ESA TERRAE NOVAE SOCIOECONOMIC IMPACTS AND BENEFITS ASSESSMENT: FINAL REPORT

BY EUROCONSULT FOR THE EUROPEAN SPACE AGENCY

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Executive summary

Context and methodology

Amid the renewed global interest for space exploration, ESA and its Directorate for Human Spaceflight and Robotic Exploration Programmes(HRE) have drawn an ambitious capability roadmap to make Europe increasingly autonomous and confirm its status as a protagonist of space exploration. Its Exploration Envelope Programme (E3P), branded Terrae novae in 2021, brings together all ESA exploration activities and missions into a single framework. The European exploration vision and strategy are to undertake exploration activities to expand Europe's Human presence in the Solar System using robotic missions as precursors, with the horizon goal of Human exploration of Mars and to create benefits for society.

In this context, ESA commissioned Euroconsult to undertake a Socio-Economic Impact (SEI) and benefit assessment of Terrae Novae activities over five impact categories – economic, strategic, technological, societal and scientific. The SEI focuses on three distinct but interconnected programme elements: **continuation activities** (missions approved at Space19+ and for which a decision to continue is required in 2022); ESA's portfolio of **space exploration technology development** (drawn largely from the ExPeRT programme); and **long-term European Exploration Strategic scenarios**, as laid out in the Strategy 2030+ Roadmap.

The primary source of information of the study was a stakeholder consultation campaign. Alongside this, six bespoke economic models were used to monetize Terrae Novae's impacts on the economies of member states in terms of gross value added (contribution to GDP), employment and tax revenues.

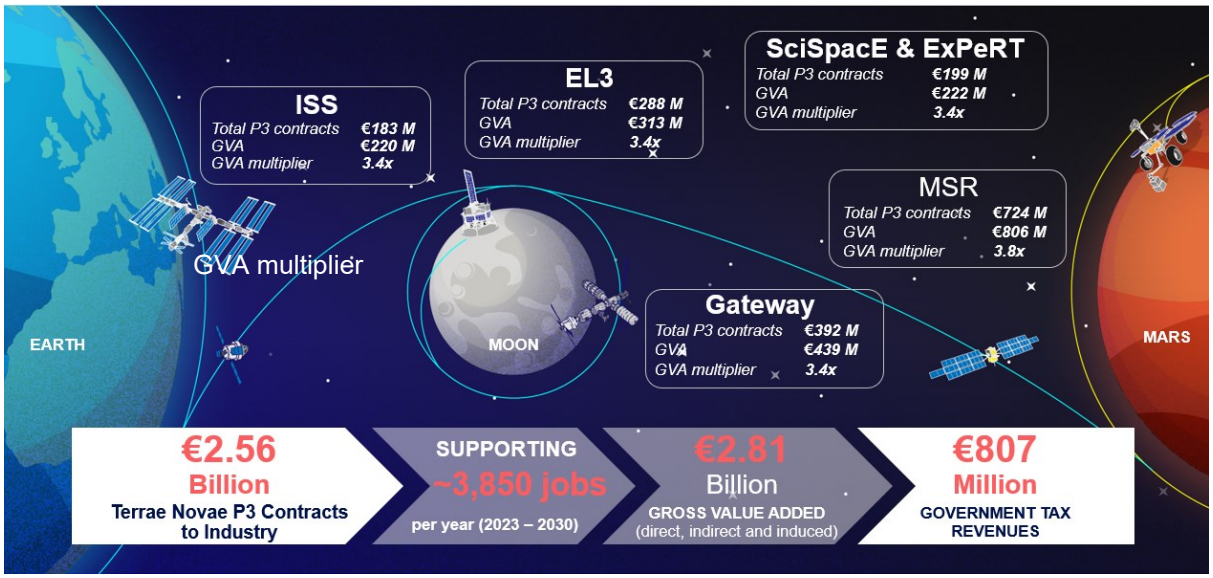
Key findings of the Terrae Novae SEI study

Economic impacts

Numerous economic benefits are generated by Terrae Novae activities. As a result of the more than the **€2.5 billion in Terrae Novae contracts to industry** (mostly concentrated in **in Period 3** (P3 – 2023 to 2025) but with lower levels of funding distributed until 2030), the programme will support an annual average of circa **7,500 jobs over P3**, and about **3,850 jobs per year from 2023 to 2030**. Over **€2.8 billion of gross value added will be added to the European economy** as a result of Terrae Novae, with European governments generating over **€800 million in taxes.** Key Terrae Novae missions were also modelled, with all generating multipliers of 3.4 to 3.8, meaning that for **every Euro generated by direct Terrae Novae activities, €3.4 to €3.8 were generated in the wider economy**.

In addition to these monetized benefits, Terrae Novae acts as strategic anchor demand **driving company growth strategies.** By repurposing space exploration products developed for ESA for new customers (for example satellite or even terrestrial markets), companies are **generating additional commercial sales.** Over 60% of respondents to the consultation have **increased their product portfolio** thanks to Terrae Novae and **20% have already achieved commercial sales**.

Terrae Novae also acts as a catalyst to **unlock private investments.** Respondents report investing over **€100 million of own capital** to expand, upgrade and modernize facilities and capabilities to meet the stringent requirements of Terrae Novae missions.



Economic benefits of Terrae Novae period 3 (P3) and 5 selected programme elements

Strategic impacts

Strategic impacts position European stakeholders favorably to address future opportunities. Working on Terrae Novae missions have allowed European companies to **access new markets**, either geographic (i.e., TAS developing modules in the US for Axiom's commercial space station thanks to its work on the ISS and Gateway) or vertical (i.e., ArianeGroupe re-purposing the electric thrusters it developed for the MSR's Earth Return Orbiter mission for conventional satellites).

Terrae Novae also builds upon **key European space exploration heritage** to continuously increase expertise and efficiency. Examples of technological continuity between programmes include **pressurized habitats technology** through the ATV to the ISS and Gateway, **propulsion elements** from the ATV to the ESM, as well as **docking interfaces, avionics, deployable elements** and more. By leveraging European heritage, Terrae Novae **ensures a key role for European players in international and European-led space exploration missions**.

Terrae Novae projects are **increasing Europe's strategic autonomy** in space. While supply chain dependencies on the US remain, an increasing number of components previously procured outside of Europe are **being replaced with European-made technologies**. Terrae Novae missions such as the European Large Logistics Lander (EL3) increase end-to-end capabilities, **reducing European reliance** and opening opportunities for **European-led missions**, including with international partners.

Technological impacts

Technology benefits are generated when new technologies are leveraged to increase efficiency and improve products. Terrae Novae projects **increase technical expertise in Europe** in mechanical, electrical and system engineering, radiation tolerance, technology miniaturization, programme

management, and more. As a result, virtually all Terrae Novae projects **drive Technology Readiness Level (TRL) increases.**

Terrae Novae programmes also build extensively on technology **spin-ins from terrestrial sectors**, such as the energy, automotive, industrial, software and submarine industries. For example, an Italian automotive SME was able to achieve mass savings of 115 kg on the Cygnus vehicle by utilizing ultra-lightweight materials used in the high-performance car racing industry without sacrificing safety. While fewer, **Terrae Novae projects also generate technological spin-outs** for other sectors in space (satellite markets, in orbit servicing, space logistics, etc.) and on Earth (maritime, energy, mining, automotive, etc.). For example, the ISS' Advanced Closed Loop System (ACLS) developed by Airbus recycles carbon dioxide exhaled by astronauts, creating water and oxygen. **Airbus is currently commercialising spin-outs of this technology for use in submarines,** whose closed environments and resource recycling requirements resemble those aboard the ISS. Other potential terrestrial applications include the airline industry to filter and purify oxygen in airplane cabins and industrial farming, as large greenhouses fill with CO2, which is currently vented out into the atmosphere.

Societal impacts

Societal benefits are those which participate in **advancing societal and environmental goals**, inspiring the public and attracting positive public attention. Terrae Novae's ability to **inspire the public** is one of its greatest benefits, with this inspiration being used to create educational value, encourage youth to pursue STEM degrees, stimulate employment and innovation in Europe, and **strengthen European identify** via collective goals to rally around.

The programmes generating the most environmental value were **those focused on long duration missions** and exploitation of the space environment. Their focus on resource recycling with little to no consumable inputs in closed cycles to reduce the reliance on costly supply chains provides technological bricks for **circular economy and recycling paradigms** on Earth, once repurposed for terrestrial applications. For example, thanks to space research on the ISS, a device using UV rather than harmful chemicals for water purification was developed and can be used by remote communities or in emergency relief situations as the device does not need to be connected to a grid.

Terrae Novae projects—especially those with a human spaceflight element—attract **significantly more media attention than conventional satellite activities,** improving corporate image and generating a level of connection with the public that is impossible with robotic exploration. This **increased corporate visibility pays additional dividends,** for example by providing a platform to attract under-represented groups such as youth and women to the space sector, attracting and maintaining skilled talent, etc.

Scientific impacts

Terrae Novae projects make an undeniable contribution to science. Of the 65 stakeholders consulted (representing a small fraction of the hundreds of organizations working on Terrae Novae), **several hundred scientific papers are published annually by over 40 respondents.** As the study assessed benefits before Terrae Novae missions had launched (except for ISS), the real scientific output is expected to be far greater, as the greatest scientific benefits are generated after the payload has been launched. Other Terrae Novae missions, while not generating scientific value directly, indirectly enable science, for example through transportation and cargo, habitability, supporting systems, etc.

Conclusions

Terrae Novae supports high-value jobs in ESA member states

The jobs created and supported by Terrae Novae maintain high-value skills in Europe in multiple engineering and scientific fields, estimated at an **annual average of circa 7,500 jobs over 2023 to 2030**. Through talent transfers, the exploration sector infuses other space markets (telecom, EO, etc.) and high technology terrestrial markets.

Terrae Novae creates strategic anchor demand for industry

Terrae Novae programmes are drivers of company growth strategies: by repurposing products developed for ESA for new customers/markets, companies can **generate additional sales and access new markets**.

Exploration programmes drive expertise increases for industry

Working on Terrae Novae projects is an **invaluable source of knowhow and expertise**, including mechanical, electrical and system engineering, miniaturization, waste management, quality control, programme management, digitalization, and many more.

Inspiration generated by space exploration is paramount

The ability of exploration programmes (principally Human spaceflight) to **inspire the public** is one of their greatest benefits. It translates into educational value, encourages youth to pursue STEM degrees, stimulates employment and innovation in Europe, encourages the retainment of talent in Europe and **strengthens European identity** via collective goals

Autonomous Human spaceflight is a guarantee of sovereignty

The geopolitical context underlines the vulnerability of an astronaut programme **relying on the political will of foreign nations**. Europe's lack of Human spaceflight capability **undermines its eye-level relationship with other space powers.**

Terrae Novae can produce societal and environmental value

Exploration technologies and programmes focused on resource recycling with little to no consumable inputs in closed cycles to reduce the reliance on costly supply chains can **participate in circular economy and resource recycling paradigms** on Earth, contributing to SDGs.

The exploration sector benefits strongly from tech spin-ins

Due to the high cost and low volumes of the space sector, especially exploration, the ability to **leverage know-how and R&D investments made in terrestrial sectors is paramount**. Several terrestrial sectors provide technology inputs (automotive, energy, industrial, robotics, big data, etc.)

Programmatic uncertainty is the most common risk

Program redefinitions and cancellations **impact stakeholders' growth strategies and product roadmaps**, often forcing them to maintain skills and technology amid uncertainty and interruptions. This is in part due to the **intergovernmental nature of ESA and the high level of international cooperation** in Terrae Novae projects.

Recommendations

Consider space exploration a geopolitical imperative

Europe must invest in next generation exploration capabilities in order to have a seat at the table, be considered an eye-level partner in international frameworks and **achieve the horizon goal of landing European astronauts on Mars**. If not, it will be **relegated to a supporting partner role** and be forced to pay in cash to participate in international partnerships.

Make select investments to secure a protagonist role

ESA cannot realistically acquire an independent capability in all segments due to comparatively low budgets. However, it can develop a select number of “must have” capabilities (Human transportation, robotic Lunar landing) to **ensure its autonomy** and **attract partners for Europe-led missions**

Move forward with the EL3 capability

The EL3 is regarded as the next key milestone by respondents as it would provide Europe with an **autonomous landing capability** (in the 2t-to-surface niche), along with access to strategic areas. As such, it is seen as an **enabler of European strategic autonomy** and of its ability to deploy independent missions and contribute barter elements to international frameworks.

Expect market uncertainty in all fields of exploration

Demand beyond ESA itself is often highly uncertain given the high specialization of their systems and overall limited demand for exploration (ESM, rovers, landers, etc.). There is no assurance that single government user markets will translate into **diversified commercial demand-driven market**

Consider a service procurement approach for exploration

NASA has pioneered the use of service procurement in the field of exploration (COTS, CCDev, HLS, CLPS and CLD). Many respondents argued Europe should take note of a **service approach’s advantages**, including lower service costs, transfer of responsibility from agency to industry, simplification of the procurement process and more room for innovation for private contractors.

Consider multi-sector technology development

Due to the high cost and low volumes of the exploration sector, **encouraging synergies with terrestrial sectors** in technology development early in its lifetime could help drive costs down through economies of scale while validating basic technology segments on Earth thanks to much larger pools of operational data.

Introduction

The study

Context

In the context of renewed political interest for Human exploration of the Solar System and the emergence of powerful space transportation companies driven by commercial spaceflight narratives and founder ideology, the space exploration sector is once again gaining strong momentum. This decade promises numerous initiatives, both robotic and crewed, involving new actors, destinations, and technologies, potentially marking the beginning of a new golden era for space exploration.

Since the beginning of space exploration by the US and the USSR in the 1960s, the number of countries engaging in it has expanded considerably to include Europe (primarily through ESA), China, Japan, India, Canada, and new players such as the UAE and South Korea. Europe has produced remarkable achievements in exploration, with a fraction of the budget of large powers. Through ESA, it is seen as a reliable and trustworthy partner by those powers, namely the U.S. and formerly, Russia. Still, despite its rich accomplishments, Europe's footprint in exploration is no match to its own economic power. It lacks several key capabilities that prevent it from deploying high-profile exploration missions autonomously. For instance, it does not have its own Human transportation system, nor a destination of its own, and lacks a landing capability to deploy payloads on the surface of the Moon or Mars.

Amid the renewed global interest for space exploration, ESA and its Directorate for Human Spaceflight and Robotic Exploration Programmes have drawn ambitious roadmaps to make Europe increasingly autonomous and confirm its status as an attractive, eye-level partner in international frameworks. Its Exploration Envelope Programme (E3P), branded Terrae Novae in 2021, was founded at the ESA Council at Ministerial level in 2016 and brings together all ESA exploration activities and missions into a single framework. The European exploration vision and strategy are to undertake exploration activities to expand Europe's Human presence in the Solar System using robotic missions as precursors, with the horizon goal of Human exploration of Mars; and to create benefits for society, such as scientific and economic benefits, while promoting global cooperation and inspire generations to come.

The Terrae Novae envelope is structured around four cornerstone mission campaigns each aiming for a different destination:

- Humans in Low Earth Orbit (LEO)
- Humans beyond LEO
- Robotic exploration of the Moon
- Robotic exploration of Mars

At capacity level, the rationale of ESA's exploration strategy is to make selected investments in critical capabilities (transportation, landing, surface mobility) to secure Europe's ability to leverage international partnerships via partnerships or the successful barter system (like on the ISS, Artemis, MSR) while maximize synergy between destinations, its missions, and leveraging past exploration missions and other satellite applications.

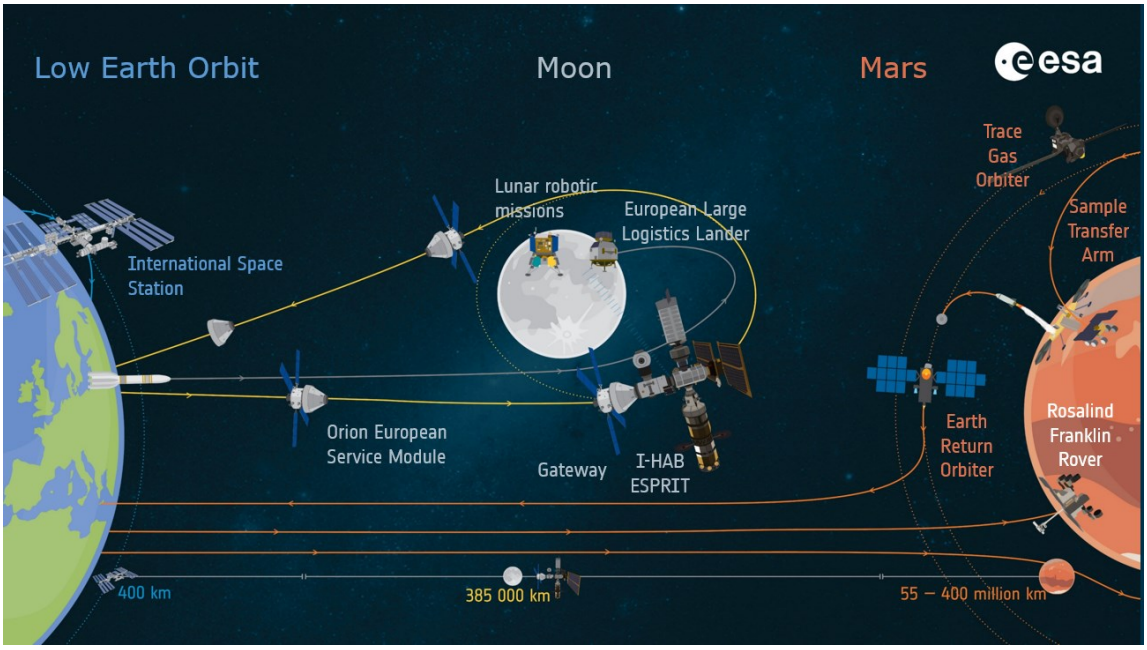


Figure 1: ESA's Human and Robotic Exploration (HRE) destinations: LEO, Moon and Mars

Objectives and scope

In this context, ESA has commissioned Euroconsult to undertake a Socio-Economic Impact (SEI) and benefit assessment of Terrae Novae activities. The analysis documents the socio-economic footprint of future Terrae Novae activities in general, and the programme proposal for the ESA Council at Ministerial (CM) level in 2022 for the third period (2023-2025) in particular.

The study therefore focuses on Europe's pre-existing commitments (ISS, ESM, Gateway, MSR, etc.), as well as new candidate projects to be proposed at ESA MC in 2022. ESA has also identified several technology areas that are essential to any future exploration scenario. Finally, its scope includes long term exploration scenarios and future capability configurations currently described in the Terrae Novae 2030+ strategy roadmap. These three separate but interconnected Terrae Novae programme elements have been organized as follows.

1. **Continuation Activities**: Terrae Novae missions approved at Space19+ and for which a decision to continue is required at the ESA Council at Ministerial level in 2022[1];

2. **Technological innovation:** The portfolio of ESA technologies for Exploration, drawn largely (but not exclusively) from Terrae Novae ExPeRT and SciSpacE[2];

3. **Long-term Strategic Scenarios**: Scenarios for future Terrae Novae missions to Earth orbit, Moon and Mars embedded in a long-term European Exploration Strategy.

[1] Due to the Russia-Ukraine war, ESA has ceased cooperation with Roscosmos on ExoMars and the LUNA 25-27 missions (Lunar missions of Opportunity PILOT and PROSPECT). Therefore, these continuation missions have been negatively impacted and recovery actions are being studied.

