The energy cost of the vacuum tube

Hyperloop offers very low energy consumption due to the minimal air resistance, but energy is required to evacuate and maintain the vacuum in the tube.

- **Large capacity pumps would be required for pumping down conventional airlocks**
- **Energy for pumping the airlocks is does not add significantly to total energy.**
- **The energy for initial pump-down of the tube is quite low, less than 1 days energy for the proposed high-speed-rail system.**

The chart below shows the 3 tube pressures which are analysed. It would seem that 1 kPa is a good compromise. The speeds in the last row show the speed at atmospheric pressure, that has similar drag at 800 km/h in the vacuum.

5 kPa (50 mBar)	1 kPa (10 mBar)	200 Pa (2 mBar)
Pressure of 'natural steam vacuum', which requires virtually no pumping after the initial pump-down.	A steam system would require pumping up to 5 kPa to the condensers.	A steam system would require pumping up to 5 kPa to the condensers.
Pressure is too high for efficiency at 1,200 km/h, maybe acceptable for 800 km/h	A good compromise for reduced aerodynamic drag and low pumping energy	Higher than Alpha's 100 Pa, but the low drag may not be worth the increased pumping energy and problems.
Aerodynamic drag similar to **180 km/h** at atmospheric pressure	Aerodynamic drag similar to **80 km/h** at atmospheric pressure	Aerodynamic drag similar to **35 km/h** at atmospheric pressure

A vacuum pump suitable for Hyperloop

The Busch R5 series is very popular oil-lubricated vane pump. The RA1600B is large model suitable for Hyperloop. There may be more efficient pump combinations, but this one is convenient with simple calculations.

- Flow at inlet 1600 M^3/h, 0.44 M^3/s
- Power 30 kW. Fairly constant during pump-down
- Lowest pressure 30 Pa, 0.3 mBar
- Weight 1,330 Kg
- Cost about US$75,000

Pump-down formula

The formula for pump-down time works for most units.

t = time
V = Volume of vacuum chamber
S = Volumetric flow rate of vacuum pump
P_1= Starting pressure
P_1= Final pressure

$$t = \frac{V}{S} \ln \frac{P_1}{P_2}$$

For example, for an airlock of 10 M^3, we would have the following figures for the final pressures of 5, 1, and 0.2 kPa.

The power of the pump is fairly constant over the whole process, so we can calculate the energy.

Final tank press kPa	5.0	1.0	0.2
Start press atmosp kPa	101	101	101
Tank volume M^3	10	10	10
Pump flow rate M^3/s	0.44	0.44	0.44
Pump power kW	30	30	30
Pump-down time s	68	105	141
Pumping energy kWh	0.57	0.87	1.18

Pump spacing along the tube

We would place vacuum pumps along the tube, at a spacing so that the pumps can evacuate the tube in a reasonable time. We can calculate the length of tube suitable for a single R5 RA1600 pump.

In this example, we need to place one pump every 6km along the tube, to give a pump-down time of 60 - 125 hours, depending on pressure.

In practice, the multiple pumps may be placed where convenient, to give an average 6km spacing for each of the two tubes.

Final tank press kPa	5.0	1.0	0.2
Start press atmosp kPa	101	101	101
Tank diameter M	2.6	2.6	2.6
Length of tube Km	**6.0**	**6.0**	**6.0**
Tank volume M^3	31,860	31,860	31,860
Pump flow rate M^3/s	0.44	0.44	0.44
Pump-down time, days	**2.5**	**3.8**	**5.2**

Number of pumps for whole Hyperloop system

The proposed LA to San Francisco route is about 600km long, so the two tubes are a combined 1,200 km.

Normally, we only need to pump down the whole system once, maintenance could be done by air-locking off sections of the tube. A complete loss of system vacuum is only likely in a severe emergency.

With a pump spacing of 6 km, we would need 200 pumps of the Busch R5 RA1600 type. This would evacuate the tube in 60 - 125 hours.

Total cost for the vacuum pumps would be about US$15 million, a small investment for such a large project.

