Public Goods and the Evaluation of Complex Outcomes in Space Exploration

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Abstract

This paper proposes a fusion of two economic paradigms, the economic goods framework and Total Economic Value (TEV), to structure the evaluation of complex space programs. It illustrates the dynamic relationship between different types of economic goods, including the institutional integration of manufactured private goods into public goods. Drawing on methodologies from environmental economics, particularly categories such as option and existential values, the approach addresses less obvious outcomes of space activities that nonetheless significantly shape public perceptions and judgments of program effectiveness. Current institutional developments in space activities demonstrate the relevance of economic goods and value epistemology as a framework for understanding and designing space policy.

Keywords

existential value, merit good, private good, public good, space exploration, total economic valuation

Abbreviations

EU	European Union
GPS	Global Positioning System
ISS	International Space Station
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
OST	Outer Space Treaty
PGIC	Public Goods Input Chain
PNT	Positioning, Navigation, Timing
TEV	Total Economic Valuation

1 Introduction

Since the first space launches in the late 1950s, the space industry has evolved into a network of actors shaping interconnected value chains that form the core structure of the space economy.

The growing dependence of global digital infrastructure on space assets [1], combined with outer space's value as both a source of human inspiration and an infinite resource for development [2], underscores the need to methodically integrate the space economy into the global economic system [3]. The conceptual foundations of this integration include measuring the size of the space economy and understanding how its outcomes are woven into the fabric of global purposeful activities.

Recent comprehensive works on measuring the global space economy include the synthesis by Jones and Weeden [4], which compiles and compares methodologies and metrics, and Crane et al. [5]. Bryce Technologies' model [6] of the space economy, featured in the Satellite Industry Association's State of the Satellite Industry Report, estimates the global space economy at approximately $415 billion, with more than 70% attributed to commercial space services and equipment, while the remainder derives from government space budgets.

The economics of commercial space equipment and services parallel those of the international information and communication sector. Public space expenditures also generate products and services, whether contracted out or directly produced by entities like NASA, but their ultimate outcomes differ from private-sector value chains. Turning to one of the fundamental concepts of microeconomics, the theory of economic goods, we identify most outcomes of public-sector space activities as pure or impure public goods [7], while noting that not everything produced by the public sector is a public good, and not all public goods originate from the public sector. Given that the relationship between public goods and the public sector is not one-to-one, we examine more closely the place and role of public goods within the broader context and outcomes of space activities.

The necessary distinction of the public good concept in studying the space economy includes differentiating naturally existing resources and human-made products. The "space as commons" framework builds on Ostrom's fundamental classification [8] and has been further developed in numerous works, including a critical analysis of space-related aspects by Hertzfeld et al. [9] and a recent overview by Patton [10]. While this perspective is essential for examining the legal and economic foundations of space resource utilization [11], our focus will be on the second aspect, the classification of space-related goods as human-made rather than naturally occurring.

Some sources [12-14] treat space exploration itself as a public good, while others [15] emphasize that it generates specific types of public goods through various applications and spillovers.

The additional motivation for categorizing space industry output stems from the historical trajectories of global space programs and their resulting intersectoral developments. The increasingly privatized approach in the U.S. [16], along with the specific institutional dynamics in Russia [17] and, to some extent, in India [18], highlights the need for a more transparent framework to structure the goods and value generated by space activities, particularly in space exploration. Given the growing interdependence between public goal-setting and corporate implementation, a more precise delineation of goods produced and their creators is essential. A good example is the concept of making humankind a multiplanetary species [19], where corporate strategizing overlaps with the pursuit of pure public good.

We apply approaches for structuring public goods from environmental and historical preservation domains [20] to space activities, aiming to improve analytical transparency and resolution. We find the concept of total economic value [21], including non-use and option values, relevant for assessing most intangible outcomes of space exploration.

This paper contributes to conceptual/theoretical research across space policy, institutional economics, and public value theory. It builds analytical clarity by synthesizing and adapting frameworks to the evolving space sector, constructing a unified model for interpreting the generation and evaluation of space economy goods across public and private domains, rather than offering empirical data or normative policy recommendations.

The text is structured to guide the reader from a general problem setting toward a detailed analytical framework for understanding and evaluating the diverse outputs of space-related activities. Section 2 presents a selective literature review, highlighting relevant economic, institutional, and policy-oriented approaches to the recognition of economic goods and value, with a particular emphasis on the space economy.

Section 3 proposes a typology of goods produced by space missions, discusses externalities and public good characteristics, and introduces the Public Goods Input Chain (PGIC). Section 4 turns to the Total Economic Value (TEV) framework and adapts it to the space context.

Concluding Section 5 reflects on the institutional implications of the goods-generating system's evaluation, summarizes the main contributions, and suggests directions for further research development.

2 Literature Review

Analyzing goods generation in the space economy and associated value-for-money involves two major components. The simpler, more transparent one is associated with the provision of intended goods and services through ordinary contractual transactions [22]. In these cases, the intended result is fully captured by the delivered product or service, and the value created is realized within the completed transaction. However, such activities may also produce externalities that extend their effects beyond direct exchange. When consumers are households or businesses, the intended value chains end here, and evaluation relies on straightforward market indicators [23]. However, this paper focuses on space exploration, understood as activities oriented toward discovery rather than application[1] and funded primarily, though not exclusively, from public expenditure. In most cases, the state acts as both initiator and primary customer, defining objectives and financing execution through public programs. Here, the intended result extends beyond the supplied goods and services, encompassing collective outcomes such as scientific knowledge, cultural or strategic gains, or other forms of non-market value.

When contract deliverables are sold to the state as part of national space exploration or defense programs within the public goods input chain (see Subsection 3.2), the outcomes require more specialized evaluation. Accordingly, specialized value metrics are critical for outcomes that are not delivered directly through transactions between economic actors.

The usefulness of space exploration can be assessed through several distinct approaches. These approaches generally examine the generation of effects that vary in their tangibility and measurability, aiming to articulate the "value for money" produced by exploration efforts [24]. Four dominant perspectives frame this value by their effects, each corresponding to a distinct type of good.

The first approach considers the direct productivity. It posits that space exploration yields outcomes justifying investment. Fundamental scientific knowledge from exploration missions is a central example [25, 26]. Ideally, these outcomes should align with those of other endeavors in the public good domain. For instance, scientometric efficacy, measured by the number and quality of research publications, is used to compare space research missions with comparably costly megascience projects such as the Large Hadron Collider or the International Thermonuclear Experimental Reactor [27].

The second approach deals with existential productivity. It suggests that the very conduct and intensity of space exploration by a nation or international body serves as a public good, regardless of how the results are measured. This value arises from societal perceptions: space exploration enhances national prestige, projects symbolic leadership, and contributes to broader dimensions of global competitiveness [28, 29]. The existential metric is either applied independently or serves as a component of the TEV (total economic value) measurement [20], which we further discuss in Section 4.

A third approach, often implicit in discussions of long-term exploration, views it as expanding the domain of future utility – effectively generating potential value by extending the scope of human activity. Crucially, this future use remains fundamentally indefinite. Space exploration is often paralleled with American expansion into the mainland, associated with the frontier concept and the broader idea of Manifest Destiny [30]. Echoing this, Donald Trump invoked 'our manifest destiny into the stars' in his

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[1] The Oxford English Dictionary defines exploration as 'the action of travelling to or around an uncharted or unknown area for the purposes of discovery and gathering information' (https://www.oed.com/search/dictionary/?scope=Entries&q=exploration). Thus, space exploration encompasses human spaceflight and basic space research but excludes space applications.

2025 inaugural address [31]. The frontier is frequently cited as a symbolic foundation of humanity's innate drive to explore, expand, and establish [32]. Yet the originator of the frontier thesis, Frederick J. Turner [33], emphasized its instrumental value, writing: '… The people of the United States have taken their tone from the incessant expansion which *has not only been open but even forced upon them*.' (italics added — D.P.) Hence, acknowledging the historical continuity in territorial expansion into space does not preclude the need to articulate its concrete motivations. In cases where these motivations are not associated with particular utilitarian goals, as in today's space exploration, one might consider them to embody option value, promising benefits deferred to an indefinite future. It is worth noting that the frontier itself is no longer universally perceived as positive. Schwartz [34] argues that 'there is much room for skepticism about the role of the space frontier with respect to cultural diversity, scientific innovation, and democratic governance.' Moreover, these days the frontier narrative is often critically associated with colonialist thinking [35].

Finally, the external productivity approach attributes the value of space exploration to the positive externalities it generates, such as improvements in infrastructure, education, scientific capability, and technological innovation. These second-order effects often form the practical justification for public funding, particularly when the direct utility of exploration may appear distant or uncertain [36].

These four perspectives are analytically distinct yet often overlapping; individual programs can contribute to multiple value categories.

