

SPACE-BASED DATA CENTERS ROADMAP: THE CASE FOR CAUTION

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CHAPTER 2.4:

Greenhouse Gases and Black Carbon

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CHAPTER 2.4:

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MAIN MESSAGES

- Although space-based data centers (SBDCs) run on solar power and therefore emit no greenhouse gases (GHGs) or black carbon once in orbit, burning the fuel required to launch SBDCs and manufacturing rockets both create considerable emissions.
- Significant uncertainties surround the life-cycle GHG and black carbon emissions of SBDCs. Key data are not publicly available, scientific understanding on key topics is limited, and estimates vary widely.
- Based on reasonable assumptions, life-cycle GHG emissions from SBDCs appear to be close to those of terrestrial data centers powered by uncontrolled natural gas and 3–6 times those of terrestrial data centers powered by solar panels or natural gas with carbon capture.
- Moreover, emissions of black carbon into the stratosphere by rockets launching SBDCs could increase SBDC life-cycle emissions by a large amount, with significant potential warming impacts. More data are needed to evaluate these risks.

A. Overview

Launching space-based data centers (SBDCs) into orbit requires large amounts of rocket fuel. Burning this fuel releases greenhouse gases (GHGs) and black carbon (a type of soot that warms the planet). So does manufacturing rockets and information technology (IT) equipment. Although SBDCs run on solar power and therefore emit no GHGs or black carbon once in orbit, SBDCs' life-cycle emissions of these climate pollutants could be very significant. At the same time, under some assumptions and scenarios, SBDCs' life-cycle emissions of these climate pollutants could be quite modest. Much more data collection and scientific analysis are needed to confidently assess the likely emissions impacts of SBDC deployment.

This chapter analyzes potential life-cycle emissions of GHGs and black carbon from SBDCs. The chapter starts by noting the limited data available on this topic. It then turns to an analysis of launch emissions, looking first at life-cycle emissions from the leading rocket fuels and then at some "known unknowns" with respect to these emissions, including in particular stratospheric black carbon. Next, the chapter examines the embodied emissions of data center IT equipment and rockets. Based on these analyses, the chapter compares SBDC life-cycle emissions with those of terrestrial data centers. The chapter closes with recommendations, including a recommendation that governments,

companies and other stakeholders begin an immediate set of studies to reduce scientific uncertainties and take other steps to reduce climate change risks related to SBDC constellations.

The analysis in this chapter is provisional and prepared under a tight deadline. It has not been subjected to external review. We look forward to refining the analysis in the months ahead and welcome comments and corrections. Please send them to SBDCRoadmap@gmail.com.

B. Data Availability

Data on rocket emissions, manufacturing, compositions and supply chains are limited for several reasons. Some data are guarded closely by aerospace companies and SBDC aspirants. Some data are guarded closely by national security agencies. The lack of available data makes it challenging to draw robust conclusions on the potential climate change impacts of SBDC systems.

Several proprietary databases reportedly contain high-quality data on environmental attributes and terms associated with rocket and satellite systems. The Strathclyde Space Systems Database[1] is regarded by workers in the field as one of the best and undergirds several key life-cycle assessment (LCA) studies for space infrastructure and launch.[2-4] The EU Space Surveillance and Tracking (SST) database[5,6] also reportedly contains such information. (The authors were not able to access either of these databases in connection with this chapter.)

Some data are publicly available, and this availability is increasing each year. For example, databases concerning launches before 2019 have been published,[7] and a recent analysis[8] integrates launch data through 2026, including the 3D trajectory through the atmosphere and emissions of GHGs. Recent publicly available data sets[9] provide information on fuels and new rocket configurations, such as those for Starship, Blue Origin and Long March 10. These databases are welcome, but incomplete—greater information is needed about the use and manufacturing of fuels, manufacture of rockets, and release of GHGs and black carbon within the atmosphere.

The European Space Agency (ESA) has launched efforts to better understand the carbon footprint and environmental risks of space activity. In addition, the proposed EU Space Act[10] currently includes the Product Environmental Footprint Category Rules (PEFCR4Space),[11] which would gather and share some key data. National Aeronautics and Space Administration (NASA) researchers proposed a comprehensive study on similar topics in 2024, but it was not funded.[12]

Much information about the weight, composition and construction of rockets and SBDCs is likely proprietary. Key data are either not accessible or not shareable, due to limits governments and their industry partners place on the databases. The lack of accessible data makes it difficult to reach confident conclusions regarding the global warming consequences associated with SBDC scale-up.