Final tank press kPa	5.0	1.0	0.2
Total number of pumps	200	200	200
Pump power kW	30.0	30.0	30.0
Power for all pumps mW	6.00	6.00	6.00
Pump-down time hours	60	93	125
Tot pump energy, mWh	**362.7**	**557.0**	**751.2**

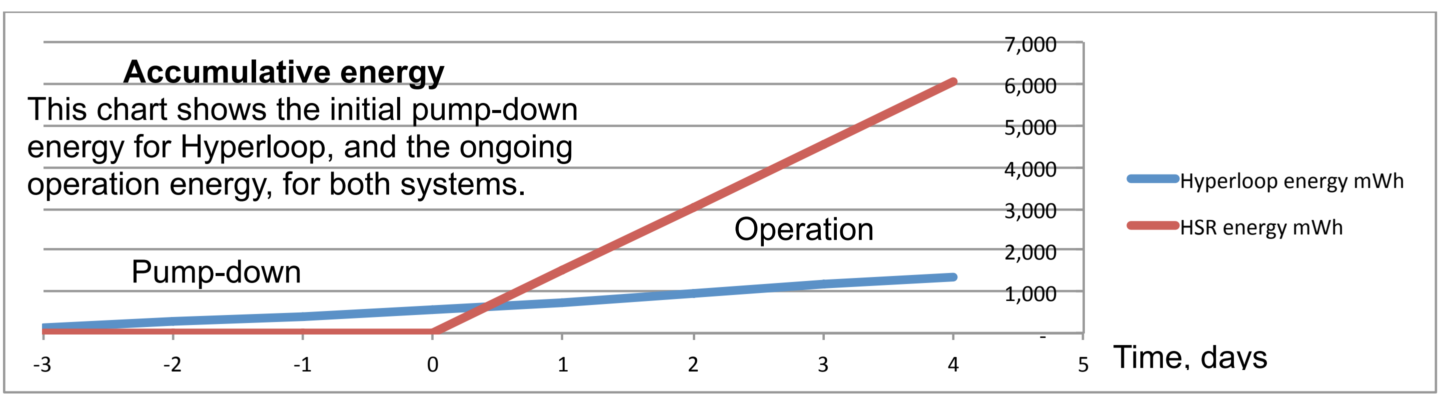
We can calculate the total energy of evacuation.

Hyperloop pays back the initial pump-down energy after first day of operation

The figures on the right estimate the total daily energy for the proposed LA-SF high-speed-rail. 8 million passengers per year is the number proposed in Hyperloop Alpha, and is consistent with the California HSR proposal.

HSR power consumption figures are hard to find, the 415 kJ/pass km comes from the Australian HSR study. Hyperloop will use 10 kWh per passenger for the LA-SF trip

Passengers / yr LA-SF	8,000,000
Passengers / day	21,918
Distance LA-SF km	600
Energy kJoule/pass km	415
Energy kWh/pass trip	69.2
Tot energy/day mWh	**1,517**

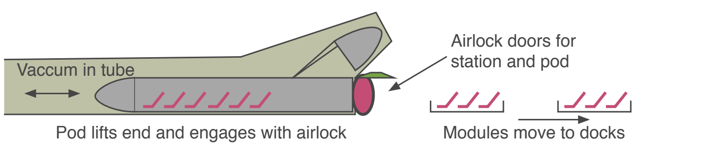


Airlock pump-down

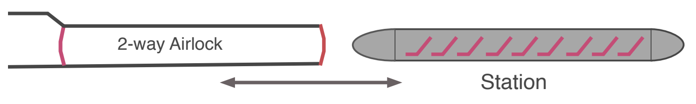
The vacuum energy for Hyperloop operations depends on airlock type, vacuum pressure, and whether we are using air in the tube, or steam that needs to be pumped to the condenser at 5 kPa.

The volume of an airlock for a 22m long pod is about 60 M^3. When occupied by a pod, the volume would decrease to about 10 M^3. The figures below assume a single Busch R5 1600 vacuum pump

The end door airlock, used by Cheetah, has virtually no pumping.



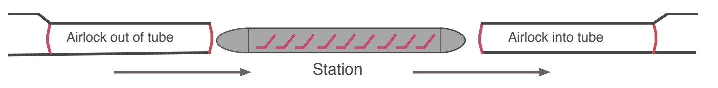
The 2-way airlock is always pumped out with a pod inside. The volume to be evacuated is 10 M^3.



Air, 1 kPa, pump time 104s, energy 0.9 kWh.
Steam, 1 kPa, pump time 36s, energy 0.3 kWh

The 'drive-thru' airlock pair is much less efficient. The first airlock needs to be pumped with no pod inside, and the second with a pod, so the total volume to be evacuated is 70 M^3.

Air, 1 kPa, pump time 735s, energy 8.3 kWh.
Steam, 1 kPa, pump time 253s, energy 0.7 kWh



Airlock pump-down conclusions

- The end door airlock is very efficient, saving both time and vacuum pumping energy
- The 'drive-through' airlock pair is very inefficient, due to pumping an empty airlock.
- Steam considerably reduces pumping energy and time
- Very large capacity vacuum pumps are required for fast pumping of airlocks.