[2] ESA's full space exploration technological portfolio includes 17 types of technologies. Due to project limitations, it was only possible to assess 7 directly, and the others indirectly (e.g., aspects of Crew Health Management are covered in ALSS).

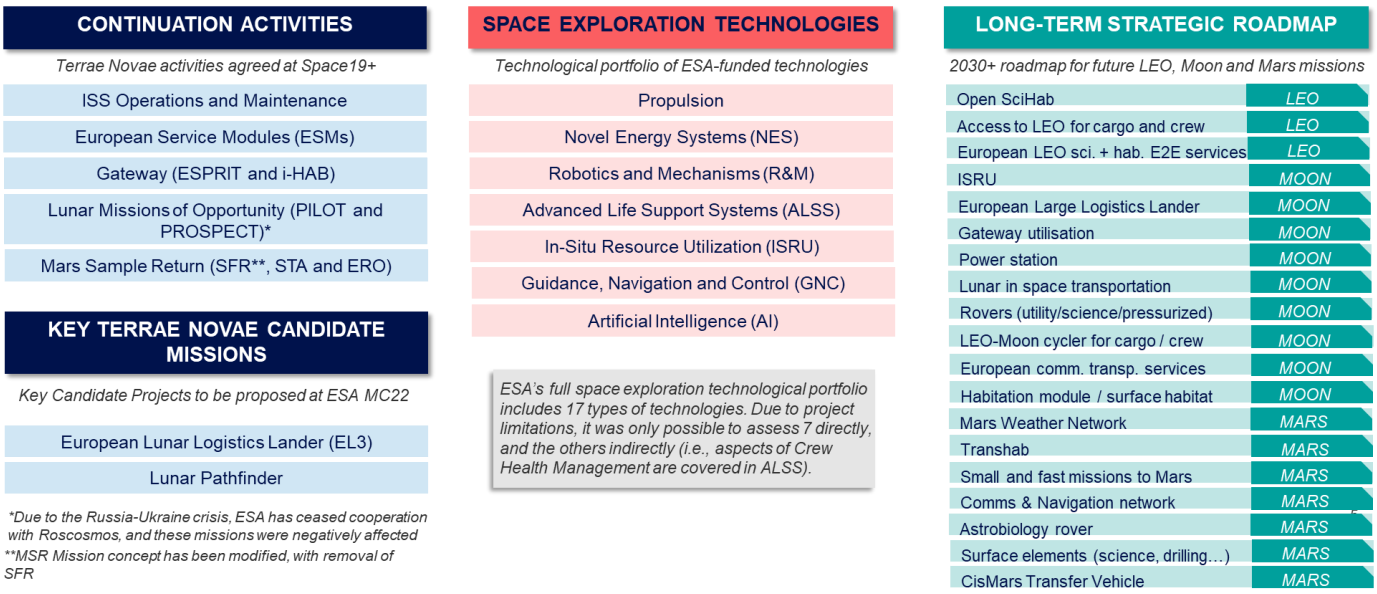


Figure 2: Mapping of the study's scope

Structure

The study is structured into five main tasks, each building on the previous inputs:

- **Task 1: Outline of the methodological approach:** defines the methodology to be adopted for the analysis.
- **Task 2: Socio-economic impact of Terrae Novae Continuation Activities:** application of the SEI analysis to the continuation of the missions approved at Space19+.
- **Task 3: Socio-economic impact of Terrae Novae Technological Innovation:** application of SEI analysis to ESA's portfolio of space exploration technologies.
- **Task 4: Socio-economic impact of the Terrae Novae Long-term Strategic Scenarios:** application of the SEI analysis to future Terrae Novae LEO, Moon and Mars scenarios
- **Task 5: Final Reporting:** consolidated reports to ESA on the socio-economic impacts of the Terrae Novae programme and relevant extracts to selected Member States.

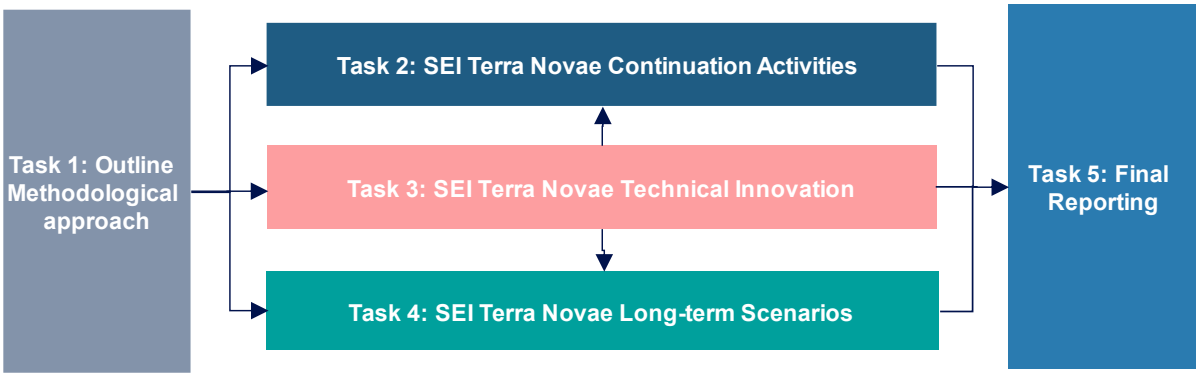


Figure 3: Tasks Workflow

Methodological outline

Overview

Considering the diverse nature of the Terrae Novae activities under study, different impact indicators have been selected for each of the three SEI exercises, allowing to better tailor the SEI results and outputs. The impact indicators are mapped to the Terrae Novae Benefits Management Framework to ensure coherence and consistency. The full list of indicators is included in the Annex 2.

5 impact categories have been retained as per best practice and for their relevance to Terrae Novae:

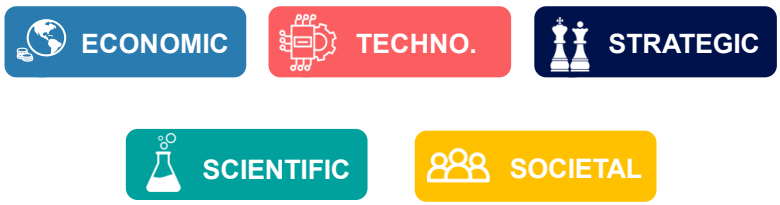


Figure 4: Five impact categories used for the study

Within each category, a number of individual impact indicators were used in order to measure the impact of Terrae Novae activities – see table below (full list of all impact indicators in Annex 2).

Impact category	Task 2	Task 3	Task 4	All 3 tasks
Economic impacts	7	5	2	**14 (7 unique)**
Strategic impacts	7	7	5	**19 (7)**
Technological impacts	6	5	2	**13 (7)**
Societal impacts	4	4	2	**10 (5)**
Scientific impacts	4	3	1	**8 (4)**
TOTAL PER TASK	**28**	**25**	**12**	**65 (30)**

Table 1: Impact indicators

Impact indicators are designed to assess as comprehensively as possible all the impacts expected to be generated by Terrae Novae activities. Indicators can be of two types:

1. **Quantitative**: jobs created/maintained, commercial revenues generated, peer-reviewed scientific publications, etc. A subset of quantitative impacts can be **monetized**, such as revenues, government taxes, etc.;

2. **Qualitative**: increase in European strategic autonomy, market share increase, societal value created, contribution to UN SDGs, etc.

As inputs, to determine the value of each impact indicator, the study relied on **ESA economic data** (i.e. contracts to industry), as well as a **detailed stakeholder consultation**, supported and augmented by **dedicated desk research** and Euroconsult in house expertise**.**

Stakeholder consultation and analysis

The objective of the interview campaign was to gather necessary inputs for the SEI analysis. ESA provided stakeholder contact details for Tasks 2 and 4; Euroconsult identified stakeholders for Task 3 with inputs from ESA. Stakeholders were classified as either **space industry** organizations, **non-space** (**terrestrial**) organizations, **academia/research** or **government**.

Figure 5: Stakeholder distribution by country

114 stakeholders were contacted, with 64 interviews conducted (a success rate of ~60%). A representative distribution was sought (geographical, technical, space vs. non-space, and stakeholder type). As European Industry players are the main beneficiaries of the majority of Terrae Novae spending, industry is proportionally more highly represented.

The 64 respondents include a variety of players: industrial actors represent the majority, at 86% of the total (55 companies). Academia represents 6% of the total, with institutional actors making up 8%.

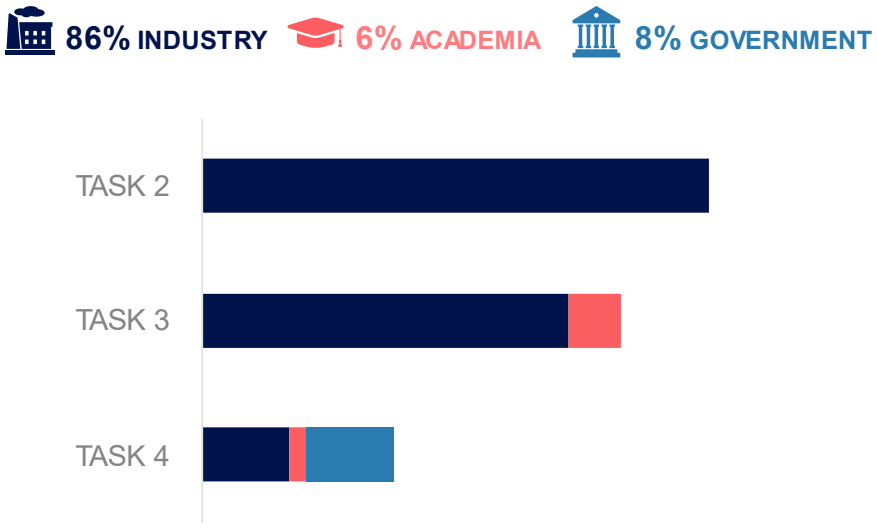


Figure 6: Stakeholder distribution by activity

Methodology for impact quantification and consolidation

Methodology for Task 2 (continuation activities) and Task 3 (technology development)

In addition to qualitative inputs, we derived, based on stakeholder answers for each question of the consultation (i.e., for each indicator) a quantitative rating from 0 (lowest score) to 3 (highest score) for benefits' time horizon as well as their intensity.

For time horizon:

- **3:** Yes, the project has already produced a measurable impact,
- **2:** No immediate impact but expected in the short-to-medium term (within ~5 years),
- **1:** No immediate impact but possible in the long term (within ~10 years),
- **0:** No impact and none expected.

For intensity:

- **3:** The project has or will produce high impacts,
- **2:** The project has or will produce medium impacts,
- **1:** The project has or will produce low impacts,
- **0:** The project has or will produce no impacts.

For each of the respective activities/technologies, individual indicator ratings from respondents have been summed up and normalized over a maximum of 100 to make results comparable despite the varying number of respondents per activity.

For instance, for the economic indicator "product portfolio increase" of the Gateway I-HAB activity, scores for time horizon and intensity were calculated as follows:

	# of respondents	Attributed scores	Sum	Maximum possible sum	Normalized result over /100
Time horizon	6	0,3,3,2,2,2	12	6*3 = 18	**(12/18)*100=66.67**
Intensity	6	0,2,3,1,1,1	8	6*3 = 18	**(8/18)*100=44.44**

Table 2: Illustrative example of scoring for impact indicators

To subsequently calculate impact scores at the level of the 5 impact categories (i.e., economic, technological, strategic, societal and scientific), a similar approach has been followed summing up and normalising scores for each of the indicators belonging to the impact category concerned.

E.g., for the overall economic impact of the Gateway I-Hab activity, the ratings from all respondents for each of the six economic indicators in the economic impact category (product portfolio increase, own funds invested, commercial sales generated, jobs created/maintained, and SME involvement) have been summed up and normalized over 100, providing a final score capturing the time horizon and intensity of the overall economic impact of the I-HAB activity:

	# of indicators	Sum of attributed scores for each indicator	Sum	Maximum possible sum	Normalized result over /100
Time horizon	6	14,11,12,14,9,12	72	6*3*6=108	**(72/108)*100=66.6**
Intensity	6	9,10,8,10,5,11	53	6*3*6 = 108	**(53/108)*100=49.1**

Table 3: Illustrative example of scoring for impact categories

A graphic representation of the economic impact scores of all continuation activities (with the above calculated I-Hab impact score in yellow) is in the figure below:

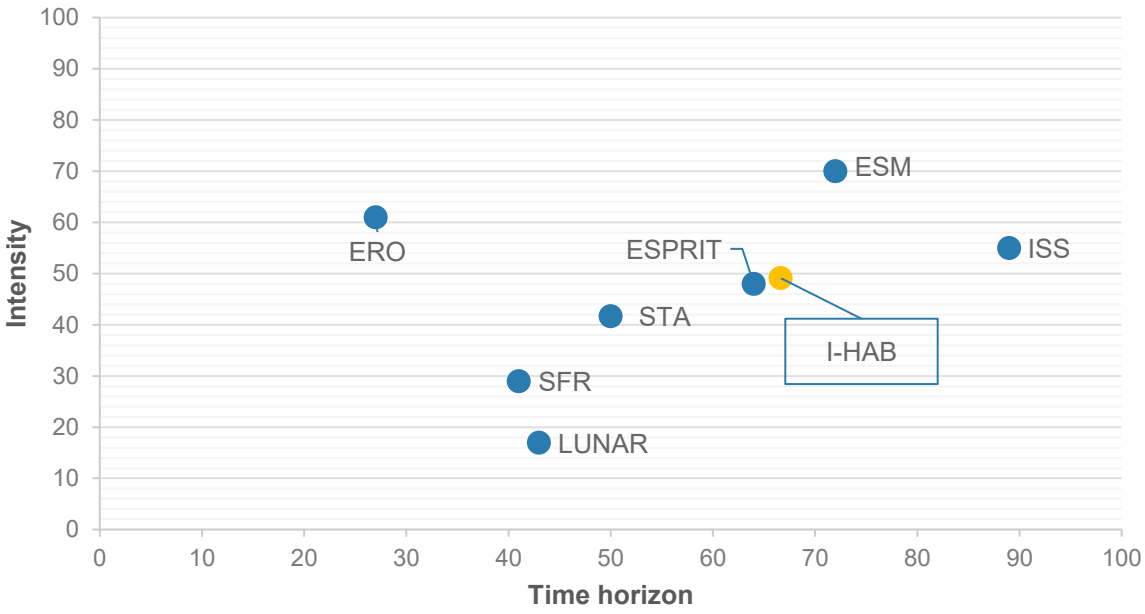


Figure 7: Economic impact scores for Continuation Activities

In some cases, the final scores have been adjusted based on qualitative and contextual considerations. For example, one LSI working with 10 SMEs ranked SME participation as very high, whereas another LSI working with over 60 SMEs provided the same scoring. As such, the scoring from the first LSI was adjusted downwards.

To more easily interpret the results, normalised thresholds are defined for both the time horizon and intensity scores:

Score	Normalised threshold
0	0*100/3=0
1	1*100/3= 33.33
2	2*100/3=66.67
3	3*100/3=100

Table 4: Normalised thresholds

The thresholds mark nine areas in the graph, which in the below chart are numbered from 1 to 9. The **time horizon is displayed along the x-axis**, indicating if benefits are felt immediately, in the short/medium term, or in the long term. The **intensity of benefits is displayed along the y-axis**, if benefits are considered to be high, medium or low intensity.

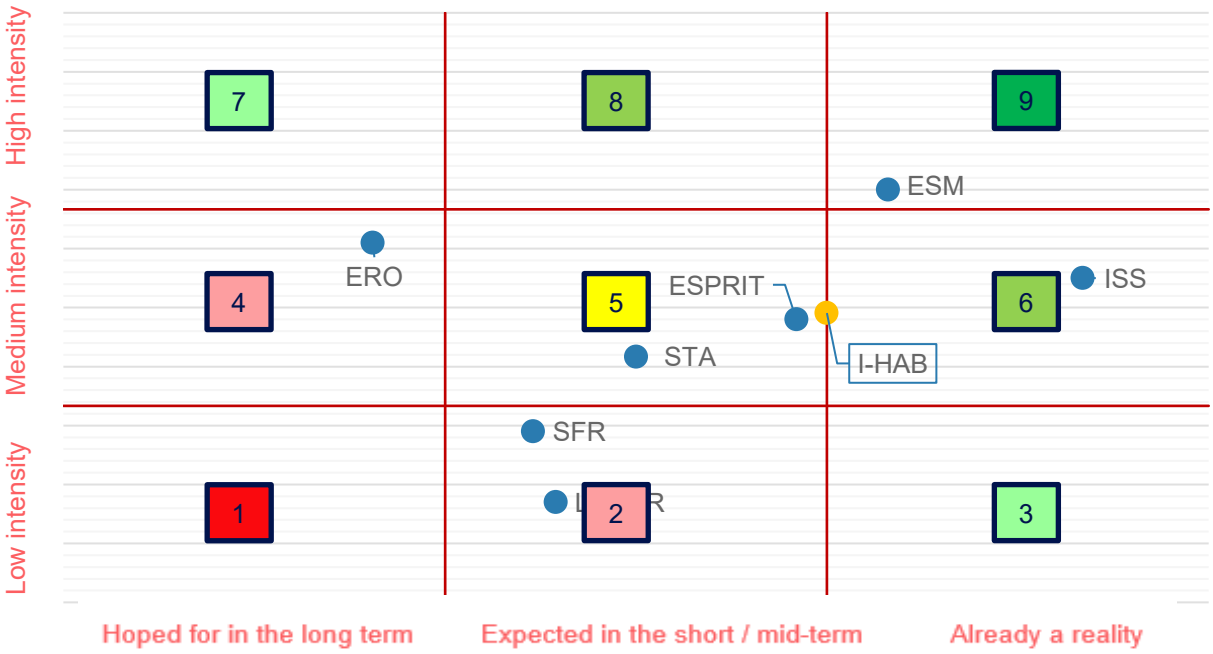


Figure 8: Time and magnitude threshold areas

Methodology for Task 4 (long term scenarios)

Alongside the assessment of Terrae Novae programme impacts and benefits, the study also assessed benefits and impacts of candidate missions and capability configurations included in ESA's 2030+ Strategy Roadmap.

Every Strategy 2030+ candidate mission has been assessed according to its potential to generate impacts for each retained benefit indicator. Due to the notional nature of the 2030+ candidate missions, a smaller number of 12 benefit indicators was retained. Qualitative scores are assigned per mission per thematic, based on longer stakeholder workshops with industry, academia and institutional space exploration experts. Scores are reported on a scale from 0 (no expected benefit) to 3 (high expected benefits). A consolidated average of the scores for each of the 12 benefit indicators is presented for each mission. The scores are normalized over a maximum of 100 to facilitate comparison between missions and impact categories. The normalization process follows the same logic as described above for continuation activities and technological developments. There is no time horizon as all benefits will be felt in the long-term (beyond 2030). Rather than ranking the missions, results per mission are presented in this report showing the benefits profile, allowing to view the relative importance of the different impact categories per mission.

Methodology for economic modeling

The full economic impact of the Terrae Novae programme was assessed using a standard economic impact assessment framework. This considers three core channels through which the programme contributes to the global economy:

- **Direct impact**: Relates to Terrae Novae's own activities, encompassing the economic activity, taxes and employment directly supported by the projects within the programme;
- **Indirect (supply chain) impact**: Encapsulates the economic activity, taxes and employment supported along supply chains, this includes multiple rounds of expenditure as suppliers buy in goods and services from other companies to enable their sales to the direct contractor, etc.;[3]
- **Induced (consumption) impact**: The economic activity sustained as workers at companies included in the direct impact and in their supply chains spend their wages in the wider economy. This provides most support to primarily consumer facing industries such as retail, restaurants, consumer goods manufacturers, and providers of recreational and leisure services.

