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Evaluating International Collaboration for Human Exploration Beyond LEO

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Abstract

Over 50 governments, intergovernmental organizations, non-governmental organizations, and private institutions are directly involved in space activities. These actors have different rationales for pursuing space-related activities and can play complementary roles in achieving ambitious space exploration efforts, which are increasingly cost-prohibitive for individual actors. Given this context, a multi-national and multi-cultural team with expertise in different fields of space exploration, led by the Massachusetts Institute of Technology and the Skolkovo Institute of Science and Technology, developed a framework for evaluating sustainable international space exploration endeavors.

The proposed framework attempts to objectively evaluate partnerships by defining evaluation metrics that consider the technical and non-technical parameters that influence future mission success. It is based on four abstractions: mission architecture, required technological capabilities, relevant participating actors, and rationales for the participation of these actors. The framework seeks to provide measures of overall suitability of a mission for particular actors based on the satisfaction of both technology and policy needs of those participating actors.

Application of the framework is demonstrated through partnership evaluations for three reference human spaceflight missions beyond Low Earth Orbit (LEO): an Earth-Moon Lagrangian Point 2 (L2) permanent station inspired by the International Space Station, a near-Earth object (NEO) rendezvous and sample return mission, and a long-duration exploration mission on the lunar surface. Potential actor partnerships are evaluated based on two sets of parameters: a technical set defines a Partnership Technology Readiness parameter, in addition to each partner's potential contributions and an assessment of critical technologies; a second analysis focuses on evaluating Rationale Satisfaction and value gain for participation in a partnership. Combined, these evaluations help identify win-win collaborations.

This exercise indicates that there are multiple combinations of actors and partnerships that can meet the identified missions by trading off technology readiness and rationale satisfaction. It further indicates that the proposed framework can also be used to identify technology gaps and capabilities that are desirable for future exploration endeavors as well as political and policy challenges that must be addressed to facilitate cooperative partnerships in the future.

Keywords: *International cooperation, Human space flight, Space exploration, Policy framework*

1. Introduction

The international space community has changed dramatically since the birth of the Space Age. In just over 55 years, the competitive space environment dominated by the Soviet Union/Russia and the United States has been replaced by a complex and diversified community of actors directly involved in space –governments, intergovernmental organizations, private institutions, and even individuals.

Despite lasting economic challenges, the global space economy grew 12 percent in 2012 to account for USD 304.3 billion [1].The majority of this growth was taken up by the private sector, which already represents nearly three-quarters of the global space economy and is looking to expand beyond traditional service-oriented activities. Intergovernmental and non-governmental institutions, universities, and research centers are helping to fill gaps to provide key services and access, including education in Science, Technology, Engineering and Math (STEM)[1].With the expansion of crowd-funded and citizen science initiatives, amateur astronomers, students, and volunteer researchers also play a direct role in making the observations and analyses, advancing Earth and space science research[2]. In an environment of growing reliance on space assets coupled with decreasing government space budgets, this multiplicity of actors presents both challenges and opportunities for the future of space exploration[3].

International space cooperation, pursued in the past by major space players as a way to reap scientific, economic, and political benefits, is now increasingly considered to be necessary for the expansion of global space exploration activities, particularly human space flight (HSF) efforts beyond low Earth orbit (LEO). Despite recurring statements from expert groups highlighting the need for international partners to come together for strategic planning activities, efforts to craft international space exploration missions have been limited in scope and have failed to consider the significant resources of non-traditional space actors such as those previously mentioned.

To address this need, in May 2013, the Skolkovo Institute of Science and Technology (Skoltech) in collaboration with the Massachusetts Institute of Technology (MIT) convened an international working group of 23 graduate students and recent graduate researchers to propose a way forward for space exploration in the coming decades. Representing over 12 countries, the members of this multi-disciplinary, multi-cultural team sought to bring together the interests of multiple potential space partners and to draw from their unique characteristics.

After an initial exchange of ideas supported by extensive background research, the MIT/Skoltech Space Exploration Strategy University Research Group identified the need to develop a framework to model and evaluate international cooperation in space among different kinds of actors.

This paper presents key observations of the group and the proposed approach towards abstracting the four key components of any proposed cooperative mission in space: mission architecture, required technological capabilities, relevant participating actors, and rationales for the participation of these actors. In proposing a way to evaluate the interaction of these four abstractions, this framework provides a tool that measures overall suitability of a mission to its actors based on the satisfaction of both technology and policy needs. This tool can also be used to identify capabilities that are desirable for future exploration endeavors as well as political and policy challenges that must be addressed to facilitate cooperative partnerships in the future.

After a discussion of the four abstractions and the workings of the framework, this paper will delve into examples of possible space exploration missions in the future. The goal of these case studies is not to advocate for specific destinations or technologies or partnerships but rather to evaluate the workings of the framework and identify limitations and benefits of this approach. This framework seeks to contribute to existing literature on international space exploration by proposing a novel approach to defining international space cooperation missions where non-traditional space actors are considered potential partners in space exploration.

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[1] In 2011, the U.S. National Aeronautics and Space Administration (NASA) selected a non-profit institution, the Center for the Advancement of Science in Space (CASIS) to be the sole manager of the International Space Station U.S. National Laboratory.

[2] Citizen science opportunities enable citizen scientists to assist in the analysis of the huge amounts of data collected from spacecraft missions or other records. For an authoritative list, see http://www.planetary.org/explore/space-topics/citizen-science/.

[3] A major challenge being explored internationally is long-term space sustainability and what constitutes responsible behavior in space.

2. Background

In July 1975, a docking exercise between the Soviet Soyuz and the US Apollo vehicles enabled a cosmonaut and an astronaut to shake hands in orbit. While this event may have been remarkable from an engineering perspective, it was charged with political symbolism. Taking place more than 15 years before the end of the Cold War, the Apollo-Soyuz Test Project was the first public demonstration of what could, and did, evolve into a lasting space partnership and the first evidence that even in the ideologically charged area of HSF, collaboration and competition could co-exist.

Since this landmark event and through the last 40 years, international space cooperation in HSF has taken many forms. Beyond the Apollo-Soyuz program, the USA and Russia collaborated in the Shuttle-Mir Program; astronauts and individuals from 16 different countries flew on US Shuttle flights, while over 20 astronauts from the European Space Agency (ESA) have flown on Russian and US missions. The largest and most successful international space cooperative HSF project has been the International Space Station (ISS), which despite a tumultuous history, has involved over 16 countries as partners and participants.

In fact, it has been argued that the most enduring legacy of the ISS will be the accomplishment of bringing together NASA, ESA, the Japanese Aerospace Exploration Agency (JAXA), the Canadian Space Agency (CSA), and Roscosmos into a major space engineering project in which each partner played a critical-path role. Basic operation of ISS Expeditions consist of integrated crews under a single commander. The US Operating Segment (combining NASA, ESA, JAXA, and CSA) shares resources for research under a "functional allocation" model, while the Russians retain control in their segment [2].

This arrangement is the result of intense negotiations over a period of years and reflects shifting priorities by the partner states over the course of the program. According to Sadeh [3], NASA originally planned for a "functionally independent [Space Station Program] where foreign partners augmented capabilities by substantial, significant, and well-defined contributions." The intent was to minimize technology transfers to other nations and ensure US control over the station. The introduction of Russia to the international partnership, however, increased the desire of the original partners to play more critical roles, and the cancellation of key US components by Congress drove NASA to reconsider its original plan.

Sadeh further notes that Russia was given an "enabling" role in the *ISS* core to address their concerns over parity with the USA and program management. This was done to ensure "functional interdependence," meaning that the system requires the contributions of the whole team to function. The benefit of functional interdependence is exemplified by the fact that the *ISS* Program survived despite the *Shuttle Columbia* accident in 2003. At present, *ISS* partnership decisions are reached by board consensus of designated representatives from each partner state, NASA, nevertheless, retains decision-making authority in the event of deadlock or a crisis.

