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Market Study on Nuclear Electric Propulsion for Space Applications

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Abstract

Nuclear electric propulsion (NEP) offers groundbreaking capabilities for both exploration missions and in-space logistics. In the context of the New Moon race and the aspiration to establish a Mars colony, NEP holds potential space transportation applications, when other propulsion means can be inefficient. This paper proposes a market study to assess the potential applications of NEP and its competitiveness with respect to other means of propulsion. The paper analyses various use cases (transfer between a low Earth orbit (LEO) and geostationary orbit (GEO), and a transfer from LEO to a lunar orbit) but also addresses other potential markets that can be enabled by NEP. This analysis is performed as a part of ESA's RocketRoll project, or "preliminary european reCKon on nuclEar elecTric pROpuLsion for space appLications".

Keywords: nuclear electric propulsion, market analysis, space transportation, space mining, on-orbit servicing

1. Introduction

Nuclear electric propulsion (NEP) holds great promise in space propulsion technology, offering high efficiency and power for future space missions. As humanity moves closer to establishing a sustained presence on the Moon and Mars, the need for reliable high-power propulsion systems becomes increasingly vital. NEP offers a distinct advantage over conventional chemical propulsion through its superior fuel efficiency while surpassing solar electric propulsion (SEP) in terms of power output and operational flexibility. Crucially, NEP systems are independent of solar energy, enabling them to operate continuously in shadowed regions or deep space. These attributes make NEP a suitable choice for long-duration cargo missions, supporting the development of space infrastructure and the long-term sustainability of human outposts on neighbouring celestial bodies. Furthermore, NEP's capacity for extended operation holds immense potential for future solar system exploration, unlocking new possibilities for ambitious, long-range missions.

This paper presents findings from the "RocketRoll" project, a European Space Agency (ESA)-driven initiative focused on evaluating the technical and economic feasibility of nuclear electric propulsion. The project *Preliminary European Reckon on Nuclear Electric Propulsion*

for Space Applications - (RocketRoll) aims to develop a conceptual design for a nuclear propulsion engine and identify the technological advances necessary to make such a system operational by 2040.

A key part of this evaluation involves understanding the technical and cost parameters that define future NEP systems. Parameters such as engine size, mass, and electrical power output remain critical unknowns that will shape the overall competitiveness and functionality of NEP. For instance, determining whether a larger, more powerful engine might offer greater advantages than a smaller, less powerful one will depend on the specific mission profiles. Although chemical propulsion is recognized for its high thrust and solar electric propulsion for its efficiency, NEP is expected to offer a middle ground, balancing efficiency with increased power output for long-duration missions and heavy payloads.

The premise of this paper is that a comprehensive market analysis can be pivotal in defining the key parameters that will guide the future development of NEP systems. By analyzing potential applications, evaluating competing technologies, and understanding the demands of upcoming space missions, critical insights can be derived for the optimal design characteristics of NEP. This market-driven approach not only ensures the technical feasibility of the

propulsion system but also positions NEP as a commercially competitive option in the evolving space propulsion market.

To this end, a market study that includes a techno-economic and cost analysis of NEP is conducted to assess the viability of NEP in various mission scenarios, comparing it with competing propulsion technologies, such as chemical propulsion and solar electric propulsion. The study includes market projections and future prospects over a 15-year period, extending the analysis to 2040 to capture long-term trends and opportunities.

The analysis begins by examining two specific mission scenarios to evaluate the competitiveness of NEP against chemical and Solar Electric Propulsion (SEP) in the current space market. The first scenario involves the deployment of large satellites into geostationary orbit (GEO), while the second focuses on a cargo mission to lunar orbit. These two cases represent key applications where propulsion efficiency and power output are critical, allowing a direct comparison of NEP's advantages over existing technologies.

Beyond these primary use cases, the paper explores additional markets that could be enabled by the capabilities of NEP. An area of particular interest is on-orbit servicing (OOS), which includes refuelling, repair, and maintenance services for space assets. The study also considers space mining and other emerging space markets that could benefit from NEP's extended operational capacity and efficiency. These applications highlight NEP's potential to unlock new commercial opportunities in space, broadening its relevance beyond traditional missions.