The sum of these channels makes up the Terrae Novae programme's total economic footprint.[4]

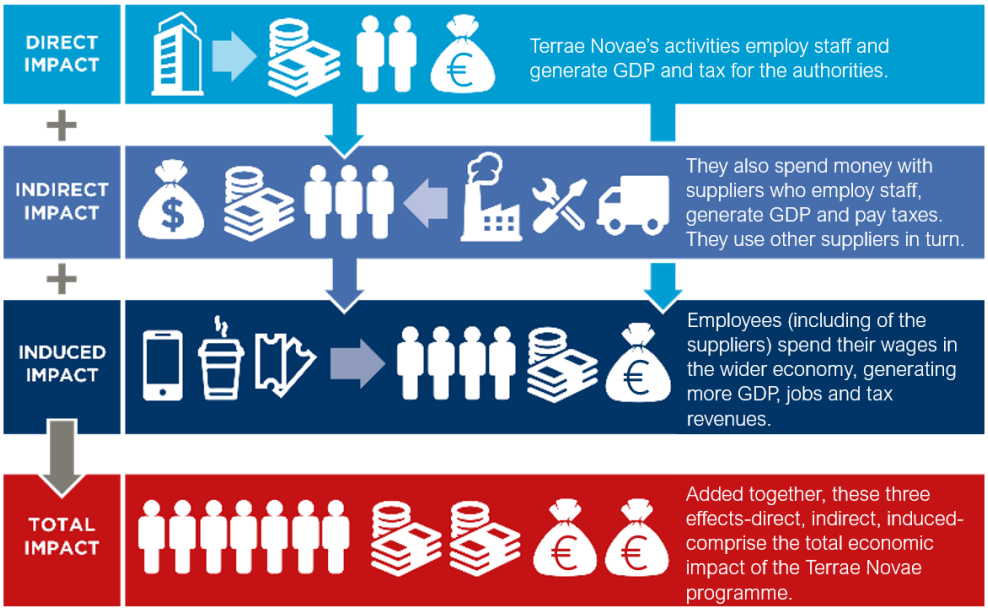


Figure 9: How we measure the Terrae Novae programme's economic impact

We quantify the Terrae Novae programme's contribution across these channels using three metrics of economic activity:

- **Gross value-added** contribution to GDP, measured in Euros for cross-country comparability.
- **Employment**, measured as the number of jobs in headcount terms, i.e., number of people employed by the program each year. As most of the jobs supported by the program are carried

[3] Note: this channel includes the impact of the programme's capital investments, such as new facilities and IT equipment, as well as that of its day-to-day purchases.

[4] The results are presented on a gross basis, meaning they do not consider what the resources used by the programme, or stimulated by its expenditure, could alternatively produce in their second most productive use.

to following years, our final employment figure for a program is **an average of the headcount jobs supported each year throughout the period.**

- **Tax revenue for governments**, including personal and business income taxes, excise and other sales taxes, social security contributions, and other taxes on production, measured in Euros.

While most economic impact studies assess these effects based only on spending that occurs within the country of interest, this report goes further by assessing the impact of the Terrae Novae programme's global activities on each economy using a proprietary Global Sustainability Model (GSM). The analysis takes a global perspective, going far beyond a standard national assessment to include global linkages. This more comprehensive approach is suited to programmes with a global footprint, such as Terrae Novae, and highlights the international nature of its supply chain. For example, in a typical in-country impact study, purchases of components by an Italian manufacturer from a German supplier would "leak" out of the model of the Italian economy and have no further impact. In contrast, within our study the impact of this purchase will be reflected in Germany, and in subsequent onward supply chains (both within Germany and beyond). A more detailed methodology discussion is featured in Annex 1.

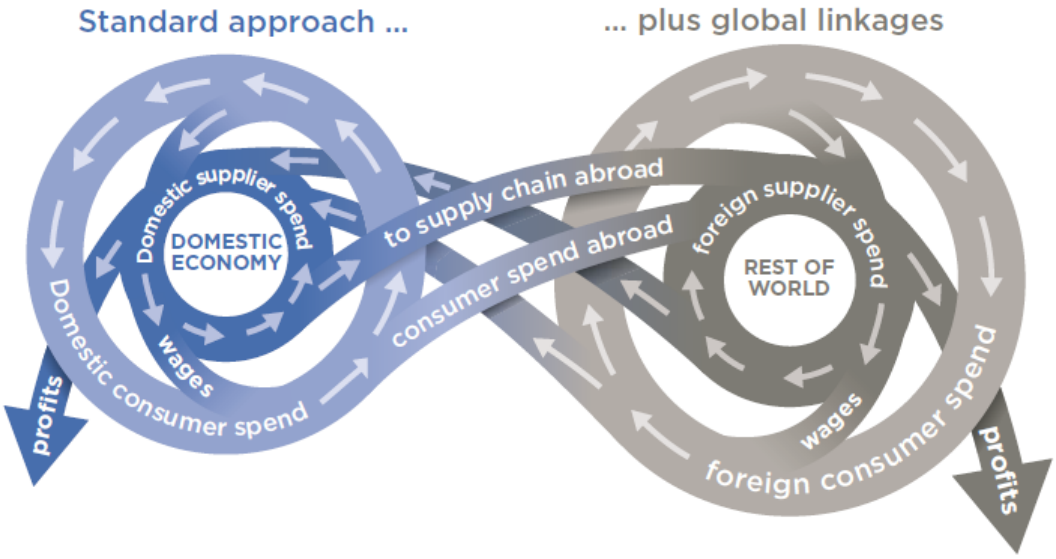


Figure 10: The Sustainability Model captures spending within countries and across borders

Socio-economic Impacts Assessment

Economic modelling

This section presents a detailed breakdown of Terrae Novae's gross value-added, tax revenue and employment contributions, for the 22 ESA Member States, plus Bulgaria, Canada, Croatia, Cyprus, Latvia, Lithuania, Malta, Slovenia and Slovakia.[5] These contributions are presented, in terms of direct, indirect and induced impacts supported by Terrae Novae. While the total Terrae Novae budget request at CM22 totals €2.98 billion to cover E3P Period 3 activities (left chart in the figure below), the economic benefits assessment is based on the portion of the Terrae Novae budget which is contracted to industry, totalling €2.56 billion (right chart in the figure below). Internal ESA costs account for the difference.

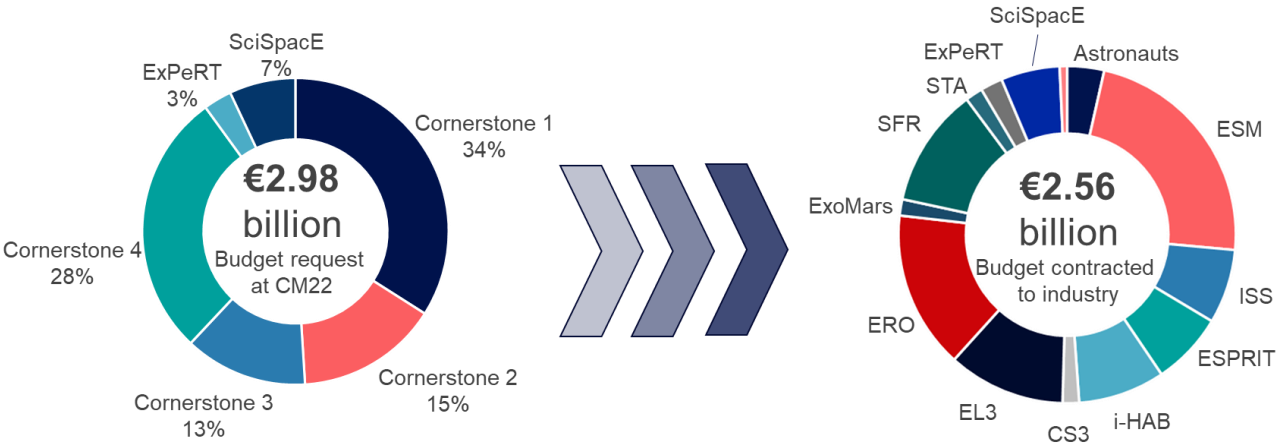


Figure 11: Terrae Novae budget request and budget contracted to industry

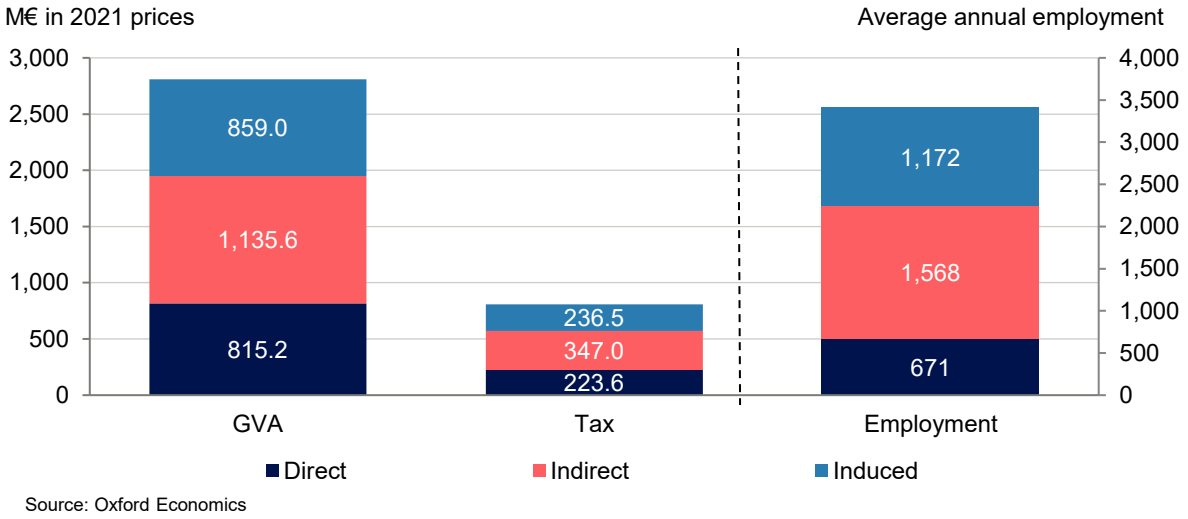
Figure 12 below shows total GVA, tax revenue and average annual employment supported by Terrae Novae period 3 activities, split by type of impact. Figure 13 details the GVA, government tax revenue and average employment supported by Terrae Novae activities by percentage of type of impact (top) and the corresponding multiplier effect (bottom).

The Gross Value-added supported by Terrae Novae's activities is estimated at a **total of about €2,809.8 million** over the period of analysis (2023-2030). For Terra Novae, **3.4 euros are generated through indirect and induced impacts** for every euro directly generated as gross value added (Type II multiplier – see info box below).

Terrae Novae **supported an average of approximately 3,850 jobs every year** from 2023 to 2030. At the height of activities in Period 3 (2023-2025), Terra Novae will support an even higher average of jobs, **supporting approximately an average of 7,550 jobs a year for the period**.

Government revenues supported by Terrae Novae were **estimated at a total of €807.1 million** over the period of analysis (2023-2030).

[5] The GVA and tax revenue supported by the activity are expressed in million euros in 2021 prices.



Source: Oxford Economics

Figure 12: Gross Value-Added, tax revenue and average annual employment supported by Terrae Novae split by type of impact

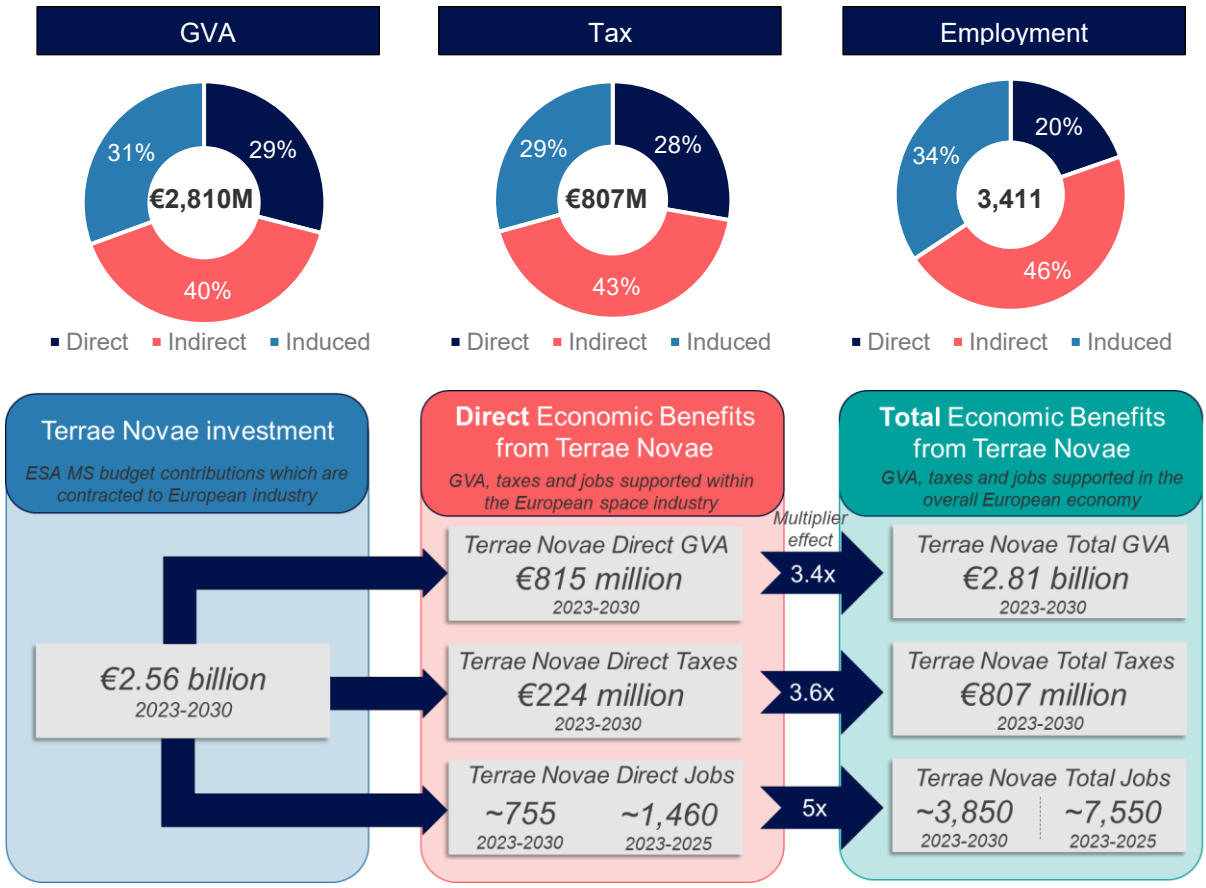


Figure 13: Gross Value-Added, government revenue and average employment supported by Terrae Novae activities by percentage of type of impact (top) and multiplier effect (bottom)

Type II Multiplier Explanation

We derived GVA's Type Two Multipliers through the input-output model to understand the project's impact on the broader economy. Type Two multiplier indicates, per euro directly generated (i.e., economic activity directly supported by the project), how many euros are generated through indirect (i.e., supply chain), and induced effects (i.e., employees spending in the broader economy).

$$Type\ II\ multiplier = \frac{direct\ GVA\ + indirect\ GVA\ + induced\ GVA}{direct\ GVA}$$

Caution is required when considering country-specific type two multipliers (reported in Table 2). The global supply chains involved in the input-output model can drive induced impacts quite significantly compared to the direct economic activity when not considered globally, increasing some countries' multipliers significantly. For example, the predominance of the American industry in the global economy, with US stakeholders representing a large portion of worldwide supply and demand, implies significant indirect and induced effects, despite almost no participation in the program. Due to the nature of the multiplier, countries with low direct impacts - with close to zero investments - yet developed economies will have very low denominators and thus large multipliers. Such is the case of Lithuania and Poland for Terra Novae activities.

Terra Novae activities affect many industries in the supply chain through indirect impacts and in the broader economies through induced impacts (for example, workers employed in Terrae Novae purchasing goods and services), generating **an indirect GVA of €1,135.6 million and an induced of €859 million**. Among the sectors supported by indirect and induced effects, the top three are reported in figure 15 below.

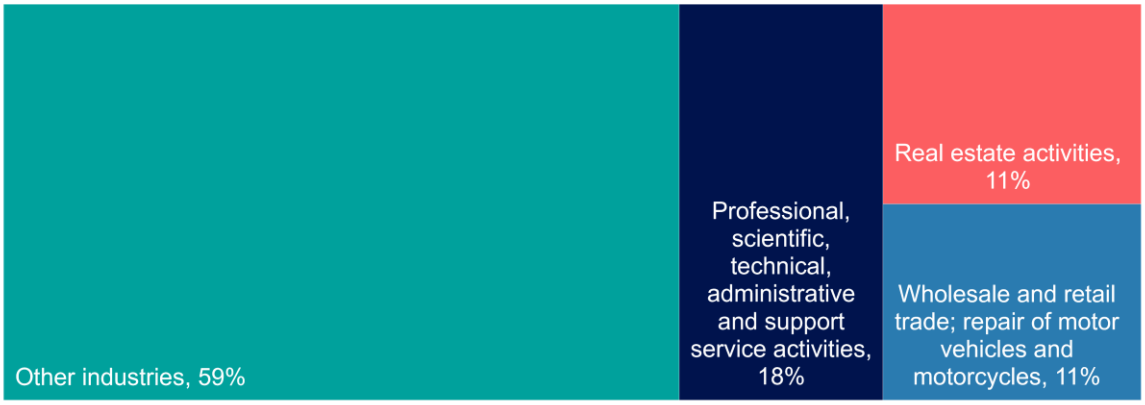


Figure 14: Industries supported by Terrae Novae indirect and induced GVA

Consultation results by impact category

In this section, the impacts and benefits of Terrae Novae continuation activities and technology development activities are assessed using the results of the stakeholder consultation, augmented by dedicated desk research conducted by Euroconsult. The intensity and time horizon of impacts are modelled based on respondents' quantitative answers based on the methodology laid out previously and a qualitative analysis built around it.

Economic impacts

The economic impacts of investments in exploration programmes relate to company sales, growth, and production capabilities and indirectly, the broader economy. Overall, respondents feel that working with ESA helps them attract and maintain high-value talent, increase their product portfolio, make additional commercial sales, invest in new capabilities, and stimulate SMEs in their supply chain. The table below showcases the individual economic indicators and selected key-findings.

INDICATOR	QUESTION	KEY FINDINGS (CONTINUATION / TECHNOLOGY)
Own investment	*Did the stakeholder invest own resources in the project alongside ESA funding?*	Respondents reported investing **over €100 million of own funding** to expand, upgrade and modernize facilities. Terrae Novae projects **act as a catalyst for additional private sector investments.**
Additional sales	*Did beneficiaries commercialize products developed for ESA to other customers?*	Multiple additional sales reported for other space markets (EO, telecom) and terrestrial markets. **About 20% of respondents had already achieved such sales**.
Increased product portfolio	*Did the beneficiary increase its product offering as a result of the TN activity?*	**60% of respondents have already increased their product portfolio because of Terrae Novae projects**.
Jobs supported by the project	*How many jobs were created or maintained as a result of the project?*	The jobs created and supported by Terrae Novae maintain **high-value skills in Europe**. **SMEs and startups benefit the most from employment stimulation**, as Terrae Novae activities represent over 10% of their workforce
Involvement of SMEs	*What was the degree of SME involvement in the project and how did they benefit from it ?*	Several projects saw a high degree of SME involvement above the mandatory 5% of project budget. SMEs reported benefits such as **new sources of funding, knowledge transfer, partnerships**, etc.