In this article, we rely on the theory of economic goods, especially in terms of public goods, to jointly analyze the products and values produced during space activities. The theory of public goods, as originally formulated by Samuelson [37] and expanded by Musgrave [38], remains foundational for understanding the government's role in providing goods that markets typically under-supply – namely, those characterized by non-rivalry and non-excludability, such as basic scientific research, free-for-all global satellite navigation service, and planetary protection [39-48]. We consider space public goods in more detail in Section 3.

In general, it is interesting to follow the different views in two major collective monographs published three decades apart. The seminal Space Economics compendium [49] mentions a concept of public good only in the context of the Landsat privatization [50] and also as part of "quasi-public good" construction when discussing the industrial spinoffs [36], while the contributors of recent Oxford Handbook on New Space Economy [51] broadly refer to this category when discussing the role of economic sectors and digital economy.

Although linking space activities with the concept of public good is common, the interpretation varies based on each researcher's approach, assuming they even recognize a public goods category (not all do; see, for instance, [52, p.137]) for a sharp criticism of the public good category as such). Given increasingly complex, interconnected intersectoral relationships [53], we argue categorical harmonization and transparency are essential for theoretically understanding the space industry's economic output.

In the next section we continue to economic goods, the first critical element of our view at space economy structuring.

3 Classifying Goods in the Space Economy

Section 3 proposes a typology of goods produced by space missions, discusses externalities and public-good characteristics, and introduces the Public Goods Input Chain (PGIC) as an analytical tool to trace how combinations of private and intermediate outputs may culminate in public value.

3.1 Conceptual and Methodological Foundations

A widely adopted classification of economic goods is presented by Ostrom [8, 41] in the form of a quadrant chart. This matrix classifies private goods, public goods, club goods, and common-pool resources (commons) based on two attributes: consumption rivalry and excludability. A good is excludable if individuals can be prevented from consuming it. A good is rivalrous if consumption by one individual diminishes others' ability to consume it [44]. Table 1 summarizes four basic types of goods and provides the most obvious examples from the space economy domain.

Table 1. Quadrant of economic goods with example produced goods from the space domain

	Rivalrous	Non-rivalrous
Excludable	**Private Good** Personal satellite communication Commercial Earth remote sensing Space tourism,	**Club Good** Direct-to-home TV Satellite navigation differential
Non-excludable	**Commons** (not produced goods)	**Public Good** National security Fundamental space research Civilian navigation field

Even if a public good is most often provided by the state, this classification reflects the goods' nature, not the economic sector (public or private) that produces or manages them.

Goods-based typology is helpful for analyzing key aspects of the modern digital economy [54], the organization of science [55], global development [56], and the governance of shared resources [57]. These areas are directly relevant to the analysis of space economics [58].

Applying this quadrant model to space, however, requires refinement. Specifically, we address the distinction between public goods and club goods when analyzing complex domains such as space activities, national defense, or education. Although such services are often considered public goods [7], examples such as national defense – clearly non-global – and space programs pursued for national prestige [59] suggest that their benefits are limited to specific populations (typically citizens). Pirtle [35] cites the original NASA mandate asking: 'How should NASA work to the 'benefit of all [humankind]'… Who is included in that statement and how should they be involved?'

Territorial scope of a good's applicability is not an explicit criterion in the standard rivalry-excludability matrix, though it often appears implicitly in related discussions. Beetsma [60] discusses a European defense as 'a public good when the public of reference is the citizens of the EU.' The idea of 'public of reference' in conventional public goods, even if not identified as such, has led to the development of the global public goods framework [43, 61], which explicitly removes these constraints. It has also stimulated interest in regional public goods [62].

Critically, territorial limitation for public goods functions similarly to club good excludability [63]. In both cases, access to a non-rivalrous good is limited to a defined group: citizens of a nation, inhabitants of a country, residents of a geographic area (as with street lighting), or other defined populations. In the case of limited (non-global) public goods, this boundary is set primarily by physical factors (geography); in club goods, it is enforced through designed exclusion. Thus, we define limited public and club goods as non-rivalrous and non-excludable within the group limited by either physical access (for limited public) or designed exclusion (for club)[2].

There is also an additional category of merit goods. We follow Fioritto & Kollintzas's [64] definition: merit goods are goods 'provided by the government on paternalistic grounds (e.g., individuals ought to consume them even if they (could) would not, acting on their own self-interest).' Here, merit goods are an intentionally produced subset of the full continuum of public goods, including government-owned space infrastructure and science research data.

On this basis, we further consider two types of space-related public goods, including territorially limited public goods and club goods, which may both be regarded as impure public goods in this context, which differ by their production value chains. The first type, *merit public goods*, includes public goods that are target outcomes of contracts and programs, most often government ones. The second type, *spillover public goods*, includes

[2] We do not delve into the subtle issues of limited public and club good differentiating for more complicated cases, for instance, when citizenship is a limiting factor and recommend insightful work [63] to those interested.

public goods generated as externalities, the indirect results of other goods' production. An example is the general stimulation of national economic activity resulting from space industry operations.

While originally linked to addressing market failures [65], recent perspectives emphasize a proactive role of the 'entrepreneurial state' in producing certain goods and assuming risks associated with innovation [66]. Given the vast scope and lack of consensus regarding the state's role, this paper focuses on the constructive aspects of goods generation in the space sector, drawing on empirical observations of existing projects and programs rather than analyzing sectoral dynamics.

Goods structure details what is produced; value frameworks detail the purposes for production [67]. The value of produced private goods is relatively straightforward, typically defined by market transactions. Evaluating public goods, both pure and impure, is more complex. Two well-established categories of public goods are national defense and fundamental science. Although less tangible than satellite application-related private goods, both have a long tradition of value-for-money assessment based on the decades-long (if not centuries-long) methodological base of public finance [68, 69].

However, the value of public space activities extends beyond defense, basic research, and industrial externalities. There is more to be considered. Scholars propose various paradigms for holistically evaluating space exploration beyond traditional metrics. Baum [70] introduces ethical dimensions, while Lawrence et al. [71] incorporate considerations of space environmentalism. In this paper, we propose a framework to discuss the full continuum of values delivered to different beneficiaries by goods generated through space activities, with particular emphasis on the 'hidden' value of space exploration that traditional paradigms do not capture.

3.2 Institutional Integration of Merit Public Goods

Private and public goods differ in consumption: non-rivalry and non-excludability (the latter applies only to public goods) define them. Despite these differences, both private and public goods must be produced first. Production involves both the physical deployment of infrastructure and the creation of an institutional environment governing consumption through specific rivalry and excludability attributes. In the space economy, a good's nature is shaped by consumption modifications at the value chain's end. Complex, multilayered technical and organizational systems in Earth observation, satellite communication, or global navigation may yield component public goods that serve national defense or commercial markets, depending on how procurement and distribution are fine-tuned [72].

The physical deployment and operation of infrastructure producing public or private goods do not fundamentally differ, especially given the growing role of public-private partnerships and Anything-as-a-Service models [73]. Typically, the industry produces goods and services that are private goods by nature. In the most common case of merit good production, governments contract with industry to produce these goods/services, add public-sector value (e.g., via state-owned enterprises or military organizations), and convert the result into public goods (pure or impure).

We introduce a new category: Public Goods Input Chain (PGIC), a sequence of intermediate goods, services, and resources required to produce a public good, excluding the final institutional integration phase that converts these inputs into the publicly accessible, non-excludable final good. It encompasses all material, technological, and human capital essential for creating the public good.

The PGIC is instrumental in clarifying the separation between the tangible production of public goods and the institutional frameworks that govern their consumption. Traditional economic models often blur this line, making valuation difficult. We use the PGIC framework further in discussions of value chain structures in the space economy.

While not ontologically novel, PGIC's utility lies in differentiating the production segment of the public good's value chain from the institutional phase that establishes the consumption mode, thereby defining whether the created good is private, public, or club.

PGIC highlights elements directly involved in production, such as infrastructure, technology, labor, and raw materials, before incorporation into policy/governance frameworks making the good available to society. Private firms or state-owned enterprises typically produce these intermediate goods; the final public good benefits all individuals within the 'public of reference.'

The reusable Crew Dragon spacecraft demonstrates how a single production and operational chain can serve different institutional contexts. The Public Goods Input Chain (PGIC), covering design, manufacture, integration, and launch, stays technically uniform across missions, though individual procedures and objectives vary.

Under NASA's Commercial Crew Program [74], Crew Dragon flights support ISS operations within a government-led PGIC that sustains collective human-spaceflight infrastructure. Within this setting, commercial activities such as Space Tango's biotechnology work, Redwire's manufacturing facilities, and the iBOSS modular system illustrate how private actors function inside a publicly managed research framework through the National Laboratory mechanism.