2. Overview of near-term market drivers for advanced space propulsion systems.

2.1 Market drivers for geostationary orbit (GEO)

Recently, the focus of space missions has shifted towards low Earth orbit (LEO) due to lower launch costs, the ability to deploy smaller and more affordable satellites and technological advancements, but geostationary orbit still offers unique advantages for specialized missions. GEO remains essential for telecommunications satellites, providing uninterrupted global coverage, especially for broadcasting, weather monitoring, and strategic defense. Importantly, the growing concern about climate change has further amplified the need for more geostationary satellites to monitor global warming and its effects on the climate systems of the Earth.*

The global satellite industry generated €253B in revenue in 2021, making up about 72% of the global space economy. Within this, satellite services such as telecommunications

and remote sensing contributed approximately €107B. In satellite manufacturing, €12.4B was generated, with 82% of launched satellites being for commercial and communications purposes, which largely dominate the GEO market [1].

The total number of launches to GEO per year is presented in Figure 1. Linear interpolation is used to project the future demand for GEO launch. Based on recent downward trends, the interpolation suggests a decreasing pattern in launches, with projections extending to 2040 reflecting this decline. However, a linear interpolation based on trends from 1960 suggests an increase in demand, and both these projections are considered for the cost calculations.

Telecommunication satellites are typically large, weighing between 3 and 5 tons, which makes it costly to launch directly to GEO. This is mainly due to the significant delta-V required by the launchers to reach GEO, which makes the cost of launches for these satellites considerably higher than for LEO.

An important objective of this study is to evaluate the use of different propulsion technologies to transport heavy satellites between orbits and compare them to NEP. In this context, launching telecommunications satellites to LEO and then using an orbital transfer vehicle (OTV) to transfer them to GEO could be more cost-effective than a direct launch to GEO. To assess the potential benefits of using NEP, we will first compare it with conventional chemical propulsion, followed by a comparison with solar electric propulsion.

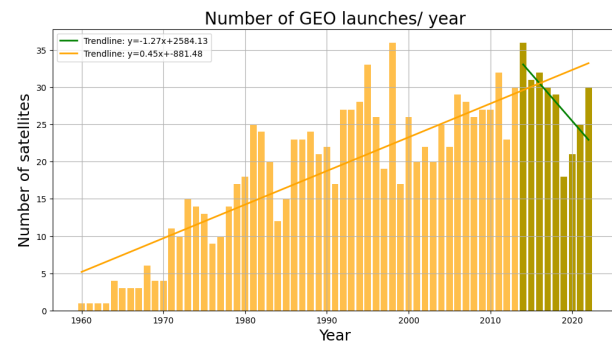


Figure 1 Total GEO launches per year (data extracted from [2])

2.2 Market drivers for Lunar transportation and In-situ activities

The main demand for lunar goods and services includes scientific exploration, lunar tourism, and resource extraction. The lunar economy is expected to increase dramatically in the coming years, particularly for human and cargo missions. Two principal drivers of this demand are government expenditures on Moon-related activities and

*https://www.nesdis.noaa.gov/s3/2023-06/22-J-833-NOAA-NESDIS-User_Needs_Requirements_and_Lifecycle_Costs_REPORT.pdf

the cost of transportation. Additionally, constructing both a lunar space station and a permanent lunar base has become a priority for many space agencies. For example, NASA’s Artemis program aims to establish a sustainable presence on the Moon, including the Gateway lunar space station. Similarly, China’s Chang’e program envisions building a lunar research station. European Space Agency also supports initiatives like Moon Village, emphasising international collaboration in lunar exploration and infrastructure development. This government-led push is fueling a derived demand for transportation systems, landers, capsules, and other lunar goods and services [3].

To capitalize on this lunar economy, projections indicate that economically viable activities will primarily revolve around lunar tourism and commercial ventures involving lunar resource extraction [3]. The use of advanced spacecraft, such as starships, is anticipated to be integral in facilitating these operations. In addition to these commercial activities, the construction of lunar infrastructure, including habitats, research facilities, and lunar bases, will require significant investment and reliable transportation systems [4]. A detailed summary of the projected costs, demand, and revenue for these economically viable activities over the next 15 years is provided in Table 1 [3, 5]. This highlights the critical economic potential of lunar commercial activities and the significant role propulsion technologies, including NEP, could play in ensuring these missions are both technically feasible and cost-effective.

Activity	Cost	Demand/ year
Lunar Tourism	€32M-68M/customer	40+ customers
Lunar commercial products	€6700/kg - 1.1M€/kg	1.8-11.3 ton

Table 1 Economically viable lunar activities

Building on these projections, a recent study estimates that the lunar transportation market for payload mass will reach 187 tonnes between 2020 and 2040, resulting in a projected total market value of approximately 72B€[6]. This growing demand is driven by a combination of commercial activities and the need to transport materials for the construction of vital lunar infrastructure, including habitats, research stations, and lunar bases. These large-scale projects will require reliable and cost-effective transportation solutions to deliver essential equipment and resources. In our cost analysis, we take this 187-tonne payload target for 2040 into account and perform a detailed evaluation based on these projections.