Table 5: Economic indicator overview

Economic impacts results for continuation activities and technology development

Among continuation activities, the ISS has the most mature benefits, having focused most science and technology budgets for several decades. **Economic benefits intensity is due to the high number of additional sales enabled for stakeholders which have repeatedly sold the products developed for the ISS to other customers and markets**. Its intensity is lower than for the ESM, which is now in

production phase and focuses most of the budgets in period 2, generating the most jobs and company own investment despite limited additional sales. Projects with lower budgets or which are in earlier development phases have less intense benefits, expected further down the line.

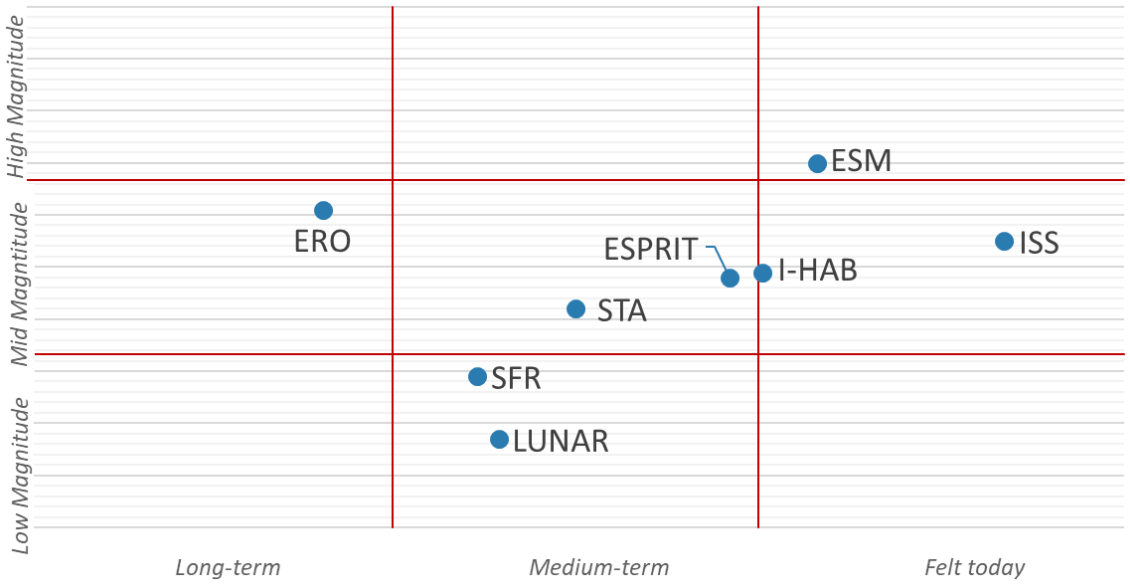


Figure 15: Economic impact of continuation activities rated by magnitude (Y axis) and time horizon (X axis)

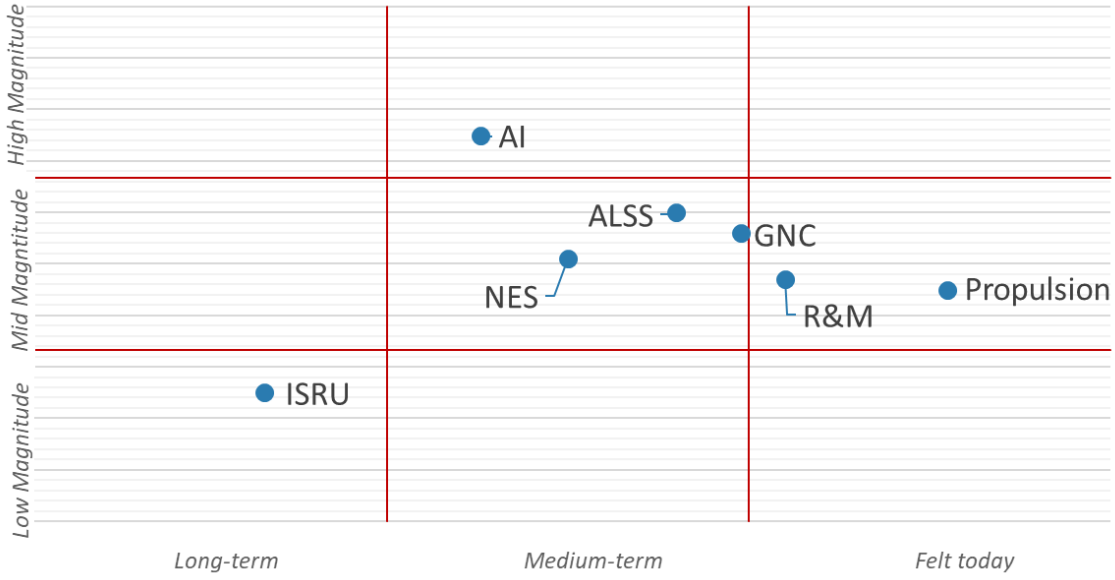


Figure 16: Economic impact of technology development rated by magnitude (Y axis) and time horizon (X axis)

For technologies, propulsion scores nearest in time due to **present product portfolio increases and substantial employment**. The intensity of ALSS is due to the **multisector potential** of its technologies for additional sales (agriculture, medical, maritime, leisure) expected in the medium term. AI may have the strongest economic potential but is today still limited to marginal use cases (mostly for GNC). ISRU's

low TRL and uncertain commercial viability reduces its score, but all stakeholders recognize its strong long-term potential.

- *Terrae Novae supports high-value jobs in ESA Member States*

The jobs created and supported by Terrae Novae maintain high-value skills on member states territory, in multiple engineering (propulsion, electronics, mechanics, software, flight dynamics etc.), scientific research, advanced management for complex projects, and other fields. SMEs and startups benefit the most from employment stimulation. Indeed, on average, for an SME jobs supported by Terrae Novae activities represent over 10% of their workforce, compared to Terrae Novae-related employment representing less than 1% of total staff of LSIs.

By seeking programme continuity and repurposing technology, ESA and industry partners help maintain talent and knowhow within member states. Through talent and technology transfers, the exploration sector infuses (and in turn benefits from) other space markets (telecom, EO, etc.) and with high technology terrestrial markets.

- *Space exploration projects support company growth*

Terrae Novae programmes are drivers of company growth strategies: by repurposing technologies or products developed for ESA for new customers and markets, companies can generate additional sales that will in turn weigh in their future growth decisions. Initiating a product with ESA as anchor client before addressing new clients with the same product or a derivative is a ubiquitous strategy. Over 60% of respondents to the consultation have already increased their product portfolio because of Terrae Novae projects (or expect to do so in the short term) and are now aiming for additional sales, which nearly 20% of respondents have already achieved.

Additional sales are usually the result of innovative and superior products being developed for the extreme constraints of deep space missions, with more stringent mass and volume requirements, more efficient power units, lighter and stronger materials, autonomous navigation, etc. The products are then repurposed either for identical exploration markets, conventional satellite applications (satcoms, EO, navigation, etc.), or even for large volume terrestrial applications (typically in the energy, maritime, automotive or agriculture sectors). The stakeholder consultation and desk research uncovered numerous such examples of additional product sales, from pressurized habitats being sold for commercial space stations, interplanetary spacecraft thrusters being used for communication satellites, ISS cryogenic storage unit reused for liquid natural gas transportation, etc.

- *An investment multiplicator effect*

In most cases, when receiving agency funding for a Terrae Novae project, companies tend to invest some of their own resources to be able to meet mission requirements, which are designed in most cases to produce next-generation products. Consultation respondents report investing over €100 million of own funding (the 64 respondents represent only a fraction of the hundreds of beneficiaries). Such expenditures usually aim at expanding, upgrading, or modernizing existing capabilities (machinery, testbeds, etc.), furthering R&D, integrating more efficient processes or equipment, increasing competitivity, or expanding the workforce. As such, ESA Terrae Novae funds **act as a catalyst for additional private sector investments.** This positive multiplicator effect results in more funds being injected in the economy, jobs creation and development and modernization of the industrial base. In

some cases, however, industry partners deplore high paperwork costs due to heavy procurement processes and agency micromanagement, rather than beneficial investments. Cost-constrained users such as start-ups often find the cost of bidding for ESA projects almost unbearable. Respondents hope to see program management evolve toward a lighter agency footprint in the future so that they can focus their resources on hardware development.

- *Toward a service procurement approach for exploration*

In order to increase efficiency, cut costs and stimulate the commercial sector in the long term, it is often argued that European exploration programmes must **begin their transition to a service procurement approach** over the traditional hardware procurement approach and operation by the space agency. This new approach, pioneered by NASA on the COTS, CCDev, HLS, CLPS and CLD programmes, tends to result in lower service costs, transfer of responsibility from agency to industry, simplification of the procurement process and more room for innovation for private contractors. Furthermore, it enables the Agency to lower its expenses in mission architecture, infrastructure, operational and transportation costs and focus its resources in high-value payloads. In European exploration programmes, this approach is being tested on a small scale with the Lunar Pathfinder and subsequent Moonlight communications project (not a continuation activity and outside the E3P programmatic context). Throughout the study, many respondents (mostly emerging actors rather than incumbents) have called for its extension to more segments of the European exploration programme.

Strategic impacts

The strategic impacts cover benefits which **position European stakeholders favourably to address future opportunities**. For instance, technological leadership gained through Terrae Novae projects will allow companies to compete in existing or new markets. In some cases, they help increase their cost competitiveness over competitors, resulting in a stronger market position. Meanwhile, ESA exploration programmes push industry to develop capabilities indigenously, increasing strategic autonomy (although the supply chain is still reliant on the US). The table below showcases the individual strategic indicators and selected key-findings.

INDICATOR	QUESTION	KEY FINDINGS (CONTINUATION / TECHNOLOGY)
Access to new markets	*Is the beneficiary now positioned to gain access to new markets?*	Terrae Novae projects often put companies on track to address **new, high potential markets** in space and terrestrial sectors.
Increased cost-competitiveness	*Has the beneficiary been able to reduce costs for this specific project or for other activities?*	Overall challenging to reduce costs on single-customer exploration missions **due to the lack of economies of scale.** However**, batch production** for certain systems (ESM, EL3) increases production volumes
First mover advantage	*Does the project put him in a position to generate or maintain a first mover advantage in a market?*	European companies occasionally **initiate a market,** but most based in the US
Technological leadership	*Has the company generated or maintained a leadership role in a*	There are **several key fields** in which Europe enjoys leadership (pressurized habitats, vision-based GNC and subsegments of robotics and mechanisms).

	specific technological field?	
Increased European non-dependance	*Has the company acquired a capability replacing one which was previously procured from a foreign supplier?*	Strategic autonomy is increasing in several fields (power systems, propulsion, GNC and EDL) but supply chain remains largely **dependent on US suppliers**.
Stimulation of LTAs	*Is he making any additions to his supply chain (contract new suppliers)?*	In general, stakeholders relied on their existing supply chain. **The more heritage a project had and the lower the demand volumes**, the more stable the supply chain was.
Heritage from past projects	*To what extent does the project reuse knowhow and technology developed during previous programmes?*	Repurposing and improving existing technologies and know-how is actively sought by European industry **to save costs, time and maximize the utility of past investments**.

Table 6: Strategic indicators overview

Strategic impacts results for continuation activities and technology development

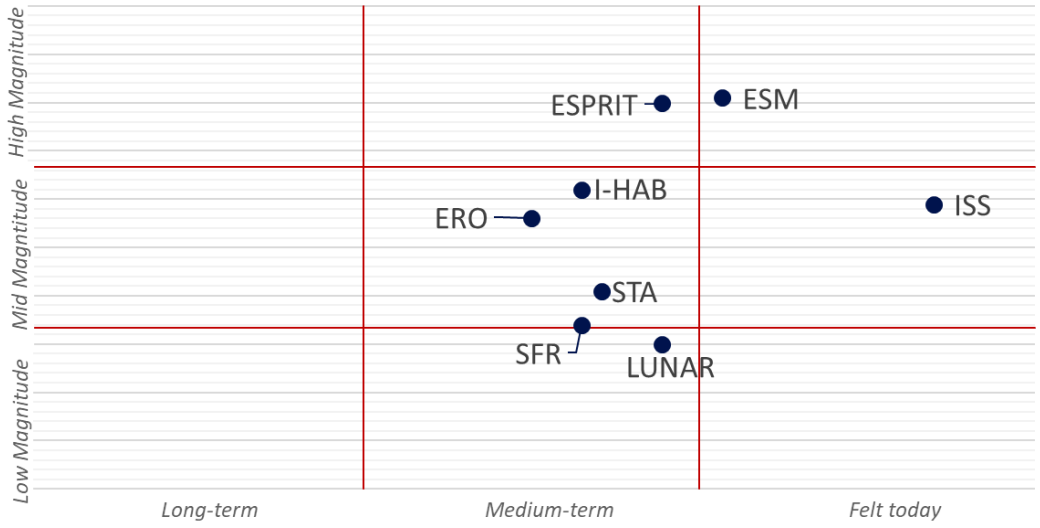


Figure 17: Strategic impact of continuation activities rated by magnitude and time horizon

The ESM, Europe's main barter element for cooperation with the US and used to offset the ISS common station operating costs as well as astronaut seats (the latter make up a minority of the overall costs) and in the Gateway, receives the highest strategic rating. Gateway elements ESPRIT and I-HAB also rate highly, as Europe's main contributions to the Gateway infrastructure, and representing a key contribution to Artemis. Finally, ERO, as the most complex sub-component of the MSR mission, rates highly on most strategic indicators, particularly technological leadership for its electrical propulsion and GNC subsystems. Although the study didn't collect quantified interviewee ratings for the EL3 (not a continuation activity), **it can be argued that the EL3 would receive an even higher intensity rating** as key sovereignty-enabling element, with a capability planned for multi-mission exploration campaigns launched every 2 – 3 years, comparable to the ESM series production.

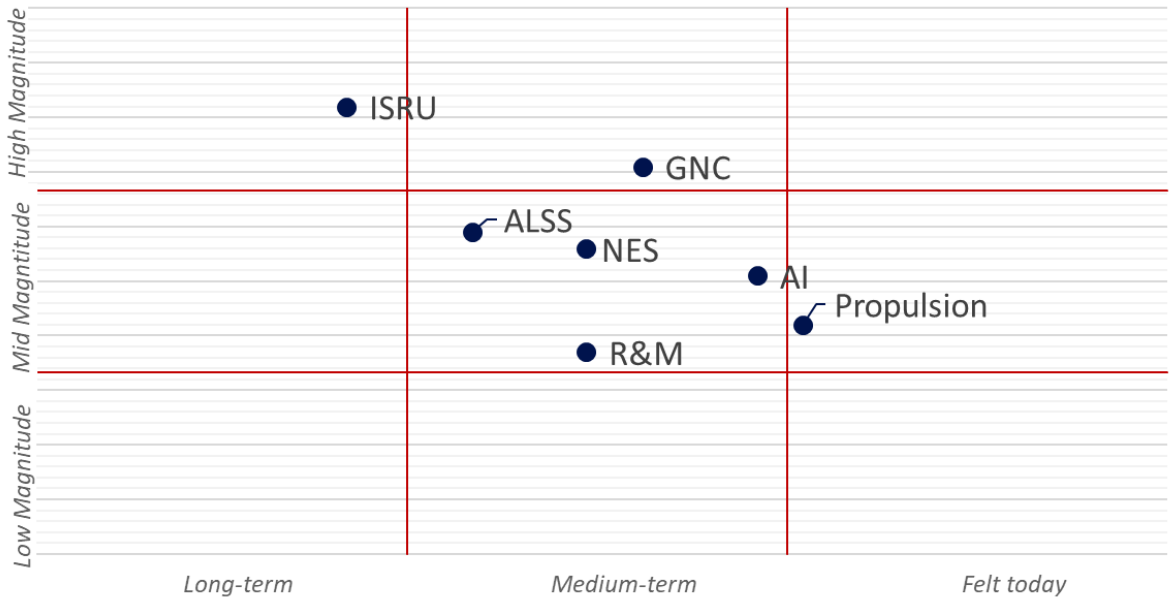


Figure 18: Strategic impact of technology development rated by magnitude and time horizon

All 7 technology groups are essential to any long-term exploration scenario. However, **their criticality peaks at different times in the future**. The most urgent technology groups for the exploration roadmap are propulsion and GNC (extendable to EDL) as they will enable the next flagship missions (EL3, MSR, ESM, etc) and be the foundation of all future transportation architectures. Once these are secured and when considering prolonged and sustainable Human presence in space and especially on the Lunar surface, **technologies reducing the reliance on space transportation and consumable inputs** take on a leading role, namely ISRU, ALSS and NES.

- *Increasing European strategic autonomy and non-dependence*

Terrae Novae projects are **increasing Europe's strategic autonomy** in space. Indeed, according to the consultation, systems or components which were previously procured outside of Europe (i.e., in the US) are being increasingly developed indigenously. This reduces Europe's reliance on foreign actors while making it increasingly attractive for international commercial partners and cooperation frameworks. Still, many respondents underline that the supply chain remains largely dependant on the US to this day, especially at component level. In Europe, due to limited demand of institutional volumes (compared to the US typically), it will often be cheaper to outsource exploration programme components rather than developing them in-house.

The next key milestone on the road to autonomy for Europe is **acquiring a landing capability to be able to deploy surface missions autonomously**. Its reliance on third parties to reach the surface has caused several setbacks recently and in the past such as ExoMars 2020 and Luna 25 and 26, with this vulnerability made clearer than ever by the suspension of cooperation with Russia. In this context, the EL3 is considered the missing link of **such end-to-end capability**. In addition to increasing autonomy, it could be offered as a contribution to the Artemis international human architecture, at the same time opening opportunities for Europe-led missions and cooperation frameworks diversifying ESAs international partnerships.

- *Leveraging programme heritage to increase leadership and maximize past investments*

Seeking maximum continuity between programmes is a highly strategic behaviour which space agencies and industry naturally endorse. Repurposing and improving existing technologies, processes and know-how is a way to save costs, time and maximize the utility of past investments, which is paramount in the context of limited exploration budgets in Europe. Building upon European heritage is also a way to maintain or extend industrial leadership, as well as finding new roles for European industry in future missions. There are many examples of technological continuity between programmes, such as the **repurposing of European pressurized habitats technology** through the ATV, ISS and Gateway, or of propulsion elements from the ATV to the ESM, or of their **docking interfaces, avionics, deployable elements, mechanisms**, etc. There is, however, one identified key capability through past and present programmes, that of **autonomous flight and GNC**, which was developed for the ATV but is not required for the ESM.

- *Terrae Novae paving the way to new markets for the industry*

After leveraging past mission heritage, **stakeholders are often positioned to address new, high potential markets**, both within and outside the space sector. For instance, on the side of continuation activities, respondents involved in pressurized habitats for the Gateway are targeting future commercial space stations (Axiom, Orbital Reef or Starlab stations). Those responsible for the fuel interfaces, piping and docking systems for the ESPRIT hope to repurpose this technology for the nascent **satellite servicing market** which they expect to be a high-growth area over the decade. Those developing the PILOT GNC assembly see opportunities in upcoming commercial landers in the US (CLPS landers) and future government missions (including EL3 missions) to the Moon or Mars.

When looking through the lens of the study's selected technology areas, it appears that for the most mature technology groups with the most flight heritage (namely propulsion, R&M, and GNC), respondents have plans to repurpose near-final products and technologies developed as part of Terrae Novae projects and generate sales in other space markets with higher volumes. For instance, engine makers plan on **deriving ERO electric thrusters for conventional satellite markets** and other exploration spacecraft. Robotics and Mechanisms providers for surface rovers are positioning themselves to sell their motors and actuators to **high-volume satellite constellation clients and markets**. For less mature technology groups related to exploiting and optimising the utilization of the space and surface environments (ISRU, Advanced Life Support Systems, Novel Energy Systems), business opportunities were instead sought in **terrestrial markets** (energy, maritime, farming, waste management, etc.) as these represent **more tangible business opportunities** and as **pivots to reach economic viability** than long-term, low-volume, one-off space markets.