Privately financed missions such as Inspiration4 [75] and Polaris Dawn [76] use the same PGIC but combine private outcomes - corporate visibility, technological validation, and mission participation - with deliberately public components such as scientific and biomedical research or philanthropic fundraising supporting merit- or public-good-oriented activities. Educational and outreach effects are treated here as co-produced externalities, positive spillovers accompanying public communication and engagement.

The PGIC concept, therefore, shows that technically similar supply chains can yield different mixes of intentionally produced goods, depending on institutional integration, the "last link" connecting production to its final public or private outcomes.

3.3 Externalities and Spillover Public Goods

Spillover public goods arise as side effects (externalities) of public or commercial programs.

The GPS satellite navigation system exemplifies the transition from a club good to a public good. Initially a military club good providing positioning, navigation, and timing (PNT) signals, GPS gained public good status after Reagan permitted commercial airline use (1983) and Clinton stopped degrading civilian accuracy (2000) [77]. GPS as a public good might be considered a positive externality resulting from the military system operations.

Benefits (e.g., free navigation) spill over to non-contracting parties (global population, businesses) who do not pay for the development and operations. This unaccounted benefit is an externality, an unintended side effect of the primary contract purpose (national defense), additionally adopted for civilian/commercial use without compensating original stakeholders.

Internalizing this externality may involve licensing agreements or user fees, public-private partnerships to share costs and benefits, or taxes or fees on companies heavily relying on the publicly built system for commercial operations.

3.4 Typology of Outputs in the Space Economy

Figure 1 illustrates the genesis of major types of goods in the space economy, originating from ‘physically manufactured’ core private goods. Beyond merit public goods, we include two types of spillover goods. Both arise during the core private goods manufacturing. Spillover public/club goods – accessible beyond core private good customers and contractors – emerge as positive externalities [63]. In contrast, spillover private goods relate to industry development as a side effect of producing core private goods [36].

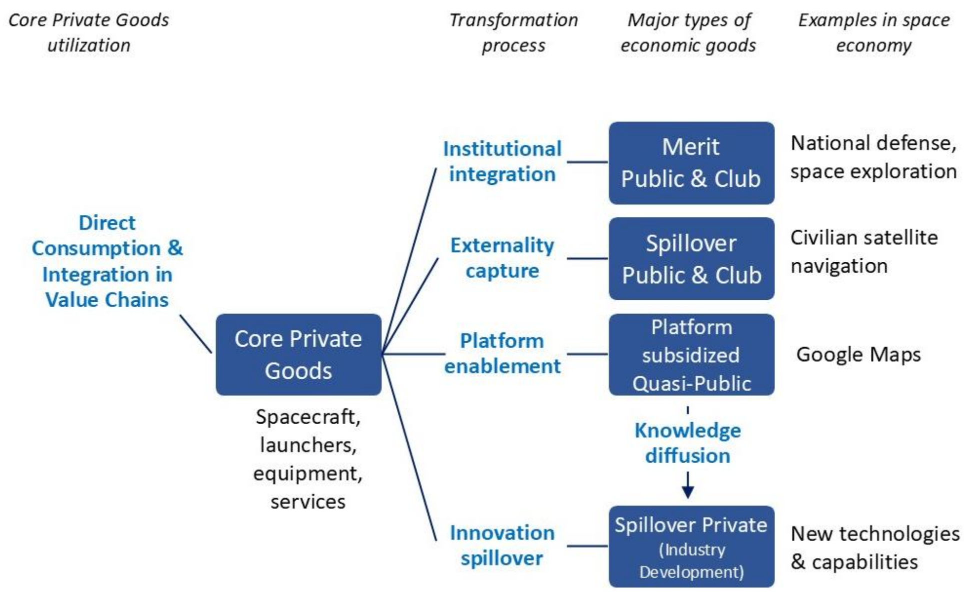

Figure 1. Economic goods in the space economy

A special category is platform-subsidized quasi-private goods. These services are offered free or at low cost via a platform, financed indirectly (e.g., through advertising or data licensing), fostering broad ecosystems. Google Maps, closely related to Earth remote sensing, is a well-known example. We include this category due to its growing prominence and its classificatory complexity within the traditional public/private framework.

The next session considers values and valuation and introduces our suggestion of adopting the Total Economic Value framework. At the end of Section 4, we use the presented goods structurization for cross-referencing with values.

4 Valuation Through the Total Economic Value (TEV) Framework

Section 4 turns to the Total Economic Value framework, adapting it to the space context and expanding it to capture both direct and indirect values, including option, heritage, existential, and bequest values.

4.1 Applying TEV to Space Economy Goods

Beyond the tangible outcomes like commercial or military use, space endeavors produce scientific knowledge, indirect effects (both internal and external, as noted by Bach et al. [36] and others), and complex public goods. These public goods range from national pride to comprehending humankind’s unlimited developmental future in space.

This value arises from goods generated either as externalities of specific projects or intended outcomes of activities, most often by the public sector, which take the form of impure public goods limited by access (Section 3). Despite frequent references to education, inspiration, and intangible benefits linked to space programs, these elements remain conceptually underdeveloped.

Comprehensive identification and evaluation of indirect value are crucial: they underpin the continued legitimacy of the public sector as a core actor in space exploration. A robust framework accommodating non-market effects tailored to the space domain, but it must remain compatible with evaluative methodologies used in other policy fields.

Given the acknowledged importance of the existential dimension of space economy [2, p.1], along with other forms of indirect value previously discussed, we use the framework of Total Economic Value.

Figure 2 summarizes the conceptual relationships among direct and indirect components of TEV relevant to space activities; it does not imply a quantitative aggregation procedure, which would require a separate methodological framework.

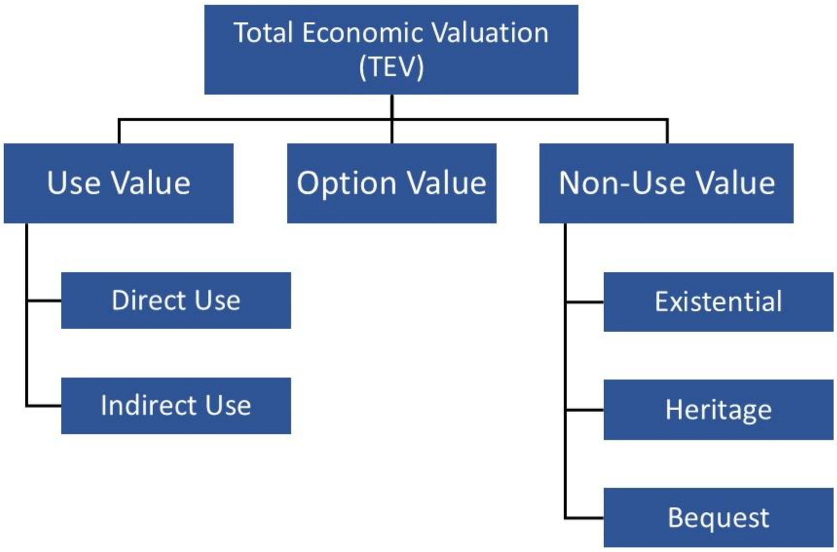

Figure 2. Framework of Total Economic Value (compiled from [20, 21])

TEV accounts for tangible benefits gained from the direct and indirect use of goods and services, and intangible benefits that exist regardless of direct consumer engagement [21, 78]. Traditionally applied to environmental considerations within cost-benefit analyses of development projects [79], it also has the potential for evaluating other complex socioeconomic phenomena.

It provides a structured framework for assessing the full range of value generated by goods and services, especially when traditional market valuation fails to capture their broader societal impact. TEV distinguishes **use values** (benefits derived from actual or potential use) from **non-use values** (importance of a good or service independent of its consumption).

Use values are typically divided into two categories. **Direct use values** arise from immediate interactions (e.g., utility gained from using a service, product, or public infrastructure). **Indirect use values** capture secondary benefits (e.g., environmental, educational, or systemic advantages from a good's existence).

Option value is the value of preserving the possibility of future use.

Non-use values are independent of use: **existence value** (knowing something exists), **bequest value** (leaving it for future generations), **heritage value** (its relevance to present identity or continuity). Together, these categories ensure that the TEV framework encompasses both measurable utility and more abstract, but socially relevant, sources of value.

A novel aspect is the recognition that goods that give rise to all included types of value can be purposefully generated, rather than treated as given inputs. Thus, their value not only justifies efforts to preserve them but also supports investing in their creation.

Applying this framework provides a holistic perspective on the value created by space-related activities. This structured approach is crucial for understanding consumption patterns and evaluating long-term economic impacts beyond immediate commercial outcomes.