Despite the apparent success of the interdependent model, it cannot be taken for granted that major nation states will continue with this approach. For example, NASA's Constellation Program for human lunar exploration did not obtain international cooperation on critical path items like the crew vehicle, crew launch vehicle, cargo launch vehicle, or lunar lander. After the program was canceled in favor of extending *ISS* operations and developing more generic heavy-lift launch capabilities, the only notable international participation in US HSF deep space exploration development today is the recent negotiation for ESA to provide the first Orion Multi-Purpose Crew Vehicle with a service module derived from the Automated Transfer Vehicle.

According to Gibbs [4], the International Space Exploration Coordination Group (ISECG), hosted by the ESA Directorate of Human Space Flight, was created to "reflect a consensus among the world's space agencies." He adds that is important policy-wise because ISECG is "product-oriented" with Global Exploration Roadmaps and similar advisory documents [5]. While participation in ISECG is voluntary and group recommendations are not binding on member space agencies, ISECG counsel is based on lessons learned from the *ISS* Program and has the benefit of hindsight spanning the past three decades.

In the mid-2000s, an MIT student group attempted to provide a framework for evaluating future cooperative proposals by simultaneously considering technical and political issues. Broniatowski et al. [6] suggest that the analysis rests on three technical parameters (cost, schedule, and performance), two policy parameters (respective political utility for each partner), and six forms of international cooperation (the null case, short-term niche, long-term niche, critical path, parallel missions, and multinational institutional) for each proposed participant.

The MIT case study analyzed potential opportunities for cooperation between the United States and Italy on future human exploration missions. Only three of the six forms of collaborations were seriously considered; the null case was discarded since Italy does not have the capability to carry out parallel missions with the USA, and it was deemed unlikely that either nation would cede responsibility to a multinational institution. The MIT evaluation model recommended that the USA and Italy pursue short-term niche cooperation options, such as an Italian instrument on a US science mission, due to unfavorable cost and schedule risks that the USA would perceive with regard to long-term niche and critical path options.

While the ISS program will continue through 2020 and space research and operations in other areas progresses, the future of HSF beyond LEO remains in question. This uncertainty is particularly evident in the United States. Although the USA has traditionally assumed a leadership role in HSF exploration, political instability in the United States over the last five years has led to an ambiguous future in HSF and beyond. In 2012, the National Research Council evaluated NASA's strategic plans and their achievability and concluded that "there is no national consensus on strategic goals and objectives" for the agency [7]. In a highly interdependent space community this uncertainty affects and impacts US partners in space, particularly those who were engaged in a meaningful role in now-canceled or restructured programs.

3. Presentation and Validation of the Framework

3.1. Framework Overview

The objective of this paper is to present a framework to evaluate international partnerships for future HSF missions. This framework builds upon four relevant high-level abstractions:

- *Actors*: the group of space agencies or entities participating in the collaboration;
- *Missions*: the destinations and related reference mission architecture concepts for which the partnership is set in place;
- *Technologies*: the capabilities required to implement a mission, owned at different technology readiness levels by the actors; and
- *Rationales*: the logical basis for an actor to participate in a partnership based on stated principles or justifications.

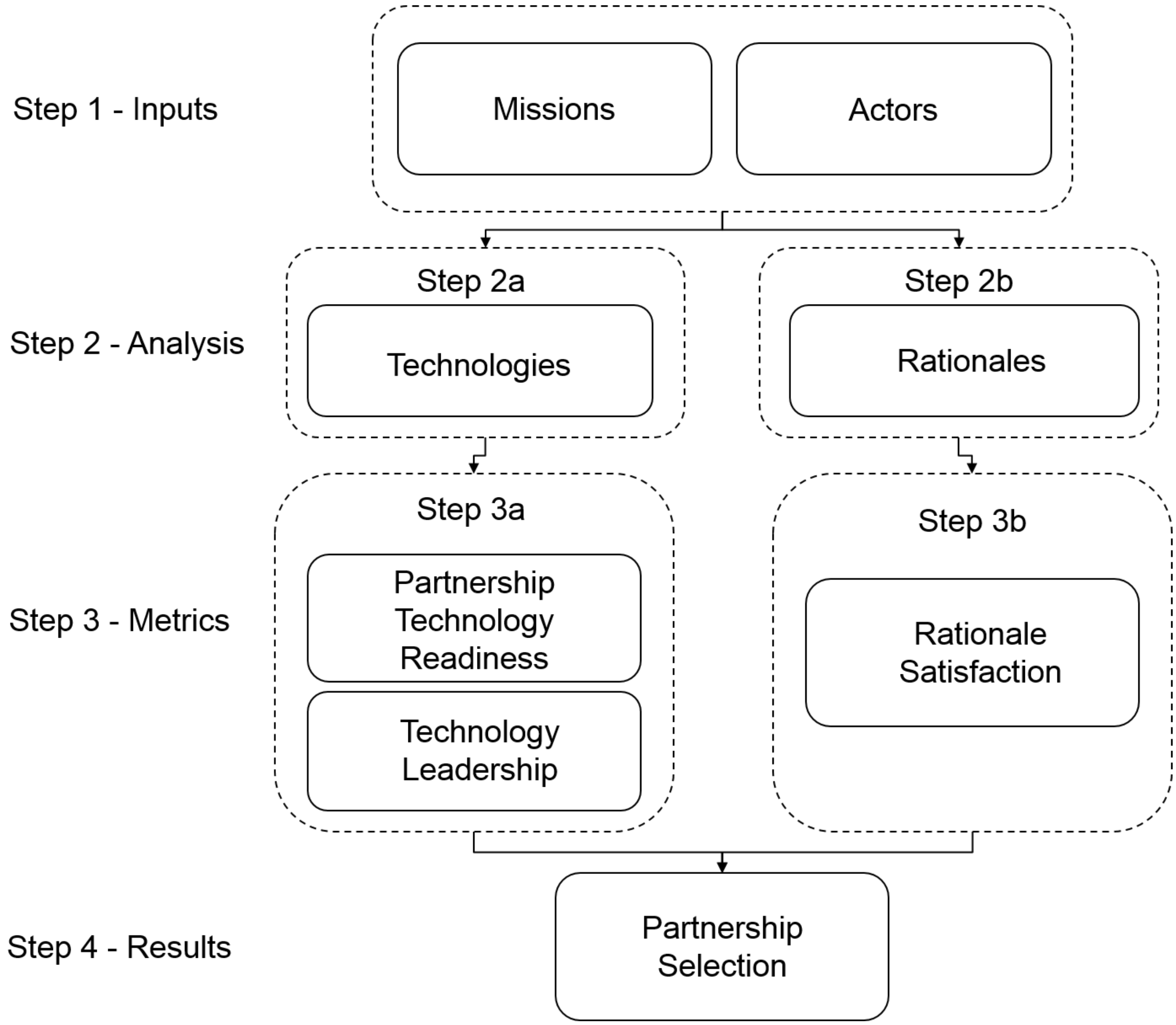


Figure 1 - Framework flow diagram. Graphic representation of the framework and its four steps: inputs, analysis, metrics and results.

As indicated in Figure 1 the framework is divided into four steps:

1. Inputs – In Step 1, the assumptions and scope of the analysis are defined, and then divided into two categories: missions and actors. By defining the missions, a set of destinations and reference mission architectures that the partnership is going to pursue are identified. Second, the set of actors that will be considered in the evaluation are defined. These decisions provide the scope of analysis.
2. Analysis – In Step 2, two distinct analyses of the inputs are carried out in which both technical and policy aspects are considered. The two analyses are separate and performed individually without a preferred order. Step 2a presents a technical analysis where missions and actors are matched by defining the required technologies. Input mission architectures are functionally decomposed in required capabilities at a high level of abstraction, and the current technology readiness of these capabilities is then evaluated for each input actor. Step 2b consists of a policy analysis where rationales for partnerships are enumerated and selected. The analysis of the current technical and non-technical aspects is the basis upon which metrics are defined and recommendations derived.