In sum, the extreme constraints of space exploration missions produce cutting-edge technology which can, under the right conditions, be commercialized or spun-off in higher-volume and higher-margin terrestrial and space markets.

Technological impacts

Technological benefits occur when a company makes use of **new production techniques or leverages new technologies to increase efficiency and improve its products**. Certain Terrae Novae projects enable the repurposing of technology developed outside the space sector and thus exploiting investments made in other industries (spin-in), whereas others find ways to spin-out

technologies developed for exploration. In some cases, this will result in efficiency gains and new expertise for stakeholders. For virtually all Terrae Novae projects and technologies, beneficiaries report TRL increases. **As space players borrow technologies and processes from other sectors, the space sector becomes more mature.** The table below showcases the individual technology indicators and selected key-findings.

INDICATOR	QUESTION	KEY FINDINGS (CONTINUATION / TECHNOLOGY)
Efficiency gains	*Has the stakeholder used technology to improve internal processes and operations due to the project?*	Due to their complexity (especially in Human spaceflight), exploration projects **increase requirements for certain processes including quality control, security, decontamination.**
TRL progression	*Is the project leading to any Technology Readiness Level (TRL) increases?*	For **virtually all Terrae Novae projects** and technologies, beneficiaries report TRL increases with varying degrees.
Increased technical expertise	*Is it enabling the respondent's organization and staff to improve their expertise level?*	Increased technical expertise for respondents stems from **both in-house technology development and technology transfers.**
Technology spin-ins	*Does it involve the use of technology, products or processes developed outside the space sector?*	Terrae Novae projects build extensively on spin-ins. Due to the high cost and low volumes, the ability to **leverage know-how and past R&D investments made in terrestrial sectors** is paramount.
Technology spin-outs	*Are technologies developed as part of the project being spun-out to terrestrial sectors?*	Looking beyond technology transfer once it is mature, new paradigm emerging: **multisector technology development** from inception
Intellectual property creation	*Is the project leading to the stakeholder filing new patents or other IP?*	In most cases interviewees do not file for patents as part of Terrae Novae projects and **instead relied on industrial secrecy** to protect their technology.

Table 7: Technological impacts overview

Technological impacts results for continuation activities and technology development

The more a technology investment for exploration advances its readiness for collateral purposes in different sectors (including non-space), the more useful it will be. This is even more relevant in the context of limited exploration budgets in Europe.

Among continuation activities, the ISS scores high in intensity due to it being a historical technological testbed that has generated **many spill overs in multiple technology sectors back on Earth**. The **ESM follows due to the numerous** process improvements and efficiency gains inherent to batch production, which are already being felt as is has entered production phase. **ERO onboards significant technological advances** such as multi-layered insulation and piping routing and welding for thruster pointers and the Power Conditioning and Distribution Unit (PCDU), all of which were brought

approximately from TRL 5 up to TRL 8 and eventually, TRL 9 (flight readiness). Positioning of the other programmes varies depending on their multisector potential and budget levels.

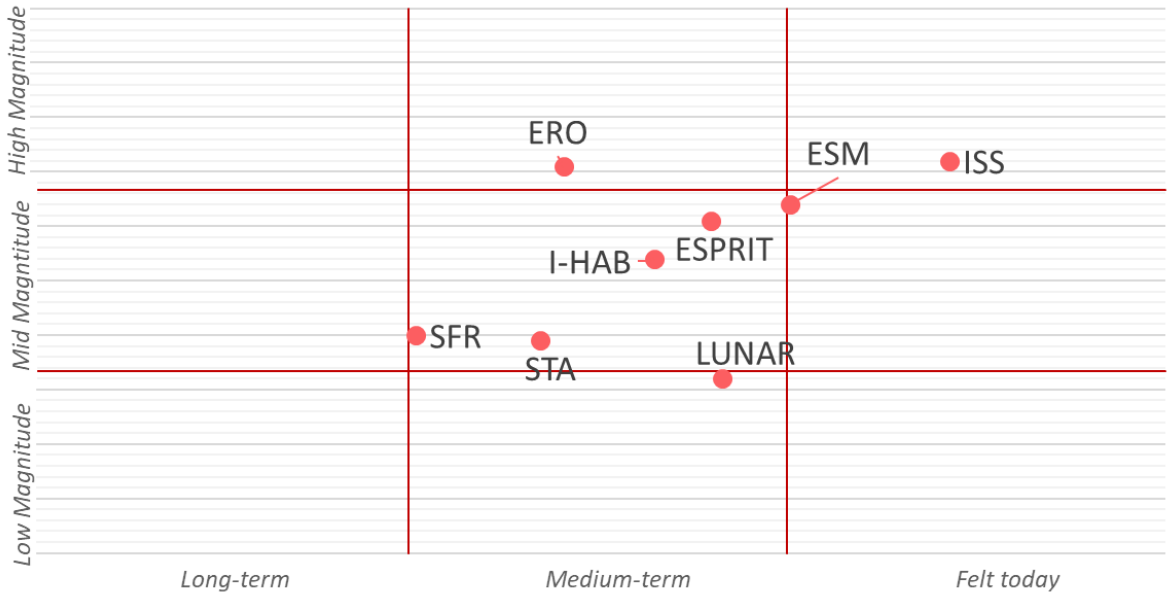


Figure 19: Technological impact of continuation activities rated by magnitude and time horizon

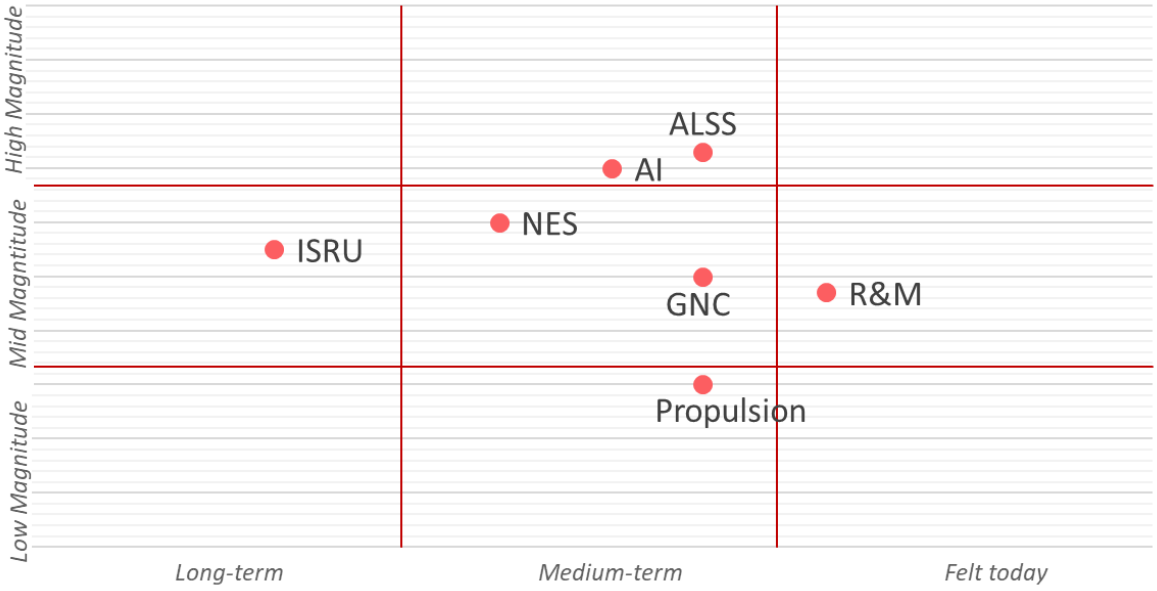


Figure 20: Technological impact of technology development rated by magnitude and time horizon

Technology areas which see the strongest benefits from multi-sector development are typically ALSS, AI and NES. ALSS has strong potential in terrestrial applications such as **waste management, smart farming, the maritime and submarine sectors, the medical sector, etc**. AI for instance, although its role in exploration missions in the short term is marginal compared to other technology groups, obtained a strong intensity rating because of **the inherent reusability of algorithmic elements from one project to another** (compared to hardware elements). As for NES, it shares tight links with energy systems development on Earth (denser energy storage, more efficient production).

- *New expertise, efficiency gains and improved processes for the industry*

Increased technical expertise stems from both **in-house technology development** and **technology transfers** via cooperation with other companies or space agencies. The ISS has generated the most technical expertise increases due to the weight of past investments in fields such as mechanical, electrical and system engineering, radiation tolerance, technology miniaturization, waste management and many more. The involvement of companies in human-rated programmes (ISS, ESM, I-HAB, ESPRIT) **drives up quality control expertise**. Even processes not specific to exploration may be improved. For instance, several respondents feel that Terrae Novae has benefited their **digitalization strategy and helped them increase their use of manufacturing data**. As Terrae Novae projects are very complex (large-scale, multi-year, multi-partner, and technically demanding), respondents also report **gaining new managerial, organisational, and strategic skills and expertise**.

Admittedly, efficiency gains are hard to make on exploration programmes, which are usually stand-alone products with no recurrence to improve processes over time. In some cases, however, a limited level of serial production is possible through batch production (ESM, EL3). This **enables cost reduction and the optimization of processes and implementation of new ones** such as automation, digitalization, 3D printing, etc., while allowing for evolution of technology and performance over time. Further down the road, the EL3 will also be procured in batches. To lower unit costs for the EL3 for serial production, stakeholders plan on maximizing the use of COTS components (which are increasingly finding their way in exploration missions) and implementing a higher degree of serial production techniques and processes.

- *Spinning-in technology to build on existing investments*

Terrae Novae projects build extensively on technologies and processes imported from terrestrial sectors. Indeed, due to the high cost and low volumes of the space sector, especially exploration, the ability to leverage know-how and past R&D investments in terrestrial sectors are paramount. For instant, **the racing and commercial automotive industries are at the sources of multiple spin-ins due to high production volumes married with stringent quality and safety requirements**, especially in the field of materials, software, engineering models and mechanisms. Space station interior design and life support technologies were imported from the submarine sector; 3D printing techniques, materials, actuators and heat shielding technics from the energy and heavy industry sectors.

- *The benefits of multisector technology development*

Looking beyond technology spin-in or spin-out, several interviewees (especially emerging space companies or companies originating from non-space sectors) promoted a **multisector technology development approach** common to other high-innovation areas but still largely unfamiliar to the space sector**.** While the transfer of a technology to other sectors is generally considered the last step of its lifecycle, respondents argued that technologies should be **developed for space and terrestrial applications simultaneously, from their inception**. By cultivating terrestrial/space synergies, stakeholders could leverage **economies of scale through serial production** (Earth applications compensating for the low volumes of the space sector), driving cost down, while validating basic technology segments on Earth and obtaining **much larger pools of operational data**. Indeed, the

relevance of a more technologically porous space sector able to multiply the impact of investments is amplified given Europe's relatively low space budgets compared to other leading space powers.

- *Industrial secrets preferred to intellectual property according to the consultation*

One remarkable trend in the technological impacts category throughout the consultation was the **general lack of interest for intellectual property creation**. In most cases and regardless of the technology group, interviewees (both incumbent and emerging) declared that they had not filed for patents to protect their technology as part of ESA projects, nor were they planning on doing so. **This is due to export control concerns**: space technologies tend to fall under regulatory protection to avoid their draining by foreign competition. As such, they are not compatible with patenting which requires a detailed and public description of their technology, making it vulnerable to reverse-engineering and reproduction. **Protection of technology usually relies on "industrial secret**" methods instead.

Societal impacts

Thanks to their work in Terrae Novae projects, stakeholders sometimes contribute to **advancing societal and environmental goals such as the UN SDGs**. Terrae Novae projects indeed can contribute to environmental and sustainability objectives, especially by promoting circular economy paradigms.

Space exploration also holds inherent inspirational value that creates educational, innovation and identity benefits. It can generate strong public interest for industrial stakeholders which can in turn attract new talent and encourage positive societal outcomes, such as increasing the participation of women in space and encourage youth to pursue STEM degrees. The table below showcases the individual societal indicators and selected key-findings.

INDICATOR	QUESTION	KEY FINDINGS (CONTINUATION / TECHNOLOGY)
Environmental value creation	*Is the project encouraging the stakeholder to participate in sustainability goals (such as the SGDs) and generate environmental value?*	**Long duration missions** and exploitation of the space environment focus on resource recycling with little consumable inputs in closed cycles. Repurposed for terrestrial applications, they support **circular economy and recycling**
Societal value creation	*Does the project lead the stakeholder to take part in societal goals (such as the UN SDGs) and generate societal value?*	The same technology groups can lead to **increased resilience for isolated or developing communities** on Earth. In general, Terrae Novae projects support key societal fields (education, medicine, science).
Ability to inspire the public	*Does the project have the ability to inspire the European public?*	The ability of exploration programmes (Human spaceflight) to inspire the public is one of their most common justifications. **It is highly transversal**, translating into **educational value, targeting underrepresented groups and innovation**
Increased public visibility	*Is the project receiving public recognition and increasing visibility for*	Respondents report that space exploration activities generated **significantly more media attention than conventional satellite activities**. Public visibility

	the stakeholder (media coverage, press releases, etc.)?	dividends include improved corporate branding, attracting new talent, etc.

Table 8: Societal impacts overview

Societal impacts results for continuation activities and technology development

The continuation activities with the strongest intensity ratings are the human/crewed programmes due to the inspirational value they create and the media attention they bring to industrial stakeholders. Interestingly, the ESM is slightly below the Gateway modules, indicating that public attention is more riveted by complete elements of the Gateway which can better showcase European leadership and identity rather than the ESM, which is a subsystem of the larger Orion capsule. For all continuation activities, those indicators associated with public visibility and inspiring the public score significantly higher than those associated with environmental and societal benefits.

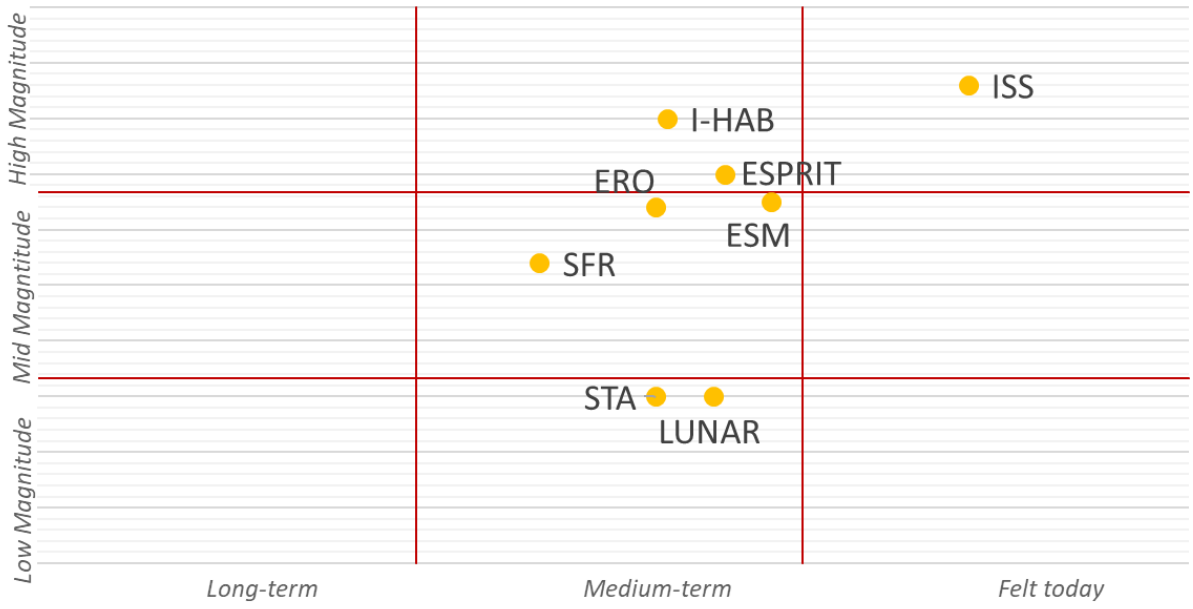


Figure 21: Societal impact of continuation activities rated by magnitude and time horizon

In contrast to continuation activities, the majority of the societal benefits for technology groups stems from environmental indicators, and in particular their sustainability potential for terrestrial applications. ALSS, NES and ISRU have as common denominators the exploitation of on-hand resources and resource recycling to **reduce reliance on long and complex supply chains**, key parameters of numerous SDGs focusing on sustainability and empowerment. These technologies focus on maximizing the efficient utilization of resources, resource recycling, and de-centralized energy and resource generation and production – all of which have obvious environmental benefits here on Earth in terms of environmental sustainability. AI owes its intensity rating to the inherent multisector potential

of its algorithms, which can be repurposed for resource consumption optimisation and environment monitoring applications.

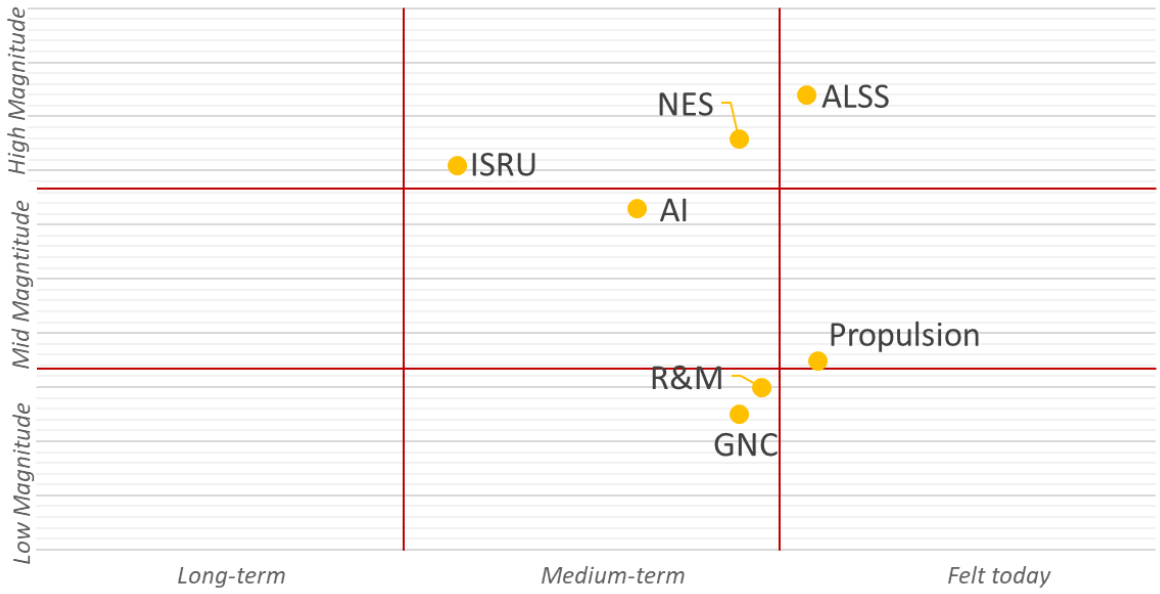


Figure 22: Societal impact of technology development rated by magnitude and time horizon

- *Inspirational and educational value of exploration and Human spaceflight*

The ability of exploration programmes to inspire the public is one of their **most common justifications – but is also one of the hardest benefits to measure**. Inspiration is a transversal concept. It translates into **educational value**, by encouraging the interest of youth for science and STEM and through the popularisation of space and science communication for broad audiences. Certain Terrae Novae missions seek to answer some of the most **fundamental questions asked by people** throughout time and around the world, such as the origin of life and if there is life present on other planets. It has a direct impact on **employment and innovation**, by encouraging talents (including under-represented groups such as women and minorities) to join space companies or space agencies as well as maintaining and developing skills in Europe – if successfully retained on the territory. It also **participates to national and European identity** by federating public opinion around complex and fascinating goals.