Use values in private and public goods are a practical category for assessing the commercial component of the space economy. In contrast, option and non-use values capture the broader societal and economic effects of an asset or service, irrespective of whether individuals personally utilize them.

Applying the TEV to created goods entails significant challenges. Created goods, such as space infrastructure and technological systems, differ fundamentally: intentionally designed, dynamically evolving, and embedded in complex institutional and value chains. These distinctions raise the need to reconsider how traditional TEV components–use, option, and non-use values–are defined and measured in this context.

The TEV framework identifies the full spectrum of potential value categories rather than their quantitative measure. In practical decision-making, these values must be considered relative to the costs, risks, and opportunity constraints associated with each alternative, but the cost–benefit comparison itself lies outside the present conceptual focus.

The following subsection illustrates this by focusing on option value, examining how temporal uncertainty and long investment horizons shape value realization for created goods.

4.2 Option Value in Created Goods: Temporal Framing

Option value [20] reflects willingness to invest in maintaining access for potential future use, despite lacking immediate benefits. For created goods, such as advanced infrastructure or emerging technologies, the temporal dimension is especially salient. Often, the expected payback period for these goods extends beyond conventional planning or forecast horizons, challenging standard investment appraisal methods.

Comparing hypothetical extraterrestrial infrastructures illustrates this. A lunar base mining Helium-3 [80], once a popular candidate for thermonuclear fuel, exhibits use-type characteristics, with foreseeable and reasonably planned payback. This enables private investment via commercial returns and discounted cash flow valuation. Nonetheless, substantial risks remain–technological, market, and regulatory uncertainties–that continue to challenge investors despite the clearer economic outlook. In contrast, a Mars colony [81], as seen today, embodies option value: its potential benefits, such as terraforming or resource exploitation, are distant and fundamentally uncertain. These features place the Mars settlement beyond typical private investment horizons, necessitating sustained public funding justified by long-term societal interests and intergenerational equity.

Evaluating option value thus demands frameworks incorporating temporal uncertainty, irreversibility, and institutional capacity to manage long-term commitments. This temporal and institutional perspective is essential for adapting TEV methodologies to capture the unique valuation challenges posed by created goods with extended and unpredictable benefit horizons.

China's strategic planning document [82] exemplifies this. It integrates diverse exploration fields, such as aerospace, deep sea, and deep Earth, under a unified 'Future Space' framework, treating them as a single spectrum distinguished by differing time horizons. Such integration aligns with the concept of option value, which emphasizes the significance of maintaining access to uncertain future opportunities across domains with variable and often extended temporal profiles.

4.3 Non-Use Values: Intergenerational Connection

Non-use values are traditionally subdivided into existential, bequest, and heritage values. Among these, the existential value of space exploration is the most frequently discussed, often associated with grand visions such as space colonization, transhumanism, and terraforming [84]. However, the TEV interpretation is more restrained: while popular discourse links existential value with survival and continuity of humankind and civilization, the canonical TEV framework designates existential value to goods whose worth lies in the mere knowledge of their existence.

In environmental contexts, existential value reflects awareness that a site/object exists – even if inaccessible for any form of use, including aesthetic appreciation. Similarly, celestial objects like Saturn's rings hold this value. Yet a crucial distinction arises: the environmental TEV model primarily aims to justify conservation efforts against anthropogenic destruction, whereas the suggested space exploration TEV framework seeks to encompass the full array of benefits and values that humanity associates with actively performed extraterrestrial endeavors and goods created in this way.

We argue space exploration embodies distinct locational existential value based on ‘awareness of accessibility’ rather than solely ‘awareness of existence.’ Its worth is framed as ‘It is good that it is accessible to humankind’ rather than ‘It is good that it exists.’ This emphasis on accessibility complements the traditional notion of existence, serving a similar functional role in the valuation of space exploration despite diverging from the classical existential value definition.

Bequest and heritage values complement this, intersecting with concepts like the common heritage of humankind [84]. Bequest value transmits non-use values (e.g., national pride and social identity) to future generations; heritage value inherits accomplishments/cultural identity from ancestors.

Non-use goods encapsulate critical ‘intangible social affection’ underpinning space programs. Launius [85] summarizes multiple surveys: ‘.while Americans may not know much about the space program, they have a largely favorable opinion of it–over 70 percent say they have a favorable impression…The American public has long held generally positive attitudes toward the space program, but is not very familiar with its details.’ Mahoney [86] notes that ‘for most people, space exploration is, and will forever remain, primarily an emotional pursuit.’

Another example is sustained Russian human spaceflight through the politically and economically challenging 1990s and 2000s [87]. A recent survey [88] reveals enduring public interest in space exploration and its specific facets. More broadly, values tied to intergenerational continuity hold special significance in cultures where preserving social values and achievements across generations forms a cornerstone of national identity and policy frameworks [89].

This conceptual exercise connects value types to underlying goods via temporal distinctions. It differentiates use, option, and non-use values for created goods by time-to-utilization profiles: use value corresponds to goods with predictable, though possibly variable, timing of benefit realization; option value involves goods whose time to value generation is fundamentally uncertain or depends on unforeseeable developments (such as “black swan” events [90]; and non-use value pertains to goods whose benefits are not associated with utilization as such and therefore lack a definable time of commencement. This demonstration serves as a foundation for further refinement in adapting TEV methodologies to created goods.

4.4 Cross-Referencing Goods and Value Categories

This subsection attempts to map economic goods produced by space activities to core components of the Total Economic Value framework. Table 2 is structured with rows corresponding to the primary categories of generated goods (see Subsection 3.4) and columns representing the principal elements of the TEV framework (see Subsection 4.1).

Evaluation applies to specific goods at a particular value-chain tier. Since it reflects consumer value, evaluation depends on the consumer type and the utility derived from the good. The same good holds different values for different consumers. For instance, a communication satellite holds different values for its manufacturer, operator, and user—contract revenue, operational efficiency, and service utility, respectively – illustrating that evaluation depends on consumer type and context. This contrasts with environmental TEV, which evaluates natural objects holistically for all users and 'no-user' beneficiaries.

Most physical outputs are core private goods associated with direct use value, whereas merit public or club goods are intentionally developed to serve collective needs. Distinguishing direct from indirect use values often depends on system architecture and purpose.

The widely held notion that 'space exploration has existential value' can be formalized as a spillover public good – 'Awareness and Recognition of Extending Human Knowing and Presence in Space' – which, lacking contractual deliverables yet being non-excludable and non-rivalrous, fulfills the criteria of a public good. Within the TEV framework, its existential value is a non-use value derived from mere knowledge of this collective endeavor. Analogous spillover goods arise from public perception of corporate or technological contributions to exploration.

We also include a non-obvious pair of goods related to extraterrestrial resources to illustrate the suggested differentiation between option and bequest values when it comes to created goods. Option value applies when future utilization is feasible under current institutional and legal frameworks, regardless of technological or economic hurdles, which may evolve independently. Bequest value applies when institutional or legal frameworks currently preclude utilization, preserving the good for future generations who may benefit once those frameworks change. For example, 'IP and technologies for space resource excavation' may align with either option or bequest value, depending on interpretation of the Outer Space Treaty (OST) [91]. Under a restrictive reading that precludes commercial exploitation, such goods represent bequest value – preserved for future use once frameworks change. Under a permissive interpretation, they represent option value – future benefits feasible within existing law.

This mapping provides a basis for developing evaluation models to rank goods – especially those with non-use values – and potentially to associate them with quantitative indicators within the TEV framework. Although preliminary, this represents, to our knowledge, the first attempt to apply TEV systematically to the space economy and its outputs, and it may serve as a foundation for further multidimensional 'value-for-money' analyses in space exploration.

Table 2. Goods and Value Categories in the Space Economy

Good Types	Use values		Option values	Non-use values		
	DU	IU		EX	HE	BQ
Core Private						
Spacecraft, systems, equipment & constellations	X					
Enabling infrastructure and data ecosystems supporting multiple applications	X					
Commercial satellite services	X					
Third-party applications	X					
Human capital	X					
Emerging technologies		X				
IP and technologies for space resources excavating (permissive OST)			X			
IP and technologies for space resources excavating (restrictive OST)						X
Spillover Private						
Pilot deployments and prototypes enabling near-term commercial use	X					
New technologies and capabilities	X					
Emerging applications		X				
Collateral IP			X			
Knowledge transfer			X			
Merit Public (incl. territorially limited)						
Government civilian & military space infrastructure	X					
Earth observation & navigation services with public access	X					
Open-access data platforms	X					
Scientific knowledge	X					
Global space situational awareness		X				
National security assurance		X				
Space-environment sustainability assurance		X				
Weather-forecasting capability		X				
Public education and outreach		X				
Spillover Public (incl. territorially limited)						
Incidental environmental monitoring data	X					
Indirect benefits from public-private partnerships		X				
Stimulation of economic activity		X				
Awareness and recognition of extending human knowing of and presence in space				X		
Awareness and recognition of outer space as an infinite potential resource for humankind				X		
Entrepreneurial inspiration to increase involvement in space activities				X		
Awareness and recognition of national input into the historical achievements in space activities					X	

Good Types	Use values		Option values	Non-use values		
	DU	IU		EX	HE	BQ
Awareness and recognition of transferring the national achievements in space activities to future generations						X
Merit Club						
Licensed technical standards actively used within membership groups	X					
Collaborative development platforms with controlled access		X				
Spillover Club						
Spillovers from club innovation		X				
Awareness and recognition of corporate (group) input in space activities				X		
Platform Subsidized						
Free-access digital platforms		X				
Citizen science contribution		X				

DU – direct use; IU – indirect use; EX – existence; HE – heritage; BQ - bequest

4.5 Measuring Challenge

Associating goods with value is a necessary step toward developing detailed valuation methods that enable comparisons across space projects and with initiatives in other domains, such as fundamental science, environmental protection, or cultural heritage.

