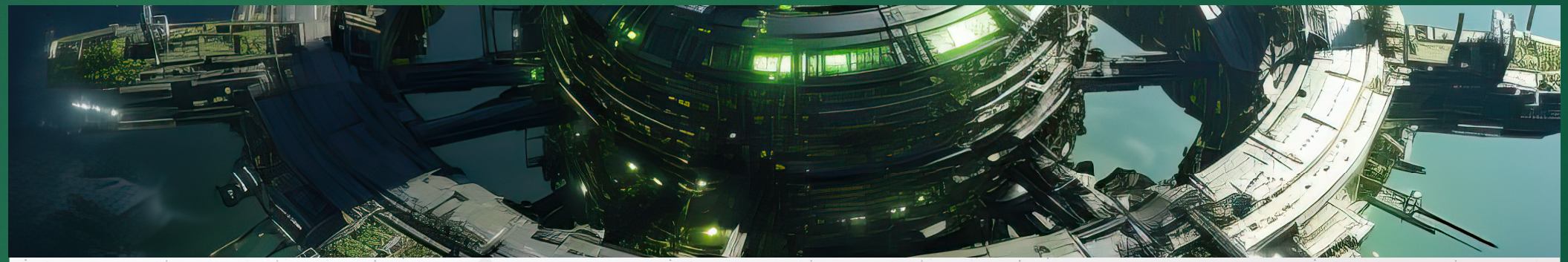


Economically Sustainable Industries in Space – Future Visions and Genesis

Erik Kulu

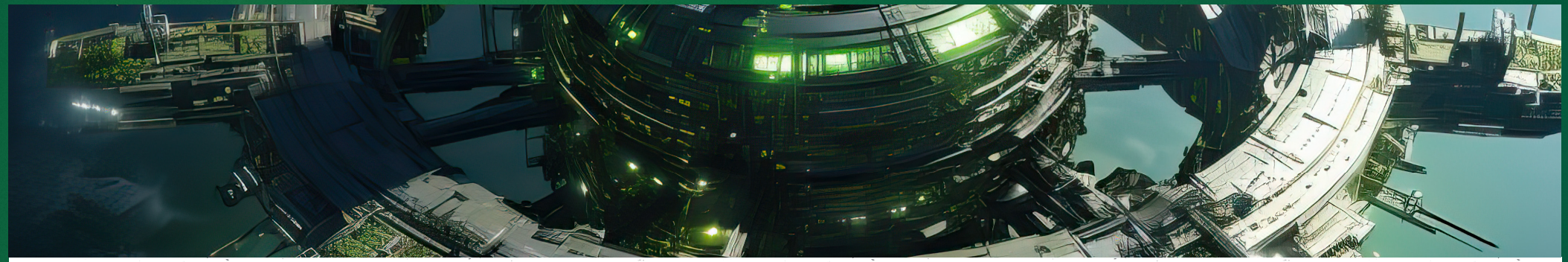
Space Resources Week 2024

2024-03-26

Factories in Space

Factories in Space (factories-in-space.com)

- First public database of commercial entities in the emerging in-space economy, space resources, and microgravity manufacturing fields.
- The directory was started in 2018 and currently has over 920 entries.
- New in-space economy is the new extraterrestrial space industries.
  - In-space economy means generating revenue in space, using assets in space to provide services to other assets in orbit or beyond.
  - Alternative names: space-based economy, space-for-space, on-orbit economy, LEO economy, etc. Includes: space resources, cislunar, Moon and Mars economies.
  - Predicted to drive the $1 trillion space economy, but currently most have small or no (commercial) revenues.
- This presentation is about the forefront of in-space economy, going into the nascent beginnings and future visions.
- By examining early milestones and emerging trends, we envision a future where orbital factories hum with activity, uniting space solar power, in-space manufacturing, and resource utilization.



In-Space Economy

The new extraterrestrial space industries.

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In-Space Economy Classification

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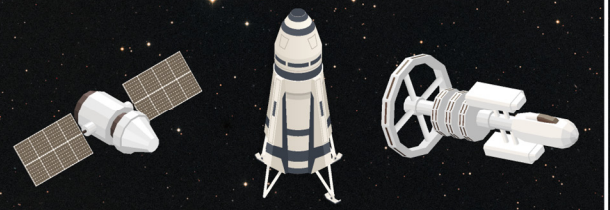
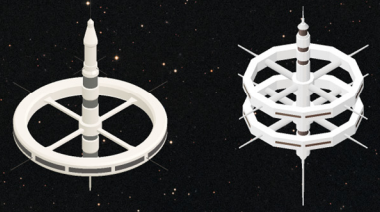
Human Spaceflight & Landers



