Shipping costs for Earth, Moon & Mars commerce: A tool to identify worthy space businesses.

@eswak 25/08/2019

The "Starship architecture", or using numerous times the same reusable vehicle in LEO for refueling the main payload-bearing ship before departure to deep space, is really a game-changing paradigm. A lot of ideas for industrializing space are actually challenged by the decrease in costs permitted by such architecture. It also has an interesting step behavior, where thresholds of Delta-Vs increase the number of required launches one by one. This has the effect of giving the same price to destinations that have different Delta-Vs, but fall in the same bucket of number of refuel missions required. If you don't share the same optimism as me regarding cost per launch, hopefully this chart can still help you, as I tried to include the number of launches for each case, so you can make the computations yourself and get the updated numbers. In any case, this chart should demonstrate the benefit of such launch architecture.

Assumptions for SpaceX Starship* (blue lines):

* This won't be the cost when Starship releases, but when it starts to be regularly used, and launches almost every week. It is an expected price for a market standard in the 2020s,-2030s. Plans for space settlements and private space economies should build upon these assumptions to be sustainable.

- 30M$ per launch (30 million dollars)
- 150 tonnes payload max.
- 1100 tonnes of propellant max.
- 85 tonnes dry mass
- 380s specific impulse
- 3.8 mixture ratio

Assumptions for LVOHV* (pink lines):

* Large Vacuum-Optimized Hydrolox Vehicle (an hypothetical hydrolox Starship-like vehicle that stays in space). Starship can't refuel methane on the Moon, because there is no carbon there. So the LVOHV is a theoretical spacecraft that make maximum use of Moon-derived fuels, LOX/LH2. It is a required interface to make the lunar surface & ISRU economy capable of addressing other markets than the lunar surface.

- 30M$ per launch (30 million dollars)
- 250 tonnes payload (operates in vacuum, no fairing, so virtually unlimited)
- 1100 tonnes of propellant max.
- 130 tonnes dry mass (hydrogen...)
- 440s specific impulse
- 6.0 mixture ratio

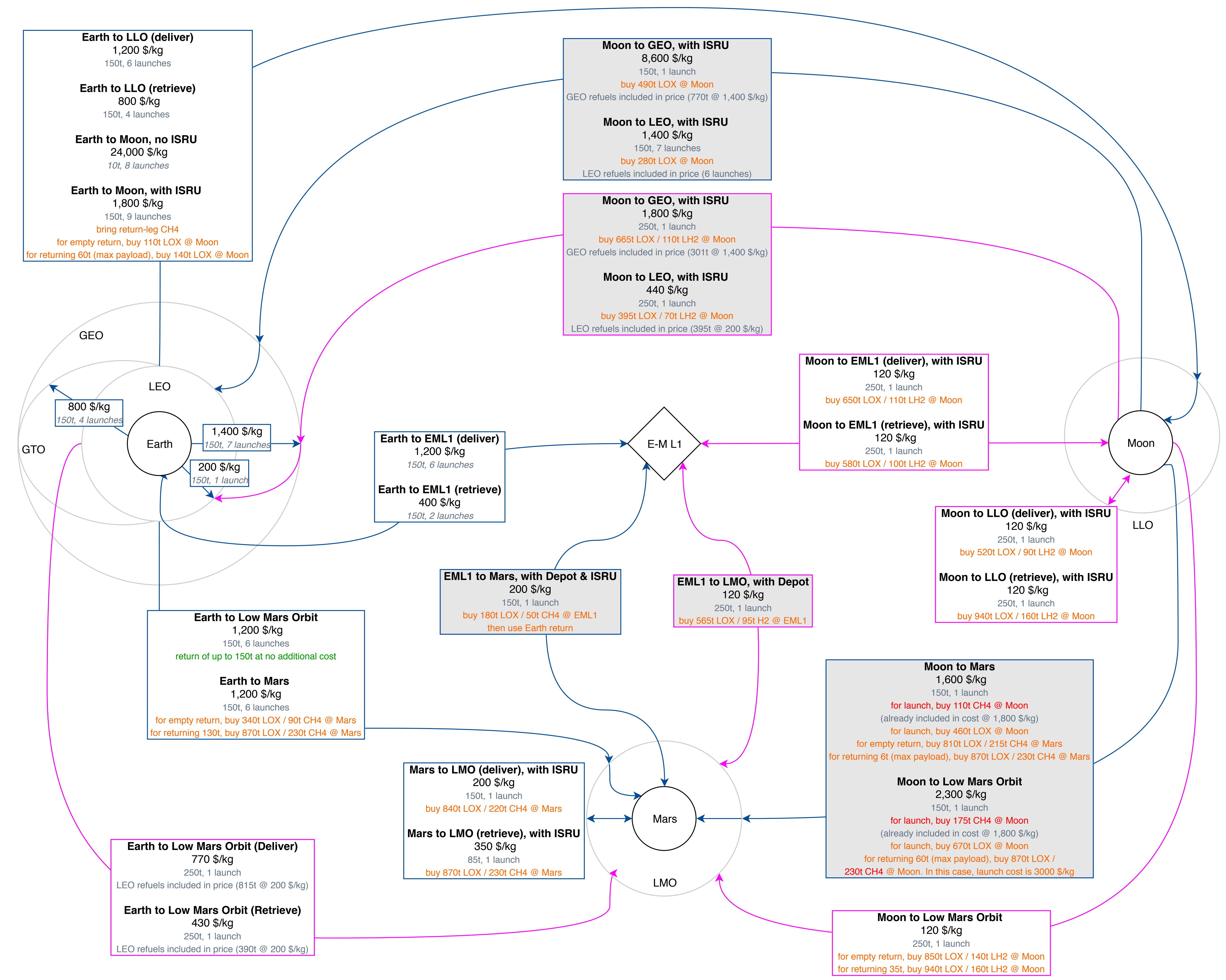
Refuels from space-made propellant are in orange.

