I. Discussion

This section presents estimates of the cost-per-flight of various reuse strategies. Two strategies, (downrange, rocket-propelled, propulsive landing, full recovery) and (downrange, no propulsion, parachute, full recovery), are shown to dominate the other strategies on cost. However, parachute recovery of the full first stage is likely only practical for small launch vehicles*, and it will also be shown that first stage reuse is not favorable for small launch vehicles. Thus, downrange propulsive landing appears to be the dominant strategy.

Launch rate is also a critical factor in the economics of reuse. Increasing launch rate further reduces cost-per-flight, and also allows the investment in reuse development to be paid off more quickly. Efficient first stage reuse may allow for an increase in launch rate. A market that can support a high (>20 flights/year) launch rate may be a critical factor for the economic viability of a first stage reuse.

The discussion is organized as follows: the first subsection shows the distribution of cost-per-flight estimates under a generic dispersion of the model input parameters. The subsequent subsections examine the effect of number of reuses, launch rate, and launch vehicle size on cost. Finally, the last section discusses whether the present value of cost savings from reuse is enough to justify the initial investment in its development.

A. Strategy cost-per-flight estimates

In order to evaluate the cost per flight distributions for various first stage reuse strategies, we again perform a Monte Carlo analysis. This is implemented by evaluating the performance and cost models in sequence, sampling from generic distributions of model input parameters. For a given payload, we first evaluate the required masses of the launch vehicle elements for different reuse strategies using the performance model. Then, those resulting masses are used with the cost model to evaluate the cost per flight of the launch vehicles for each reuse strategy. Some of these cost per flight distributions are shown in Figures 1- 2.
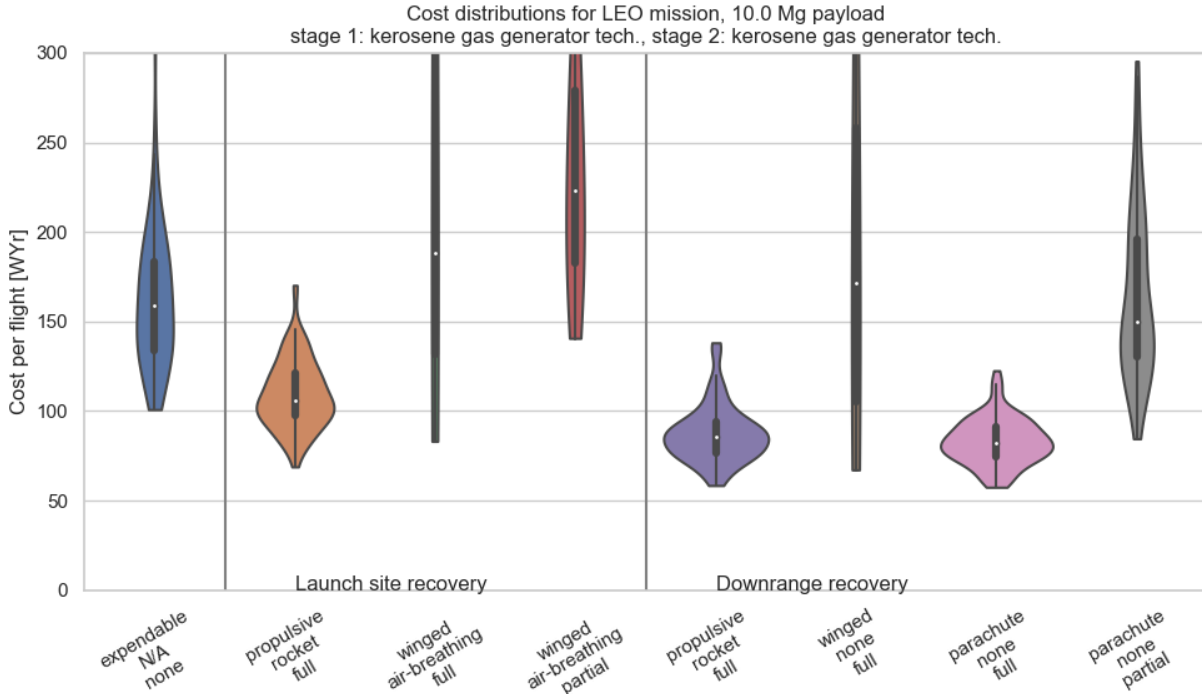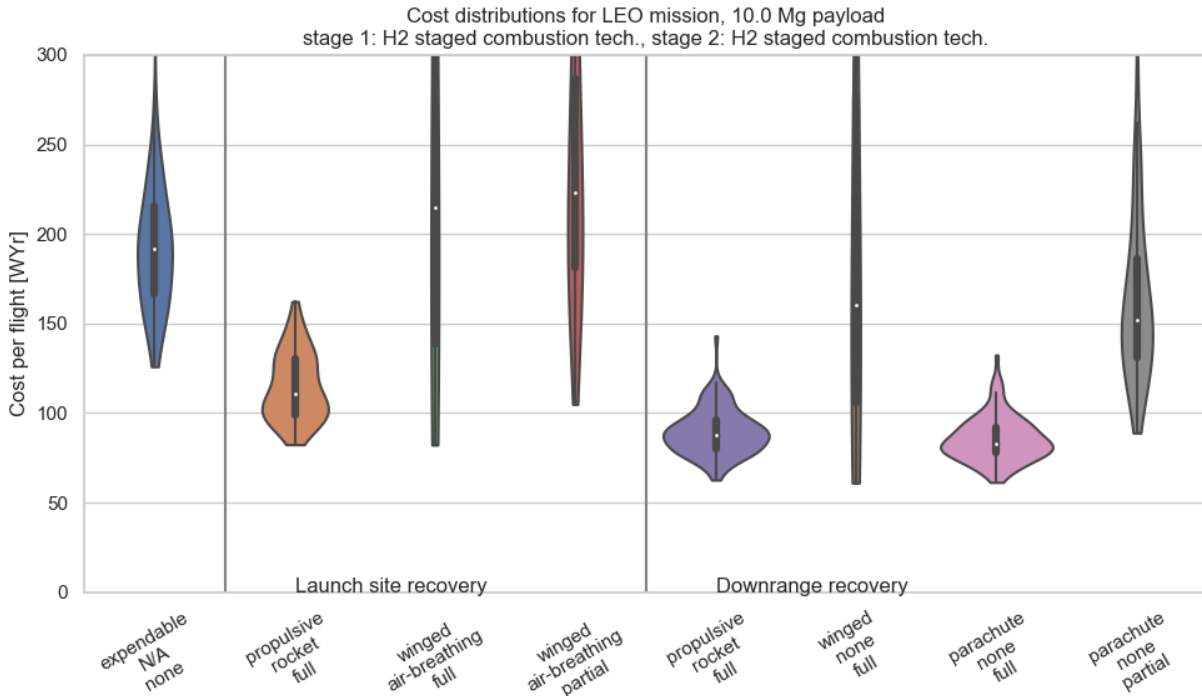