3. Metrics – In Step 3, three evaluation metrics define measurements and criteria for prioritizing and comparing different partnership scenarios. In Step 3a, two metrics to represent technical aspects are given which aim to consider an overall partnership technology readiness and partners' technical contributions and commitment. Step 3b presents a rationale satisfaction metric that compares the involved partners' interests and measures the likelihood of collaboration between two partners.
4. Results – In Step 4, partnerships are evaluated and selected based on both the technical and policy analysis metrics.

The rest of section 3 provides a detailed explanation of each step of the framework. A case study involving four actors and three reference missions is used to validate the framework and initial recommendations and findings are given.

3.2. Inputs

In Step 1 of the presented framework, two categories of inputs—missions and actors—are defined in order to create the basis upon which we operate the analysis.

3.2.1. Missions

The Missions input represents the list of missions and reference architectures that the partnerships are set in place to pursue. Three reference missions have been selected to perform a validation of the presented framework:

- Deployment of an *ISS*-derived module at the EM-L2 to operate as a periodically occupied orbital research station and a gateway to further destinations [8]
- *Constellation* Program-derived extended Moon surface exploration [9]
- Low-energy Near Earth Object (NEO) rendezvous and sample return of four to seven months in duration and supporting a crew of three astronauts using near-term technological capabilities [10]

In order to give breadth to the analysis the chosen missions span different destinations and objectives. For the sake of simplicity, the mission architectures have been derived from detailed point design studies and are therefore reliant on fixed references. However, different reference missions can be used without affecting the validity of this framework.

3.2.2. Actors

The Actors input represents the list of actors potentially participating in a partnership. Four actors have been selected for the validation of the framework:

- United States
- Russia
- Europe
- China

The geographical abstractions are dictated by the necessity to consider both national space agencies and commercial entities in the evaluation. While in the United States and Europe a distinction between governmental and commercial (nongovernmental) partners can be more easily drawn, in Russia and China the two concepts are more closely linked and, therefore, clarifying distinct partners becomes a challenging task. These two entities are therefore merged into a single regional actor, which encompasses the capabilities of both space agencies and industries. The presented list of actors is not exhaustive but is only intended as an example to present and validate the framework. A further breakdown of European countries or the inclusion of other *ISS* participants and emerging actors such as India and Brazil could add granularity to the results and are suggested as next iterations of the presented case study.

Furthermore, with appropriate understanding of the distinct policy needs of private industry as separate from the national agencies they serve, individual organizations could be included alongside agencies for more detailed partnership modeling.

3.3. Technical Analysis and Metrics

Step 2a represents a technical analysis of the chosen missions and actors, in order to define required technologies and their current Technology Readiness Level (TRL) by actor.

The reference architectures have been broken down into 23 required technologies, which encompass distinct capabilities, operations, and sub-systems required by the reference missions. This decomposition seeks to simplify and abstract technologies while maintaining a sufficient level of fidelity to distinguish readiness capabilities between nations. As an additional simplification, the common technologies are assumed to have a similar amount of complexity between different missions. Table 1 below presents the list of technologies for the three reference architectures.

Table 1 - Functional decomposition of the required capabilities for the selected reference architectures. Dots indicate that the technology is included in the related architecture.

Technology	**EM-L2**	**Moon**	**NEO**
Autonomous rendezvous	●	●	
Pressurized habitat and cargo modules	●		
Cryogenic propellant storage and transfer	●	●	●
International docking standard interface	●		
Re-ignitable cryogenic engines	●	●	●
High-thrust electric propulsion	●		
> 250 kW power source	●		
Environmental Control and Life Support System (ECLSS)	●	●	●
Radiation/Micro-Meteoroid protection	●	●	●
High velocity re-entry system		●	●
Crew vehicle	●	●	●
Surface power generation		●	
Low-g and zero-g health countermeasures	●	●	●
Dust mitigation		●	●
In-Situ Resource Utilization (ISRU)		●	
Surface long-distance mobility		●	
Autonomous landing and hazard avoidance		●	
Human-rated Heavy Lift Launch Vehicle (HLLV)		●	●
HLLV launch facilities		●	●
In-space science and sample collection			●
Anchoring			●
Astronaut in-space mobility systems			●
Long-duration storage of power			●

The technologies associated with each mission can therefore be scored based on the TRL of each capability at the current state of the art for each actor [11]. Since a precise TRL assessment of each partner is not an easy task, a scoring conversion criterion has been defined as to simply the selection of each readiness level. The nine levels are reduced to four scores ranging from 0 to 1, as presented in Table 2. The division between one score and the next represents a major development gap between two different readiness levels. TRL 1 to 3 consider conceptual definition and validation, TRL 4 to 5 define component level testing, TRL 6 to 7 are related to the sub-system level, and TRL 8 to 9 present flight qualified technologies.

Table 2 - TRL scoring conversion criterion.

TRL	1	2	3	4	5	6	7	8	9
Score	0	0	0	0.33	0.33	0.66	0.66	1	1

Scores are then assigned for each technology for all the reference actors as seen in Table 3. These are allocated by matching the complexity requirements of the selected technologies and available reference literature and public assessments on the selected actors' capabilities. Complexity requirements are based on minimum required performances of the technologies in the mission operational environments. In this sense, a technology developed by an actor for LEO applications but with different deep space operational requirements would get a lower score than dedicated deep space developed capabilities. This is the main reason why China is considered to have many capabilities at a low TRL: these technologies have been mostly developed for a LEO reference environment, and there is not any public evidence of Chinese deep space rated capabilities developed beyond conceptual level. Since the scores are derived from public sources it is not possible to directly validate this information.

Table 3 - Technology vs. actor scores.

Technology	**USA**	**Russia**	**Europe**	**China**
Autonomous rendezvous	1 [12,13]	1 [14]	1 [15]	1 [16]
Pressurized habitat and cargo modules	1	1	1	1
Cryogenic propellant storage and transfer	0.33 [17]	0.33	0 [18]	0
International docking standard interface	0.66 [19-22]	0.66 [19-22]	0.33 [19-22]	0 [19-22]
Re-ignitable cryogenic engines	0.33 [17]	0.33	0.33 [23]	0.33
High-thrust electric propulsion	0.33 [17]	0.33	0 [24]	0
> 250 kW power source	0 [17,25]	0 [26]	0 [27]	0
ECLSS	0.66 [28-31]	0.66 [32]	0.33 [33]	0 [34]
Radiation/MMOD	0.33 [25,35-37]	0.33	0 [38]	0
High velocity re-entry system	0.66	0.33	0	0
Crew vehicle	0.66	0.33	0	0
Surface power generation	0	0	0	0
Low-g and zero-g health counter-measures	0.33	0	0	0
Dust mitigation	0.33 [39]	0	0	0
ISRU	0.33 [40]	0	0	0
Surface long-distance mobility	0.66	0	0	0
Autonomous landing and hazard avoidance	0.33 [41]	0	0	0.33
Human-rated heavy lift launch vehicle	0.66 [42]	0	0	0
HLLV launch facilities	1 [43]	0.33 [44]	0	0

In-space science and sample collection	0.66	0.33	0.66	0
Anchoring	0.33	0	0.33	0
Astronaut in-space mobility systems	1	1	0	0
Long-duration storage of power	0.33	0.33	0	0

The first metric to be defined is the Partnership Technology Readiness (PTR). This metric is evaluated per partnership, per mission. The PTR is defined as:

$$PTR = \sum_{j}^{T} \frac{\max_{i}\{t_{ij}\}}{T}$$

where t_{ij} is the readiness score for each combination of actor *i* and technology *j*, as presented in Step 2a, and T is total number of distinct technologies for the mission. For each technology, the maximum score among the partnership actors is selected and normalized by the number of required distinct technologies for that mission. In this sense, the PTR considers only the highest possible contributions from the partners and assesses the overall partnership TRL for the selected mission. This score therefore ranges from 0 to 1, where 0 stands for a partnership where no technology is currently available at the required level of complexity, and 1 stands for a full flight-ready portfolio of capabilities.