Cargo Transportation & Landers

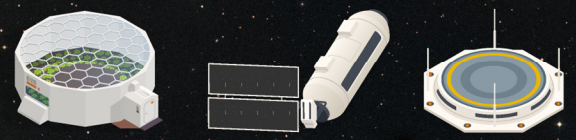
Surface Spacecraft & Mobility

Space Stations & Habitats



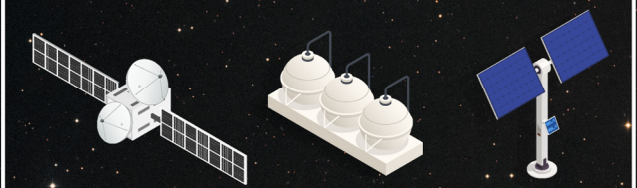
Surface Habitats & Structures

In-Space Manufacturing

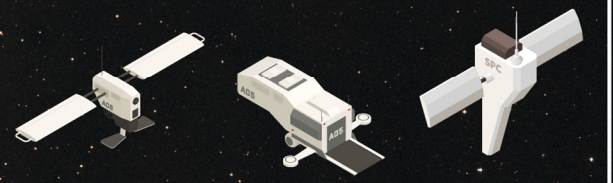


Space Resources

Space Utilities



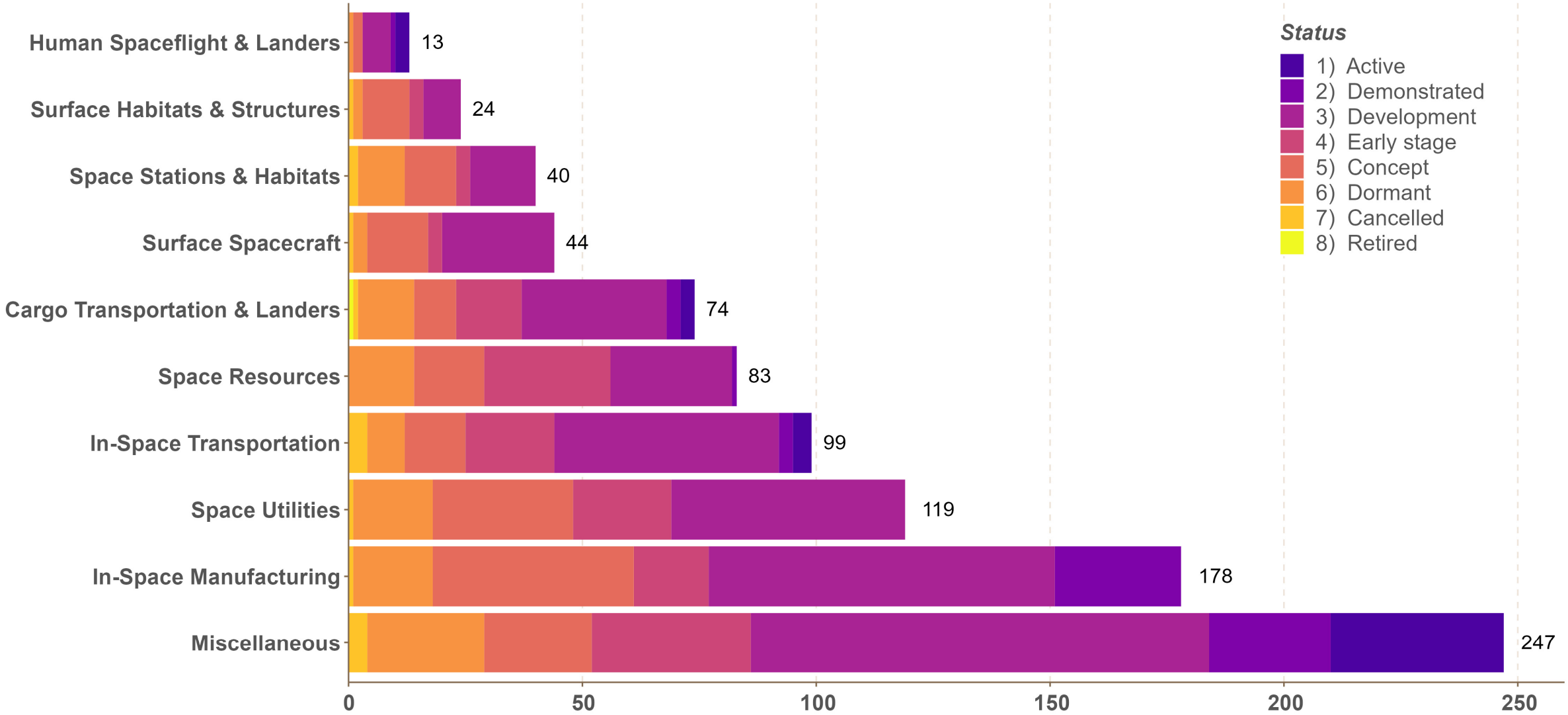
In-Space Transportation

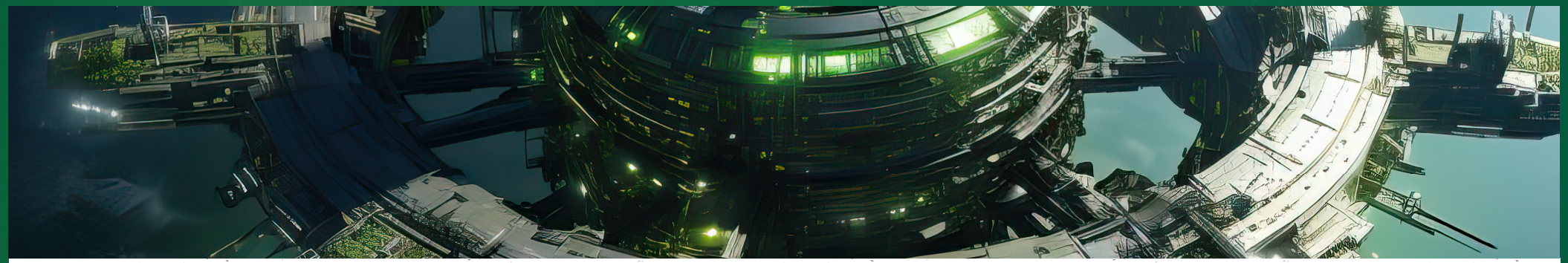


Miscellaneous

