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Energy estimates of non-geostationary satellite orbit (NGSO) internet

Data network infrastructure in a connected economy

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1. Energy Estimates of NGSO Internet

A significant energy input for non-geostationary satellite orbit (NGSO) internet is the energy of the launch. Here we focus on Starlink because it is the largest currently operating network. As of January 2023, Starlink is still being launched on the SpaceX Falcon 9 rocket, but it will likely begin to use the SpaceX Starship rocket with a considerably larger payload within a few years' time. Competing NGSO satellite systems have used or plan to use other types of rockets.

Table 1 shows embodied energy parameter estimates from ecoinvent (2010), while Table 2 shows estimated masses for Falcon 9 (Spaceflight 101.com 2017) and Starship (SpaceX n.d.; Wikipedia 2023a, 2023b) rockets, yielding embodied energies of propellants for each type.

Table 1. Embodied energy parameter estimates

Parameter	Value	Units
Kerosene	54.0	MJ/kg
Natural gas (liquefied)	68.9	MJ/kg
Oxygen liquefaction energy	8.8	MJ/kg
Steel	25	MJ/kg
Aluminum (primary)	190	MJ/kg
Specialty metals	175	MJ/kg
Electronics	5,000	MJ/kg
Photovoltaics	2,200	MJ/kg
Propellants (NTO/MMH)	10.0	MJ/kg

Table 2. Propellants for Falcon 9 and Starship rockets

Parameter	Mass		Embodied energy	
	Falcon 9	Starship	Falcon 9	Starship
	kg	kg	MJ	MJ
Kerosene	155,893	0	8.4	0.0
Methane	0	1,000,000	0.0	68.9
Oxygen	362,607	3,600,000	3.2	31.7
Total propellants	518,500	4,600,000	11.6	100.5

The Falcon 9 rocket has an expendable payload capacity of 22,800 kilograms (kg) to low Earth orbit (LEO) (SpaceX 2022), but is almost exclusively used in its reusable configuration, where the payload capacity is reduced to 17,400 kg (SpaceX 2023). This rocket consumes 155,900 kg of RP-1 (a type of kerosene) liquid fuel and 362,600 kg of liquid oxygen per launch. These liquids, together called *propellants,* have a total embodied energy of 11.6 terajoules (TJ). While the mass per Starlink satellite had been estimated at 260 kg (Clark 2021), SpaceX's January 2023 launch (SpaceX 2023) indicated the mass has increased to close to 310 kg/satellite. At 56 satellites per Falcon 9, this equates to a propellant energy of 207 gigajoules (GJ)/satellite.

The Starship rocket (including its Super Heavy stage 1 booster) has a payload capacity of up to 150,000 kg (depending on orbit) and will consume 1,000,000 kg of liquid methane and 3,600,000 kg of liquid oxygen per launch once it is operational. These liquids have a total embodied energy of 101 TJ. Each Starship launch can therefore accommodate up to 484 satellites, equating to an embodied propellant energy of 208 GJ/satellite—nearly identical to that of Falcon 9.

The embodied energy of NGSO satellites is difficult to determine, but we have developed a rough estimate based on Springmann and de Weck (2004), together with estimates from ecoinvent (2010), obtaining a total embodied energy of ~690 GJ/satellite, more than three times the propellant embodied energy. See Table 3. This estimate is driven primarily by the high fraction of photovoltaics and electronics (30% each) in these satellites, together with the high embodied energies of these components (2,200 and 5,000 MJ/kg, respectively).

Table 3. Space hardware

Parameter	Satellite	Falcon 9			Starship			Units
		Stage 1	Stage 2	Total	Stage 1	Stage 2	Total	
Steel	0.0%	5.0%	5.0%		10.0%	50.0%		%mass
Aluminum (primary)	20.0%	73.1%	77.8%		58.6%	35.4%		%mass
Specialty metals	14.0%	16.9%	12.3%		26.4%	9.6%		%mass
Electronics	30.0%	5.0%	5.0%		5.0%	5.0%		%mass
Photovoltaics	30.0%							%mass
Propellant (NTO/MMH)	6.0%							%mass
Total mass	310	3,760	490	4,250	200,000	100,000	300,000	kg
Total embodied energy	0.689	9.32	1.68	11.00	82.0	34.7	116.7	TJ
Payload mass				17,400			150,000	kg
Number of launches		10	1		1,000	12		
Total rocket embodied energy per satellite		16.6	30.0	46.6	0.17	5.97	6.14	GJ

The manufacturing energy of rockets, also shown in Table C.3, was even more difficult to estimate, because the composition of components is not well known. Nonetheless, we have attempted rough estimates based on known components of the frame (steel and/or aluminum), rocket engines (specialty metals), and electronics, again using ecoinvent to provide embodied energies of components. For Falcon 9, we obtained a total embodied energy of 11.0 TJ, whereas for the much larger Starship, the total embodied energy was 117 TJ. Both vehicles are designed to be reusable, but Starship will be much more reusable than Falcon 9, which can only reuse its first stage, and is not intended to be used much more than 10 times (Berger 2021), as opposed to up to 1,000 times for Starship's Super Heavy first stage, and at least a dozen times for Starship itself (Musk 2017). Here we assume these maximum numbers of reuses, resulting in much lower manufacturing energies, particularly for Super Heavy, which constitutes ~70% of the embodied energy of the Starship system. Thus, the rocket manufacturing energy per satellite is estimated to be 47 GJ for Falcon 9 and 6.1 GJ for Starship.