The second technical metric that is defined to evaluate partnerships is the Technology Leadership (TL). While the PTR metric is evaluated for each partnership per mission, the TL is defined per actor in a partnership per mission. The TL definition is

$$TL_i = \sum_{j}^{T} \frac{L_{ij}}{T}$$

$$L_{ij} = \begin{cases} 1 & t_{ij} = \max_{i}\{t_{ij}\} \\ 0 & otherwise \end{cases}$$

where L_{ij} is a binary coefficient and t_{ij} and T have the same meaning as described for the PTR metric. For a given actor in a given partnership, if the technology score is the maximum among the partners, a leadership score $L_{ij} = 1$ is assigned to the actor. The sum of the leadership scores is then normalized by the total number of required distinct technologies. In this sense, this metric assesses the percentage of unique contributions of an actor in a partnership. This score, as the PTR, ranges from 0 to 1, where 0 means that the actor does not provide any technology that is at a higher score than the other partners' scores, and 1 stands for an actor whose portfolio of technologies exceeds every other partner for each technology. TL scores do not indicate overall readiness for a partner. Rather, they indicate the amount of unique contributions partners can make that would potentially drive them to a critical-path contribution.

3.4. Policy Analysis and Metrics

In Step 2b, rationales for participating in a partnership are defined in order to provide the basis for a policy evaluation of the potential partnerships.

A variety of rationales for human space exploration exist and are identifiable throughout the literature but a clear unbiased list of motivations and justifications to collaborate in space has not yet been defined. National policies and public statements by space actors, however, indicate a set of recurring rationales that involve national goals and objectives that may affect participation in an international program. Six rationales have been selected as key policy aspects that can affect a given partnership:

- National pride
- Demonstration of solidarity with allies
- Ability to shape global space policy
- Self-sufficiency in space
- Support for domestic capabilities
- National security

In addition to these six rationales, many other motivations to pursue a space program exist, but can be considered non-distinguishing for the scope of this framework as they likely do not significantly affect participation in an international program. Some examples of non-distinguishing rationales are:

- Scientific return
- Exploration of the solar system
- General technology development

The six selected rationales provide the basis to derive a Rationale Satisfaction (RS) metric to evaluate non-technical aspects of a given partnership. While the non-distinguishing rationales are important for overall mission concept selection, it is not expected that they will influence the likelihood of success for a given partnership in the context of this framework.

Step 3b builds upon Step 3a by defining a RS metric to analyze the non-technical aspects of a partnership. The Rationale Satisfaction metric is defined for each possible combination of two actors in a partnership, and is meant to provide information on how an actor's rationales are satisfied by collaborating with another actor. This metric is decoupled from the technical analysis, since the evaluation is only made between two actors regardless of the missions and technologies. The Rationales Satisfaction metric is therefore a measure of the likelihood of collaboration between two partners.

The Rationale Satisfaction metric builds upon scoring criteria that are defined to evaluate satisfaction of each rationale. Table 4 provides the criteria for assigning ordinal quantitative measures, where "first actor" refers to the actor whose rationales are being scored, and "second actor" refers to the other partner in the collaboration.

Table 4 - Rationale satisfaction scoring criterion

Score	**Collaboration with the second actor "…" the first actor's rationale**
+2	…will positively affect…
+1	…may positively affect…
0	…will not affect…
-1	…may negatively affect…
-2	…will negatively affect…

For each possible coupling of actors, each partner's six rationales for collaborating with the other actor are evaluated based on the presented scoring criteria. In order to match the scores to each rationale and refine the criteria, additional "interaction" criteria are defined. Table 5 explains in detail the criteria used to define positive and negative interactions between two partners for each of the selected rationales.

Table 5 - Rationale satisfaction positive and negative interaction criteria

Rationale	**Positive Interaction**	**Negative Interaction**

National Pride	The collaboration boosts the actor's national pride	The collaboration diminishes the actor's national pride
Demonstration of solidarity with allies	An alliance exists between the partners, or the collaboration with the second actor is compliant with the international policy of the first actor's allies	The collaboration is not compliant with the first actor's or its allies international policy
Ability to shape global space policy	The collaboration allows the partner to influence space policy-making at a regional or global scale	The collaboration forces the first actor to accept foreign policies or to diminish its international role
Self-sufficiency in space	The collaboration allows the first actor to gain critical knowledge to pursue self-sufficient access to space in the future	The collaboration prevents the first actor to develop self-sufficient access to space in the future
Support for domestic capabilities	The collaboration allows the first actor to develop and support critical domestic industries and capabilities	The collaboration forces the first actor to reduce domestic production due to overlapping capabilities with the second actor or conflicting trade policies
National security	The collaboration matches the first actor's national security policy, or key national security goals are enabled by the collaboration	The collaboration is in conflict with the first actor's national security policy or a national threat is created by collaborating with the second actor

By assigning the scores for both partners, the difference in satisfaction between the two actors can be calculated. A graphical spider plot representation helps to visualize the discrepancies in Rationale Satisfaction. Figure 2 – USA-Europe Rationale Satisfaction Spider Plotshows an example spider plot for the USA-Europe collaboration.

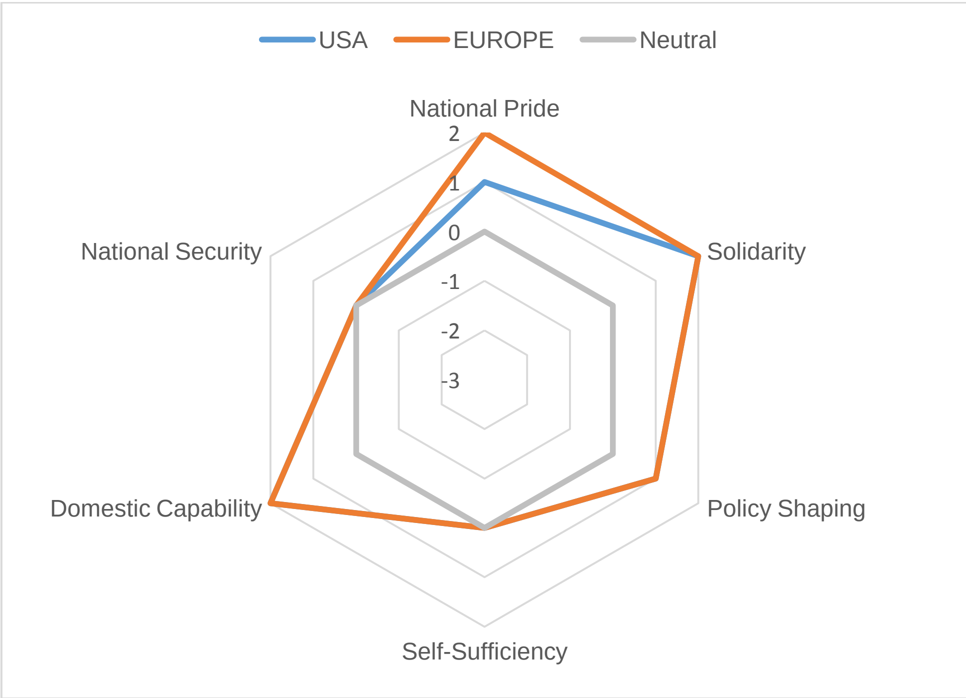


Figure 2 – USA-Europe Rationale Satisfaction Spider Plot. Each corner of the hexagonal plot represents one of the six rationales, and a radial plot for each partner's scores is drawn inside.

Scores are assigned by reasoning through the described criteria as informed by publicly available documentation of policy. As an example, the reasoning behind the USA-Europe evaluation is given:

- *National pride:* Both the United States and Europe receive a positive national pride effect by collaborating with each other. However, as Europe does not have an indigenous HSF program, its national pride will get a more definite boost, and is therefore given a higher score.
- *Demonstration of solidarity with allies:* As the United States and Europe are known allies, a maximum score is given to both partners.
- *Ability to shape global policy:* Collaboration between these two partners might improve space policy development both regionally and globally. However, since both actors play a major role in the space community, it is not possible to clarify which actor could have a major influence and are, therefore, scored equally.
- *Self-sufficiency in space:* The collaboration does not affect partners' potential self-sufficient future access to space, since the USA is developing a human heavy lift launcher and Europe is explicitly not planning to do so.
- *Support for domestic capabilities:* There are complementarities between the partners' capabilities. US capabilities cover most of the European technologies but the federal budget situation at the time of this writing prevents the USA from developing all the required capabilities for a selected mission. Therefore, as Europe owns a relatively small portfolio of critical technologies, contributions between the two partners can be shared to prevent an overlap of technical developments.
- *National Security:* The collaboration does not strongly influence national security policies for either of the partners.