Classification with Status of In-Space Economy Entities

Number of entries in the FactoriesInSpace.com database as of 2024-03-01





Visions

Coherent visions about in-space economy in 2050 with bustling multidisciplinary activities around Moon, Mars, and asteroids.

Factories in Space

In-Space Economy

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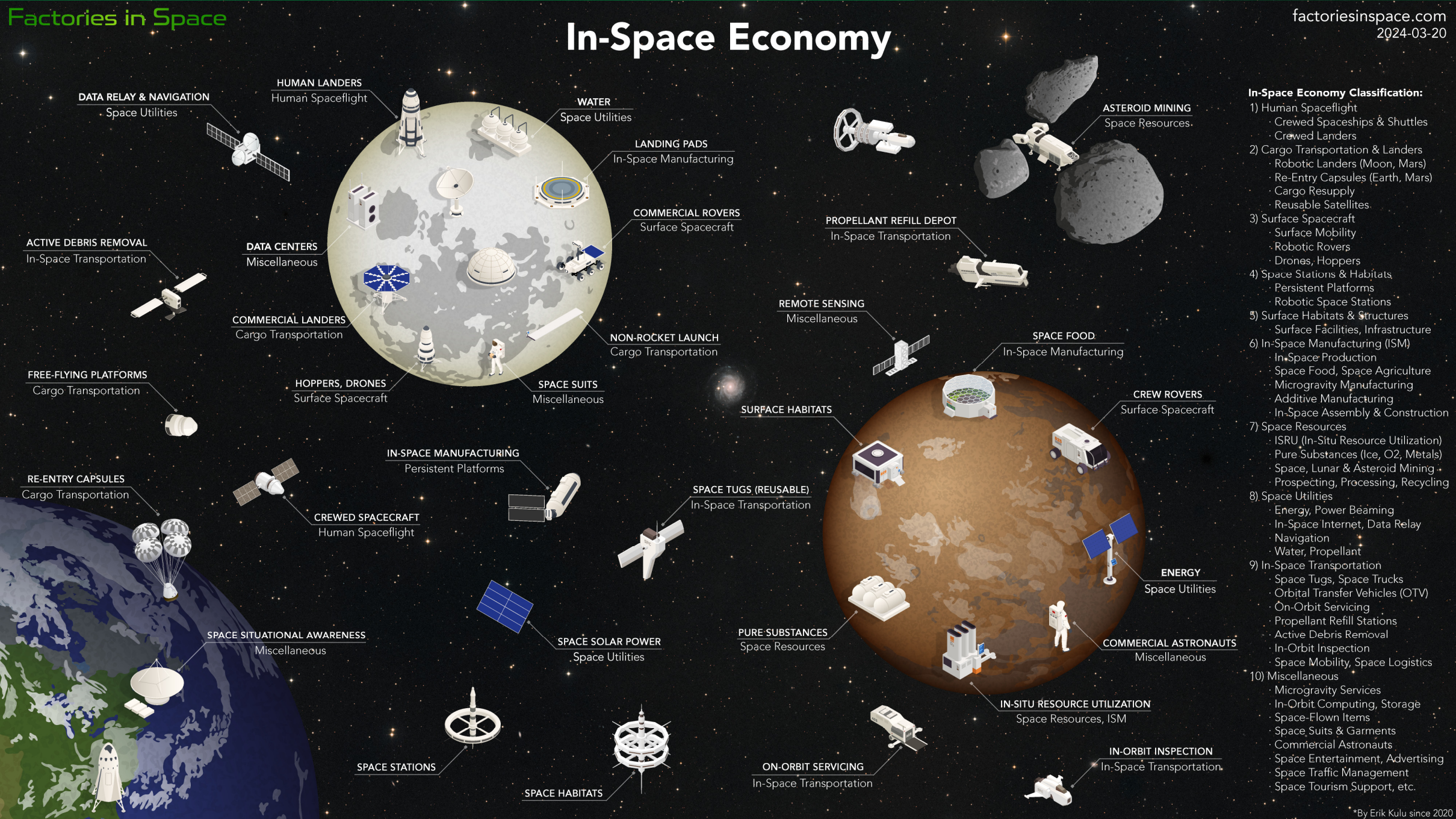
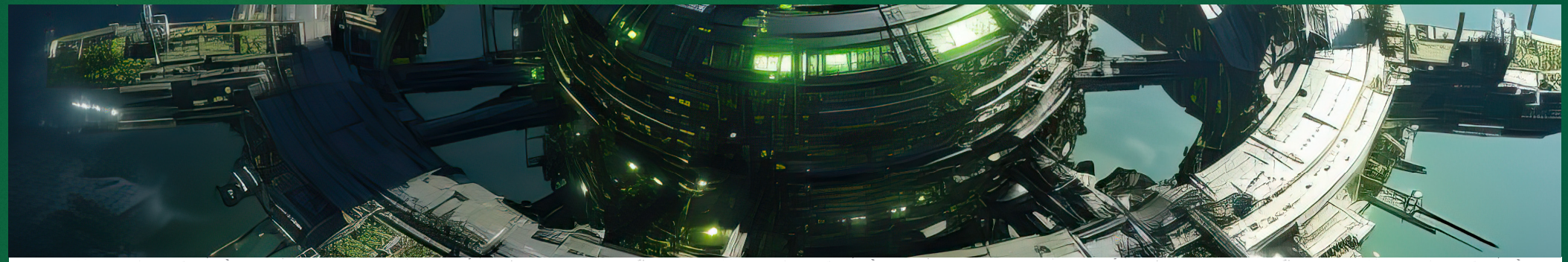