The amount of inspirational value generated varies greatly depending on the programme, but Human spaceflight is by far the **strongest generator of public interest and inspirational value**. Astronauts create empathy in the public in ways that are impossible for robotic missions, enabling individuals in the audience to project themselves in the space and even interact, via social media, with the programmes. The ISS stands out from other programmes as a long-standing flagship project having been the only Human spaceflight destination for decades. Its contribution to many societal fields such as technology development, medicine, physiology, biology and education, and resource recycling, all of which help increase quality of life on Earth, is generally well known and appreciated by the public.

- *The benefits of media attention for companies*

Respondents feel that their involvement in Terrae Novae programmes (and exploration projects in general) generates more public attention than other conventional satellite activity due to the **fascination of humans in space for the public**. Those involved in Human spaceflight projects, namely the ISS, ESM and Gateway modules, saw **unprecedented media attention** due to proactive public outreach strategies on social media. Indeed, Humans in space enable a **level of connection with the public** that conventional satellites or robotic exploration fails to reach. As they point out, the fact that European industry is contributing critical, mission-enabling elements to a return of astronauts to the Moon makes for a strong communication narrative. Some warn that it is important for **Europe to properly exploit this narrative to keep Europe out of the US's shadow** in the Artemis programme.

- *Contributing to sustainability and the circular economy*

Terrae Novae exploration programmes can also generate environmental value and promote sustainable development. Life support systems for long duration and/or deep space human exploration missions and platforms, for instance, contribute to **local and circular economy paradigms**. Their focus on **resources recycling with little to no consumable inputs in closed cycles** to reduce the reliance on costly supply chains, could encourage the emergence of **new waste treatment paradigms increasing the resilience of isolated or developing communities on Earth.** Numerous examples were put forward during the study, such as ISS UV water treatment units now used for individual leisure vehicles or remote settlements and camps, or biochemistry knowledge and software for oxygen generation which can be repurposed for the low-consumption / high yield smart farming sector.

In the field of spacecraft fuel systems, respondents involved in the ESPRIT fuel piping and interfaces plan to move on to **satellite life extension markets** and see environmental value in their participation to a **more sustainable space environment**. Others involved in electric thrusters feel that they are helping to transition away from toxic propulsion and toward greener and more efficient propellants.

Finally, ISRU technologies developed for space, if brought back to Earth, could play a key role in **reducing the logistical and carbon footprint of industrial activities** by concentrating them geographically and consuming resources that are immediately available instead of relying on carbon-heavy imports and long logistics. Novel Energy Systems such as regenerative fuel cells can also help **increase local energy autonomy and community resilience**. Radioisotope power generation could be used to repurpose the conventional radioactive waste of nuclear power plants.

Scientific impacts

Scientific progress remains a main goal of space exploration programmes. **ESA beneficiaries help create scientific value, directly and indirectly, by taking part in Terrae Novae projects**. Scientific value is measured through the project's **record or ability to generate quantifiable scientific value** or by its **potential to unlock future scientific benefits** in fields such as astrophysics, heliophysics, geology, planetary climatology, data science, etc. Because the analysed Terrae Novae activities are in the engineering development phase (except for the ISS), they are not yet generating peak scientific returns, expected once they have launched (and often extending for years or even decades after launch). Despite this, respondents state they are already generating pre-mission scientific value in the form of scientific publications (several hundred reported by over 40 interviewed stakeholders), scientific conferences and technical working groups, etc. Respondents are unanimous in that they see scientific

returns as one of the main end goals of their engineering projects. The table below showcases the individual science indicators and selected key-findings.

INDICATOR	QUESTION	KEY FINDINGS (CONTINUATION / TECHNOLOGY)
Scientific knowledge production	*Is the project generating scientific knowledge and under what form?*	Although Terrae Novae projects are still in development phase (except for ISS-related), they are **already generating science** in the form of scientific publications, PhDs, attendance to scientific conferences and more.
Number of scientific publications	*How many scientific publications has the project generated so far?*	~40 respondents actively produce scientific outputs, totaling several hundred publications annually. **The real number of publications is far greater occurring** later in the project lifecycle, during exploitation phase.
Ability to generate future scientific advancements	*What scientific advancements or breakthroughs could the project unlock in the future?*	Science generation appeared counter-proportional to technology readiness: the less mature the technology group, **the more unlocked scientific value it has**. The higher the TRL, the lower the associated scientific output.

Table 9: Scientific indicators overview

Scientific impacts results for continuation activities and technology development

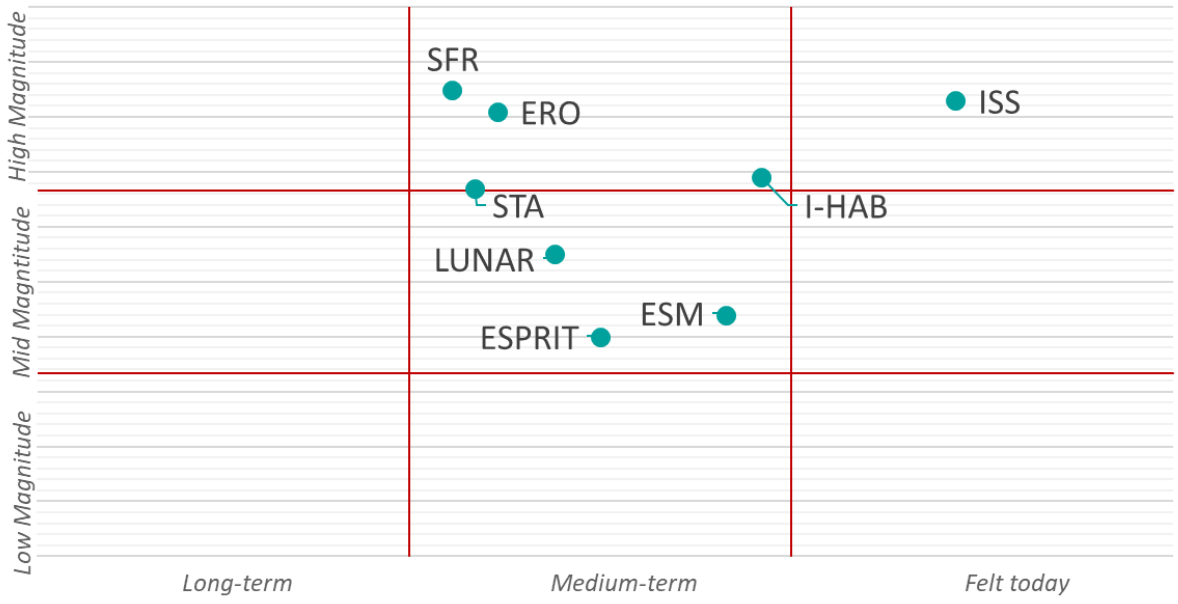


Figure 23: Scientific impact of continuation activities rated by magnitude and time horizon

The ISS dominates scientific production among continuation activities, being the main long-standing scientific flagship mission. Indeed, the ISS has been a technological testbed for four decades. **All other continuation missions have yet to be launched**. As such, their scientific high-yield phases are situated in the future. While the peak scientific output phase is years or even a decade away, the fact that pre-mission scientific benefits are starting to be generated pushes this timeline forward somewhat.

The only programme with intensity as high as the ISS is the MSR programme's constitutive elements, whose yields are expected in the 2030s. The MSR is one of the most high-anticipated scientific planetary missions in decades and is expected to result in breakthrough science.

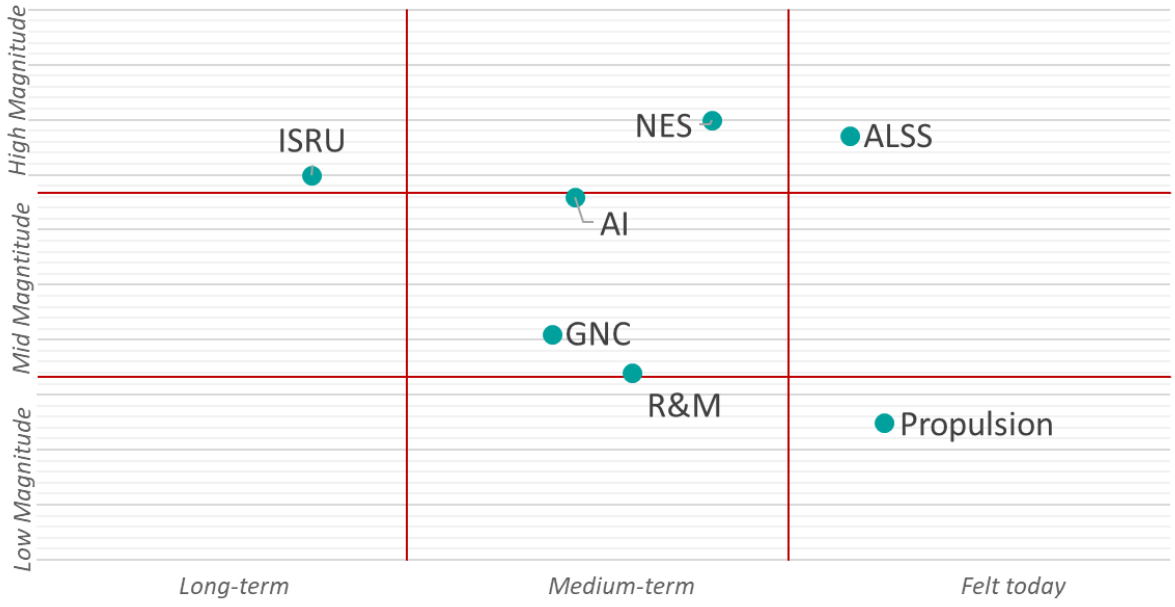


Figure 24: Scientific impact of technology development rated by magnitude and time horizon

The technology cluster illustrates the inverse relationship between readiness and fundamental scientific production. ALSS's benefits are in the near term as it has been advancing multiple existing research fields simultaneously (the MELISSA programme has been running for over 20 years), including in biology and biochemistry. The low TRL levels of NES and ISRU represent significant scientific potential, with both fundamental and applied scientific discoveries expected, in the medium-term for NES and longer-term for ISRU. In contrast, the most mature groups, propulsion and R&M, produce comparatively little scientific value.

- *From marginal science in programme development to high endgame scientific yields*

Programmes generate very different amounts of science depending on where they stand in their lifecycle: there is a **fundamental difference between the science created as part of a programme's development and production phase and during the mission phase, after launch**. During development and production, science production is usually limited, as most fundamental research has already been done upstream. While there is some scientific value in industrial R&D, especially applied sciences, and Terrae Novae project beneficiaries report scientific publications, PhDs, attendance to scientific conferences and more, there is consensus that Terrae Novae's largely engineering projects generate limited scientific value in design and development phases.

However, once the mission has been launched and the payloads are deployed and collecting data, **the missions enter the phase of strongest scientific yield of their lifecycle**. The MSR mission for instance produces little scientific value as part of its development and production (it requires TRL advances but few scientific and technological breakthroughs). On the other hand, once the samples are

returned to Earth, the mission is expected to unlock some of the most highly anticipated scientific breakthroughs in decades in research fields such as planetary sciences, geology and climatology. Unsurprisingly, **the ISS stands out as the programme creating the most scientific value by far**. As a long-standing, international flagship scientific programme, it has been generating extensive scientific value in the form of thousands of publications and advancements in numerous research fields such as physiology, bioscience, chemistry, medicine, fundamental physics, etc. Furthermore, being crewed, the ISS can produce research in very diverse fields, its payloads being inherently reconfigurable.

It must be stressed that **not all programmes have a scientific finality**. Some, such as the ESM or the I-HAB and ESPRIT are transportation or habitability elements. As such, they do not unlock inherent scientific value, even when launched. Instead, they **unlock scientific value in an indirect way by enabling the deployment of scientific payloads and missions as secondary missions**. For those missions, **science is more of a by-product than their main objective**. For instance, unlike the ISS, the Gateway is a logistical outpost and mission staging point rather than a flagship scientific project. It is smaller and will not have dedicated laboratory modules in its current planned configuration. Nevertheless, it will produce scientific research and host experiments as secondary functionality.

However, **science remains one of the main justifications and expected benefits of space exploration missions**, underpinning nearly all pre-, during and post-mission activities. For example, understanding the radiation environment of deep space is essential for future deep space travel, and the Gateway is a new platform that will enable advancing this knowledge, just as the ISS advanced scientific knowledge of humans in space. The first payloads on Artemis 1 are radiation experiments, which incidentally benefited from strong involvement and contributions from European scientists.

- *An inverse relationship between technology readiness and science generation*

When zooming into the technological bricks of exploration programmes, the consultation indicates that (indicators for) **science generation are counter-proportional to technology** readiness (based on to the science indicators used for the study). The less mature the technology group is, the more scientific value it was reported to be generating in the present and near-term, especially ISRU, ALSS and NES. This could be because important **fundamental scientific research and applied science research must still be accomplished before functional and scalable demonstrators can be built**. Therefore, ongoing technology development is associated to scientific effervescence. The less mature the technology, the more science would be generated as a direct consequence of its ongoing development.

Risks and challenges

Depending on the type of respondent (SME, startup, incumbent, university, etc.), their role in ESA programs (prime, subcontractor), and the type of mission and technologies, etc., risk is perceived and measured differently. A wide array of risks and challenges were reported, including technological risks, financial risks, organisational risks, market risks, regulatory and political risks of all sorts.

Programmatic uncertainty is one of the most cited risks. Program redefinitions and cancellations impact stakeholders' growth strategies and product roadmaps, often **forcing them to maintain skills and technology amid uncertainty during interruptions**. This is mostly due to the intergovernmental nature of ESA and the **high level of international cooperation** inherent to the various continuation activities. Any change of NASA requirements translates into costly redesigns and delays. As such, stakeholders feel there is a strong degree of instability over which they have no control. When programmes are moving ahead, stakeholders also feel strong schedule pressure despite **the complexity of the systems**, often due to the US political agenda.

Schedule pressure combines to increasing financial pressure. Indeed, interviewees feel that ESA is asking for increasing **compromises on price** (often for products with little market potential beyond ESA) while maintaining strong quality requirements. This is largely due to the commercialization of the space sector, which is putting strong pressure on costs. This adds to heavy costs induced by bidding processes with ESA. Agency initiatives in the field of commercialisation with different procurement mechanisms may **reduce bidding costs, increase agility, and result in a lighter agency managerial footprint.**

There is also consensus that the European exploration roadmap tends to lack clarity for industry stakeholders. However, steps have been taken to address this issue including extensive discussions and consultations with industry, a commitment to co-creation, political endorsements at the highest political levels, and the public dissemination of the Strategy.

Certain political risks weigh over the different continuation activities. For instance, several missions have been directly impacted by the **end of political cooperation with Russia over its war in Ukraine**. **ExoMars** for instance, must find a new launcher and a new lander and will likely be delayed until the second half of the decade. The **Pilot and Prospects missions**, which were part of the Russian Luna missions, were also affected in the immediate aftermath of the war. However, ESA has taken steps to mitigate these disruptions, and agreements are currently in place with the US on CLPS missions. Despite these mitigation measures, the drawbacks of over-reliance have become apparent.

Meanwhile, all missions are subject to **several market risks**. For instance, **available demand beyond ESA itself is often highly uncertain** given the high specialization of their systems and overall limited demand for exploration (ESM, rovers, landers, etc.). Although stakeholders hope that new customers will manifest themselves once their systems are flight-demonstrated, there is **no assurance that this single, government user market will translate into a diversified demand-driven market** with additional commercial opportunities. Other market risks include the current shortage of electronic components, and the fact that Europe could lose its advantages to emerging competition if it fails to deliver programmes on time.

Strategic trajectories through 2030 to 2040

Alongside its assessment of Terrae Novae continuation activities and technology development impacts and benefits, the study has also assessed the benefits of 18 candidate missions and capabilities included in ESA's 2030+ Strategy Roadmap. Impacts were measured through 12 indicators as detailed in the methodology section and annex 2.

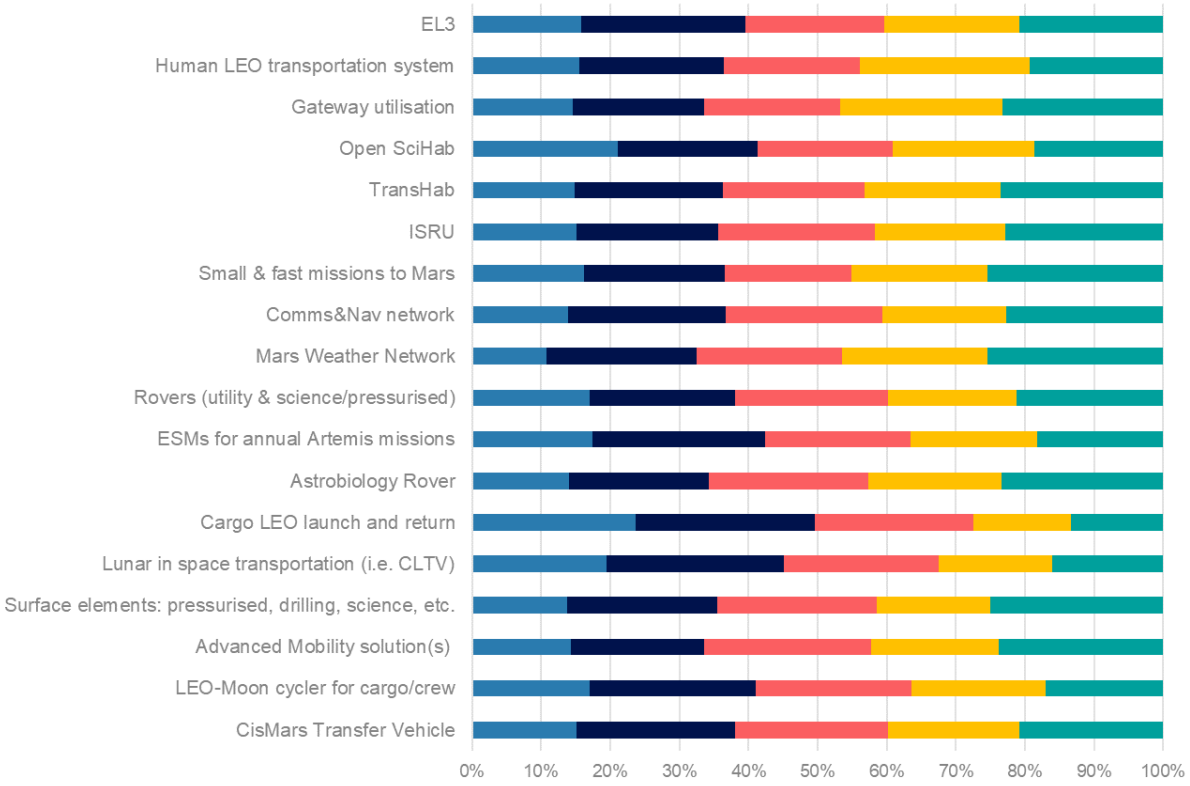
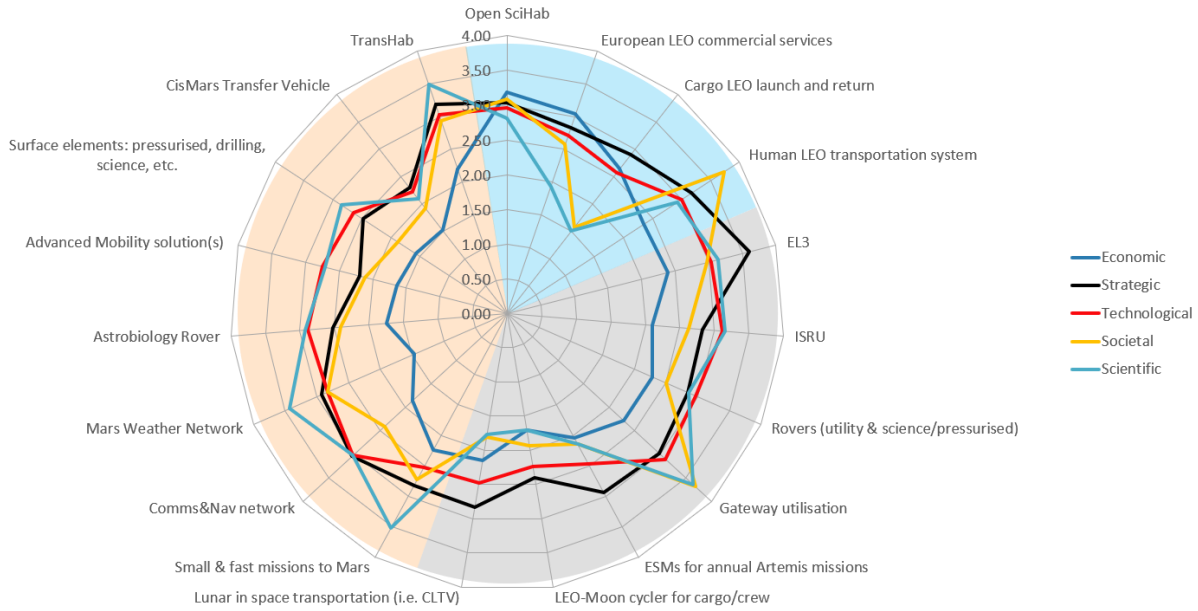