After the scores have been assigned to every possible combination of two actors, it is necessary to analyze the results in order to identify win-win partnerships, where both partners benefit from the collaboration.

We define a "win-win partnership" as one that lacks a negative interaction between the partners. Based on this definition, the USA-Europe partnership presented in the previous paragraph is considered a win-win partnership.

An example of collaboration that is not considered a win-win partnership is the USA-China case. Figure 3 shows this partnership's Rationale Satisfaction spider plot.

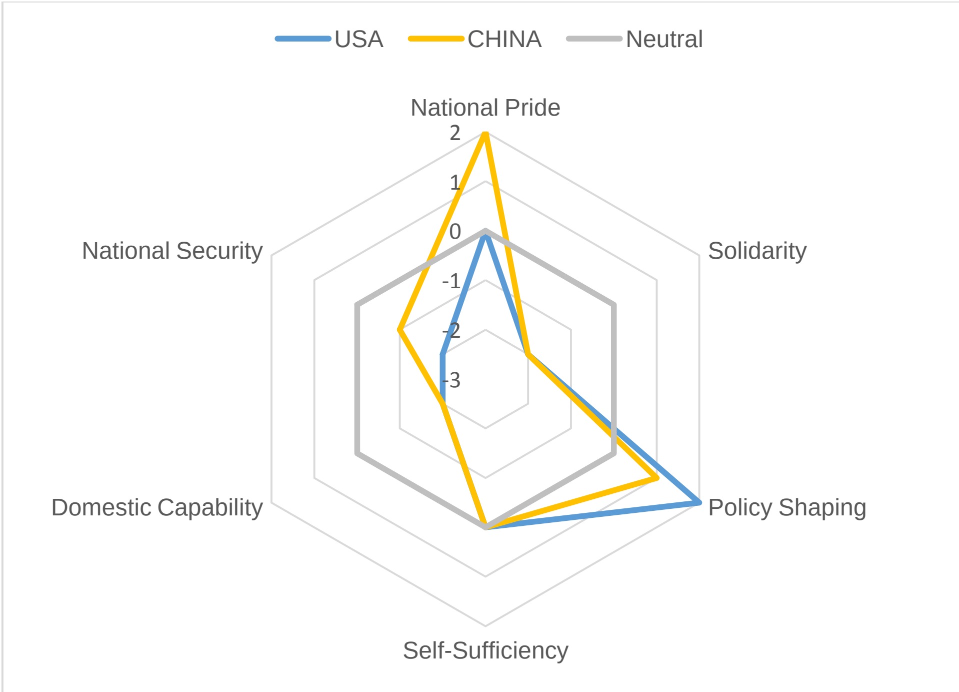


Figure 3 - USA-China Rationale Satisfaction spider plot. Each corner of the hexagonal plot represents one of the six rationales, and a radial plot for each partner's scores is drawn inside

The reasoning behind the scoring is given:

- *National Pride*: Collaboration between USA and China would see a definite national pride boost from the Chinese perspective, while it is unclear if the United States would benefit or not from this collaboration. China is seen as an emerging space leader. and the collaboration would not diminish U.S. national pride. The rationale is therefore considered unaffected from the American point of view.
- *Demonstration of solidarity with allies:* Both the USA and China have seen an emergent negative consideration of each other in the recent past. An alliance between these two countries is not easily foreseeable in the near future. Neither actor has allies that would benefit from this collaboration. The score is therefore considered negative for both.
- *Ability to shape global policy:* Collaboration between these two partners might improve space policy development both regionally and globally as compared to the current lack of coordination between their space programs. The USA, however, may have more opportunity to shape international policies in space if a collaboration with China was established. Therefore, the two scores have a discrepancy.
- *Self-sufficiency in space:* The collaboration does not affect the potential self-sufficient future access to space of the partners, as both countries are developing capabilities whose development would not be hampered in any tangible way.
- *Support for domestic capabilities:* US policy prohibits commercial collaboration between American and Chinese space industries. Unless the relevant national security and trade policies are changed, domestic industries on both sides could not benefit from the collaboration. The scores are therefore considered negative for both actors.
- *National security:* China is considered a major national security threat to the USA. On the flip side, collaboration with the US could be seen as a possible negative interaction with Chinese national security policies. Therefore, both scores are considered negative with a discrepancy.

The USA-China partnership develops only two positive interactions out of six. Consequently, it is not considered a win-win partnership. Table 6 - Rationale Satisfaction matrix shows the possible interactions between the four reference actors. Two combinations out of six indicate negative interactions and these partnerships are therefore not considered win-win partnerships. Every possible combination containing USA and China or Russia and China is therefore discarded by the metric. The corresponding spider plots are shown in Appendix A.

Table 6 - Rationale Satisfaction matrix.

Actor	**USA**	**Russia**	**Europe**	**China**
USA		✓	✓	✗
Russia	✓		✓	✗
Europe	✓	✓		✓
China	✗	✓	✓	

4. Results

After analyzing the inputs and evaluating the relevant metrics, we combine the technical and policy analysis in order to evaluate and select potential partnerships through the use of the defined metrics.

4.1. Partnership Evaluation

Table 7 enumerates the 11 possible combinations of actors and the relative Rationale Satisfaction (RS) and Partnership Technology Readiness (PTR) scores. Grey cells indicate that the actor is participating in the partnership. Through the Rationale Satisfaction metric, partnerships are considered win-win when there are no negative interactions between the actors' rationales, as described previously. For the PTR scores, a difference of 10 percent from the maximum score is considered a threshold for selecting the partnerships. If two combinations have a major technical gap, the least score is not considered a viable option between the two.

Table 7 - Partnerships evaluation

Actors				**RS**	**PTR**		
USA	**Russia**	**Europe**	**China**		**EM-L2**	**Moon**	**NEO**
				✓	0.50	0.51	0.55
				✓	0.50	0.51	0.55
				✗	0.50	0.51	0.55
				✓	0.47	0.24	0.36
				✓	0.30	0.11	0.12
				✗	0.47	0.24	0.31
				✓	0.50	0.51	0.55
				✗	0.50	0.51	0.55
				✗	0.50	0.51	0.55
				✗	0.47	0.24	0.36
				✗	0.50	0.51	0.55

4.1.2. Findings

Four out of eleven possible combinations are identified as potential partnerships and only three can perform all three of the selected missions.

Potential partnerships for every reference mission:

- USA – Russia
- USA – Europe
- USA – Russia – Europe

Potential partnership for the EM-L2 mission only:

- Russia – Europe

Based on the discarded options, it is interesting to observe that the Europe-China partnership is considered win-win but does not have the technical capabilities to fulfill any of the selected missions. The Russia-China option, in turn, would have a sufficient technical portfolio to be considered for an EM-L2 mission but the rationale metric does not support this partnership as a win-win collaboration. All four selected partnerships have similar Technology Readiness scores, with a slight decrease in the absence of the USA. In order to define the degree of commitment of the selected actors, the Technology Leadership metric defined in Step 3a is considered.

4.2. Technology Leadership Evaluation

The Technology Leadership metric defines the unique technical contributions of the actors in the selected potential partnerships. As an example, Figure 4 - Technology Leadership bar chartsshows this metric in a bar chart for the first three selected partnerships: USA-Russia-Europe, USA-Europe and USA-Russia. The blue bars represent the percentage of technologies that are shared by the actors (i.e. the percentage of technologies at the same TRL for all partners). The green bars represent the percentage of technologies owned by a single actor. In these cases, only the USA owns unique higher TRL technologies compared to the other actors and, therefore, all the green bars refer to this actor. As both blue and green bars represent percentages, the two bars stacked together refer to the full portfolio of capabilities for the selected mission.