3. Comparison of nuclear electric propulsion with competing propulsion technologies

3.1 Orbital transfer from low Earth orbit to geostationary orbit

The idea is to compare the cost of transporting cargo directly to GEO using chemical propulsion versus a two-step approach: first bringing it to low Earth orbit with a conventional rocket launcher, and then using nuclear electric propulsion or solar electric propulsion to move it to the designated orbit. Figure 2 shows the described scenarios. Table 2 summarised the required ΔV needed by low-thrust propulsion for such a mission.

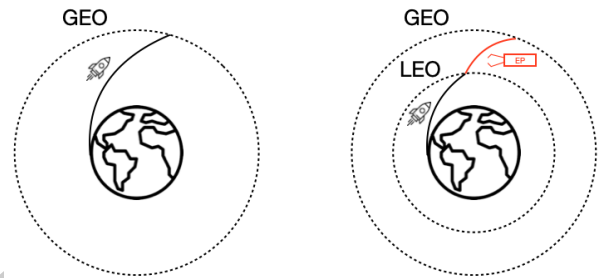


Figure 2 Comparison of chemical and electric propulsion for LEO-GEO transfer.

Transfer LEO-GEO	Required ΔV [km/s]
One way	4.33
Roundtrip	8.66

Table 2 ΔV budget for the LEO-GEO transfer

3.1.1 Chemical propulsion

In this example, to compare with traditional chemical propulsion, we consider the European launcher Ariane 6, alongside two existing SpaceX launchers, Falcon 9 and Falcon Heavy. Additionally, we include the potential low-cost launcher like Starship, which is expected to enter the market in the coming years. The cost of the low-cost launcher is based on projections, as precise figures are not yet available. Table 3 highlights the costs of orbit insertion using different launchers.

Let us imagine a scenario where 5 satellites of 4 tonnes, making 20 tonnes in total, are launched 3 times a year to GEO, which is 15 satellites per year in coherence with the decreasing trend of Figure 1. The total mass is then 60 tonnes. Bringing these satellites to GEO with launchers is 1380M€ using the European launcher or 340M€ using the SpaceX launcher. Bringing the same payload to LEO costs 320M€ and 141M€, respectively. Thus, to be competitive

	Ariane 64	Falcon 9	Falcon Heavy	Low-cost launcher
Cost [€]	115M	67M	150M	37.5M
Payload to LEO [kg]	21650	22000	63800	150000
Payload to GEO [kg]	5000	8300	26700	27000
Specific cost LEO [€/kg]	5312	3045	2351	250
Specific cost GEO [€/kg]	23000	8072	5618	1000
Launches per year	7	91	5	≥10?

Table 3 Comparison of launchers: cost, payload capacity, and specific cost to LEO and GEO

even with a less expensive launcher, transferring 60 tonnes of satellites in one year from LEO to GEO with OTV should cost less than 200M€ for three transfers. If we assume that the OTV is capable of transferring 20 tonnes in two months from LEO to GEO in one way, it is capable of achieving the yearly goal of 60 tonnes. Such a scenario fixes the power of the NEP (depending on the mass of the payload and the time of transfer), as well as gives an initial maximum cost limit for one transfer, which is 65M€ in this particular example. These costs should account for the cost of the propellant but also the cost of the OTV itself, its development and insurance, as well as its positioning in orbit. The economy of scale allows for the amortisation of these costs over multiple years.

Tables 4 and 5 summarise different costs implicated in the orbital transfer using NEP.