Figure 25: Benefits profile per mission (blue: economic, dark blue: strategic, red: technology, yellow: societal, green: science)

All Strategy 2030+ missions generate significant impacts – indeed, if they did not, they would not be included in the Roadmap. The chart in Figure 28 above showcases the relative importance of each impact category contributing to the overall benefits generation of each Strategy 2030+ mission (in the bars above, the impact categories are, in order: economic, strategic, technological, societal and scientific). Overall, while certain missions score higher on one benefits category or another, it is evident that all missions are relatively balanced in terms of benefits. As such, one of the strengths is that the Strategy 2030+ Roadmap as a whole, while designed "bottom-up" with no financial considerations, is a remarkably well-balanced overall strategy, with missions generating benefits across all 5 impact categories. The strong diversity of benefits across the different missions means that should one or more missions not be funded, the overall long-term program will still generate a large variety of benefits, showcasing the Strategy 2030+'s resilience.

The radar plot in Figure 29 (top) positions the magnitude of each of the impact categories for each of the candidate missions. The total area enclosed by each of the lines is proportional to the overall impact of the entire roadmap for the corresponding impact area. Overall, the radar plot evidences for each of the impact categories a substantial basic benefits realization for each of the missions. Notwithstanding

the well-balanced spread of benefits embedded within the Strategy 2030+ roadmap, as evidenced by Figures 28 and 29 (top), there is some variation between missions. For example, regarding the economic impact areas, the magnitude consistently increases from low economic impact of Mars missions over medium impact for Moon missions, to the highest expected impact for LEO missions, logically reflecting an expectation of economic benefits proportional to the maturity of the destinations.



	Open SciHab	Cargo LEO launch and return	Human LEO transport system	EL3	ISRU	Rovers (utility & science / pressurised)	Gateway utilisation	ESMs for annual Artemis missions	LEO-Moon cycler for cargo / crew	Lunar in space transport (i.e. CLTV)	Small & fast missions to Mars	Comms & Nav network	Mars Weather Network	Astrobiology Rover	Advanced Mobility solutions	Surface elements: pressurised drilling, science	CisMars Transfer Vehicle	TransHab
Economic	●	●	●	●			●											
Strategic	●		●	●								●						●
Techno.				●	●		●					●						●
Societal	●		●	●			●											●
Scientific					●		●				●		●					●

Figure 26: Strategy 2030+ missions with top 5 scores per impact category

Even if all missions are expected to deliver a basic level of impact, a few “mission roadmap highlights” can be observed. E.g. averaging the scores for each of the impact areas results in an overall impact score, allowing a ranking of the candidate missions. The order of the missions in Figure 28 reflects this overall ranking with EL3 on top (highest average impact), followed by a Human LEO transportation system, Gateway utilization, Open SciHab and the Transhab completing the top five. Another approach to identify the highest performers is focusing on missions which score highly across at least two different impact categories. This is illustrated in Figure 29 identifying SciHab, a Human LEO transportation system, EL3, ISRU, Gateway utilization, Mars comms and nav network, and the TransHab as high-impact missions.

High-level takeaways for selected high impact missions are below.

EL3

- Enables **critical lunar surface activities** such as mobility, science, exploration, ISRU, etc.
- Represents missing landing capability for **end-to-end mission capability**
- Key **sovereignty-enabling** element to reduce reliance
- Barter element for **European boots on the moon**
- Opens **European-led missions** and cooperation

Human LEO Transportation System

- Europe as sole space superpower with no capability
- Ability to launch astronauts as **highest degree of sovereignty in space**
- US commercial launch solutions risk eroding **eye-level relationship**: ESA as customer, not equal partner
- Increases European participation / role in a **growing commercial LEO ecosystem**

Lunar Gateway utilisation

- Europe providing **mission-critical capabilities** (ESPRIT's communications module, ESM transport)
- Post-ISS, will be **main institutional destination** for Western astronauts
- Represents logistical staging post for Lunar surface missions, emergence of a Lunar economy and starting point for deeper exploration
- Starship as HLS erodes justification for Gateway?

Open SciHab

- Key to ensure **continuity in LEO** and ensure a smooth transition to the **post-ISS world**.
- **Building upon and extending European heritage** and expertise developed on the ISS and Gateway
- Boost international cooperation, permit **European leadership and non-dependence**
- Flexible approach, allowing **greater European commercial activity in space**

Mars TransHab

- Contributes to TN's horizon goal of **Europeans on Mars**
- TransHab as key contribution putting **Europe on US critical path to Mars as a key and equal partner**
- Leverages **European heritage** in pressurised modules
- **Spin-in / -outs** synergies
- Strong **SME interest**, lower **barriers to entry**
- Strong **visibility**, **inspirational, motivational** impacts

ISRU

- Europe is at **forefront** of this nascent field
- Targeted investments and missions could propel Europe to a **global leadership position**
- **Potential first-mover advantage** as well as decreased European dependence
- **Strong spin-in and spin-out potential** with terrestrial indsutries

Small and Fast Mars Missions

- Multiple opportunities for less complex and costly missions and **greater SME participation**
- Increasing cooperation opportunities for Europe, including **international contributions to Europe-led missions**
- Mars has **high scientific** (origins of life, climate change, etc.) and **societal** (inspiration, public visibility) interest

Mars Weather Network

- **Scientific and technological leadership / first mover advantage potential**, as few weather instruments on Mars (most missions focus on geology)
- Strong **European scientific expertise and heritage** could be leveraged to focus on Mars weather
- Ties with **Copernicus** and Earth **climate change**, which is high in the global political agenda

EL3: enabling an end-to-end European Lunar transportation capability

The EL3 ranks as top mission in the roadmap, generating the most benefits according to stakeholders. It consistently ranks high across all 12 indicators, as well as fulfilling critical ESA space exploration objectives, such as acquiring an autonomous landing capability and maintaining an eye-level relationship with international partners by providing important barter opportunities. Indeed, the EL3 would occupy **a strategic transportation niche consisting in the agile delivery of cargo in the 2t-class.** As such, it would be complementary to the Artemis Starship Human Landing System (HLS). The

HLS is highly capable (capacity of 100t to the surface) but also very complex (requiring at least a dozen refuelings in LEO, and as many launches), **and can only land on even Lunar surfaces.** As such, the EL3 is well positioned to complement it, offering both significant cargo capacity as well as versatility and agility to land in rough areas on the Moon nearer to key sites of interest. It would **complement the HLS's high capacity with versatility, range, easy access to strategic areas and mission speed.**

On the other end of the spectrum, **EL3 complements the US commercial exploration landers** currently in development under NASA's CLPS program. CLPS landers currently under development and study may be very versatile, but their capacity is limited to 100kg-class payloads. However, over time, it is likely that CLPS landers become more performant and with higher capacity limits, eroding EL3's unique value offering.

As such, the EL3 today sits in a sweet spot, offering both significant payload capacity as well as versatility and agility to land in rough areas on the Moon. It would **complement the HLS's high capacity with versatility, range, easy access to strategic areas and mission speed** while also enabling more ambitious missions (including crew-supporting missions) than CLPS vehicles. As such it is seen as a future **transportation "workhorse"** for Europe and for international frameworks. Should it materialize, the EL3 program would greatly increase European strategic autonomy in space exploration, by presenting Europe with three international cooperation options:

1. **Full autonomy**: projection of entirely European robotic missions on the Moon (and in the long-term, crewed missions as the EL3 is being designed with future man-rating in mind). Past European experience on the previous HERACLES lander program (from which the EL3 derives) highlighted the need for full autonomy. Indeed, HERACLES relied on industrial cooperation with Japan and Canada (driving down cost and responsibility) but priority shifts of the partners' national programs created instability and eventually brought the program to an end.
2. **European-led cooperation**: missions and exploration frameworks utilizing European critical end-to-end transportation capabilities and incorporating international secondary contributions from other (especially emerging) space powers for support services.
3. **Missions of opportunity**: contribution of EL3-enabled transportation services to missions and exploration frameworks led by international partners (only NASA so far). In this case, ESA would provide a secondary—but nevertheless indispensable—support and logistical role.

European crew transportation: achieving full European sovereignty in LEO

- *European autonomous crew transportation*

Europe remains the only historical space power to lack an autonomous Human spaceflight capability, despite having come close to acquiring one in the 1990s. This is widely regarded as the **missing step to it becoming a fully capable space power**. As Manned spaceflight is one of the strongest generators of different kinds of benefits for society as discussed throughout this study, the ability to perform astronaut missions independently can be seen as the **highest degree of sovereignty in space**.

Considering its comparatively low financial capacity, Europe has made the rational choice to leverage partner Human spaceflight programmes. However, recent developments in the sector have again shown the vulnerability of an astronaut programme **relying on the political will of foreign nations**. For instance, the Ukraine war has cut off access to Soyuz transportation – had the SpaceX Dragon not become operational in 2020, both Europe and the US would have lost access to the ISS altogether (or

forced them to continue cooperating with Russia, undermining the political pressure and isolation of Russia by the West as a consequence of its invasion of Ukraine).

But even the ongoing collaboration with the US **is not an eye-level partnership**. For instance, SpaceX does not have the over 40 years of cooperation with ESA that NASA does, and a partnership of equals has not been established. Indeed, as a commercial entity intent on selling seats, SpaceX may view ESA more as a customer than a partner. As long as Europe does not have redundancy in Human transportation, or its own transportation means, it will not be in a position to influence this relationship. Furthermore, this reliance implies that if Europe stops contributing barter elements to pay for astronaut seats, it will have to pay them in cash, **effectively resulting in European investment to US industry to the detriment of its own, as well as a likely loss of jobs and skills in its own territory**.

In this context and considering the strong upswing of political interest for space exploration globally, ESA is in favour of acquiring an autonomous Human spaceflight capability and is promoting this goal to Member States. Its lead argument, which was widely shared by respondents to the consultation, begins with the fact that other space powers are now firmly committed to land astronauts on the Moon around 2030 as a starting point for Human exploration of the Solar System. **In these conditions, if Europe wants to be a protagonist of these initiatives and not only a supporting partner, it should start investing in a crew capability immediately for it to be ready by 2030**. As such, Europe would finally reach full strategic autonomy, ensure **full equality with other space powers**, and be in a position to contribute crew transportation services as barter elements to international frameworks as well as act as instigator and senior partner in Human exploration missions.

Furthermore, as private sector players and commercial initiatives proliferate in LEO, respondents felt that a European human launch capability would allow European industry and institutional players to fully participate in and enjoy the benefits of the LEO commercial ecosystem.

- *Need for a destination: integrating the commercial LEO ecosystem post-ISS (SciHab)*

Acquiring a means of crew transportation is regarded as a priority by many stakeholders, but it raises the question of Europe's crewed destination in LEO after the ISS. After initial free-flying missions at the beginning of a crewed programme, it will have to lead to a space station to generate the bulk of scientific and societal benefits associated with Human spaceflight. It can be anticipated that the spacecraft will first focus on LEO destinations before an augmented version is eventually aimed at the Moon.

Anticipating the post-ISS era in the 2030s, ESA is considering options to keep satisfying European needs in LEO through the SciHab project. SciHab is envisioned as a multi-layer ecosystem of commercial services (for transportation, destination, and logistics) and various platforms (some crewed and potentially some only robotic), operated by several actors (both governmental and commercial) within a cooperation architecture instigated by ESA. The SciHab would not be a space station follow-on *per say* but instead have a more scattered architecture, aimed maintaining providing a similar volume for activities than with the ISS while remaining within the same cost trajectory.

Different combinations of procurement types could be involved, including the traditional hardware procurement approach, public-private partnerships (PPP), or the more recent service procurement approach which is progressively making its way in exploration. SciHab's objective, beyond satisfying ESA activity volume requirements, would be to participate to the ecosystem of commercial business models in LEO, for instance those aiming to serve government Human spaceflight needs, robotic

payload exploitation (for technology or science), space tourism, but also communications services, SSA etc. As such, it could involve a degree of cooperations with the current commercial space stations currently in development in the U.S (Axiom station, Orbital Reef, Starlab, etc.).

Building upon and extending European heritage and expertise developed through the ISS, the SciHab's flexible approach would boost international cooperation and help European non-dependence and leadership, while allowing for a greater European commercial activity in space.

Lunar Gateway post-2030: a relevant starting point for the future Lunar economy?

The Lunar Gateway is now a firm part of the Artemis programme (although no longer part of the CONOPS of the first Moon landing). Its rationale is to **offer a logistical staging post** for missions to the Lunar surface, as opposed to settling directly on the surface. This approach greatly limits **the amount of payload requiring costly descent into the Lunar gravity well, as systems supporting long-term habitability remain on orbit.** Furthermore, the Gateway is to replace the ISS as main Western institutional destination for astronauts, as the ISS is decommissioned in the early 2030s and LEO destinations are progressively taken over by commercial actors.

In medium term up to 2030, Europe's involvement in the Gateway project and responsibility for the two modules brings substantial benefits to European industry and ESA. Although operating within a US framework, they have positioned themselves as **NASA's key partner on the project** (opening on strong returns such as astronaut worktime), **even providing mission-critical capabilities** like the ESPRIT's Lunar communications module (and not counting the transportation capability of the ESM).

In the long term, the Lunar Gateway sets the stage for a permanent presence in cislunar space. It could progressively lead to establishing a permanent presence on the surface and to the **emergence of a Lunar economy and serve as a starting point for exploration of the deeper Solar System**. As such, stakeholders felt that it was in Europe's interest in the long term to remain committed to the Gateway and keep contributing barter elements as habitability modules or transportation systems throughout the 2030s. For instance, several companies are considering cargo transportation systems to resupply the Gateway, making use of existing European expertise.

Nevertheless, there remain arguments against the relevance of the Gateway in the long term. Critics argue that the Gateway **diverts efforts to the Lunar orbit when they should be focused directly on the surface**, and that the station was partly designed to generate much-needed demand for the upcoming SLS. But most of all, the Gateway may already be an obsolete programme. Indeed, its tacit justification **is the capacity limitation of conventional launchers and Lunar landers**. Conventional lander CONOPS without refueling are typically limited to a few tons of payload, hence the need for a logistical staging point in orbit **where capacities for long-term habitability a kept.** As such, **the selection of the Lunar Starship as Human Landing System for the Artemis hurts the economic model of the Gateway**. Indeed, the future lander will offer a capacity of up to 100 tons to the surface (albeit for a highly complex CONOPS involving 12 refueling missions in LEO), lifting historical capacity limitations, and enabling highly ambitious missions to the surface. This future capability, if it materializes, **could remove the need for a logistical staging point in orbit as all the systems to support long-duration missions could be brought directly to the surface**.

TransHab: making Europe a protagonist in a partner's manned exploration of Mars

Looking forward to 2040, **the endgame objective of Terrae Novae is the Human exploration of the Martian surface**. After the initial "boots on Mars" accomplishment, this endeavour supposedly calls for establishing a semi-permanent Human presence on Mars between 2040 and 2050 (or at the very least allowing for extended stays and expeditions beyond the lander).

Missions to Mars (even robotic ones) are highly complex due to multiple factors including launch windows, duration of travel in deep space, signal latency, Martian weather, radiation, and many others. The difficulty rises sharply when considering Human spaceflight. From a 2022 observer's perspective, Europe can not accomplish this by itself, unless its exploration budgets are increased by an order of magnitude for decades. It stems from this that the most likely way for Europe to land its Astronauts on Mars within the next two decades is not independently, but **through cooperation with NASA and providing critical capabilities to the US's critical path to Mars**. As such, Europe would **contribute barter elements to a US-led transportation and habitability architectur**e, that may take shape, for instance, in the form of a SpaceX Starship descendant with NASA as operator. The main question which arises is **what is the best-fit barter element (greatest value for lowest cost)**?

Various long-term concepts for Mars missions are being considered as European contributions to a future architecture. This contribution should check several prerequisites. First, due to strong uncertainty looking two decades in the future and to the Mars mission architecture not being known, the contribution should be chosen to **remain relevant in any exploration scenario**. Second, it should find the **proper balance between affordability for Europe and high visibility and strategic importance**. Third, it should leverage European technical expertise and heritage. Finally, it should be realistic and achievable with European budgets in a reasonable time horizon while simultaneously being a high-value, manned element to ensure **that Europe is seen as a protagonist in the mission and not only a supporting contributor**.

It stems from these considerations that **the Mars TransHab, a pressurised habitability module for human missions to Mars (surface or orbital) is identified as a leading candidate offering the most strategic capability** for long term scenarios by stakeholders. TransHab would represent a key European-contributed element to the first Human Mars mission (either orbital or landed) in exchange for a European astronaut seat. TransHab builds on important European heritage on Columbus and I-HAB experience and provides the opportunity to embark cutting-edge European ECLSS capabilities as well as AI, avionics and communications systems. Based on European expertise and current knowledge of NASA Human Mars architectures—as well as based on what NASA would be willing to outsource to an international partner—the TransHab is the most likely element of a human Mars Transit Vehicle that Europe could provide.

Such contributions would leverage **Europe's global leadership** in pressurised habitats (although it may soon be lagging in the field of inflatable habitats) and, if deemed critical enough for the mission's architecture, serve as a barter element for the **transportation of European astronauts to Mars**. There are also **strong spin-in and -out synergies**, and perceived **lower barriers to entry** for ground-based technologies, leading to strong interest and involvement from **European SMEs.**

The TransHab compares favourably to other proposed European contributions. For instance, the **Mars Weather orbiter network**, although it would provide a high-value service to a partner surface mission, is likely not a sufficiently-vital contribution (it is not crewed and would not make contact with the surface).