In-Space Economy Classification:

1) Human Spaceflight
   - Crewed Spaceships & Shuttles
   - Crewed Landers
2) Cargo Transportation & Landers
   - Robotic Landers (Moon, Mars)
   - Re-Entry Capsules (Earth, Mars)
   - Cargo Resupply
   - Reusable Satellites
3) Surface Spacecraft
   - Surface Mobility
   - Robotic Rovers
   - Drones, Hoppers
4) Space Stations & Habitats
   - Persistent Platforms
   - Robotic Space Stations
5) Surface Habitats & Structures
   - Surface Facilities, Infrastructure
6) In-Space Manufacturing (ISM)
   - In-Space Production
   - Space Food, Space Agriculture
   - Microgravity Manufacturing
   - Additive Manufacturing
   - In-Space Assembly & Construction
7) Space Resources
   - ISRU (In-Situ Resource Utilization)
   - Pure Substances (Ice, O2, Metals)
   - Space, Lunar & Asteroid Mining
   - Prospecting, Processing, Recycling
8) Space Utilities
   - Energy, Power Beaming
   - In-Space Internet, Data Relay
   - Navigation
   - Water, Propellant
9) In-Space Transportation
   - Space Tugs, Space Trucks
   - Orbital Transfer Vehicles (OTV)
   - On-Orbit Servicing
   - Propellant Refill Stations
   - Active Debris Removal
   - In-Orbit Inspection
   - Space Mobility, Space Logistics
10) Miscellaneous
   - Microgravity Services
   - In-Orbit Computing, Storage
   - Space-Flown Items
   - Space Suits & Garments
   - Commercial Astronauts
   - Space Entertainment, Advertising
   - Space Traffic Management
   - Space Tourism Support, etc.

*By Erik Kulu since 2020



Why & Challenges

The dawn of sustainable in-space industries beckons, promising a future where endeavors in space are both pioneering and economically viable.

However, to achieve that, humanity needs to find new economic drivers for spaceflight.

Space Helps to Solve Earth's Problems

Humankind settling space will help to solve some of the biggest problems here:

1. It will create the technologies.
2. It will change us (Overview Effect, common positive goals, zero-sum bias etc).

Some example solutions:

1. Abundant cheap green energy would make carbon capture, vertical farming and water desalination commercially sustainable.
2. Moving most heavy manufacturing to space, where there is no life to harm and already full of planet formation debris, would decrease environmental impact.

Need New Drivers to go to Space

- Need new economic drivers for spaceflight.
  - National budgets will not increase much.
  - Something bigger than industries of communications, remote sensing, launch and research.
  - This is the missing piece to speed up development for the exciting Star Trek-like future.
- Not many "picks & shovels" will be sold until we find "gold" in space or the "killer app".
- Railways were built where it made sense, because of people, activities and resources.
- Profit may have a bad reputation in some circles, but it enables a lot of R&D.