For **direct-use** private goods, valuation follows traditional market-based approaches, relying on ex ante pricing and supply–demand dynamics.

Option value differs from anticipated future value primarily by its temporal uncertainty. While future profits are typically discounted over time [92], the TEV framework captures the subjective value of potential use at an indefinite future moment (see [77] for an overview). Beyond contingent valuation, option value can be modeled by treating the discounting period as a stochastic parameter. The state usually assumes funding responsibility for programs with such indefinite horizons [93].

Non-use values are usually assessed through expert-based approaches such as Delphi surveys and benefit transfer [94], or contingent valuation methods, including willingness-to-pay and stakeholder consultations [95]. Survey techniques are popular for assessing existential values [85, 88, 96], but they present specific challenges in the space domain.

First, most TEV studies evaluate naturally existing public goods: landscapes, ecosystems, or heritage sites, rather than intentionally created non-use goods [67]. Second, space infrastructure costs far exceed those of preserving terrestrial or heritage assets in an object-to-object comparison, complicating direct stakeholder surveys, especially when beneficiaries are the national or global population [97]. Finally, generating new non-use goods is inherently more complex than maintaining existing ones. Existential value, while secondary, remains notable in human spaceflight programs, where social preference studies confirm persistent public support [19, 88, 98].

At present, comprehensive valuation methods primarily legitimize option and non-use values rather than provide operational tools. Before quantification, recognizing these intangible benefits in planning frameworks is critical [99]; qualitative expert ranking may suffice initially, while developing quantitative models remains a demanding next step [100].

We conclude this initial examination of TEV adaptation for the space economy and proceed to the institutional implications of the proposed frameworks.

5 Application and Conclusion

5.1 Institutional Implications

To demonstrate the relevance of applying public goods and TEV concepts, this section considers the features of today's global space-economy landscape, emphasizing the renewed salience of public goods and the need for multiparametric evaluation methods beyond purely monetary approaches.

Space securitization has accelerated markedly since 2022 amid resurgent multipolarity. Governments, especially in Europe, which is experiencing its most serious security crisis since World War II, are relearning public-goods discourse and reclaiming proactive roles in deploying additional layers of satellite infrastructure [101]. This shift has sparked fundamental debates about the institutional understanding of emerging roles and challenges in the space domain [102].

The growing threats to the long-term sustainability of space underscore the urgent need for rigorous research to substantiate international regimes and collaborative projects aimed at mitigating space debris and orbital congestion [103]. Given the "first-come, first-served" legal regime governing popular near-Earth orbits, particularly low Earth orbit, preventing catastrophic debris chain reactions exemplifies a rare pure global public good. Near-Earth space is thus frequently conceptualized as a commons [104].

The momentum gained by private enterprises, catalyzed by early NASA public-private partnerships, has led to a growing push from companies such as SpaceX and Blue Origin. They assert a role in space resource exploration and broader space exploration activities [105]. The anticipated human-LEO transition from public to private actors [106], coupled with imminent deployment and operations of lunar infrastructure within a complex public-private environment [107, 108], further strengthens the call for greater legal autonomy. Their pursuit of independence necessitates reconsidering the role of non-public actors in producing public goods and the legal framework that restricts significant private entities from full autonomy in space, requiring them to operate under the jurisdictional umbrella of their respective states [109, p. 389].

Finally, two homophonous yet distinct subfields illustrate different applications of public-goods logic. Planetary protection, concerned with safeguarding extraterrestrial environments from contamination following Earth spacecraft landings [110], parallels canonical environmental TEV modeling. Meanwhile, planetary defense, which involves protecting Earth from hazardous near-Earth objects, exemplifies the potential for deploying a previously unseen form of pure public good with defense characteristics [111].

5.2. Operational and Policy Applications

The combined PGIC–TEV framework (as well as each construct individually) has several analytical and policy-level applications that can be summarized across four functional domains.

Research and Analytics.

An in-depth analysis of the production of various types of economic goods during space activities aligns conceptually with contemporary research paradigms in public-choice theory [112] and welfare economics [113], thereby expanding the epistemological foundation of space economics. The TEV–PGIC framework provides an additional lens for analyzing new projects in the public and private domains, enabling a clearer understanding of stakeholders' interests, incentives, and investment directions. Together, these analytical perspectives form the foundation for applied domains such as evaluation, communication, and strategy.

Evaluation and Budgeting.

The TEV-based approach allows for the evaluation of space-exploration programs in a broader context and the justification of their value across a wider spectrum of societal impacts, thereby structuring the argumentation for setting priorities and allocating resources. This is particularly useful when discussing high-level preferences for various areas of non-commercial, non-market activities in the formulation of public budgets.

Communication and Public Perception.

The TEV framework can also be used to structure public discourse, helping to separate symbolic and existential values from market-based arguments. This framework helps shape more balanced communication strategies between agencies, businesses, and society by linking measurable results to cultural and existential values, which is especially important when discussing missions with a strong symbolic or inspirational component.

Strategy and Policy.

A focused look at the common features and differing characteristics of generating various types of goods in the public and private sectors is particularly relevant in the context of the private sector's ongoing expansion into domains of space activity previously reserved exclusively for governments – including space exploration [105], habitable LEO infrastructure [106], and the commercialization of various forms of space situational awareness [114]. A PGIC-focused approach helps project architects identify intersections between public and private interests. This is particularly useful when designing architectures of shared-value creation in public–private partnership projects such as IRIS[2] [115], where a common supply chain supporting the creation of physical and organizational infrastructure eventually branches to generate value for distinct commercial and public users.

5.3 Summary of Contributions

To summarize the preceding analysis, we highlight the following key contributions that advance the understanding and development of space-economy scholarship and governance doctrine.

1. Comprehensive overview of the classification of goods produced by space activities, clarifying the distinctions among private goods, club goods, territorially limited public goods, and pure public goods, establishing a foundation for analyzing outputs across diverse space missions and programs.

2. Structural refinements enhancing the classical goods framework's applicability to space economics. These include explicitly accounting for territorial limitations that function analogously to excludability in club goods; the concept of "goods created," highlighting that many space-related public goods are actively produced outputs rather than naturally existing resources; and the Public Goods Input Chain (PGIC), a conceptual model distinguishing between the physical production of goods and their institutional consumption environments. Together, these elements improve analytical clarity and provide a more symmetrical and realistic representation of space-economy goods.

3. TEV framework adaptation for holistic and structured evaluation that incorporates both direct-use values, such as commercial satellite services, and indirect, option, existential, symbolic, and non-use values that are often intangible yet critical. Its current utility lies more in legitimizing recognition than in producing operational models.

4. Highlighting governance dynamics of space-generated value, including the re-consolidation of oligopolistic market power in satellite mega-constellations and reusable

launch systems, alongside geopolitical securitization repositioning public goods within multipolar global frameworks.

In conclusion, we emphasize that this work represents an initial effort to apply the fusion of economic goods theory and economic valuation approaches to contemporary space economy challenges. Further development and practical adaptation of the proposed directions and approaches will require intensive methodological and empirical research. We consider our goal achieved if this work stimulates further dialogue and methodological development among colleagues in both industry and academia.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author used ChatGPT AI Assistant in order to check grammar, syntax, and the structuring of the narrative. After using this service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

References

[1] C. Giannopapa, A. Staveris-Poykalas, S. Metallinos, Space as an enabler for sustainable digital transformation, Acta Astronaut. 198 (2022) 728-732. https://doi.org/10.1016/j.actaastro.2022.06.005.

[2] European Space Policy Institute, More than a space program: the value of space exploration to empower the future of Europe. https://www.espi.or.at/reports/more-than-a-space-programme-the-value-of-space-exploration-to-empower-the-future-of-europe/ , 2023 (accessed 21 July 2025).