Reactor specific cost [€/kg]	5000
Licensing cost [€]	30M

Table 4 Costs for Nuclear Electric Propulsion

Specific impulse [s]	2000	2000	9000
Propellant	H_2O	Kr	H_2
Propellant cost [€/kg]	10	200	100
Propellant cost for one roundtrip LEO-GEO [€]	11100	222000	20000

Table 5 NEP parameters used for the study

Table 6 summarises the estimation of costs for the mission duration of 10 years aiming at moving 20 tonnes of payloads between LEO and GEO depending on the one-way

time of flight (TOF) needed for the NEP: 1, 2 or 3 months, making it to 2, 4 or 6 months a roundtrip. Fixing TOF allows us to fix the total number of cargo missions per year. The costs are given for the chemical propulsion (CP) and for the total estimation of the NEP cost to satisfy the 50% or 75% cost-efficiency (η) when compared to the chemical propulsion for the same mission parameters. In other words, $\eta = 50\%$ means that the NEP costs are half of the costs needed with the chemical propulsion for the same mission scenario. Thus, CP costs 13800M € for bringing the cargo directly to GEO over 10 years with Ariane 6. If we want NEP to cost less than half of it, it makes 6900M €. The cost of launching the cargo to LEO with the same launcher has to be considered, which is 3200M €. Thus, NEP's total costs should be a maximum of 3700M € to decrease the mission cost by 2 when compared to CP. The costs of using CP to bring cargo to LEO first are considered. The time of flight plays a major role in the competitiveness of NEP: the faster it is, the more cargo can be transferred, but the more the power of the reactor, and, therefore, its cost. The total cost comprehends the development of the OTV, the licensing, production of the nuclear reactor, launch of the OTV to LEO, the total amount of the propellant needed, and the refilling of the vehicle. The duration of the mission is 10 years. Comparison with the European launcher Ariane 6 gives the most positive value for the NEP cost estimation, but to ensure its profitability, we should expect the OTV to be competitive with the other launchers. Some of the numbers in Table 6 are too low to be feasible, for example, when compared to the low-cost launchers.

Launch using Ariane 6			
TOF	CP	NEP $\eta = 50\%$	NEP $\eta = 75\%$
1	27600	7430	14330
2	13800	3700	7160
3	9200	2500	4800
Launch using Falcon Heavy			
TOF	CP	NEP $\eta = 50\%$	NEP $\eta = 75\%$
1	6740	550	2230
2	3370	275	1120
3	2250	185	750
Launch using a low-cost launcher			
TOF	CP	NEP $\eta = 50\%$	NEP $\eta = 75\%$
1	1200	300	600
2	600	150	300
3	400	100	200

Table 6 Total maximum required NEP costs [M€] over 10 years for LEO-GEO transfer

3.1.2 Solar electric propulsion

The use of SEP on satellites for commercial, defense, and space science missions has grown substantially over the past decades. Since its first successful operation in 1964 onboard the Zond-2 spacecraft, SEP has demonstrated its potential to revolutionize space transportation [7].

To compare the techno-economic viability of NEP with SEP, the thrust, velocity, time, and power levels of SEP are calculated based on the methodologies provided in [8, 9]. These frameworks are used to determine the thrust duration, the total duration of orbit transfers, and the amount of propellant needed for SEP.

In this section, we perform a cost analysis for different mission scenarios to evaluate the economic feasibility of NEP versus SEP. To provide a practical basis for this comparison, we consider a transferable mass of 20 tons of LEO to be transported to GEO by the propulsion system in a single operation. This mass is selected based on launcher capacities and costs discussed in Section 3.1.1.

Parameter	Considered value
Payload	10/20 tons/vehicle
ToF	1 - 2 - 3 months (one way)
Power(Thruster)	Solar electric (HALL effect)
Thruster capacity	20-80kW
Isp	2000
Propellant	Krypton
ΔV	6 km/s
Mission period	10 years

Table 7 Requirements of the Orbital Transfer Vehicle (OTV) from LEO to GEO

The parameters shown in Table 7 are assumed for the mission. Different payloads of (10 or 20) tons/vehicle are considered to be transferred from LEO to GEO using SEP, and vehicle sizing and propellant sizing are calculated accordingly. Different TOFs are considered, which would affect the power levels required from the thruster and panels. The analysis considers Kr propellant.

The total transportation cost is estimated by:

$$C_{\text{total}} = C_{\text{LEO-GEO}} + C_{\text{prop-launch}} + C_{\text{OTV-launch}}$$

The transportation elements from LEO to GEO can also be divided into two parts from the point of view of costs: propellant and OTVs. Thus, in-space transportation cost is estimated using the following equation:

$$C_{\text{LEO-GEO}} = N_{\text{flight}} \cdot c_{\text{prop}} + N_{\text{vehicle}} \cdot c_{\text{vehicle}}$$

$C_{\text{OTV-launch}}$ is the cost required to transfer OTV to LEO. $C_{\text{prop-launch}}$ is the cost to put propellant from Earth to LEO,

which is then used by the OTV to transfer the payload from LEO to GEO. N_{flight} is the number of flights from LEO-GEO. c_{prop} indicates the cost of the propellant used to put everything in LEO. N_{vehicle} indicates the number of vehicles used and c_{vehicle} indicates cost to manufacture a SEP vehicle. SEP is used to transfer a spacecraft from LEO to GEO with the payload. The process involves iterative calculations to determine the necessary parameters, such as propellant mass, power requirements, and costs [10].