Fig. 1   **TODO caption.**

The downrange propulsive landing and parachute strategies for full first stage recovery show very similar distributions with the lowest cost per flight distributions among all the strategies. However, as mentioned previously, parachute

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*A small stage on parachutes could be recovered in midair or on a ship, or survive landing on land. A large stage on parachutes may need to land directly in the ocean, which would increase recovery and refurbishment expenses.

Fig. 2   TODO caption.

recovery of the full first stage is not very feasible for large vehicles. Therefore downrange propulsive landing is the most effective strategy for achieving the lowest cost per flight.

We see broad distributions for winged recovery strategies due to a small number of historical reference projects available for fitting the production CER coefficients. This lack of data leads to large uncertainties in the coefficient values, resulting in large uncertainties in the output cost per flight distributions.

It is also interesting to compare the cost per flight distributions for the two different technology choices (kerosene with gas generator and H2 with staged combustion). Despite the hydrogen technology choice yielding slightly better payload performance, the cost per flight distributions show slightly lower costs for kerosene. This result likely stems from two reasons:

- The cost per kilogram of inert mass for producing a vehicle using hydrogen propellant is greater than that for kerosene.
- The inert mass of a vehicle using hydrogen propellant is generally greater than that of kerosene for a given payload mass.

Additionally, partial reuse strategies do not seem to yield substantial cost per flight savings relative to full reuse strategies. For these reuse strategies, the extra mass required to make a first stage vehicle partially recoverable does not make up for any cost savings achieved by reusing the high-value components.

B. Effect of number of reuses and launch rate

stack plot with reuse sweep- show why cost declines with number of reuses cpf vs. reuse plot with varying launch rate curves - shows significant decrease in cost with increasing launch rate for low launch rates cpf vs. reuse plot for different strategies

In order to look at the breakdown of costs for a launch vehicle with a reusable first stage, we consider a point cost estimate to demonstrate general trends. The following example evaluates a two stage launch vehicle carrying a 10,000 kg payload to LEO using kerosene and liquid oxygen propellants at a launch rate of 15 launches per year. We consider the case of a propulsive downrange landing to recover and reuse the entire first stage. The cost per flight is determined over a range of number of first stage uses. The results of this analysis are shown in Figure 3.

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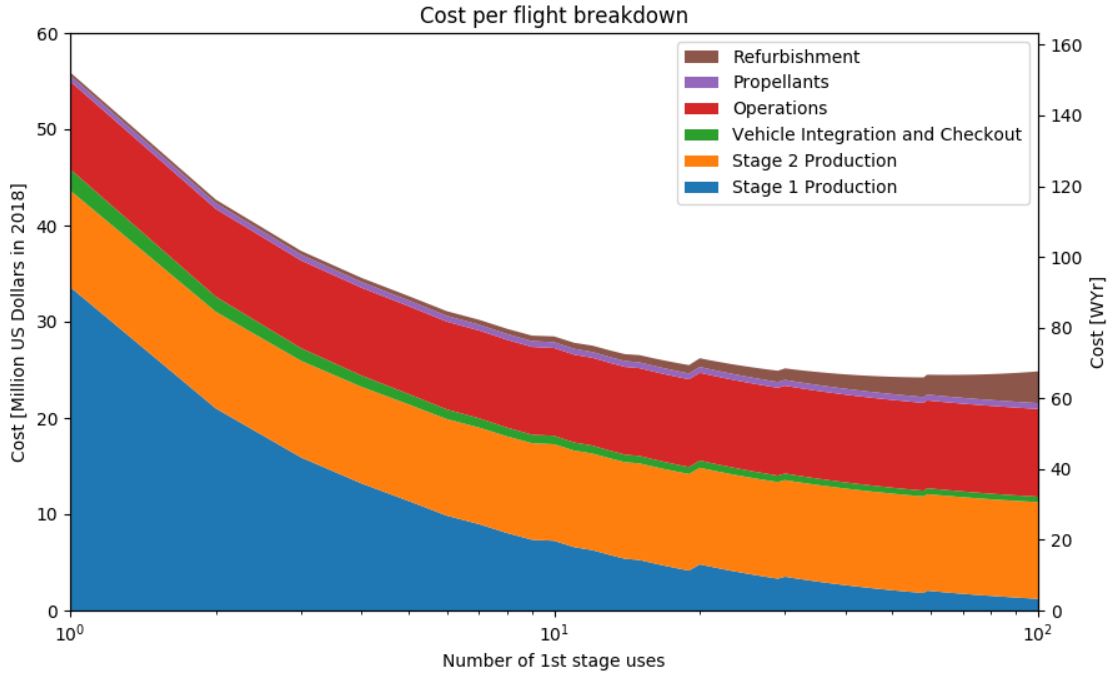
Fig. 3 TODO caption.

Several things should be noticed from the results in Figure 3. First, the stage one productions costs per flight decrease dramatically as we increase the number of first stage reuses. This result is very intuitive – as the cost of first stage production is spread over a larger number of flights, the per flight amortization share of the first stage production cost decreases. This leads to a reduction in the cost per flight. However, this trend of decreasing amortization share of first stage production costs is opposed by the refurbishment cost trends. As the number of first stage uses increases, the refurbishment cost per flight also increases. This is due to the fact that more components on the first stage will need inspected or replaced as the number of reuses increases.

These opposing trends lead to an interesting result: the total cost per flight trend achieves a minimum value. Under the assumptions used in Figure 3, the minimum cost per flight occurs near 60 reuses, but the exact location is highly dependent the model parameters, especially refurbishment costs. Generally though, there will be some number of reuses beyond which further reuse is not cost effective.