"If we can establish a Mars colony, we can almost certainly colonize the whole Solar System, because we'll have created a strong economic forcing function for the improvement of space travel."

Elon Musk, Aeon, Sept 2014

"Most important would be the construction of factories that could make use of the special properties of space - to manufacture objects that could be difficult or impossible to manufacture on Earth.

Asimov predictions for 2019 in 1983 in The Stare

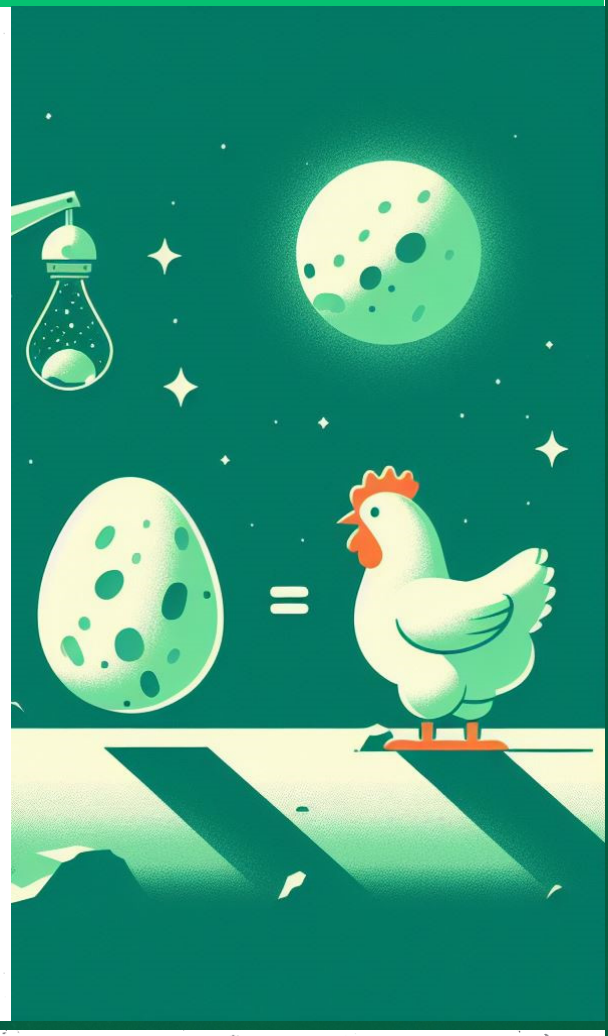
Space Forecasts & Economic Sustainability

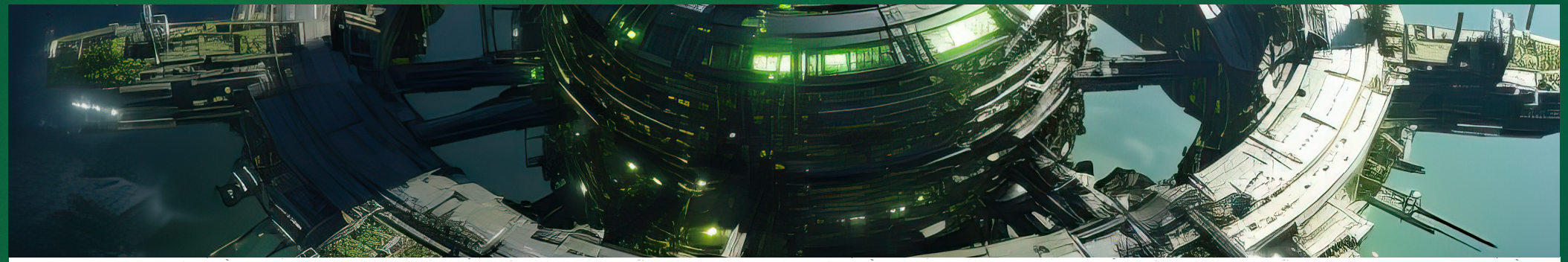
- Space has an optimistic forecast problems. Or alternatively very pessimistic, but rarely realistic.
- Space economy has been estimated at $400-500 billion annually and predicted to grow to $1T by 2040.
  - However, the "real space" of launch, satellite manufacturing, telecommunications and remote sensing etc., are only approximately tens of billions each, broadly up to about $100 billion in yearly total. [see e.g., Pierre Lionnet]
  - Emerging markets like satellite servicing, lunar landers, space mining are a fraction of that.
- **In-Space Economy**
  - Space mining market was $0.49 billion in 2017 and expected $2.84B by 2025. (Markets and Markets, 2018 Oct)
  - Euroconsult predicts on-orbit services will generate over $4B in 2031 in "Space Logistics Markets, 2nd Ed" from 2023.
  - NSR's In-Orbit Services - 2nd Ed from 2019 forecast $4.5B in cumulative revenues by 2028.
- **In-Space Manufacturing**
  - 1987 - Perfect Latex Spheres: Estimates that market for 100-micron spheres could be $200-300M annually.[2]
  - 1996 – Semiconductors: "Independent projections for electronic materials have estimated a long-term, space-based economic contribution of between $6 billion (Rockwell International) and $31 billion annually."[1]
  - 1998 - ZBLAN: News in 1998 estimated ZBLAN commercial potential at $2.5 billion.[3]

