

**Some Mass-to-Orbit Numbers I Pulled From the Internet:**

| \$/kg LEO 1970s   | \$/kg LEO 2022 | \$/kg LEO 2040 projection                           |
|---|----------------|---|
| \$10,000/kg (based on launch cost, LEO capacity of <a href="#">Saturn V</a> ) | \$1500/kg      | \$33-100/kg ( <a href="#">Citi group analysis</a> ) |

The purpose of the following paper is to analyze these results from the internet. Do they fit with our understanding of propellant and oxidizer costs? Reusable rockets are just metal or carbon fiber tanks with engines strapped to them, and at the limit, they're entirely reusable, so their already low construction cost can be amortized.

So what are the fixed and variable costs of SpaceX's Falcon? Do the construction and fuel costs agree with our \$/kg LEO numbers? And when Starship flies, what will be the costs of it, and does it agree with the 2040 projection?

Falcon 9:

- \$1B development cost (over, say, a 500 total flights) ([Aviation Week podcast interview of Musk](#))
- \$50M construction cost of a new Falcon 9, used for ~30 launches ([Aviation Week podcast interview of Musk](#))
- \$15M refurbishment cost per launch ([Aviation Week podcast interview of Musk](#))
  - \$10M of this is the non-reusable upper stage
- 15,000kg LEO capacity

$$(1B / 500 + 50M / 30 + 15M) / (15,000kg) = \$1244/kg$$

So this is perfectly in-line with the internet. SpaceX is tacking on a ~15% profit margin to bring it up to \$1500/kg. That's satisfying!

The interesting part comes from Starship though, because over 50% of Falcon cost comes from a non-reusable upper stage, which Starship eliminates.

Starship:

- \$8B development cost, assume 1000 total flights (approximation in the footnotes)
- \$80M construction cost, assume 30 launches (approximation in the footnotes)
- \$5M refurbishment cost per launch (approximation in the footnotes)

- 150,000kg LEO capacity (god-damn that's a BFR)  
 $(8B / 1000 + 80M / 30 + 5M) / (150,000) = \$105/kg$

So that's also perfectly in-line with other estimates.

But what if the spaceflight industry was more like the commercial aviation industry? In commercial aviation, fuel represents 22% of transportation cost, and is the second greatest cost behind personnel ([source](#)). And personnel costs are not relevant to spaceflight (yet). So we can argue a lower-bound for cost-to-LEO using what the commercial aviation industry has achieved:

If you accept the propellant cost projection of \$1,400,000/launch, and then you intuit that the spaceflight industry will approach the same 22% limit as the commercial aviation industry (While this number is slightly random, we know the value is between zero and the current value of ~0.1, so it's not unreasonable), you can compute that launch cost for Starship could approach:

$$(\$1.4M * 1/.22) / 150,000 = \$42/kg$$

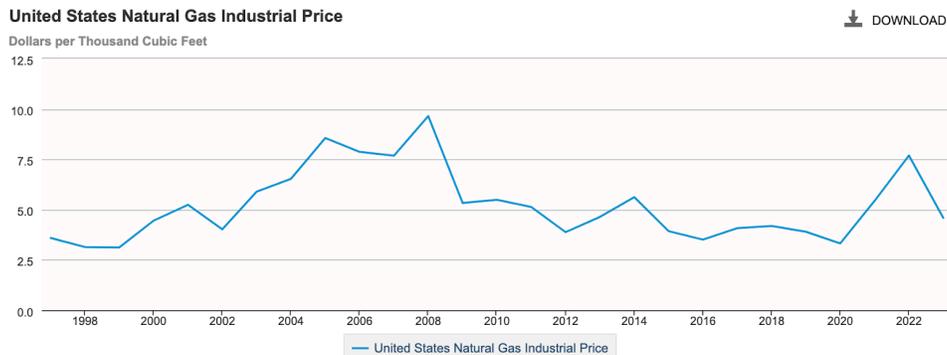
In summary my results are:

| \$/kg LEO Falcon 9 | \$/kg LEO Starship 2040 | \$/kg LEO Starship beyond 2040 |
|--------------------|-------------------------|--------------------------------|
| \$1244             | \$105                   | \$42                           |

It will be interesting to see how we take advantage of this tremendous opportunity. This is truly an exciting time to be alive.