The cost per flight is also affected by the annual launch rate. Although most components of the cost per flight do not vary with launch rate, operations costs are very sensitive to it. Launch operations require a dedicated workforce and facilities, which are underutilized at low launch rates. Therefore we see a higher operations cost per flight at low launch rates. The cost per flight trends with varied launch rates are given in Figure 4.

As expected, Figure 4 shows that the cost per flight is higher at lower launch rates, regardless of the number of first stage reuses. For low launch rates, we see a substantial decrease in the cost per flight for only a modest increase in launch rate. However, for high launch rates, further increases in launch rate do not have a large effect on the cost per flight. For instance, we see a large difference in cost per flight by increasing the launch rate from 3 to 5 launches per year. However, increasing the launch rate from 20 to 40 launches per year yields only minimal cost per flight reductions.

We next consider some of these cost per flight trends for various first stage reuse strategies. Figure 5 shows the costs per flight for selected strategies over a range of number of first stage uses. We consider two cases in this analysis:

- First stage reuse has no effect on the vehicle launch rate. The first stage production rate is not a rate-limiting step of the launch rate. In this case, a production and launch rate of 15 vehicles per year.
- First stage reuse allows the launch rate to increase beyond the first stage production rate. For illustration, we assume that the first stage production rate is 15 stages per year, and that in this case the launch rate is $min(15 * n_{reuse}, 50)$

For all strategies, we see a decrease in the cost per flight as the number of first stages uses increases. This result is
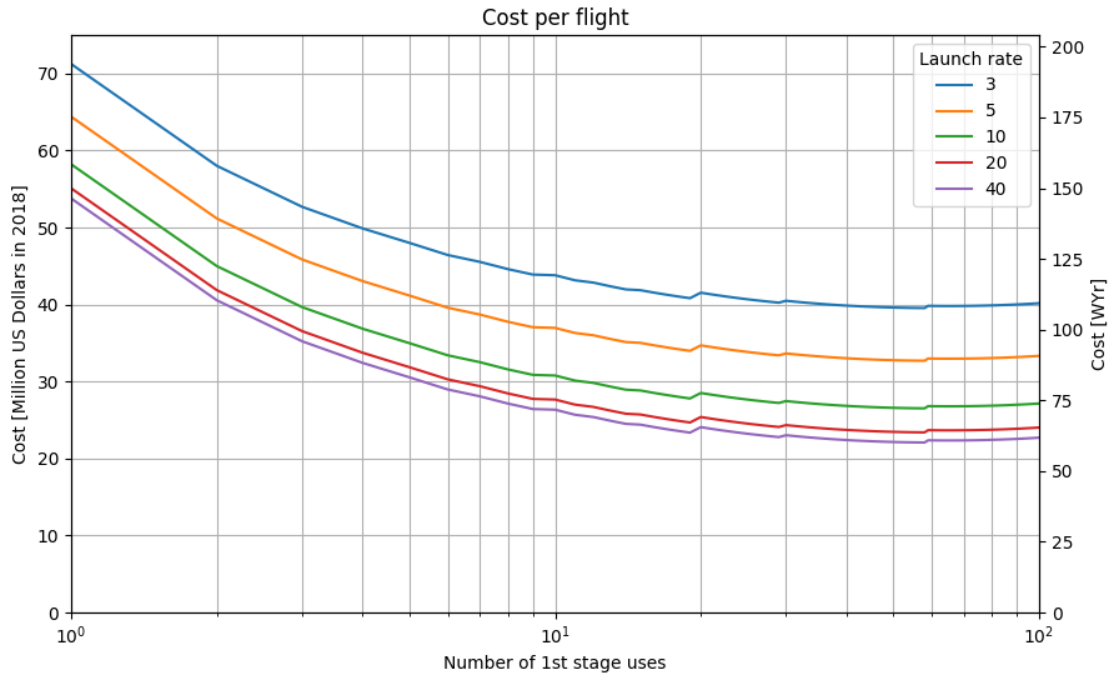
Fig. 4   TODO caption.

not surprising – increasing the launch rate decreases the operations cost per flight. It is interesting though to compare the strategy cost per flight trends with the expected cost range for an expendable vehicle. For the strategies considered in Figure 5, all but the partial parachute recovery strategy show costs per flight below that of an expendable vehicle for a certain minimum number of reuses. With partial parachute recovery, the high-value hardware reuse savings do not compensate for the additional costs of producing and operating a reusable vehicle. However, the other strategies show potential for significant cost per flight savings with a high enough number of first stage reuses.