[1] Technology Thresholds for Microgravity: Status and Prospects, 1996, D.A. Noever
[2] Harry L. Shipman. Space 2000: Meeting the Challenge of a New Era. 1987.
[3] Dave Dooling. ZBLAN Has Great Commercial Potential. February 1998.
[4] https://www.marketsandmarkets.com/Market-Reports/space-mining-market-129545886.html

“Chicken-and-Egg” Problem

- An example of space “chicken-and-egg” dilemma:
  1. Even if an asteroid mining company can raise billions to make it happen at scale, meaningful customers would likely take years to emerge.
  2. However, without raw space resources availability, the industry and supply chain will not also develop. Financially stable customers are still missing.
- Completely new markets usually grow (very) slowly and are difficult to predict. Multi-faceted competition too.
- Thus, more gradual approaches are required, often involving existing (large) markets, that could be serviced from space in new better ways.





First Steps

Emerging space industries, which plausibly already are on a path to overcome these challenges.

Hype Cycle of In-Space Economy

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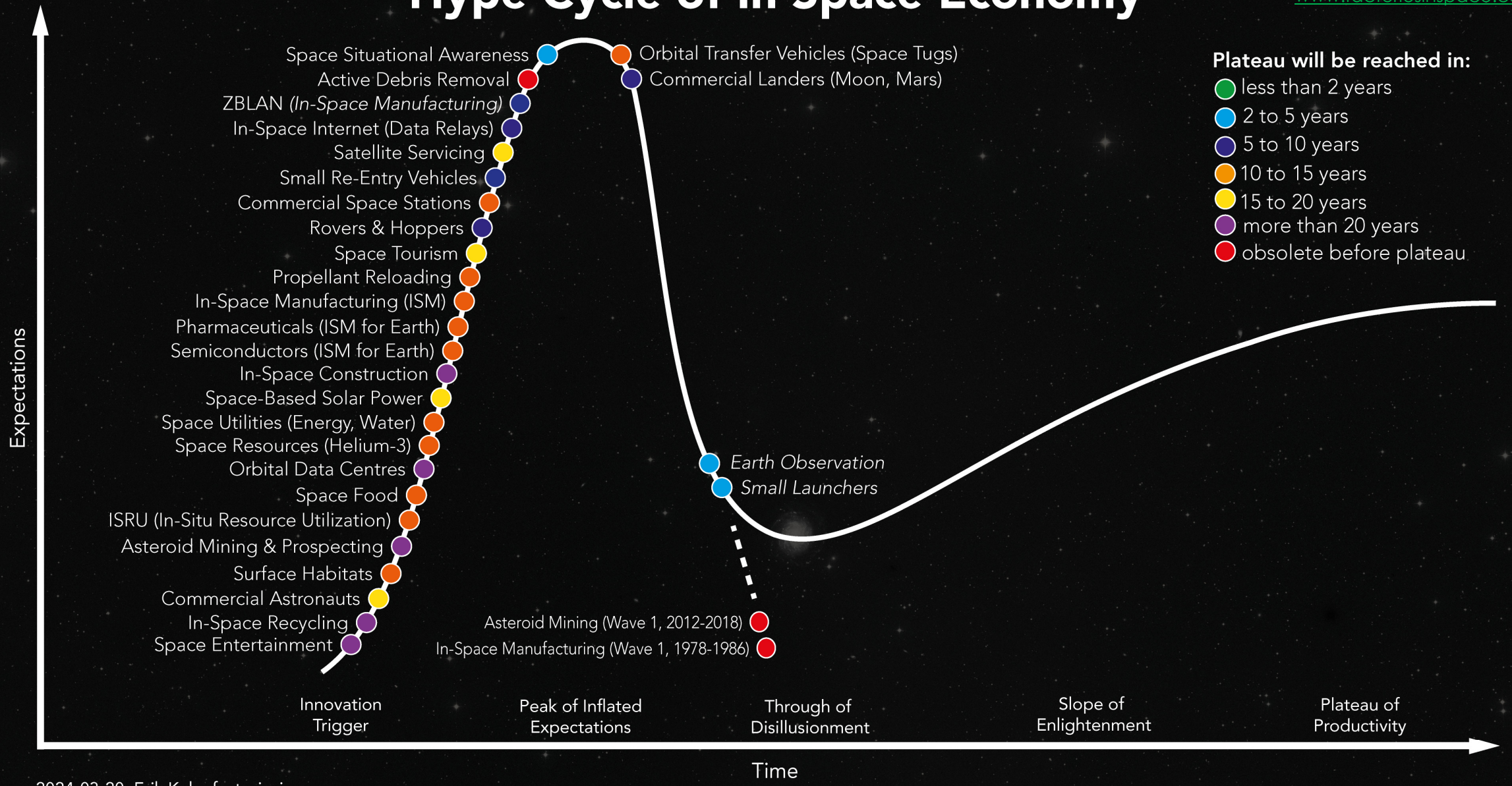

2024-03-20, Erik Kulu, factoriesinspace.com
Based on Gartner Hype Cycle methodology and inspired by Aravind's space hype charts.

