure analogues rather than from direct ISRU empirical data, which does not yet exist at scale. The analysis abstracts from political economic constraints, including congressional appropriations cycles, treaty obligations under the Outer Space Treaty, and bilateral coordination requirements, that may significantly affect which instruments are practically available to space agencies.

The framework is also static in its current form, treating each instrument in isolation rather than modeling the dynamic interactions that arise when instruments are combined or sequenced. In practice, the optimal financing structure for ISRU will likely be a portfolio of instruments deployed across a development pipeline spanning 10–30 years, with transitions between instrument types as technology matures. Extensions of the framework to dynamic and sequential settings represent a priority for ongoing work.

10. Conclusion

ISRU infrastructure presents a financing challenge with potentially significant macroeconomic implications. While the technological case for ISRU has been extensively analyzed, the choice of financing structure may be equally important in determining whether investment occurs and whether broader economic benefits are realized, particularly given the evidence that space investment spillovers have weakened since the Apollo era.

This paper develops a tool-adjusted multiplier framework that links standard macroeconomic analysis to the comparative evaluation of five financing instrument categories. The framework demonstrates that instrument choice materially affects investment magnitude, timing, and economic efficiency, independent of the underlying technology pathway. Advance market commitments and milestone-based contracts emerge as the most efficient instruments for mobilizing private capital at acceptable public risk, while direct expenditure remains essential for early-stage demand creation.

The framework is designed to be extensible to Mars and asteroid resource scenarios and to support quantitative modeling as empirical data on ISRU costs and demand matures. More immediately, it provides a structured basis for evaluating financing proposals in national lunar programs and for designing the market mechanisms that will determine whether the cislunar economy's resource infrastructure is built on public subsidy alone, or on a durable foundation of mobilized private capital.

References

[1] Corrado, L., Grassi, S., and Paolillo, A. (2025). Technology Spillovers from the Final Frontier: A Long-Run View of U.S. Space Innovation. NIESR Discussion Paper No. 573 / CEIS Research Paper No. 609. National Institute of Economic and Social Research / University of Rome Tor Vergata.

[2] Cropper, M., Corrado, C., and Rao, G. (2023). Space Exploration and Economic Growth: New Issues and Horizons. Proceedings of the National Academy of Sciences, 120(43).

[3] Deleidi, M. and Mazzucato, M. (2021). Directed Innovation Policies and the Supermultiplier: An Empirical Assessment of Mission-Oriented Policies in the US Economy. Research Policy, 50(2).

[4] Jones, C. et al. (2020). Cost Breakeven Analysis of Lunar In-Situ Propellant Production for Human Missions to the Moon and Mars. NASA Technical Reports Server (NTRS).

[5] Paulson, M., Balchanos, M., and Mavris, D. (2024). Simulating Economic and Environmental Trade-Offs in Lunar Water Supply: ISRU vs. Earth Resupply. Georgia Institute of Technology / ResearchGate.

[6] Kornuta, D. et al. (2019). Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production. Reach: Journal of Space Exploration Policy, 13.

[7] Engel, E., Fischer, R., and Galetovic, A. (2013). The Basic Public Finance of Public–Private Partnerships. Journal of the European Economic Association, 11(1), 83–111.

[8] Kremer, M., Levin, J., and Snyder, C. (2020). Advance Market Commitments: Insights from Theory and Experience. AEA Papers and Proceedings, 110, 269–273.

[9] Mazzucato, M. (2018). Mission-Oriented Innovation Policies: Challenges and Opportunities. Industrial and Corporate Change, 27(5), 803–815.

[10] Mazzucato, M. and Semieniuk, G. (2018). Financing Renewable Energy: Who is Financing What and Why It Matters. Technological Forecasting and Social Change, 127, 8–22.

[11] NASA (2020). Artemis Plan: NASA's Lunar Exploration Program Overview. National Aeronautics and Space Administration.

[12] ESA (2022). Moonlight Initiative: Lunar Communications and Navigation Services. European Space Agency.