Launch using Ariane 6			
TOF	Payload	N_{vehicle}	Cost
1	10	2	6717
2	10	2	3416
3	20	1	2297
Launch using Falcon Heavy			
TOF	Payload	N_{vehicle}	Cost
1	10	2	3164
2	10	2	1640
3	20	1	1112
Launch using a low-cost launcher			
TOF	Payload	N_{vehicle}	Cost
1	10	2	643
2	20	1	379
3	20	1	272

Table 8 Total SEP costs [M€] over 10 years for LEO-GEO transfer

Table 8 summarizes the costs of using SEP to reach GEO using demand projections for 2040. It evaluates the feasibility of transferring different sizes of payload to GEO at different durations for HET thrusters and advanced solar arrays. These projections suggest that we can carry up to 20 tons/vehicle in four months and up to 10 tons/vehicle in two months to GEO.

In comparison, the costs of NEP operating at 75% efficiency are approximately similar to those of chemical propulsion systems, albeit with some anomalies due to the high cost of the Ariane 6 launcher. NEP will become cost-competitive with SEP if it achieves 50% efficiency relative to chemical propulsion in terms of cost. An important point to consider is that SEP systems have limitations on how much payload they can carry, primarily because of the mass and sizing constraints of the required solar arrays. Consequently, multiple SEP vehicles are needed to deliver smaller payloads to match the same total payload that NEP can transport in a single flight. In this way, NEP can be beneficial in reducing costs by enabling the delivery of larger payloads in fewer missions.

3.2 Lunar cargo mission

Now, let us consider a scenario in which we want to bring a payload to build a lunar space station. Specifically, transfers between LEO and high lunar orbits, such as NRHO, play a major role in exploring the Moon. The comparison between chemical propulsion and electric propulsion can show a potential interest in nuclear electric propulsion for this type of mission. We assume that using chemical propulsion, the cargo is launched first to the lunar transfer orbit (LTO). Once arrived at the target, the injection manoeuvre has to be performed with the onboard thrusters. Moreover, an additional propellant budget is required for the correctional manoeuvres over the transfer.

Transfer LEO-Moon	Required ΔV [km/s]
One way	8.37
Roundtrip	16.74

Table 9 ΔV budget for the LEO-Moon transfer

The delta-V budget requirements for the Lunar case are computed and are summarized in Table 9.

3.2.1 Chemical propulsion

The main difference of the second use-case is that if we consider the scenario where the launchers insert the satellites into the lunar transfer orbit (LTO), then we should count on the onboard thrusters for 1) correctional manoeuvres along LTO, 2) the insertion manoeuvre into the lunar orbit. Let us consider a cargo of 4 tonnes; the lunar injection manoeuvres require $\Delta V = 0.8$ km/s, and the chemical engines have a specific impulse I_{sp} of around 300 s. To account for the correctional manoeuvres on the way to LTO, we consider a total delta-V budget of 1 km/s. For these purposes, an additional mass of propellant needed for such manoeuvres is approximately 8 tonnes, according to Equation (1). Thus, the costs of the launch of the satellites to LTO should account for the 8 additional tonnes of mass.

$$\Delta V = I_{sp} g \ln \frac{m_0}{m_f}, \quad (1)$$

where m_0 and m_f are, respectively, the wet and dry mass of the cargo.

Table 10 summarizes the cost of launching to the lunar transfer orbit. Its injection into LTO costs 69M€, against 13M€ without the propellant. Here NEP is used as an OTV from LEO to the Moon. Launch to LEO is 9M€ so the whole transfer to the Moon should cost less than 60M€ to be competitive.

Tables 11 summarise propellant costs implicated in the orbital transfer using NEP.