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Market Size vs Timeline of In-Space Economy

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Large market

Small market

Space Solar Power

Market: electricity on Earth
Technology: engineering-problem
Dependency: Starship cost & cadence
Challenge: capital needs, MVP revenue

Semiconductors (ISM)

Description: space-grown crystals
Market: Earth
Technology: technoeconomic
Dependency: new processes
Challenge: scale, unit economics

Landers

Market: in-space, transportation
Technology: spacecraft with propulsion
Dependency: launch costs
Challenge: unit economics, large landers

Satellite Servicing

Market: in-space, transportation, servicing
Technology: spacecraft with propulsion
Dependency: launch costs
Challenge: unit economics, chicken-and-egg

Space Tugs

Market: in-space, transportation, servicing
Technology: spacecraft with propulsion
Dependency: launch costs
Challenge: unit economics

Space Stations

Market: tourism, manufacturing, research
Technology: engineering-problem
Dependency: launch costs
Challenge: revenue sources

Surface Habitats

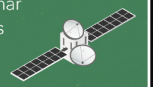
Market: in-space, transportation, servicing
Dependency: landers, launch costs
Challenge: market demand

Surface Mobility

Market: surface transportation, ISRU
Technology: rovers, hoppers
Dependency: lunar landers
Challenge: lunar night survival

In-Space Internet

Market: satellites, stations, lunar
Technology: intersatellite links
Dependency: launch costs
Challenge: chicken-and-egg



Small Re-Entry Vehicles

Market: space-made products for Earth
Technology: engineering-problem
Dependency: research funding
Challenge: market demand, unit economics
Competition: Dragon, Starship, space stations

In-Space Construction

Market: large structures, space solar power
Technology: assembly, manufacturing, ISRU
Dependency: space resources, launch
Challenge: market demand

Space & Lunar Mining

Market: in-space manufacturing
Technology: mining, beneficiation
Dependency: launch costs
Challenge: power, market demand

Active Debris Removal

Market: satellites, space debris
Technology: spacecraft with propulsion
Dependency: launch costs, regulations
Challenge: market demand, economics

Existing market

Nearby market

Distant market

Factories in Space

Silk Road & Spice Trade

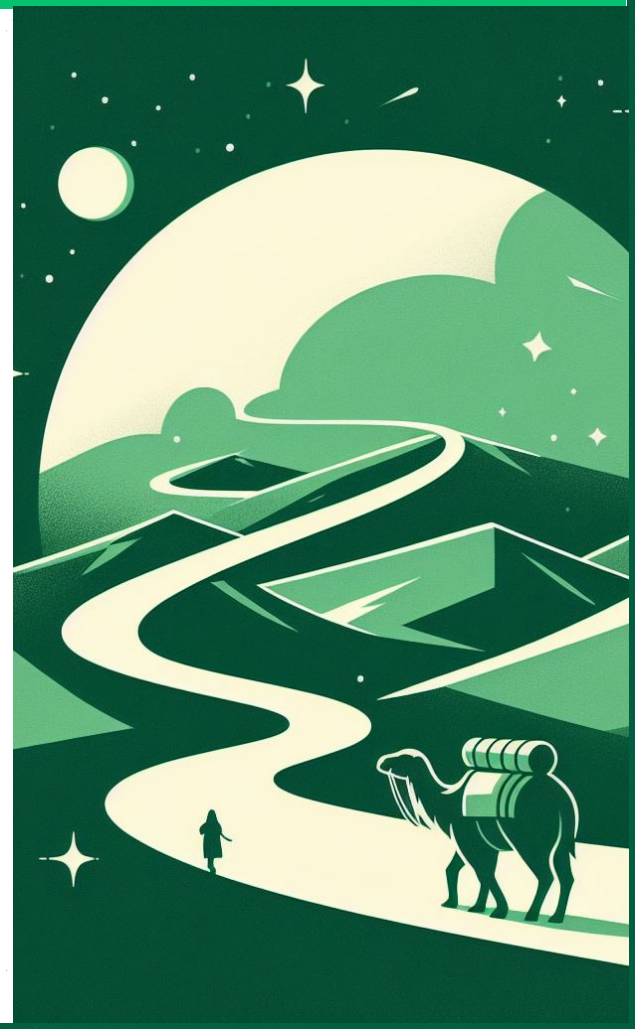
Silk Road and Spice Trade :

- Spices, coffee, tea, etc.
- Mostly luxury and novelty products, not needed for survival or industrial use.