[3] OECD, Responding to Global Challenges, OECD Publishing, Paris, 2023. https://doi.org/10.1787/fa5494aa-en .

[4] K.L. Jones, B. Weeden, Rational Exuberance: Understanding Value and Performance in the Space Economy. Center for Space Policy and Strategy (2024). https://csps.aerospace.org/sites/default/files/2024-11/05e_RationalExuberance_Jones-Weeden_20241104.pdf (accessed 21 July 2025).

[5] K.W. Crane, E. Linck, B. Lal, R.Y. Wei, Measuring the Space Economy: Estimating the Value of Economic Activities in and for Space, IDA Science & Technology Policy Institute, Washington, DC, 2020. https://www.ida.org/-/media/feature/publications/m/me/measuring-the-space-economy-estimating-the-value-of-economic-activities-in-and-for-space/d-10814.ashx (accessed 21 July 2025).

[6] Bryce Technologies, The 2025 State of the Satellite Industry Report. Executive summary, Satellite Industry Association. https://sia.org/wp-

content/uploads/2025/05/SSIR25-2025-SSIR-FY2024-1-Pager-Exec-Summary-1.pdf (accessed 21 July 2025).

[7] J. Anomaly, Public goods and government action. Polit. Philos. Econ. 14(2015) 109-128. https://doi.org/10.1177/1470594x13505414

[8] E. Ostrom, Beyond markets and states: Polycentric governance of complex economic systems. Am. Econ. Rev. 100(2010) 641-672. https://doi.org/10.1257/aer.100.3.641

[9] H. Hertzfeld, B. Weeden, C.D. Johnson, How Simple Terms Mislead Us: The Pitfalls of Thinking about Outer Space as a Commons (IAC-15 - E7.5.2 x 29369), in: Proceedings of the 66th International Astronautical Congress (IAC), Jerusalem, Israel. Paris, France: International Astronautical Federation, 2015.

[10] D. Patton, Is Space a Global Commons? Space Sustainability Briefs, 1. Secure World Foundation, 2022. https://cdn.prod.website-files.com/66dcc6872f6ed23bce1db235/68470f0b0107aa4d7a8f77bb_is-space-a-global-commons-swf-brief-2022.pdf (accessed 21 July 2025).

[11] M. de Zwart, S. Henderson, M. Neumann, Space resource activities and the evolution of international space law, Acta Astronaut. 211 (2023) 155-162, https://doi.org/10.1016/j.actaastro.2023.06.009.

[12] D. Handlin, Looking for a silver bullet, The Space Review, 2010, May 3, https://www.thespacereview.com/article/1619/1 (accessed 21 July 2025).

[13] A. Li, The Artemis Accords: Moonwalking to More Giant Leaps, TheSpaceBar 2020, August 17, https://alexsli.com/thespacebar/2020/8/17/the-artemis-accords-a-moonwalk-to-more-giant-leaps (accessed 21 July 2025).

[14] H.E. Eseceli, Space, the new address of global competition, Anadolu Ajansı, 2021, November 19. https://www.aa.com.tr/en/analysis/analysis-space-the-new-address-of-global-competition/2425107 (accessed 21 July 2025).

[15] OECD, Evolving public-private relations in the space sector, OECD Science, Technology and Industry Policy Papers, 114 , June 2021. https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/06/evolving-public-private-relations-in-the-space-sector_c865e704/b4eea6d7-en.pdf (accessed 21 July 2025).

[16] J.B. Chaben, Extending Humanity's Reach: A Public-Private Framework for Space Exploration, J. Strateg. Secur., 13, 3 (2020), 75-98. https://doi.org/10.5038/1944-0472.13.3.1811.

[17] D. Payson, I. Kosenkov, Changing Dynamics in Russia's Space Economy (in press), in: A. P. D'Costa (Ed.), Oxford Handbook of the New Space Economy. Oxford University Press.

[18] R. Pillai, N. Prasad, N., Space India 2.0. Observer Research Foundation, 2017.

[19] E. Musk, Making Humans a Multi-Planetary Species, New Space, 5(2017), 46-61. https://doi.org/10.1089/space.2017.29009.emu (accessed 21 July 2025).

[20] E. Plottu, B. Plottu, The concept of Total Economic Value of environment: A reconsideration within a hierarchical rationality. Ecol. Econ., 61(2007), 52–61. https://doi.org/10.1016/j.ecolecon.2006.09.027

[21] A. Pandolfi, The need for a wider application of the Total Economic Value theories. International Journal of Engineering and Technical Research, 9(2020), 593. https://doi.org/10.17577/IJERTV9IS120270.

[22] I. Baumann, J. Mey, E. Pellander, Industry and Agency Contracts and Procurement: A European Perspective. Oxford Research Encyclopedia of Planetary Science. Retrieved 22 May. 2025, from https://oxfordre.com/planetaryscience/view/10.1093/acrefore/9780190647926.001.0001/acrefore-9780190647926-e-180.

[23] OECD, OECD Handbook on Measuring the Space Economy, 2nd Edition, OECD Publishing, Paris, 2022. https://doi.org/10.1787/8bfef437-en.

[24] R. Lowe, The value of space activity, Econ. Aff, 44(2024), 561–571. https://doi.org/10.1111/ecaf.12676.

[25] G. Meylan, B.S. Blacker, D. Macchetto, J.P. Madrid, The scientific output of the Hubble Space Telescope from objective metrics, Proc. SPIE 5493, Optimizing Scientific Return for Astronomy through Information Technologies, (16 September 2004). https://doi.org/10.1117/12.543391.

[26] A. Tassa, S. Willekens, A. Lahcen , L. Laurich, C. Mathieu, On-Going European Space Agency Activities on Measuring the Benefits of Earth Observations to Society: Challenges, Achievements and Next Steps. Front. Environ. Sci. 10 (2022), 788843. https://doi.org/10.3389/fenvs.2022.788843.

[27] M. Jacob, O. Hallonsten, The persistence of big science and megascience in research and innovation policy. Sci. Publ. Policy, 39(2012), 411-415. https://doi.org/10.1093/scipol/scs056.

[28] D. Paikowsky, The Power of the Space Club. Cambridge University Press, Cambridge, 2017.

[29] M. Aliberti, O. Cappelli, R. Praino, Power, State and Space. Conceptualizing, Measuring and Comparing Space Actors. Springer Cham, 2023.

[30] J.T. Heidler, D.S. Heidler, Manifest Destiny: History, Examples, & Significance, in: Encyclopædia Britannica, 2018, https://www.britannica.com/event/Manifest-Destiny. (accessed 21 July 2025).

[31] D. Trump, The Inaugural Address, 2025. The White House, https://www.whitehouse.gov/remarks/2025/01/the-inaugural-address/(accessed 21 July 2025).

[32] S. Hoeser, Getting back to the historic sequence of opening our space frontiers, The Space Review, 2017, February 6, https://www.thespacereview.com/article/3165/1 (accessed 21 July 2025).

[33] F.J. Turner, The Significance of the Frontier in American History. 1893. Reprinted in Annual Report of the American Historical Association for the Year 1893, 199-227.

[34] J.S.J. Schwartz, Myth-Free Space Advocacy Part II: The Myth of the Space Frontier. Astropolitics, 15(2017), 167-184. https://doi.org/10.1080/14777622.2017.1339255.

[35] Z. Pirtle, K. McBrayer, A. Beauchemin, Artemis, Ethics and Society: Synthesis from a Workshop. NASA Office of Technology, Policy & Strategy (OTPS), 2023, https://www.nasa.gov/wp-content/uploads/2023/09/otps-artemis-ethics-and-society-report-final-9-21-02023-tagged.pdf (accessed 21 July 2025).

[36] L. Bach, P. Cohendet, G. Lambert, M. J. Ledoux, Measuring and Managing Spinoffs: The Case of the European Space Agency, in: J.S. Greenberg and H. Hertzfeld (Eds.), Space Economics, American Institute of Aeronautics and Astronautics, Washington, DC, 1992, pp. 171–206.

[37] P.A. Samuelson, The Pure Theory of Public Expenditure, Rev. Econ. Stat., 36 (1954), 387–389. https://doi.org/10.2307/1925895.

[38] R.A. Musgrave, The theory of public finance: A study in public economy. McGraw-Hill, New York, 1959.

[39] L. Corrado, M. Cropper, A. Rao, Space exploration and economic growth: New issues and horizons, Proc. Natl. Acad. Sci. U.S.A. 120 (2023) e2221341120, https://doi.org/10.1073/pnas.2221341120 .

[40] M. Pietrzak, Economic and Social Aspects of the Space Sector Development Based on the Modified Structure–Conduct–Performance Framework. World, 6(2025), 79. https://doi.org/10.3390/world6020079.