C. Effect of launch vehicle size

The potential for cost per flight savings of first stage reusability is highly dependent on the payload or vehicle size. In the previous discussion, we considered the case of a 10 Mg payload to LEO. The cost per flight breakdown for this case shown in Figure 3 shows that first stage production costs make up the majority of costs in the expendable case, and that first stage reuse can lead to significant cost per flight savings. However, the cost per flight breakdown looks very different for a smaller payload.

Let's consider the case of a small 100 kg payload to LEO. As can be seen in Figure 6, first stage production costs no longer make up the majority of the cost per flight since costs for small launch vehicles are not dominated by hardware costs. Instead, the operations costs make up the majority of the cost per flight. The operations costs per flight are largely independent of vehicle and payload mass, and therefore do not decrease substantially as the payload and vehicle mass decrease. For these reasons, first stage reusability for small launch vehicles is impractical. Amortizing the first stage production costs for a small launch vehicle over a number of flights does not lead to large cost per flight savings since the production costs were already minimal.

We next consider the cost per kilogram payload per flight over a range of payload masses, as given in Figure 7. This plot reveals a trend of decreasing cost per kilogram payload per flight as payload mass – and therefore vehicle size – increases. This trend has a few explanations. First, as previously discussed, operations costs are largely independent of payload and vehicle size. Therefore, for smaller launch vehicles, the operations costs per kilogram payload are larger than they would be for a larger launch vehicle. Second, a relatively large portion of the vehicle inert mass for small launch vehicles consists of guidance, navigation, and communications equipment, the mass of which scales only loosely
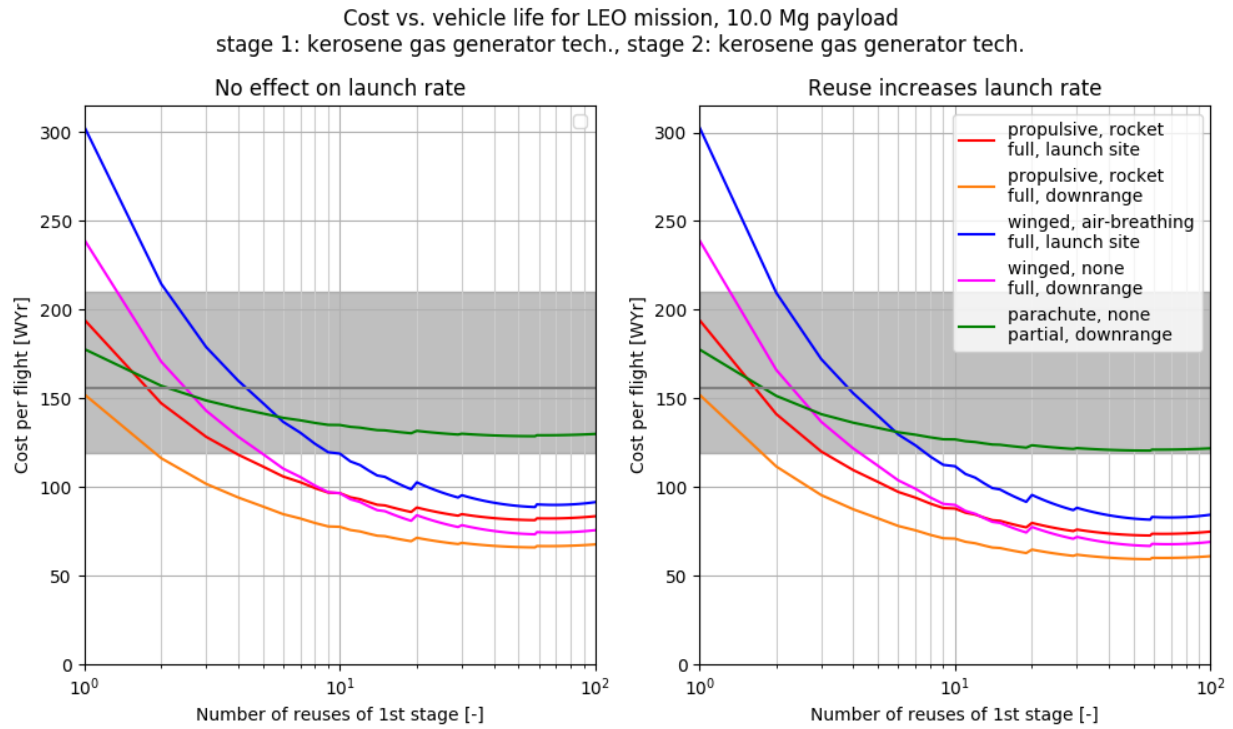
Cost vs. vehicle life for LEO mission, 10.0 Mg payload
stage 1: kerosene gas generator tech., stage 2: kerosene gas generator tech.