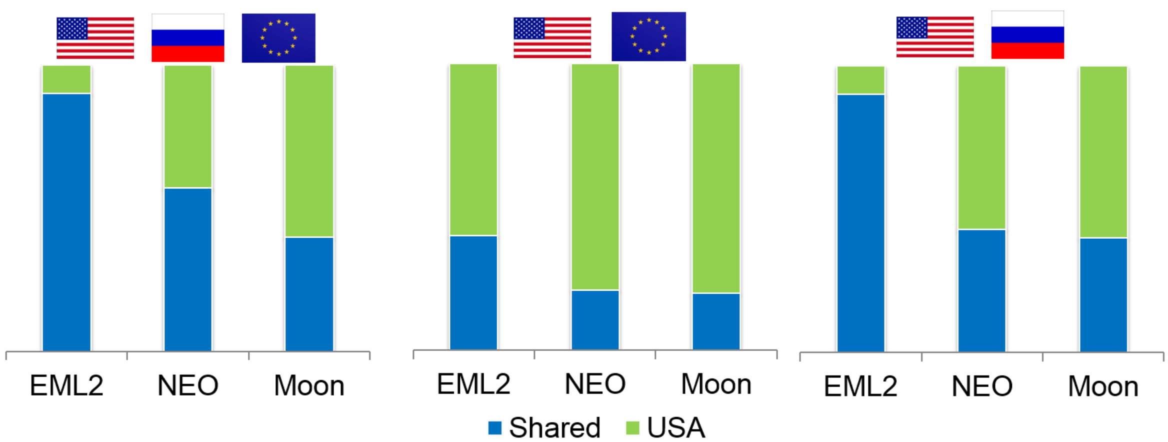


Figure 4 - Technology Leadership bar charts. Blue indicates the percentage of required technologies per reference that are shared by the actors and green indicates the percentage of technologies owned by a single actor.

The first important finding of the Technology Leadership metric is that the USA is the only actor to have a score and therefore is the only actor between the three combinations that has unique higher TRL capabilities. If we compare the three charts additional findings can be drawn.

In the first chart, all three actors participate in the partnership. The EM-L2 mission is the only one where the US' unique contributions are a small percentage of the total number of capabilities, while the USA singularly covers around 45 percent of the NEO technologies portfolio and 60 percent of the Moon portfolio. This trend shows that

US commitment in a partnership becomes critical for a Moon or NEO mission, where unique capabilities are required. Additionally, this highlights that an EM-L2 mission is the only scenario in which technical commitments can be fairly divided between the actors. This is a direct consequence of the nature of the selected reference mission, which heavily draws from existing ISS technologies, to which all the three partners have contributed so far. The importance of EM-L2 as the only feasible next step among the chosen set of missions for some of the actors is confirmed by the fact that this is the only potential partnership that could be established without US participation.

As a second analysis, we can infer the role of Russia and Europe in the three partnerships. In the second chart, Russia is not participating and as a result, the US leadership scores are much higher than in the first chart. This underlines the fact that the US and Russian technical portfolios have many capabilities in common.

In the third chart, Europe is not participating, and we see that the EM-L2 and Moon scores do not change at all from the first chart, while the US score for the NEO mission increases just by a small percentage. This fact proves that European technologies are covered for the most part by both Russia and the USA.

The Technology Leadership metric therefore shows that US participation in a partnership is mandatory for all the reference missions but for the EM-L2 concept, where different partnerships can be set in place. In this case, U.S. absence can be covered for the most part by Russia, which has a similar technical portfolio derived from the ISS program.

5. General Technology Findings

The presented framework seeks to find a methodology for evaluating partnerships for future international space programs but additional findings can be derived from the presented technical analysis.

5.1. Technology Development

The first consideration for analysis pertains to how many of the technologies needed for the selected reference missions are currently being developed by the selected actors. Figure 5 - Reference mission technology developmentsshows technology development pie charts for the three selected missions. Green slices represent available capabilities, yellow slices refer to capabilities that are under development, and red slices represent capabilities that none of the selected actors are currently developing beyond proof-of-concept level. We therefore define a technology as under development if, in the very least, a component level evaluation and testing has been reached (i.e., if the selected technology has reached TRL 4).

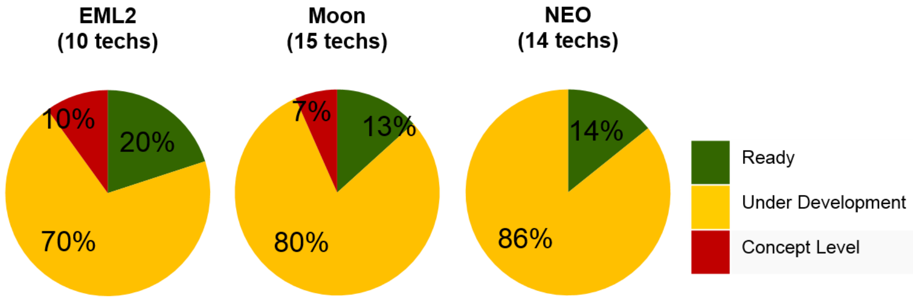


Figure 5 - Reference mission technology developments pie charts. Green indicates available capabilities, yellow indicates capabilities under development, and red indicates capabilities that are not being developed beyond a concept level.

The first consideration that can be drawn by these charts is that all the required technologies for the reference NEO mission are currently being developed or are already available for the selected actors.

In contrast, some technologies required by the EM-L2 and Moon concepts are not being developed beyond concept level, specifically:

- Power sources that provide 250kW or more, required by the EM-L2 mission
- Advanced surface power generation, required by the Moon mission

Because of this gap, development of either of these technologies would automatically give an actor, whether space agency or industry, a preferred status in a partnership to fulfill these reference missions. Therefore, opportunities for investment for critical technologies exist and could be exploited by interested actors – either private entities or government technology programs.

As the actors are currently developing most of the technologies required by the reference missions, it is significant to define who is developing which technology. As seen in the Technology Leadership findings, the USA is the only actor that is currently developing a series of technologies that include:

- Dust mitigation
- ISRU (In-Situ Resource Utilization)
- Surface long-distance mobility
- Human-rated autonomous landing and hazard avoidance
- Human-rated heavy lift launcher

As the only actor currently investing in the development of these technologies, the USA maintains a preferred position in every partnership that involves completion of either of the reference missions considered.

5.2. Sequencing

Technology developments can also be used to define mission sequencing by considering required incremental developments over time, assuming shared technologies are available from previous missions.