### Propellant Cost Projection:

1. Companies like Terraform Industries are working to make solar powered carbon-capture/hydrolysis CH4 manufacturing sites competitive with traditional oil/gas. Assume their math is approximately right, and SpaceX will be able to manufacture its own CH4 for market rates in 2040.
2. Assume they will synthesize very pure CH4, so any current premium on "rocket-grade" methane will be eliminated
3. SpaceX will obtain natural gas at ~\$5/1000ft<sup>3</sup>:



[\(link\)](#)

4.  $(\$5 / 1000ft^3 \text{ natural gas})(\text{gas is } \sim 90\% \text{ methane by mass})(19kg \text{ gas per } 1000ft^3) \sim \$0.3/kg \text{ CH}_4$

5. Liquid oxygen is also insanely cheap, call it equal
6. Starship wet mass - dry mass = (1300T - 100T = 1200T) and booster wet mass - dry mass (3600T - 200T = 3400T) for a total propellant mass of 4600T
7.  $\text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$ ; molar mass  $\text{CH}_4 = \sim 16\text{AMU}$ ,  $2 \text{O}_2 = \sim 64\text{AMU}$ ; so propellant mass is 80%  $\text{O}_2$  and 20%  $\text{CH}_4$  (not that this matters if you consider their costs equal)
8. So propellant cost for 1 starship, at the limit could be  $4600\text{T} * 1000\text{kg/T} * \$0.3/\text{kg} = \$1,400,000$

**Development Cost:** The high upfront cost needed for conceptualizing, designing, testing, and refining a new rocket design. Development cost is a one-time fee incurred almost entirely before the rocket's first profitable launch

**Construction Cost:** The cost to build 1 rocket. Since SpaceX rockets are reusable, this cost is distributed over the number of expected flights a rocket will make before it becomes too old to launch again.

**Refurbishment Cost:** The cost to "touch up" and refuel the rocket between launches. For Falcon 9, this involves desooting the engines between each launch, and also the cost of  $\text{LO}_2$  and kerosene (or  $\text{CH}_4$  in the case of Starship). This cost is incurred every time the rocket is re-launched. For Falcon 9, Refurbishment Cost also includes the price to build an entirely new upper stage (\$10M) since they don't reuse that part of the rocket

#### Extra Notes:

- Falcon burns kerosene which requires an annoying (expensive) "desooting" process between launches, whereas raptor on Starship eliminates this step
- Elon on Falcon 9: *"recovering and refurbishing the booster represents less than 10% of the overall costs"* ([source](#))
- Falcon 9 development cost was \$1B ([Aviation Week podcast interview of Musk](#))
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- Elon: "Marginal cost for reusing a Falcon 9 is about \$15M ... majority of this is building a \$10M non-reusable upper stage"
- Starship is being design to have zero disposable parts; even the interstage
- We can estimate Falcon 9 has ~\$50M construction cost, based on some of Musk's comments and a \$62M launch price tag for a new Falcon

#### Starship approximations:

Note - estimations on the internet vary by a factor of 10, conservatively, probably due to the collective space frenzy we're in. So I'm going to do some of my own estimations from logical first-principles

- Starship development cost projections are \$5B - \$10B (say \$8B)
- Starship construction cost is similar to Falcon 9 construction cost, except it's bigger. Falcon 9 is 70m tall, Starship is 130m tall. So it's going to be 1.85x as expensive, that's \$80M. This is inline with a \$90M estimate from a [Payload Space Source](#)
- Refurbishment cost is \$5M, \$10M lower than Falcon 9's because it doesn't have a disposable fairing
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