Delta-V from http://i.imgur.com/WGOy3qT.png
It's not perfect, but it's sufficient for these first-level approximations and understand the big picture.

General Assumptions:
- Trajectories that can aerobrake do so.
- Full reusability is considered, so return trips are mandatory. No one-ways. They are ok for setting up offworld settlements, but not for commerce.
- ISRU propellant price are not accounted*
- Return trips are not charged
- No maintenance costs accounted (it's included in the launch cost)

* Because these ISRU prices are not accounted, you can also use this map to understand the value of propellant at different places, and compute various shipping costs at various propellant pricings. For instance, see the "Selling LOX on the Moon" black box.

TLDR / Warning: the costs are the minimum cost achievable, if ISRU refueling is free and if the vehicles are used to full capacity. Take time to read the black boxes to make sure you read the numbers properly.



GEO/LEO Servicing

Would a Moon or Mars economy help support LEO and GEO activities?

Starting from Earth for these activities is more advantageous than starting from anywhere else, even if ISRU propellant were free. So it's better to start from Earth for these activities, whether with or not with a LEO station to support it.

Asteroid Mining

Can we mine asteroids for profit on Earth?

From LEO, the Delta-V to reach asteroids is around the same as to reach LLO (~4km/s), so you can refer to these numbers. What we mine should have a value above 800$/kg to cover for the transport costs, accounting only for the transport cost and nothing for the extraction process.

Selling LOX on the Moon

Can we generate profits with ISRU?

On the Moon, you could start by selling LOX at 25 M$/t. The assumed Starship architecture with ISRU delivers 150 tonnes for 1.8*150 ~= 250 M$. If SpaceX buys moon-made LOX at 25 M$/t, the 110 tonnes of LOX would cost 2750 M$, for a total mission cost of 3000M$, or 20 M$/t, still lower than the option without ISRU. And they would also be able to bring larger monolithic payloads (above 10 tonnes).

LOX is a good first choice for ISRU because it doesn't require to drive down frozen craters right from the start.

Growing food on Mars

Can we generate profits with Agriculture?

A person needs around 620g of dry food per day. At import prices, that would be around 2400$/day. More or less 70m² of crops would be needed to produce the food for one person, for a full diet. Assuming a crop cycle of 100 days, that is a 240k$ budget for building a greenhouse that can function for 100 days, or 3430$/m². The budget would probably be higher, because settlers will prefer fresh food, and also having a resupply ship has an indirect cost for the Mars settlement: they need to refuel it, and this requires a lot of power, that could be better used.

Selling LOX/CH4 on Mars

Can we generate profits with propellant manufacturing?

With these big reusable spacecrafts, there is no return from Mars possible without local refueling. If a launch costs 30 M$, and they expect to recover their investment after 15 flights, we can estimate the cost of a Starship to 450 M$. Returning the spacecraft by producing 430t of propellant can then be worth 450M$. The price of Martian propellant can therefore be estimated to ~1 M$/t. The charged price to deliver to Mars is then 1.2 + 430*1/150 = 4.06 M$/t.

Fuel depots in cislunar space to fuel the missions to Mars

Does it make sense to refuel in cislunar space to send missions to Mars?

If the propellant price at the EML1 space depot is equal to the cost to deliver propellant to it, i.e. 1.2 M$/t, we can compute the mission costs for delivering to Mars by refuelling at the depot.