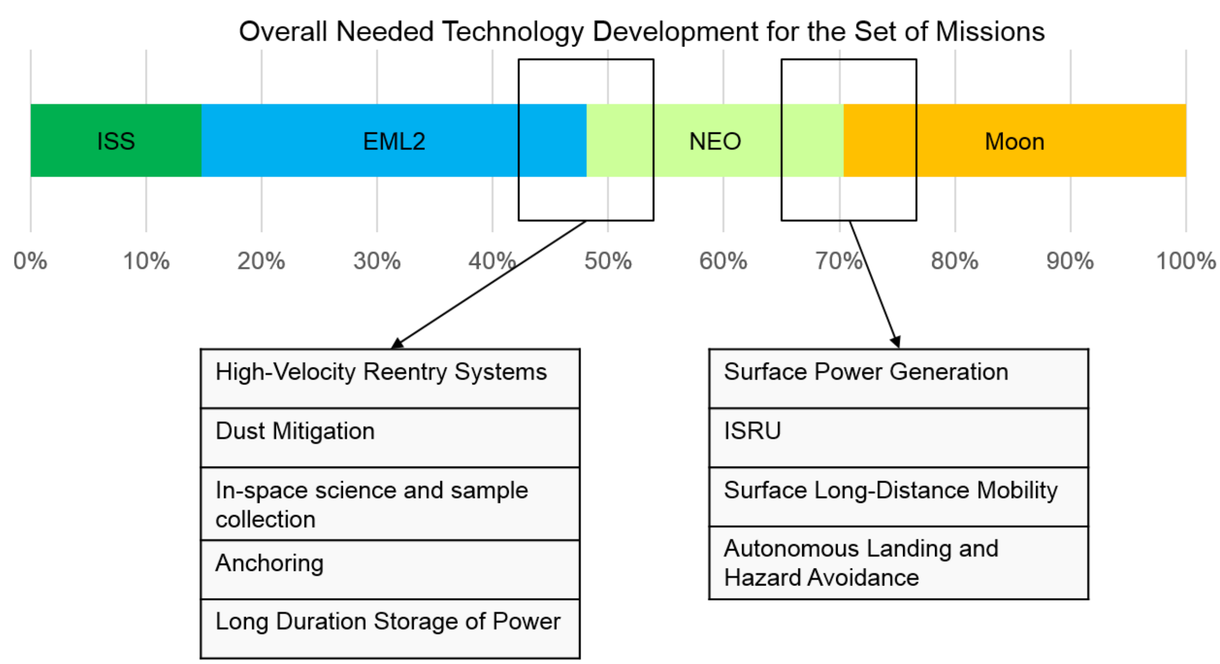


Figure 6 – Post-*ISS* mission sequencing by defining incremental technology developments over time.

Figure 7 – Examples of technology development sequencing shows a reference sequence for the selected reference missions in the form of a bar chart. The chart considers the percentage of technologies that are required by the full set of chosen missions, and the colored bars refer to the percentage of technology development that a mission will require. The width of the bars depends on the percentage of technologies that have already been developed in the previous missions. Thus, by sequencing the missions differently, we can derive the trend of development projects that the actors could pursue over time. The boxes explicitly define which technologies are required to prepare for the next mission. The green bar refers to technologies developed for the *ISS* and those required at the same level of complexity by the reference missions, thus representing the available technologies slice in the previous pie charts.

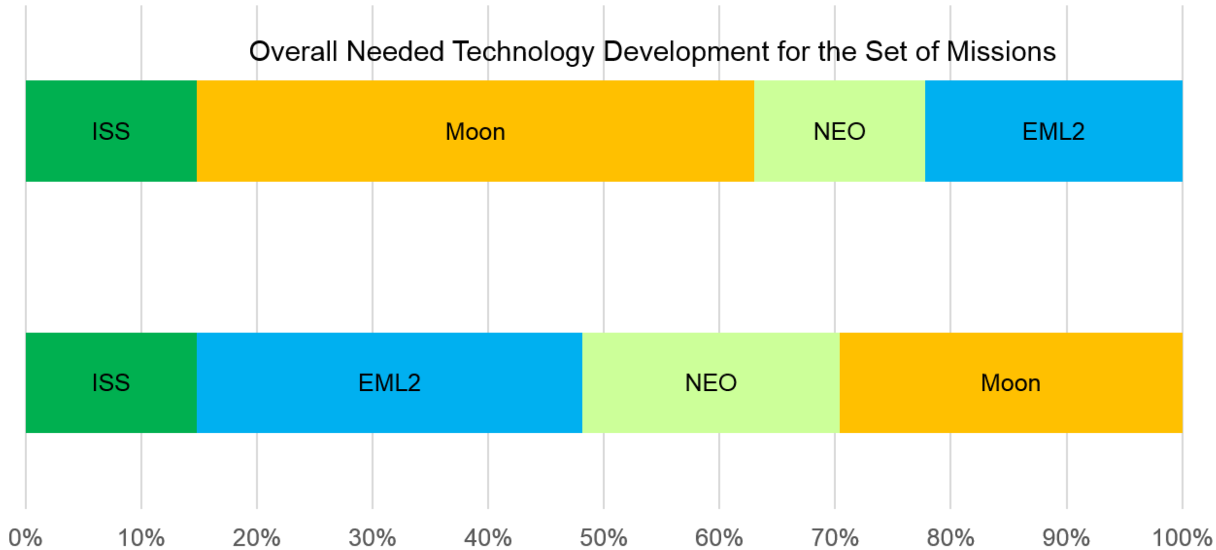


Figure 7 – Examples of technology development sequencing for post-ISS missions.

Figure 7 shows two sample sequences. In the first, the Moon mission is pursued before the others. As the Moon requires most of the technologies that are needed for the other two missions, the initial development investment is much larger. In the second chart, the order is reversed, with the EM-L2 mission being pursued first, followed by the NEO and the Moon missions. The initial investment required by the EM-L2 mission is as much as 15 percent smaller than the one required by the Moon-first sequence. Furthermore, in the second option the three bars have similar widths, suggesting that investments are more equally distributed over time.

This finding is a direct result of the amount of unique technologies that a surface mission requires, such as the Moon concept. The recent cancellation of the lunar-oriented *Constellation* program is evidence of the budgetary challenges of such a major initial investment.

6. Conclusions

International space cooperation is now increasingly considered to be necessary for the expansion of post-ISS human spaceflight exploration. The challenge remains, however, as to how to best engage a complex and diversified community of space actors to develop lasting partnerships for sustainable international space exploration.

Given this context, the MIT/Skoltech Space Exploration Strategy University Research Group sought to develop a methodology for evaluating potential partnerships between a multiplicity of space actors by considering both the technical and non-technical parameters that influence future mission success. The proposed framework contributes to the limited literature on international space partnership evaluation and offers a flexible tool that considers the fundamental aspects judged to be critical for the sustainability of cooperative efforts.

As a way to validate the tool and contribute to ongoing discussions about post-ISS HSF efforts, potential partnership for three reference missions were evaluated. The results from this exercise indicate that there are multiple combinations of actors and partnerships than can meet the missions identified, trading off technology readiness and rationale satisfaction. At the same time, it highlights the need for both parameters to be satisfied through a partnership. A Europe-China partnership, for example, is considered win-win from the rationale satisfaction aspect, but lacks the technical capabilities to fulfill any of the selected missions. Other potential partnerships – such as the Russia-China example, meet the technical requirements but fail on the rationale scale. This sort of analysis therefore suggests the kinds of challenges that need to be addressed by the potential partners in order for their collaboration to be mutually beneficial.

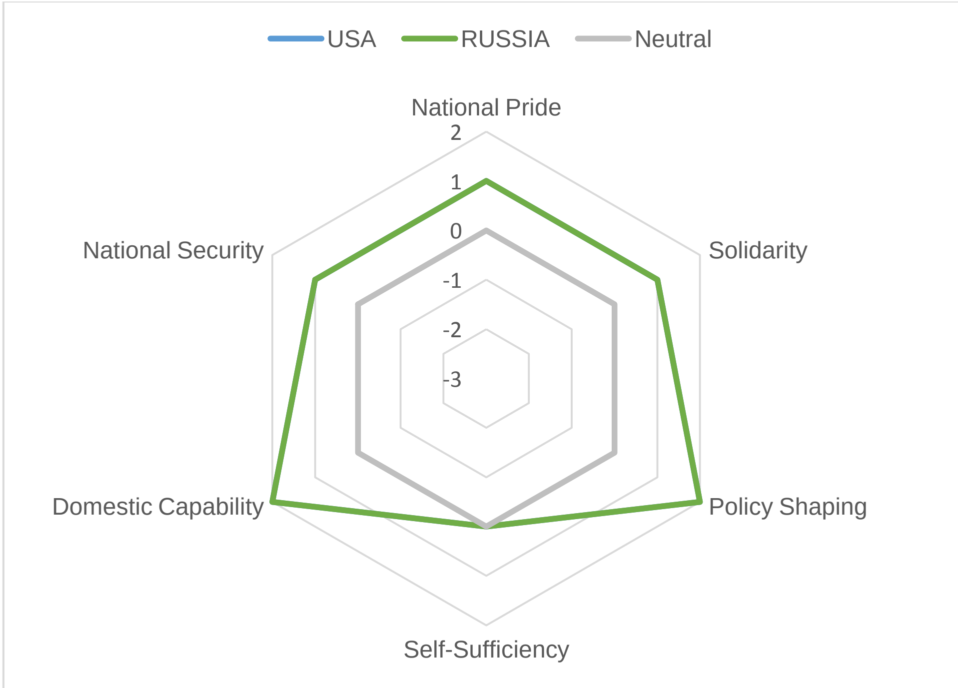
The analysis provided additional findings of value. A Technology Leadership metric, which evaluated the technical contributions of individual actors, illustrates that US participation in a partnership is essential for all the reference missions except for the EM-L2 concept, where different partnerships can be established.