[41] E. Ostrom, Governing the commons: The evolution of institutions for collective action. Cambridge University Press, Cambridge, 1990.

[42] T. Sandler, w. Schulze, The Economics of Outer Space. Nat. Resour. J., 21(1981), 371-393. http://www.jstor.org/stable/24882431

[43] I. Kaul, Global public goods: A concept for framing the post-2015 agenda? DESA Working Paper No. 130, 2013, United Nations Department of Economic and Social Affairs. https://doi.org/10.2139/ssrn.2372027

[44] J. Reiss, Public Goods, The Stanford Encyclopedia of Philosophy (Fall 2021 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/fall2021/entries/public-goods/(accessed 21 July 2025).

[45] R. Harris, L. Miller, Earth observation and the public good. Space Policy, 27(2011),194–201. https://doi.org/10.1016/j.spacepol.2011.09.010.

[46] S. Plattard, Can Global Navigation Satellite Systems Signals Qualify to Become a World Public Good? New Space, 3(2015),142-146, https://doi.org/10.1089/space.2015.0014.

[47] P. Bond, Benefits Of Human Spaceflight', ESA Publications Division, 2005, https://www.esa.int/esapub/br/br230/br230.pdf (accessed 21 July 2025).

[48] A.J. Salter, B.R. Martin, The economic benefits of publicly funded basic research: a critical review, Res. Policy, 30(2001), 509–532, https://doi.org/10.1016/S0048-7333(00)00091-3.

[49] J.S. Greenberg, H.R. Hertzfeld (Eds.), Space economics. American Institute of Aeronautics and Astronautics, Washington, DC, 1992.

[50] D. Moore, Remote Sensing, in: J.S. Greenberg, H.R. Hertzfeld (Eds.), Space Economics. American Institute of Aeronautics and Astronautics, Washington, DC, 1992, pp.233-262.

[51] D'Costa, A.P. (Ed.), The Oxford Handbook of the New Space Economy. Oxford University Press, USA. (in print).

[52] P.L. Nelson, W.E. Block, Space Capitalism: How Humans will Colonize Planets, Moons, and Asteroids (Palgrave Studies in Classical Liberalism), Palgrave Macmillan, 2018.

[53] G.C. Rausser, E.-H. Choi, A.M. Bayen, Public–private partnerships in fostering outer space innovations, in: Proceedings of the National Academy of Sciences of the United States of America, 120(2023), https://doi.org/10.1073/pnas.2222013120.

[54] T. Rayna, Understanding the Challenges of the Digital Economy: The Nature of Digital Goods, Communications & Strategies, 71 (2008), 13-16, https://ssrn.com/abstract=1353583 (accessed 21 July 2025).

[55] G.C. Boulton, Science as a Global Public Good. International Science Council Position Paper, 2021, https://council.science/wp-content/ uploads/2020/06/Science-as-a-global-public-good_v041021.pdf (accessed 21 July 2025).

[56] K. Elgar, Y. Ahmad, A. Bejraoui, E. Carey, M. Choudhury,G. De Paepe, The role of development co-operation in the provision of global public goods, OECD Development Co-operation Working Papers, No. 111, OECD Publishing, Paris, 2023.

[57] B. Adhikari , The Economics of Common Pool Resources: A Review . Ecol. Economy Soc. INSEE J., 4(2021), 71-88, https://doi.org/10.37773/ees.v4i1.377.

[58] OECD, The Economics of Space Sustainability: Delivering Economic Evidence to Guide Government Action, OECD Publishing, Paris, 2024.

[59] H. Bowser, How the Space Race Changed America. Invention and Technology, 3(1987), https://www.inventionandtech.com/content/how-space-race-changed-America-1 (accessed 21 July 2025).

[60] R. Beetsma, M. Buti, F. Nicoli, Defense as a European Public Good: Delivery and Financing. EconPol Forum 25(2024), https://www.ifo.de/DocDL/econpol-forum-2024-4-beetsma-etal-defense-eu.pdf (accessed 21 July 2025).

[61] I. Kaul, I Grunberg, M. A. Stern, Defining Global Public Goods, in: I. Kaul, I. Grunberg, M.A. Stern (Eds.), Global Public Goods: International Cooperation in the 21st Century, New York: Oxford Academic 1999; online edn, 1 Nov. 2003, https://doi.org/10.1093/0195130529.003.0001(accessed 21 July 2025).

[62] D.G. Arce, T. Sandler, Regional Public Goods: Typologies, Provision, Financing, and Development Assistance, Almkvist & Wiksell International, 2022. https://eba.se/wp-content/uploads/2021/04/2002.1-Regional-Public-Goods-Typologies-Provision-Financing-and-Development-Assistance.pdf (accessed 21 July 2025).

[63] J.R. Sanson, The Conceptual Overlap Between Public Goods, Externalities and Merit Goods, Cadernos de Financas Publicas, 20(2020), https://doi.org/10.55532/1806-8944.2020.89.

[64] R. Fiorito, T. Kollintzas, Public goods, merit goods, and the relation between private and government consumption. Eur. Econ. Rev. 48(2024),1367-1398. https://doi.org/10.1016/j.euroecorev.2004.01.004.

[65] NSW Department of Industry, Market failure guide: A guide to categorising market failures for government policy development and evaluation (PUB17/509), 2017, https://www.productivity.nsw.gov.au/sites/default/files/2025-01/PUB17_509_Market__failure_guide.pdf (accessed 21 July 2025).

[66] M. Mazzucato, The Entrepreneurial State: Debunking Public vs Private Sector Myths. UK: Penguin Books, 2013.

[67] D. Pearce, Economic Valuation and the Natural World. Background paper for World Development Report 1992. The World Bank, October 1992, https://documents1.worldbank.org/curated/en/721891468764692718/pdf/multi0page.pdf (accessed 21 July 2025).

[68] G. F-de-Córdoba, J.L. Torres, National security, military spending and the business cycle. Def. Peace Econ, 27(2014), 549-570, https://doi.org/10.1080/10242694.2014.891353.

[69] Royal Society, Science 2040: The economic value of science (Policy briefing), 2024, https://royalsociety.org/-/media/policy/publications/2024/science-2040-economic-value-of-science.pdf (accessed 21 July 2025).

[70] S.D. Baum, Cost–benefit analysis of space exploration: Some ethical considerations. Space Policy, 25(2009), 75-80. https://doi.org/10.1016/j.spacepol.2009.01.002

[71] A. Lawrence, M.L. Rawls, M. Jah et al., The case for space environmentalism. Nat. Astron. 6 (2022),428-435, https://doi.org/10.1038/s41550-022-01655-6

[72] K. Sienkiewicz-Małyjurek, M. Szymczak, Understanding public service supply chain management: a systematic literature review, Manag. Rev.Q. 74 (2024), 1879–1943, https://doi.org/10.1007/s11301-023-00350-8

[73] K. L. Jones, Public-Private Partnerships: Stimulating Innovation in the Space Sector. The Aerospace Corporation, 2018, https://aerospace.org/sites/default/files/2018-06/Partnerships_Rev_5-4-18.pdf (accessed 21 July 2025).

[74] L. Kirk, Commercial Crew Program Overview. NASA EDL Summer Seminar, 2022, https://ntrs.nasa.gov/api/citations/20220010912/downloads/EDLSummerSeminar2022_CCP.pdf (accessed 21 July 2025).

[75] C.W. Jones, E.G. Overbey, J. Lacombe, A.J. Ecker et al. Molecular and physiological changes in the SpaceX Inspiration4 civilian crew. Nature, 632(8027), 2024. 1155–1164. https://doi.org/10.1038/s41586-024-07648-x.

[76] Polaris Program. Science & research. Polaris Program. 2024. https://polarisprogram.com/science-research/ (accessed 20 October 2025).

[77] S. Kumar, K.B. Moore, The Evolution of Global Positioning System (GPS) Technology, J. Sci. Educ. Technol., 11 (2002), 59–80 (2002). https://doi.org/10.1023/A:1013999415003

[78] M. Albani, D. Romano, Total Economic Value and Evaluation Techniques, in: R.C. Bishop, D. Romano, D. (Eds.), Environmental Resource Valuation. Studies in Risk and Uncertainty, vol 11. Springer, Boston, MA,1998.

[79] J.F. Admiraal, A. Wossink, W.T. de Groot, G.R. de Snoo, More than total economic value: How to combine economic valuation of biodiversity with ecological resilience. Ecol. Econ., 89(2013), 115–122, doi:https://doi.org/10.1016/j.ecolecon.2013.02.009.

[80] A.D. Olson, Lunar Helium-3: Mining Concepts, Extraction Research, and Potential ISRU Synergies, AIAA 2021-4237. ASCEND 2021, https://doi.org/10.2514/6.2021-4237.