The resulting requirements in terms of costs for NEP for the lunar cargo mission are illustrated in Table 12. The total

	Ariane 64	Falcon Heavy
Payload to LTO [kg]	8500	45000
Specific cost LTO [€/kg]	13530	3310

Table 10 Comparison of launchers to LTO

Specific impulse [s]	2000	2000	9000
Propellant	H_2O	Kr	H_2
Propellant cost [€/kg]	10	200	100
Propellant cost for one roundtrip LEO-Moon [€]	26000	520000	40000

Table 11 NEP parameters used for the study

NEP costs include the development and production of the OTV, the launch of the OTV to the initial orbit, LEO, the insurance, the propellant cost, refilling and launch of the propellant. We note that it is impossible to achieve $\eta = 50\%$ using Falcon Heavy because of the relatively small cost difference between launching cargo to LEO and to LTO.

Launch using Ariane 6			
TOF	CP	NEP $\eta = 50\%$	NEP $\eta = 75\%$
2	11365	2500	5340
3	7560	1670	3560
6	3780	830	1780
Launch using Falcon Heavy			
TOF	CP	NEP $\eta = 50\%$	NEP $\eta = 75\%$
2	2780	-	670
3	1850	-	450
6	925	-	225

Table 12 Total maximum required NEP costs [M€] over 10 years for the Lunar cargo mission

3.2.2 Solar electric propulsion

The low thrust calculation methodology proposed in [8, 9] is used for lunar cargo mission calculations similar to the previous case study.

The considered technological projections for thrusters and solar panel advancements are shown in Table 13. They are assumed for the cost analysis for lunar cargo. It is obviously not possible to make a SEP cargo mission to LLO before 2025 because of a lack of maturity in the technology. The cost analysis is done using the technology

projection for 2040, by which the thrusters of high power and panels producing high solar electric power are assumed to be ready.

Parameter	Considered value
Payload	5/10/15/22 tons
ToF	2 - 4 - 6 months (one way)
Power(Thruster)	Solar electric (HALL effect)
Thruster capacity	450-600kW
Isp	2500/3000/3500
Propellant	Xenon
ΔV	8 km/s
Mission period	10 years

Table 13 Requirements of the OTV from LEO to Lunar

The configuration used for the transfer of cargo from Earth to LLO is done in two phases. OTV and Cargo delivery vehicle (CDV) are used. It is assumed that both OTV + CDV are launched together to LEO, and OTV carries the CDV to reach LLO. The CDV is made to descend to the surface of the Moon. The OTV returns back to LEO and carries more CDVs until it reaches its end of life. All reusable components of the system, including the solar arrays, thrusters, and PPU's, are on the OTV. All components that are used only for the duration of the specific delivery mission, including the cargo and propellant tanks, are on the CDV. The OTV is the main vehicle in all docking operations.

Launch using Ariane 6		
TOF	Power (kW)	Cost (M€)
2	450	-
3	450	12120
6	450	3061
Launch using Falcon heavy		
TOF	Power (kW)	Cost (M€)
2	450	-
3	450	10946
6	450	2469

Table 14 Total SEP costs [M€] over 10 years for the Lunar cargo mission

Tables 14 & 15 present the estimated cost for lunar cargo missions with different power levels of 450 and 600kW. The transport (OTV+CDV) is assumed to cost 750M€ for 450kW power level and 1000M€ for 600kW power level. The OTV lasts for (4-6) missions based on the thruster's lifetime. Multiple OTVs and CDVs are assumed according

Launch using Ariane 6		
TOF	Power (kW)	Cost (M€)
2	600	18180
3	600	8793
6	600	3728
Launch using Falcon heavy		
TOF	Power (kW)	Cost (M€)
2	600	16410
3	600	7606
6	600	3136

Table 15 Total SEP costs [M€] over 10 years for the Lunar cargo mission

to the TOF and power levels to match the payload delivered as chemical and NEP in section 3.2.1 over 10 years. Similar to the LEO-GEO scenario, NEP could be a competitive technology for lunar cargo delivery when compared to SEP. SEP systems have limitations regarding the time required to reach lunar orbit, and achieving shorter travel times necessitates the development of higher power levels. NEP can overcome these constraints by providing greater power output, thereby reducing travel times and enhancing the feasibility of lunar cargo missions.

4. New potential markets that can be supported by NEP from 2035 onward

4.1 On-orbit servicing (OOS)

On-orbit servicing (OOS) involves providing various support services by a spacecraft, known as the servicer, to another spacecraft, referred to as the serviced spacecraft, while both are in orbit. These services can be conducted regardless of whether the serviced spacecraft is cooperative or non-cooperative [11]. OOS missions typically consist of several key phases: the servicer first transitions to the target's orbit, engages in proximity operations, performs an inspection, and proceeds with docking or capture. Upon completing the intended service, such as refueling, repair, or debris removal, the servicer undocks or releases the serviced spacecraft. Following this, the servicer may move to another servicing target, return to a designated parking orbit, or initiate deorbiting. This systematic approach facilitates a broad range of critical space operations, enhancing spacecraft longevity and contributing to debris mitigation [12].