It would not grant Europe with sufficient visibility and may not be enough to barter for European astronaut seats. The proposed CisMars transfer vehicle is a high-value interplanetary transportation piece of infrastructure but today considered too ambitious for Europe to undertake by its own from a 2022 perspective in the current state of budgets and of its chosen strategic trajectory to reach Mars. However, it could be a valuable contribution by Europe in exchange for a seat on a human mission to Mars. It could take the form of a SEP-based cargo transfer vehicle to support human missions, pushing large volumes of cargo between an Earth-Moon system and Mars orbit. Future iterations could eventually be refuellable, and build upon the heritage gained from MSR-ERO and high-power electric propulsion systems. This capability could be used autonomously by Europe for stand-alone, very large missions to Moon/Mars and even beyond in the 2040+ timeframe. However, this remains speculative and consultation respondents favoured the TransHab concept over the Cismars Transfer Vehicle.

Meanwhile, alongside flagship crewed programmes, it should be added that stakeholders often manifested their interest for the **Small and Fast Missions to Mars concept**. For European players and SMEs, gaining more recurrent access to smaller, less complex and costly missions would help them **expand expertise and technology base and spawn new products** while opening up new cooperation opportunities. It remains to be determined which will be the economic model chosen for said missions, whether the hardware is procured and operated by the Agency, integrating various commercial and partner payloads on the platform, or if the missions are procured as services altogether, with ESA providing payloads to work alongside others, **in a payload hosting model**.

Conclusions and Recommendations

Conclusions

Overall, the Terrae Novae project delivers benefits across all five impact categories in a balanced and holistic way. The Technology Development work as well as the Continuation activities provide high-value, cutting-edge projects for European researchers, engineers, scientists and space professionals, creating and sustaining valuable jobs in Europe and ensuring that European space firms can attract and retain top talent. The programme leverages the highly inspirational value of space to increase the visibility of European expertise and ensure that European contributions remain indispensable to international collaborative initiatives, such as the ISS and the Gateway. The programme strategically exploits European heritage and expertise, providing opportunities for European firms to build further on this experience to maintain world-class technological and engineering skills, and provides the flexibility for innovative ideas building upon European excellence to develop and contribute to European and international space initiatives. As a result of this European proven excellence, Europe maintains its eye-level relationship with the US and other leading space powers, while also allowing for European-led missions to embark payloads and contributions from emerging countries, furthering Europe's projection of soft power and leadership qualities. Finally, Terrae Novae allows for the gradual build-up of European strategic autonomy, from the development of end-to-end mission capabilities, to replacing elements procured elsewhere with European-made technology and parts.

As a result of Terrae Novae, Europe is considered a key, irreplaceable partner of the US, and Europe is an active contributor and essential participant to some of the most ambitious space exploration projects ever envisaged, including the Mars Sample Return Mission, the Gateway, and others.

Below, specific conclusions from the ESA Terrae Novae SEI study are included.

- **Terrae Novae supports high-value jobs in ESA member states**

The jobs created and supported by Terrae Novae maintain high-value skills in Europe in multiple engineering and scientific fields, estimated at an **average annual of circa 7,500 jobs over 2023 to 2030**. Through talent transfers, the exploration sector infuses other space markets (telecom, EO, etc.) and high technology terrestrial markets.

- **Terrae Novae creates strategic anchor demand for industry**

Terrae Novae programmes are drivers of company growth strategies: by repurposing products developed for ESA for new customers/markets, companies can **generate additional sales and access new markets**.

- **Exploration programmes drive expertise increases for industry**

Working on Terrae Novae projects is an **invaluable source of knowhow and expertise**, including mechanical, electrical and system engineering, miniaturization, waste management, quality control, planetary protection, programme management, digitalization, and many more.)

- **Inspiration generated by space exploration is paramount**

The ability of exploration programmes (principally Human spaceflight) to **inspire the public** is one of their greatest benefits. It translates into educational value, encourages youth to pursue STEM degrees, stimulates employment and innovation in Europe, encourages the retainment of talent in Europe and **strengthens European identify** via collective goals to rally around

- **Autonomous Human spaceflight is a guarantee of sovereignty**

The geopolitical context underlines the vulnerability of an astronaut programme **relying on the political will of foreign nations**. Europe's lack of Human spaceflight capability **undermines its eye-level relationship with other space powers.**

- **Terrae Novae can produce societal and environmental value**

Exploration technologies and programmes focused on resource recycling with little to no consumable inputs in closed cycles to reduce the reliance on costly supply chains can **participate in circular economy and resource recycling paradigms** on Earth, contributing to SDGs.

- **The exploration sector benefits strongly from tech spin-ins**

Due to the high cost and low volumes of the space sector, especially exploration, the ability to **leverage know-how and R&D investments made in terrestrial sectors is paramount**. Several terrestrial sectors provide technology inputs (automotive, energy, industrial, robotics, big data, etc.)

- **Programmatic uncertainty is the most common risk**

Program redefinitions and cancellations **impact stakeholders' growth strategies and product roadmaps**, often forcing them to maintain skills and technology amid uncertainty and interruptions. This is in part due to the **intergovernmental nature of ESA and the high level of international cooperation** in Terrae Novae projects.

Recommendations

Key recommendations and lessons leaned from the study are included here.

- **Consider space exploration a geopolitical imperative**

Europe must invest in next generation exploration capabilities in order to have a seat at the table, be considered an eye-level partner in international frameworks and **achieve the horizon goal of landing European astronauts on Mars**. If not, it will be **relegated to a supporting partner role** and be forced to pay in cash to participate in international partnerships.

- **Make select investments to secure a protagonist role**

ESA cannot realistically acquire an independent capability in all segments due to comparatively low budgets. However, it can develop a select number of "must have" capabilities (Human transportation, robotic Lunar landing) to **ensure its autonomy** and **attract partners for Europe-led missions**

- **Move forward with the EL3 programme**

The EL3 is regarded as the next key milestone by respondents as it would provide Europe with an **autonomous landing capability** (in the 2t-to-surface niche), along with access to strategic areas. As such, it is seen as an **enabler of European strategic autonomy** and of its ability to deploy independent missions and contribute barter elements to international frameworks.

- **Expect market uncertainty in all fields of exploration**

Demand beyond ESA itself is often highly uncertain given the high specialization of their systems and overall limited demand for exploration (ESM, rovers, landers, etc.). There is no assurance that single government user markets will translate into **diversified commercial demand-driven market**

- **Consider a service procurement approach for exploration**

NASA has pioneered the use of service procurement in the field of exploration (COTS, CCDev, HLS, CLPS and CLD). Many respondents argued Europe should take note of a **service approach's advantages**, including lower service costs, transfer of responsibility from agency to industry, simplification of the procurement process and more room for innovation for private contractors.

- **Consider multi-sector technology development**

Due to the high cost and low volumes of the exploration sector, **encouraging synergies with terrestrial sectors** in technology development early in its lifetime could help drive costs down through economies of scale while validating basic technology segments on Earth thanks to much larger pools of operational data.

Annexes

Annex 1 – detailed methodology of economic modelling

Data sources

The key public data sources used in the analysis were Eurostat 'Structural Business Statistics', United States Bureau of Labor Statistics, United States Bureau of Economic Analysis and IMPLAN. ESA also shared essential detailed data on project funding for each activity under the Terrae Novae programme.

The Global Sustainability Model

Oxford Economics' **Global Sustainability Model** (GSM) is a bespoke input output model covering 96 countries that account for 97% of global GDP, and a "rest of the world" category. Each country's economy is split into 36 industries that are defined by the ISIC Revision 4 classification.[6]

The model takes advantage of techniques originally developed by the Nobel Prize winning economist Wassily Leontief. These techniques allow us to trace supply chain and consumer spending within countries and across their borders (figure 83). Because money cycles through the economy via multiple levels of supply chain relationships, our model reveals what is commonly called a 'multiplier effect' for a given spend impetus.

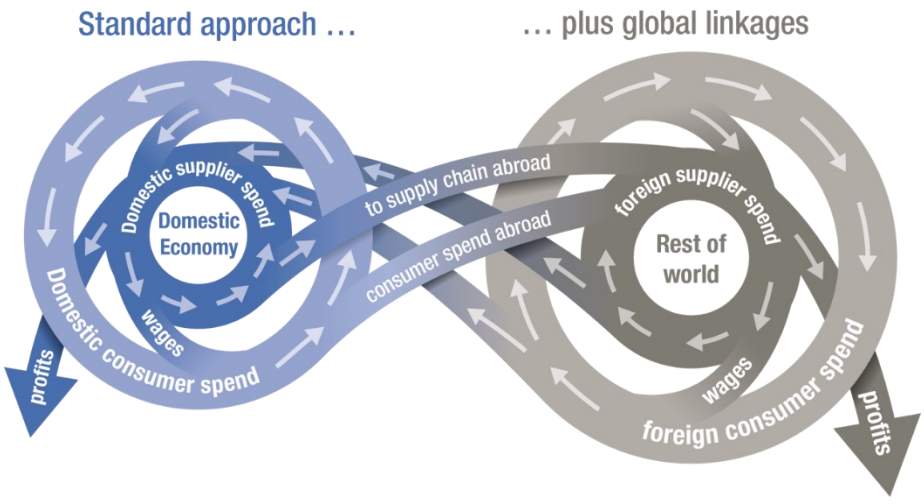


Figure 27 Our bespoke Global Economic Impact Model captures spending within countries and across their borders

The input-output table that is the backbone of the Global Sustainability Model is based on OECD data and trade patterns, and custom input-output tables created by Oxford Economics. The resulting global

[6] United Nations, "International Standard Industrial Classification of All Economic Activities (ISIC), Rev.4", 2008

input-output framework estimates how the world's major economies and industries interact with each other in a single year.

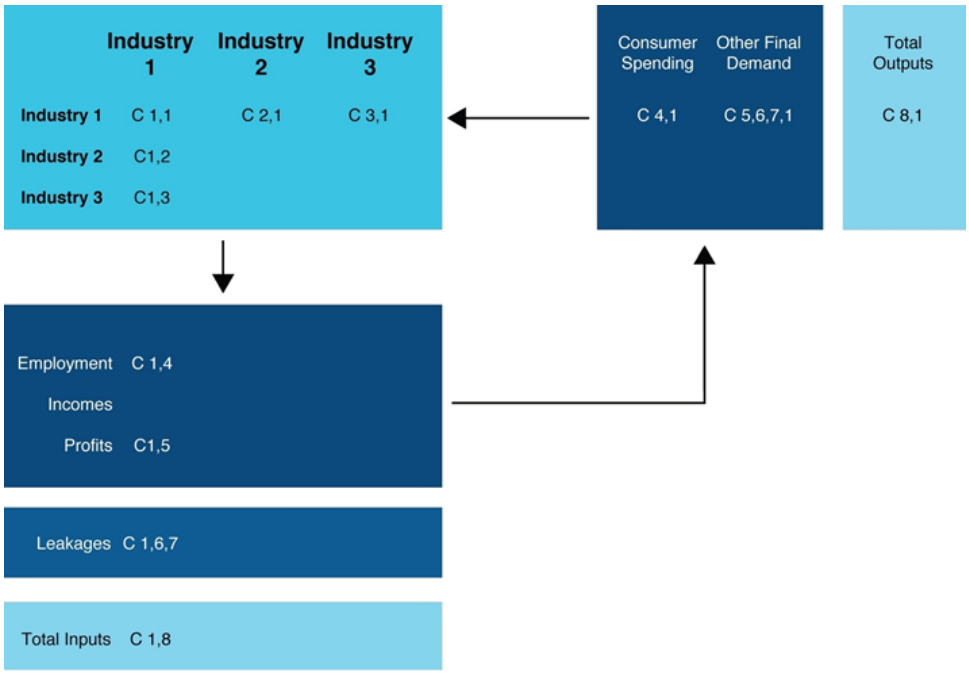


Figure 28: Stylistic representation of an input-output table

In addition, so that we can estimate wage-induced channel of impacts, we have added rows for compensation of employees to our global input-output table. Where possible these data are sourced from the OECD, and elsewhere they consist of estimates produced by Oxford Economics.

To model the wage-induced impacts as accurately as possible, we also adjust the Household Fixed Consumption Expenditure (HHFCE) columns. The adjustments take into account households' propensity to spend and save in each country. They do so by multiplying the HHFCE columns by the ratio of household final consumption expenditure divided by household income from the sum of employee compensation, property income, social and other transfers, and company profits, as reported by the United Nations.[7]

From the adjusted input-output tables, Oxford Economics generates Type 1 and Type 2 Leontief Inverse matrices. When combined with a final demand spending shock, these provide an estimate of the sum of the internal and external production activity—across each geography and 36 industries—that is required to satisfy that final demand. In other words, the model estimates all the economic activity that is stimulated by, say, a business's supply chain purchase or a consumer spending money at a retail outlet.

[7] United Nations Statistics Division, "National Accounts Official Country Data", data downloaded November 2019. Data pertains to 1999-2017 depending on the country.

Once we have estimated the output that is associated with a particular spend impetus, we estimate gross value added. This is done by multiplying the model's estimate of output by gross value added to output ratios that are specific to each country and industry.

Finally, we convert our GVA estimates to employment estimates. To do so, we divide our GVA estimates by estimates and/or forecasts of the ratio of gross value added to workers in each country and industry.

The Global Sustainability Model for Terrae Novae

We used the GSM to assess Terrae Novae's economic footprint across the 22 ESA Member States, plus Bulgaria, Canada, Croatia, Cyprus, Latvia, Lithuania, Malta, Slovenia, Slovakia and the United States for the years 2022-2030. This time period is selected because it corresponds to the entire period of Terrae Novae Period 3 funding levels being invested and generating impacts in the economy. If all spending was in a single year, the results would remain generally proportional to the investment for the single year, affected by al assumptions for that given year (productivity rates, taxes, supply and demand prices, etc.).

The GSM leverages the knowledge and techniques we have developed in mapping economic relationships between countries and industries across the world. The model includes information about global supply chains that are typically excluded from standard economic impact assessments, enabling comprehensive measurement of economic footprints.

The ability to trace how global supply chains stimulate activity in different economies is essential for developing a comprehensive measure of Terrae Novae's footprint in any given country. For example, it enables us to trace how the Italian spending from Terrae Novae with suppliers in France can stimulate supply chains that pass in and out of France further up the value chain. Consequently, the GSM provides a comprehensive measure of the Terrae Novae programme's total impact on a given economy.

We assess the economic contribution of the programme across the following three channels:

- **Direct impact**: relates to Terrae Novae's own activities, encompassing the economic activity, taxes and employment directly supported by the projects within the programme;
- **Indirect (supply chain) impact**: encapsulates the economic activity, taxes and employment supported along supply chains. This includes multiple rounds of expenditure as suppliers buy in goods and services from other companies to enable their sales to the direct contractor, etc.;[8]
- **Induced (consumption) impact**: The economic activity sustained as workers at companies included in the direct impact and in their supply chains spend their wages in the wider economy. This provides most support to primarily consumer facing industries such as retail, restaurants, consumer goods manufacturers, and providers of recreational and leisure services.

Methodological details and assumptions

[8] Note: this channel includes the impact of the programme's capital investments, such as new facilities and IT equipment, as well as that of its day-to-day purchases.

A. Gross output

To estimate direct, indirect, and induced impacts, we first needed the gross output of the Terrae Novae project in each of the 32 countries in the study. ESA provided data on the funding of different activities which was taken as our gross output measure in the economic impact models.

In some cases, the expected recipient country was uncertain. In such cases, funding allocations were proportionately distributed according to the profile of all other funding.

While recognising that a lot of the economic activity funded will occur over extended time periods, we have focused on activities funded during 2023 to 2025 and have split the funding evenly across the three-year period.

The EL3 activity involves uncertainty over the final engine configuration and consortium delivering the work. As such, we used the average of the four alternative scenarios based on ESA inputs for our economic model to ensure there is no bias towards any one of the four alternatives.

B. Direct Gross Value-Added

We used Eurostat and our global input-output table (derived from OECD data) to calculate country and sector specific ratios of GVA as a share of output. Where possible, we used more granular US data to adjust our broader sector data to more detailed and representative sub-sectors.

Direct GVA is comprised of producers' gross operating surplus (referred to as profitability hereafter), Compensation of Employees (CoE) and taxes on production. We introduced a profitability threshold of 8% in line with ESA's funding requirements. Any profitability above 8% was distributed across CoE and procurement spending resulting in adjusted GVA and procurement ratios.

To estimate each activity's direct GVA, we applied the adjusted country and sector specific GVA ratios to the funding data.

C. Procurement

We used Eurostat and our global input-output table (derived from OECD data) to calculate country and sector specific ratios of intermediate consumption as a share of output. Where possible, we used more granular US data to adjust our broader data to more detailed and relevant sub-sectors.

We then applied the adjusted country and sector specific intermediate consumption ratios to the funding data and used these estimates to calculate Terrae Novae's indirect impacts.

D. Direct employment

We used Eurostat and IMPLAN to collect information and estimate 2021 labour productivity for the most relevant sectors in each country. We then divided our direct GVA estimates by our productivity estimates to obtain direct employment figures.

E. Compensation of Employees

We used Eurostat and our Global IO table (derived from OECD data) to calculate country and sector specific ratios of CoE as a share of output. Where possible, we used more granular US data to adjust our broader data to more detailed and relevant sub-sectors.

To arrive at each activity's CoE, we applied each country and sector's CoE to gross output ratio to the funding data and then used these wage estimates to calculate Terrae Novae activities' induced impacts.

F. Taxes

For each Terrae Novae activity, country and year, the GSM estimated the indirect and induced tax revenues and we used those to calculate the ratio of indirect and induced tax revenue as a share of the indirect and induced GVA contribution for each country.

We then applied this ratio to the direct GVA to estimate direct tax revenues.

Annex 2 – List of indicators

Task 2 – Continuation activities

Economic indicators

- Additional sales (if any)
- Increased product portfolio
- Long-term partnerships
- Gross value-Added (GVA)
- Jobs supported by the project
- Jobs supported by additional sales
- Involvement of SMEs

Strategic indicators

- Market share increase
- Access to new geographical markets
- Access to new vertical markets
- Cost competitiveness
- First mover advantage
- Heritage from international projects
- European non dependence

Technological indicators

- Efficiency gains
- Technological advancement (TRL)
- Advanced technical expertise of staff
- Technological transfers
- Intellectual property

Societal indicators

- Societal value creation
- Environmental value creation
- Scientific knowledge production
- Inspiration and motivation
- Public recognition

Scientific indicators

- Scientific value generation
- Ability to produce new scientific advances
- Number of publications

Task 3 – Technology development

Economic indicators

- Additional sales (if any)
- Increased product portfolio
- Long-term partnerships
- Jobs supported by the project
- Jobs supported by additional sales
- Involvement of SMEs

Strategic indicators

- Access to new markets
- Cost competitiveness / Cost savings
- First mover advantage
- European non-dependence

Technological indicators

- Efficiency gains
- Technological advancement
- Advance technical expertise
- Technological transfers
- Intellectual property

Societal indicators

- Societal value creation
- Environmental value creation
- Ability for the project to inspire the public
- Media attention due to the project

Scientific indicators

- Scientific value generation
- Ability to produce new scientific advances
- Number of publications

Task 4 – Long term strategic scenarios

Economic indicators

- Additional sales (if any)
- Involvement of SMEs

Strategic indicators

- First Mover advantage
- Technological leadership
- European non-dependence
- International partnerships
- Heritage from past projects

Technological indicators

- Mastering capabilities for more ambitious missions
- Technological transfers: spin-in and spin-out

Societal indicators

- Societal value creation
- Inspiration and awareness

Scientific indicators

- Scientific knowledge creation