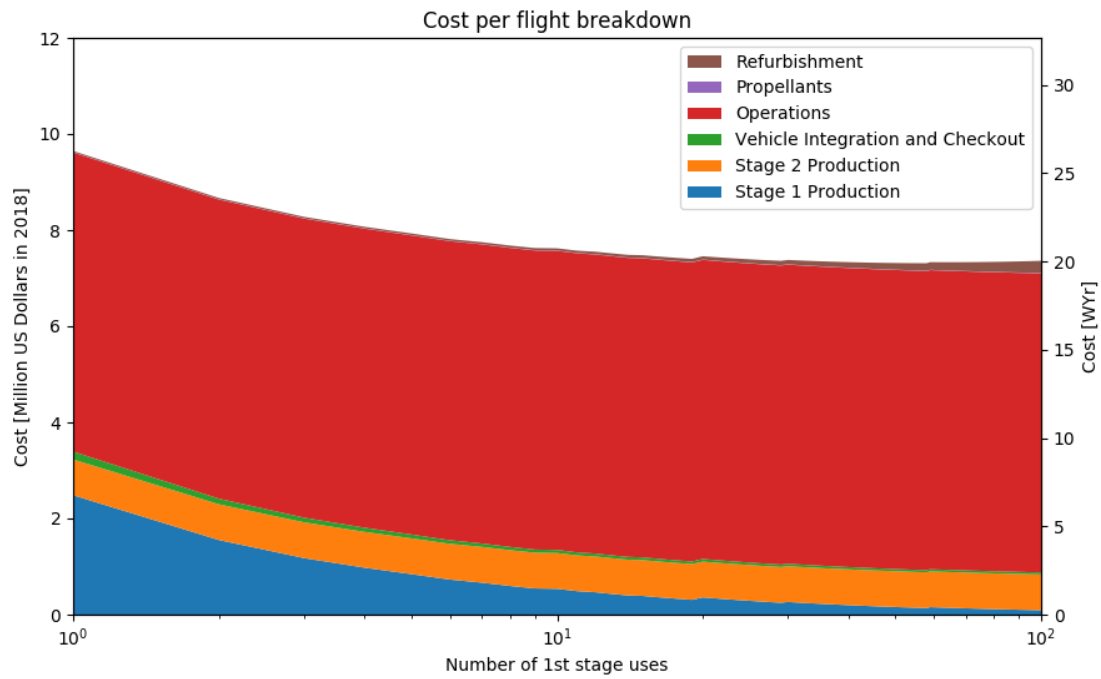**Fig. 5   TODO caption.**

Fig. 6   TODO caption.