Missions to Mars surface:
Using a Starship that is already in EML1, we need to buy 230 tonnes of propellant. That will cost 230*1.2 = 276 M$. That is an additional 1.84 M$ per tonne delivered, so our total cost for delivering is 1.84 + 0.2 = 2.04 M$/tonne. It is more convenient to go directly from Earth (1.2 M$/t), than to refuel in EML1 (2.04 M$/t).

Missions to Low Mars Orbit:
Using a LVOHV that is already in EML1, we need to buy 660 tonnes of propellant for making the return trip and deliver 250 tonnes to LMO. That is an additional 660*1.2/250 = 3.17 M$/t, for a total cost of 0.12 + 3.17 = 3.29 M$/t. It is more convenient to go directly from Earth with Starships (1.2 M$/t), than to use the LVOHV refueled in EML1 (3.29 M$/t).

Moon Reusable Landers

Is there a business in operating reusable landers to shuttle between the lunar surface and orbit?

Delivering to LLO with Starship is 1.2 M$/t, and landing ("LLO retrieve") on the Moon costs 0.12 M$/t with the LVOHV. The whole process therefore costs 1.32 M$/t of payload landed on the Moon without accounting for Moon propellant price. Landing uses (940+160)/250 = 4.4t of propellant per ton landed.

The cost difference with a Starship direct delivery without ISRU is 24 M$/t - 1.32 M$/t = 22.68 M$/t. Therefore, a reusable lander company can buy the Moon propellant at a maximum of 22.68 / 4.4 = 5.15 M$/t.

But if the Moon propellant price is 5.15 M$/t, then Starship direct delivery can refuel there too. Starship with ISRU costs 1.8 M$/t. Starship direct buys 110 tonnes of LOX at 5.15 M$/t = 566 M$ for each 150 tonnes delivered (to return), adding 3.78 M$/t to the delivery cost. Therefore, Starship direct delivery can deliver on the Moon surface for 5.58 M$/t.

To match this price, the LVOHV should buy the propellant at (5.58 - 1.32)/4.4 = 0.97 M$/t. This loop iterates over and over, driving down the cost of propellant down, but there is probably a limit under which the Lunar Port won't be willing to sell propellant, so they will prefer the Starship architecture.

What if the Lunar Port is addressing the E-M L1 propellant depot market, and is capable to make profit by selling propellant at 0.267 M$/t on the lunar surface, what is the situation ?

Starship direct delivery to the lunar surface is 1.8 + (110*0.267)/150 = 2M$/t. LVOHV delivery to the lunar surface is 1.32 + (1100*0.267)/250 = 2.49M$/t. The Starship direct is a more advantageous strategy to deliver cargo to the lunar surface than using it to deliver to LLO and using a reusable lander. In fact, the crossing point for a reusable lander to be advantageous over the Starship direct architecture, is when propellant price on the Lunar surface drops below 0.13 M$/t, half the price of what the Lunar Port should achieve for its cost in order to address tje E-M L1 fuel depot market. They probably won't manage to sell for that low, so a Starship direct delivery strategy is better than opting for a reusable lander.

It is very conterintuitive, but the higher dry mass of LOX/LH2 rockets compared to LOX/CH4 makes them require larger refueling on the lunar surface, and that's what makes them less competitive. Also, fetching payloads in LLO with the LVOHV makes the first leg of the trip (ascent to LLO) consume a lot of propellant, because the propellant for landing the large payload also has to be lifted, while the Starship is on the end of its trip, just before a refueling and returning home.

Moon to Mars: Delivering to LMO

Could we export goods from the Moon to support the growth of human settlements on Mars?

Starship can deliver payloads to LMO at 1.2 M$/t. LVOHV, coming from the Moon, costs only 0.12 M$/t, but has to buy 990 tonnes of propellant. At 0.267 M$/t, fueling the LVOHV costs 264 M$. Divided by 250 tonnes delivered, that is an added cost of 1.06 M$/tonne, only 0.02 M$/tonne less than the Starship delivery. Since the goods manufactured on the Moon will probably be more expensive than the ones made on Earth, delivering to LMO from Earth using the Starship is a better architecture than delivering Moon-made elements.

E-M L1 Fuel Depot & Lunar Port

Can lunar-made propellant be cheaper to refill space depots?

We have 1.2 - 0.12 M$ = 1.08 M$/t of margin for Moon-made propellant to beat Earth-brought propellant on price, to refuel an EML1 Depot. 650+110=760t of propellant are used to deliver 250t there. So, for 250*1.08 = 270 M$, we need to extract 250+760 = 1010 tonnes of water and electrolyze/cryocool the LOX/LH2. Our Lunar Port then needs to beat a cost of 270M$/1010t = 267 $ per kg of extracted water processed to propellant to generate profits. A Lunar Port producing 1000 t/y for 15 years shouldn't cost more than 4005 M$. If you think launch costs will be twice more the assumed one (30M$), double the maximum costs.