OOS is projected to increase significantly over the next decade, driven primarily by the increasing number of satellites approaching their end-of-life. Satellite operators, particularly those in geostationary orbit, will face critical decisions about replacing ageing satellites or extending

their operational lifespans through OOS. In addition, there is a growing need to deploy satellite constellations into their intended orbits, as many are currently launched via cost-effective ride-sharing missions that leave them on suboptimal trajectories. This trend presents substantial opportunities for emerging companies to provide "last-mile" orbital transfer solutions with OOS vehicles, especially in LEO [13].

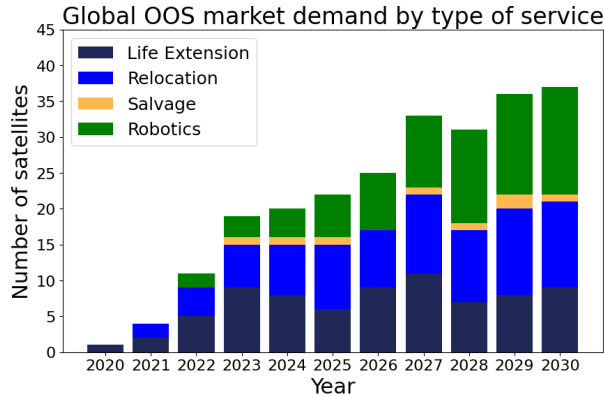


Figure 3 Global OOS demand in terms of life extension, relocation, salvage, and robotics. (Data extracted from [13])

Over the forecast period, more than 230 satellites are expected to undergo servicing, with government and military customers showing a preference for robotics and relocation services. While life extension currently dominates the market, the increasing diversity of service offerings is anticipated to drive greater demand for relocation and robotics 3.

Figure 1 shows the number of GEO satellites launched per year. The operational lifetime of such satellites is typically constrained to 15–20 years, largely due to the depletion of onboard propellant required for orbit maintenance and station-keeping. Once the fuel is exhausted, even otherwise functional satellites become space debris. Additionally, hardware failures and malfunctions represent a significant cause of premature mission termination. These challenges have highlighted the urgent need for in-space servicing technologies, including refueling and hardware repairs, to extend the functional life of these critical assets.

For example, NASA’s GOES-R Series consists of four advanced weather satellites operated by the National Oceanic and Atmospheric Administration (NOAA). These satellites represent the current generation of weather monitoring systems, each with an expected operational lifespan of approximately 15 years. The total cost for the four satellites is \$11.7 billion, averaging around \$3 billion per satellite.

The GOES-18 satellite, one of the series, has a launch mass of 5.2 tonnes and a dry mass of 2.9 tonnes, leaving 2.3 tonnes allocated for propellant. OrbitFab, a US-based

company, for example, proposes refuelling in GEO for \$200,000 per kilogram of hydrazine beginning in 2025. Thus, refuelling the GOES-18 satellite with 2.3 tons of propellant is estimated to cost \$460 million. This cost represents approximately 15.3% of the total cost of the satellite. Thus, a single refueling could potentially save \$2.5 billion over the satellite’s 15-year operational period.

Transporting propellant to geostationary orbit (GEO) with current estimates costs approximately \$1,500 per kilogram. For refueling a satellite with 2.3 metric tons (2,300 kilograms) of propellant, this results in a total cost of \$3.45 million. The refueling service company could potentially earn \$460 million from such a service.

Assuming the company refuels three satellites annually over a five-year period, this yields a total revenue of \$4.35 billion. To achieve a gross profit margin of 80%, the cost of such a NEP vehicle operating for 15 years, including its propulsion, launch, insurance, operational costs, and refuelling capabilities, should be about \$4 billion. This estimate accounts for the initial investment and operational costs.

Given that the number of potential clients is expected to increase, not limited to GEO but potentially extending to other orbits and missions, the cost per vehicle could decrease as economies of scale are realized.

Nuclear electric propulsion (NEP) is highly suitable for building the necessary infrastructure for satellite servicing, thanks to its low-thrust but high-power characteristics. NEP satellites can deliver refueling capabilities to various Earth-centered orbits and even enable in-space repair services. This technology allows for the retrieval of non-functional satellites to a repair station and their subsequent return to operational orbits, offering a practical solution for satellite maintenance and life extension.