Finally, the framework also provided ways to identify critical-path technology gaps, which may present opportunities for additional actors to play a meaningful role in the partnership.

While the reference missions considered here apply to future HSF efforts, the four key abstractions defined for this framework apply to every other domain, such as space science or Earth science, and the process may help to identify win-win collaborations in these areas. The approach presented here is also unique in that it is not limited to a governmental point of view but assumes that non-governmental actors at different levels can be meaningful partners in ambitious space exploration efforts.

While beyond the scope of this paper, future work could examine relevant issues including: technology evolution, specific policy challenges between a particular set of actors and how to address them, and the contributions of different kinds of actors within a country.

Appendix A – Partnership Rationale Spider-Plots


USA
RUSSIA
Neutral
National Pride
Solidarity
Policy Shaping
Self-Sufficiency
Domestic Capability
National Security
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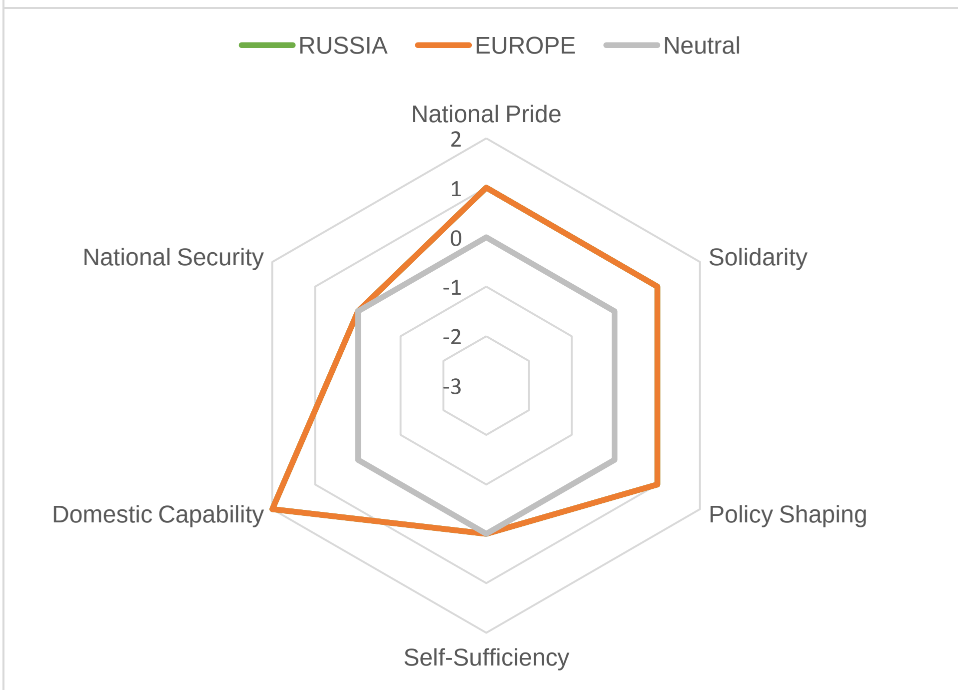
RUSSIA
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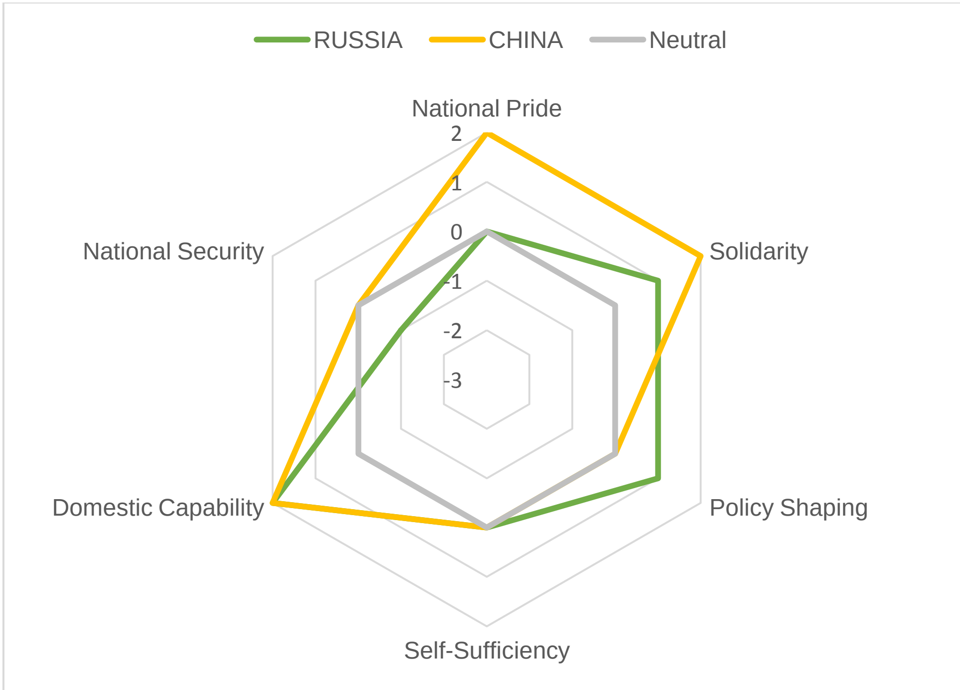

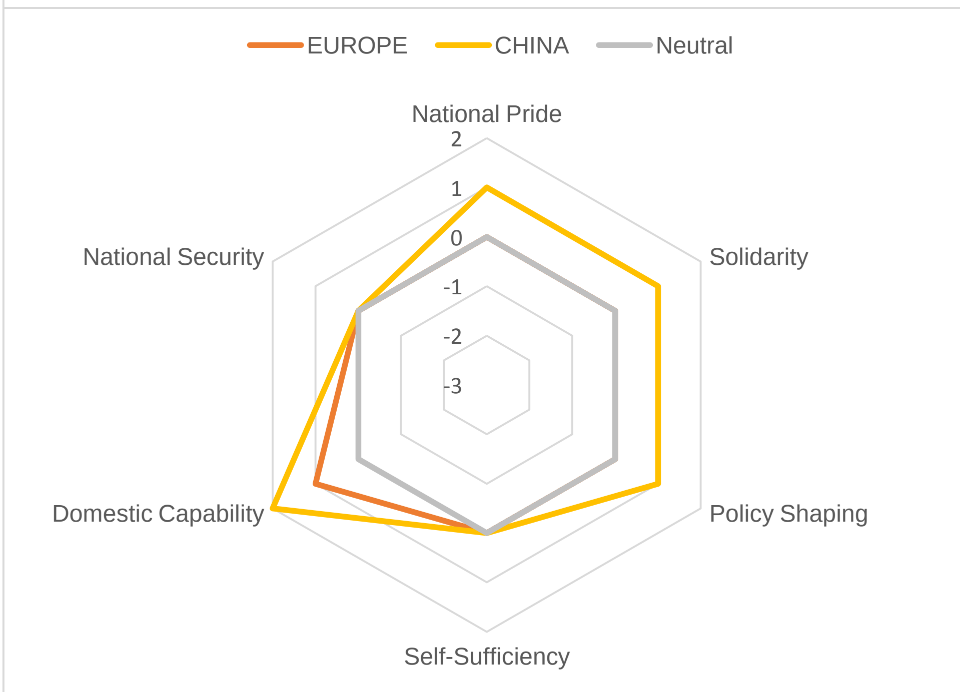

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