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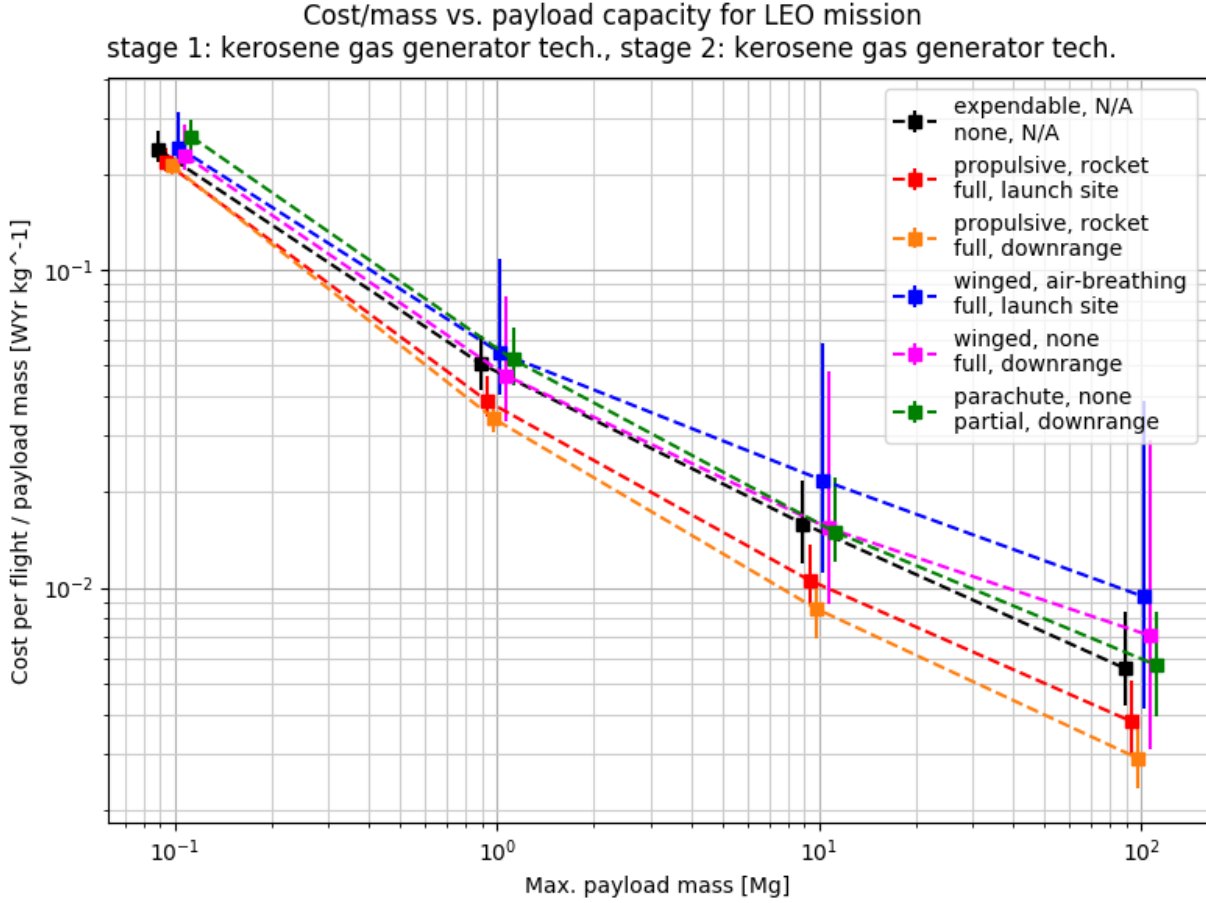with vehicle size [1].

Fig. 7   TODO caption.

D. Paying off development costs

In our models and discussion so far, we have yet to consider the development costs of the reuse strategies. The development costs of reusable launch vehicles can generally be expected to be greater than a similar expendable vehicle. However, the cost per flight savings for reusable vehicles can also be substantial, as shown in Figure 5. These opposing trends lead to an important question: do the cost per flight savings of reusable launch vehicles pay off their increased development costs?

In order to explore this question, we first define a cost per flight ratio. This will be defined as the ratio between the cost per flight of a vehicle with first stage reuse and the cost per flight of a similar expendable vehicle, and should be in the range [0, 1]. Next we consider the present value of the total savings due to reusability of a launch vehicle over a 20 year timespan with a 20% discount rate. We evaluate the present value over the full range of cost per flight ratios for selected annual launch rates, and then compare these curves to a credible range of development costs. The results of this analysis are shown in Figure 8.

For low launch rates, it is unlikely that the development costs could be paid off by the cost per flight savings brought by first stage reusability. The investment in development costs loses value faster than any savings from reuse could compensate for it. However, for launch rates greater than 20 launches per year, first stage reusability does appear to be economically viable. With higher launch rates, we see a lower cost per flight ratio since operations costs decrease with increased launch rate. Additionally, higher launch rates mean the investment in the development costs of the reusable vehicle can be paid off sooner, so the development investment will have lost less value. High launch rates are essential for the economic viability of reusable launch vehicles.