New ship-based routes changed the trade:

- Ships filled with other cargo for the first leg.
- Created demand for outposts, resupply, better ships, cafes etc.
- Broadly kickstarted the world economy.

Will an ethical version of “spice trade” happen for/in space? Chocolate, beer, etc.?



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Factories in Space

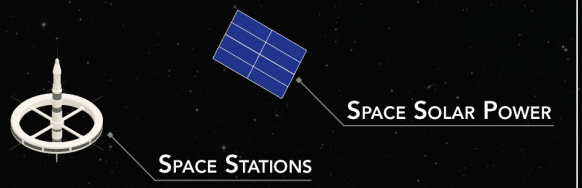
Flywheel Effect / Kickstarter

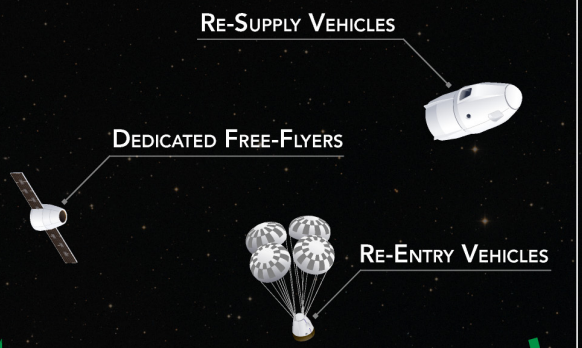
After finding the "killer app" or "space gold" for In Space Manufacturing and In Space Economy

SHORT-TERM

1. Launching parts and raw materials from Earth.
2. In case of in-space manufacturing, using the ISS or freeflyers to make products.
3. Serving existing terrestrial markets.

- Likely activity: Microgravity manufacturing or space solar power.
- Assumption: New revenue and profit sources in space
- Stimulates: cheaper launch, recycling, space resources,
- Customer for: freeflyers, space stations, in-space mobility, in-space services





MATERIALS: from Earth

MARKET: on Earth

MEDIUM-TERM

1. Recurring profitable activities in space have been economically proven.
2. Creating a potential market and becoming the first customer for many other in-space economy services if the price is lower.
3. First commercial steps towards using space resources and space utilities.
4. In case of in-space manufacturing, activities are moved to larger (dedicated) space stations or persistent platforms where the equipment stays in orbit.
5. Stimulates faster/cheaper services and economies of scale starts to lower costs.

MATERIALS: some from space

MARKET: some in space

MATERIALS: most from Earth, some from space

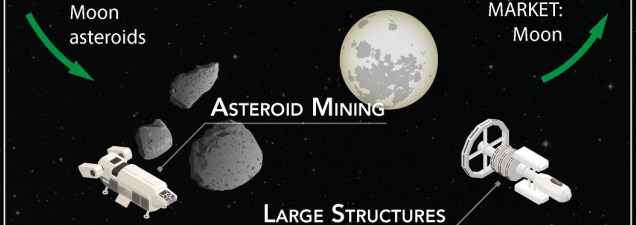
MARKET: most on Earth, some in space

LONG-TERM

1. Drive towards lower costs creates competition and market for better solutions.
2. Whole ecosystems and supply chains are now in space.
3. Lower costs bring out the elastisticity in markets making further commercial activities feasible.
4. The new technologies also improve space exploration and space settlement, while enabling even more industries to be moved off-Earth.

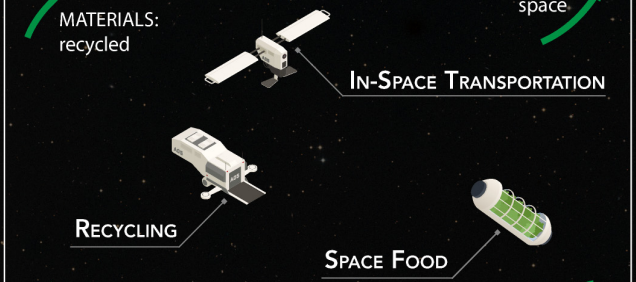
MATERIALS: Moon asteroids

MARKET: Moon



MATERIALS: recycled

MARKET: space



MATERIALS: some from Earth, most from space

MARKET: some on Earth, some in space

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Roadmap & Timeline
of In-Space Economy & Manufacturing

Factories in Space

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Conclusions

Possible paths?

1. Slow growth path – primarily government funding and buying COTS services (resupply, space station, landers, etc.), with slowly increasing B2B activities on the side. [see e.g., Philip Metzger]
2. Flywheel path – discovering the "killer app" or "space gold".

Flywheel industries?

- Novelty/luxury products made in space?
- Unique/advanced product/material made in space?
- Helium-3? Not a blocker for fusion, but other uses?
- Space solar power? Energy market is huge and solves problems.

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