While the non-satellite embodied energy is 18% higher on Falcon 9 (253 GJ/satellite) as compared to Starship (214 GJ/satellite), making the latter platform more desirable from an energy perspective, the total embodied energy is still dominated by the satellite, and is only ~4% higher on Falcon 9 (943 GJ) as compared to Starship (903 GJ/satellite). Expressed per satellite unit mass, this is 3,040 and 2,910 MJ/kg, respectively.

As satellites are expected to last about five years (Handmer 2019), this yields an average energy flow rate of 5.7 (Starship) to 6.0 (Falcon 9) kW. While a wide range of bandwidth estimates current exist for Starlink, we will base our calculations on SpaceX's CEO's claim that 60 Starlink NGSO satellites could provide 1 Tb/s (Musk 2019), or 17 Gb/s each. As noted by Handmer, however, satellites only spend ~2% of each orbit over inhabited land, so the average effective bandwidth is 315 Mb/s. Given the above embodied energy flow, this translates into an energy consumption of 18.2 (Starship) to 19.0 (Falcon 9) J/Mb. Note that for other launch platforms that might be less reusable, this value could be many times higher.

We also estimated the energy consumption of sending signals from the ground to NGSO satellites based on known energy consumption of GEO transceivers. The typical energy consumption of HughesNet equipment is 46 watts (W) (HughesNet 2016), which includes the power needed to operate a Wi-Fi transmitter (~6 W; Energy Use Calculator n.d.). An older version of the HughesNet system provides power consumption for the radio alone: 10 W for 1.024 Mb/s or 9.8 J/Mb (Hughes 2009). Using this same metric with a more current typical uplink (ground to satellite) bandwidth of 3 Mb/s yields 29 W transmission power. Therefore, we find that the total power consumption is ~75 W, with the radio consuming ~40% of the power. GEO satellites utilize the Ka band (26.5 to 40 GHz), and Starlink satellites use both the Ku and Ka bands (12-40 GHz) (Nambiampurath 2021). Since transmission power scales with the inverse-square of distance, transmission to a typical Starlink altitude of ~900 km would consume ~650 times less power than transmission to GEO altitude, even after imposing a distance-correction factor for non-zenith orientations, or 0.015 J/Mb. While both GEO and NGSO ground antennas are very directional, typical GEO antennas are larger (~0.75 m^2) than the standard Starlink antenna for NGSO operations (~0.16 m^2) (Starlink 2023); therefore, assuming an operating frequency of 28 GHz, we estimate that the GEO antenna has a beam angle of 0.8°, whereas the NGSO antenna beam angle is 1.7°. Moreover, because NGSO satellites are in constant motion relative to the ground, an active phased-array antenna must be utilized to steer the beam (Mosher 2020), which could result in a degradation (increase) in effective beam angle; here we assume a factor-of-six increase or ~10°. As a result, we estimate the total transmission power is 2.61 J/Mb, or ~40 W for a 15 Mb/s upload rate reported in 2021 (Nambiampurath 2021). Together with an estimated idle power use of ~20 W (Clarke 2023), the total power compares favorably with 50-75 W reported for Starlink's standard antenna (Starlink 2023).

Ultimate Starlink upload speeds are assumed to be 1 Gb/s (Brown 2020), implying 17 simultaneous channels assuming 17 Gb/s per satellite (note Handmer [2019] speculated that perhaps as much as 100 simultaneous beams could operate per Starlink). Assuming the 20 W of non-satellite transmission power is relatively constant regardless of data transmission rate, at 1 Gb/s this contribution is small (0.02 J/Mb) compared with the transmission power. Therefore, our estimate for total NGSO ground station energy use is 2.63 J/Mb, or as much as 2.6 kW per ground station. However, future versions of NGSO antennas could be considerably more energy efficient than this.

Altogether, the total energy requirements to operate an NGSO satellite internet system such as Starlink is dominated by launch embodied energy, which for a reusable rocket system ranges from 20.8 (Starship) to 21.6 (Falcon 9) J/Mb. Table 4 summarizes our energy estimates.

Table 4. Energy estimates for NGSO satellite internet

Parameter	Falcon 9	Starship	Units
Satellite embodied energy	689		GJ
Propellant energy per satellite	207	208	GJ
Rocket embodied energy per satellite	47	6.1	GJ
Non-satellite energy subtotal per satellite	253	214	GJ
Total energy per satellite	943	903	GJ
Assumed lifetime	5		y
Embodied energy flow rate	6.0	5.7	kW
Maximum downlink bandwidth	17,000		Mb/s
Transmission fraction of orbit	1.9%		
Time-averaged downlink bandwidth	315		Mb/s
Embodied energy of satellite hardware	19.0	18.2	J/Mb
Assumed uplink bandwidth	1,000		Mb/s
Uplink transmission power	2.61		J/Mb
Non-transmission power	0.02		J/Mb
Total ground link power	2.63		J/Mb
Total NGSO energy use	21.6	20.8	J/Mb

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