Present value of reuse cost per flight savings
20 %/year discount rate, 20 year horizon
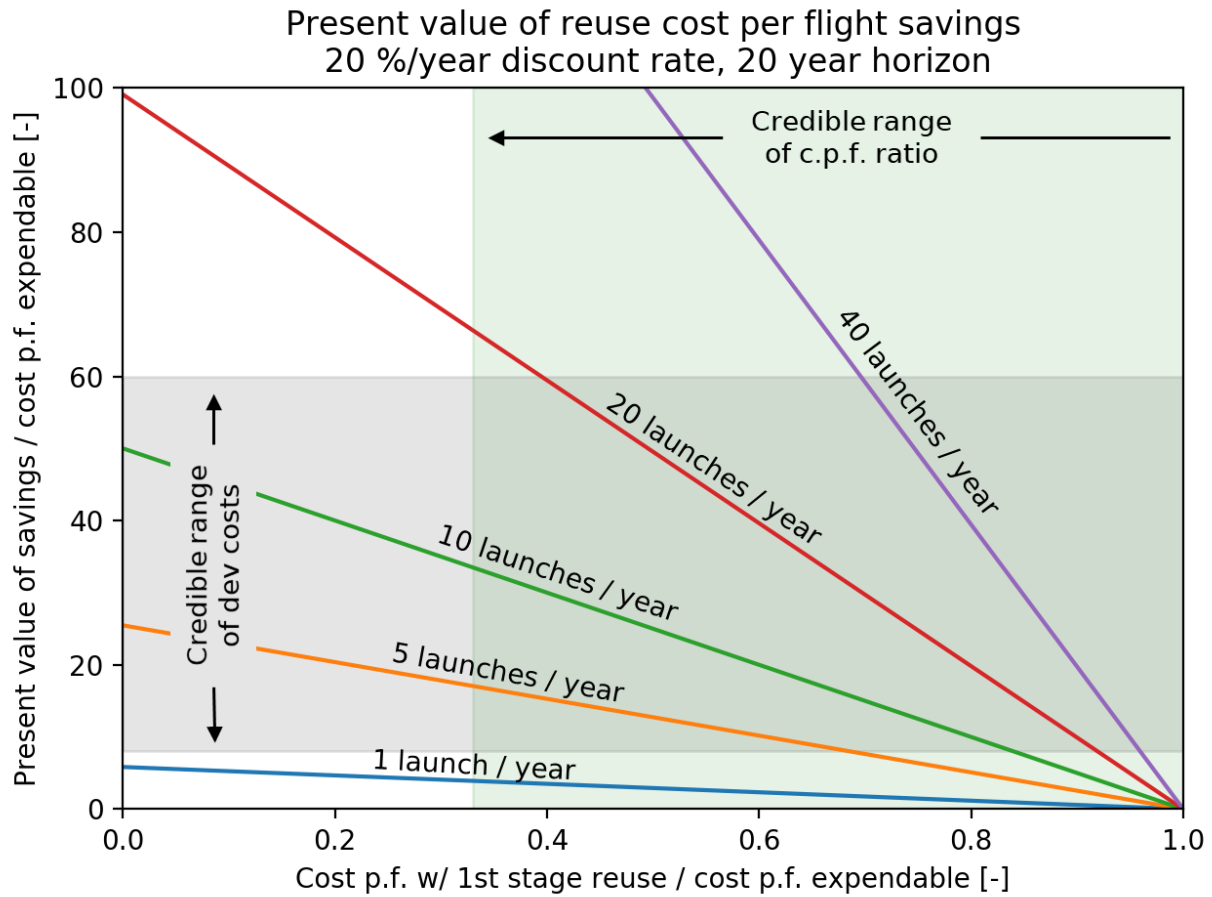
Fig. 8   TODO caption.

References

[1] Koelle, D. E., *Handbook of Cost Engineering for Space Transportation Systems with TRANSCOST 8.2*, Trans Cost Systems, Ottobrunn, Germany, 2013.