This approach aligns with the broader trend of hosting payloads in space, as seen by the growing number of companies offering payload-hosting and payload-sharing services. Additionally, on-demand computing in space is emerging as a new frontier. We anticipate that this "servitization" trend will continue to intensify, driving the need for more efficient resource utilization in space operations. NEP is a key enabler of these emerging services, playing a pivotal role in their development and implementation.

4.2 Space mining

Space mining, in a broader sense, indicates mining activities on celestial bodies. Our focus in the following will be on mining near-earth asteroids (NEAs) and the Moon, as these are considered to be the economically most promising mining locations. According to [14], mining activities can be decomposed into the following elements:

- Launch and flight to the celestial body
- Deployment of mining equipment

- Resource processing
- Transportation of processed resources to the target destination

There is a large number of alternatives regarding the sequencing of these activities, their location, and allocation to different space systems. For example, resource processing may take place at the celestial body or may take place at the target destination. The processing plant may be transported to the celestial body by a spacecraft different from those transporting the processed resources to the target destination, or they may be performed by a single spacecraft. Regarding the economic viability of space mining, there is a general consensus in the literature that a) mining will take place to supply resources to targets in space and b) volatiles (water, oxygen, etc.) are the more promising resources to be mined, mainly due to their use as propellant and their relative ease of extraction. A more far-term application of space mining is the extraction of metals, in particular platinum-group metals (PGM), which are relatively rare on Earth but in high demand and, therefore, expensive. Most studies on space mining have so far focused on mining volatiles to provide propellant to rocket stages in cis-lunar space. A few studies [14, 15] have also focused on PGM mining, where [15] consider NEP and [14] propellant-less, sail-based propulsion. The main obstacle to NEA mining is considered the combination of long-term R and D investments to develop the underlying technologies (and the associated risk), the long duration to generate a return on investment, and the duration and risk of the mining mission itself [16], [14]. For lunar mining, the risk profile is different, as the processing plant is likely located near the location where the volatiles are used. However, a lunar landing is an additional risk element compared to the proximity operations around an NEA. As a general principle, NEP is attractive for applications where combined power and propulsion efficiency are important (bigger is more efficient) and time is abundant (low thrust levels). Or, more colloquially, use cases should “move big things slowly”. A few applications may match this profile:

- Transportation of large initial infrastructure elements to the mining location, which are prohibitive for chemical propulsion and decomposition into smaller elements is not possible;
- Transportation of large quantities of unprocessed or partly processed resources. In general, processing resources at the celestial body is better than transporting unprocessed resources. For example, if the mass ratio of unprocessed to processed ratio is 10:1, which is fairly realistic for volatiles, transportation would require ten times less propellant if processing takes place at the celestial body. However, in certain cases, the trade-off might be in favour of transporting the unprocessed resources, in particular, if the processing plant has an excessively high mass or its operations

are constrained to certain locations, e.g. where a crew is available for maintenance.

4.3 Other potential markets for NEP

Continuous thrust combined with a relatively high specific impulse makes NEP an ideal candidate for enabling new capabilities in space exploration:

- On-ground energy production: With the future development of the lunar and the Martian stations, the energy needs will appear to provide life support for the astronauts and the habitats. NEP can address these needs by being adaptive for on-surface energy production.
- Planetary sunshade: Due to the large mass of the system, NEP might be an attractive option for transporting elements for the geoengineering mission aiming at building a sunshade at the Sun-Earth Lagrange point.
- Scientific exploration: The high velocities and manoeuvrability provided by NEP enable deep space exploration, allowing spacecraft to reach distant planets, study asteroids, or even travel beyond the solar system into interstellar space.

5. Conclusion

Nuclear electric propulsion (NEP) is a promising technology that combines the advantages of low-thrust propulsion with the power of a nuclear reactor. As a result, it is a suitable candidate for a wide range of space applications, from scientific exploration and lunar base construction to planetary defense and the development of space tourism infrastructure. However, the development of NEP introduces many unknown variables, such as its mass, power requirements, and operational capabilities. We believe that a thorough market analysis can help identify the optimal parameters for NEP based on its potential demand in various sectors.

This paper analyzes two case studies: the transfer from LEO to GEO and the transfer to lunar orbit, comparing NEP with chemical and solar electric propulsion systems. Our findings suggest that NEP is well-positioned between these two propulsion types, offering a balance of power and low thrust that could provide significant advantages for specific mission profiles.

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