[81] F. Neukart, Towards sustainable horizons: A comprehensive blueprint for Mars colonization, Heliyon, 10(2024), e26180, https://doi.org/10.1016/j.heliyon.2024.e26180.

[82] 工业和信息化部, 关于推动未来产业创新发展的实施意见 [Implementation Opinions on Promoting the Innovative Development of Future Industries] (Accessed via Google Translate). Ministry of Industry and Information Technology of the People's Republic of China, 2024, March 19, https://www.miit.gov.cn/zwgk/zcwj/wjfb/yj/art/2024/art_ad15b0f08a714fd8888c0e31468b8c54.html (accessed 21 July 2025).

[83] J. Gottlieb, Discounting, Buck-Passing, and Existential Risk Mitigation: The Case of Space Colonization, Space Policy, 60(2022), 101486, https://doi.org/10.1016/j.spacepol.2022.101486.

[84] G. Wang, X. Huang, On the common heritage of mankind principle in space. Acta Astronaut., 211 (2023), 926–938. https://doi.org/10.1016/j.actaastro.2023.07.002

[85] R.D. Launius, Public opinion polls and perceptions of US human spaceflight, Space Policy, 19(2003), 163–175, https://doi.org/10.1016/s0265-9646(03)00039-0.

[86] B. Mahoney, B. Space for improvement: re-engaging the public with the greatest adventure of our time (part 1), The Space Review, 2007, February 5, https://www.thespacereview.com/article/802/1 (accessed 21 July 2025).

[87] B. Harvey, Russia in space: the failed frontier? Praxis, Chichester, UK, Praxis, 2001.

[88] S. Fehrler, L. Hornuf, D. Vrankar, What do citizens expect from space? Acta Astronaut., 235 (2025), 660-669, https://doi.org/10.1016/j.actaastro.2025.05.056.

[89] C.L. Cobb, S.J. Schwartz, C.R. Martinez, A theory of cultural continuity: Heritage culture retention as an important psychological motivation. Psychological Review. Advance online publication, 2025, https://doi.org/10.1037/rev0000561

[90] N.N. Taleb, The Black Swan: The Impact of the Highly Improbable (2nd ed.), Penguin, London, 2010 [2007]

[91] United Nations, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies [Outer Space Treaty], 1967, https://www.unoosa.org/pdf/publications/ST_PUBLICATION_490_Annex.pdf (accessed 21 July 2025).

[92] S. Frederick, G. Loewenstein, T. O'donoghue, T., Time Discounting and Time Preference: A Critical Review. J. Econ. Lit. [online], 40(2002), 351–401, https://doi.org/10.1257/jel.40.2.351.

[93] K.J. Arrow, M.L. Cropper, C. Gollier, B. Groom, G.M. Heal, R.G. Newell, W.D. Nordhaus, R.S. Pindyck, W.A. Pizer, P.R. Portney, T. Sterner, R.S.J. Tol, M.L. Weitzman, Should Governments Use a Declining Discount Rate in Project Analysis? Rev. Environ. Econ. Policy., 8(2014), 145–163. https://doi.org/10.1093/reep/reu008

[94] A.M. Hein, Heritage technologies in space programs – Assessment methodology and statistical analysis (Doctoral dissertation, Technische Universität München). TUM, 2016, https://mediatum.ub.tum.de/doc/1308879/document.pdf (accessed 21 July 2025).

[95] R.C. Bishop, P.A. Champ, T.C. Brown, D.W. McCollum, Measuring Non-Use Values: Theory and Empirical Applications, in: R.J. Kopp, W.W. Pommerehne, N. Schwarz (Eds.), Determining the Value of Non-Marketed Goods. Studies in Risk and Uncertainty, vol. 10, Springer, Dordrecht, 1997.

[96] J.S.J Schwartz, The value of science in space exploration. Oxford University Press, New York, 2020.

[97] D. Fujiwara, D. Dass, Measuring social value in infrastructure projects: insights from the public sector. 1st ed., Royal Institution of Chartered Surveyors, London, 2020 https://www.rics.org/content/dam/ricsglobal/documents/to-be-sorted/measuring-social-value_1st-edition.pdf (accessed 21 July 2025).

[98] S. Krichevsky, Creation of a 'Cosmic' Human: Ideas, Technologies, Projects, Experience, Risks, Limitations, and Prospects Future Hum. Image, 13(2020), 32–45 https://doi.org/10.29202/fhi/13/4.

[99] P. Bennetch, Benefits of future space program are intangible. [online] Phys.org, 2011, https://phys.org/news/2011-11-benefits-future-space-intangible.html (accessed 21 July 2025).

[100] S. Abdullah, A. Markandya, P.A.L.D. Nunes, Introduction to Economic Valuation Methods, in: A. Batabyal, P. Nijkamp (Eds.), Research Tools in Natural Resource and Environmental Economics, World Scientific, 2011, pp.143-187.

[101] P.J. Blount, The Discourse of Space Securitization, in: S. M. Pekkanen, P.J. Blount (Eds.), The Oxford Handbook of Space Security, Oxford Handbooks, 2024; online edn, Oxford Academic, 22 Feb. 2024), https://doi.org/10.1093/oxfordhb/9780197582671.013.4 (accessed 21 July 2025).

[102] C. Cellerino, EU space policy and strategic autonomy: Tackling legal complexities in the enhancement of the 'security and defence dimension of the Union in space, Eur. Pap., 8(2023), 487-501. https://doi.org/10.15166/2499-8249/669.

[103] T. Hrozensky, G. Redigonda, C. Beahan, D. Leichte, C. Vogt, Space Safety and Sustainability Momentum, ESPI, Vienna, 2023, https://www.espi.or.at/wp-content/uploads/2023/09/ESPI-Report-86-Space-Safety-and-Sustainabiliy-Momentum.pdf (accessed 21 July 2025).

[104] D. Lambach, L. Wesel, Tackling the space debris problem: A global commons perspective, in: T. Flohrer, S. Lemmens, F. Schmitz (Eds.), Proceedings of the 8th European Conference on Space Debris (virtual, Darmstadt, Germany, 20–23 April 2021), ESA Space Debris Office, 2021, https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/230/SDC8-paper230.pdf (accessed 21 July 2025).

[105] R. Lindbergh, Space resource extraction: Overview and issues for Congress (Report No. R48144). Congressional Research Service, 2024, https://crsreports.congress.gov/product/pdf/R/R48144 (accessed 21 July 2025).

[106] A. Paravano, B. Rosseau, G. Locatelli, M. Weinzierl, P. Trucco, Toward the LEO economy: A value assessment of commercial space stations for space and non-space users, Acta Astronaut., 228(2025), 453-473, https://doi.org/10.1016/j.actaastro.2024.11.060.

[107] A. Zuniga, H. Modi, A. Kaluthantrige, H. Vertadier, Building an Economical and Sustainable Lunar Infrastructure to Enable Human Lunar Missions, in: 70th International Astronautical Congress, IAC, Washington, DC, 2019, https://dl.iafastro.directory/event/IAC-2019/paper/54311/ (accessed 21 July 2025).

[108] P. Kawade, Moon-as-a-service' business models: The next leap for commercial space players, Analysys Mason, 2024, https://www.analysysmason.com/contentassets/caf47a20ec324c159535ee8192fabeb1/analysys_mason_moon_economy_space_may2024_nsi015.pdf (accessed 21 July 2025).

[109] F. Lyall, P.B. Larsen, Space Law: A Treatise, 3rd edn.,Routlege, New York, 2025.

[110] J.D. Hader, J.D., A.G. Fairén, M. MacLeod, Planetary Protection requirements should address pollution from chemicals and materials. Proceedings of the National Academy of Sciences of the United States of America, 120(2023). https://doi.org/10.1073/pnas.2310792120.

[111] C.D. Johnson, Security, policy, and legal challenges of planetary defense, in: Oxford Research Encyclopedias, Oxford University Press, Oxford, 2025.

[112] J.M. Buchanan, G.Tullock, The Calculus of Consent: Logical Foundations of Constitutional Democracy. University of Michigan Press, Ann Arbor, 1962.

[113] M.D. Adler, Measuring Social Welfare: An Introduction. Oxford University Press, New York, 2019

[114] M. Borowitz, Examining the Growth of the Global Space Situational Awareness Sector: A Network Analysis Approach, Space Policy, 59(101444), 2022. https://doi.org/10.1016/j.spacepol.2021.101444.

[115] European Space Policy Institute. IRIS2: The new (material) girl on the block. Brief No. 61, December 2022. European Space Policy Institute. https://www.espi.or.at/wp-content/uploads/2022/12/ESPI-Brief-NO-61-Secure-Connectivity_Final.pdf (accessed 21 October 2025).