C. Launch Emissions

Launching SBDCs into low Earth orbit (LEO) produces significant GHG and black carbon emissions.[13] The amounts depend on fuel type, rocket type, payload and other factors. This section assesses the propellants, launch-related terms and operational impacts separately.

i. Fuel emissions based on available data

Choice of fuel is critical in determining life-cycle GHG emissions from any launch. Three fuels are the likeliest candidates for SBDC launches going forward: liquid natural gas (LNG), kerosene (typically a highly refined type called RP-1) and liquid hydrogen.

LNG is the fuel of choice for SpaceX Falcon-9s, Starships and Blue Origin BE-4s, making it a likely option for SBDCs. Kerosene is a regular workhorse for rocket propulsion, especially for first stages. Liquid hydrogen has been used for rockets over the last 70 years, mostly for the second stage.

When used for rocket launches, all three fuels require liquid oxygen (LOX) as the oxidizer. (While hypergolic fuels (e.g., hydrazine) have seen significant use as propellants and efforts are underway to identify novel variants,[14] they are unlikely to be used at scale for SBDC deployment given the fuel choices made by leading heavy-lift rocket developers. Similarly, while solid propellants are used in some current rocket platforms (e.g., Arianne 6 boosters), they are unlikely to be adopted for SBDC deployment at scale.[15] We do not include either in our analysis.)

In this section, we provide background on each of these fuels and estimate their carbon intensities. Table 2.4-1 provides detailed background on a range of characteristics of these fuels in combination with LOX.

Table 2.4-1: *Physical and chemical properties of modern rocket propellants.*

Metric/Attribute	Liquid Natural Gas (LNG)/LOX(Liquid Oxygen)	RP-1 (Kerosene)/LOX	Liquid hydrogen/LOX
Leading rocket platforms using the fuel	Starship; New Glenn (stage 1); Terran R; Long March 9 (stage 1 & 2); Long March 10B; Vulcan Centaur (stage 1)	Falcon 9; Falcon Heavy; Neutron	New Glenn (stage 2); Long March 9 (stage 3); Vulcan Centaur (stage 2); JAXA/MHI H3
Direct emissions (ton of carbon dioxide (tCO_2) per ton of fuel)[16]	2.6–2.75	3.16–3.5	0
Boiling Point	-161 °C (cryogenic)	Ambient (highly stable)	-253 °C (deep cryogenic)
Density	~0.42 g/cm³ (medium)	~0.81 g/cm³ (highest)	~0.07 g/cm³ (lowest)
Efficiency (I_{sp})	Medium (~330–380s)	Lowest (~300–350s)	Highest (~390–450s)
Sooting/Coking	Extremely low (clean burn)	High (requires engine teardown)	None (produces water)
Tank Size & Weight	Medium	Smallest & lightest	Largest & heaviest

a) Liquid Natural Gas (LNG)

Natural gas is a dense, low-cost, high-energy fuel. When liquified through purification, compression and refrigeration, its energy density increases greatly, making it a viable rocket fuel. Many companies use LNG as a rocket fuel, most commonly for the first stage of liftoff and return. These companies include SpaceX (Starship), Blue Origin (BE-4)[17] and China's Long March 9 (first stage),[18] 10B (second stage) and LandSpace Zhuque-2 and -3.[19,20] India also has several LNG-fueled rockets, including the Skyroot Aerospace[21] (Dhawan series)[22] and Astrobase.[23] After significant investment by the Ministry of Economy, Trade and Industry (METI) in LNG-fueled rockets, Japan expects to use the new Zero rocket,[24] developed by the private company Interstellar Technologies.

Burning LNG produces carbon dioxide (CO_2), the most important GHG. Methane, the chief constituent of natural gas, is a strong GHG itself. Standard operating procedure for LNG rockets upon return is to vent remaining fuel, adding to climate impacts.

The most important components in the overall GHG emissions intensity footprint of LNG as a rocket fuel are as follows:

- Carbon in the fuel itself, roughly 2.75 kg CO_2/kg LNG, is the chief component. While this physical carbon content cannot be modified, the net CO_2 emissions can be reduced through use of renewable natural gas (RNG) or synthetic e-methane, which today would add significant cost and greatly limit supply. This chapter does not consider e-fuels or RNG in footprint estimation.
- Upstream fugitive emissions of methane associated with flaring or leakage from production and transportation infrastructure are also potentially important. Many companies have banned conventional flaring and have instituted low-upstream method protocols and verification,[25] but practices vary widely by geography and regulatory requirements. Upstream leakage rates range between less than 0.5% of produced volume to over 6%.[26,27] (In this chapter we use a 100-year CO_2 equivalent (CO_2e) impact for methane according to the Intergovernmental Panel on Climate Change (IPCC) Working Group III's Sixth Assessment Report (AR6 WG1) report[28] and also include the 20-year impact for illustrative purposes.)
- Liquefaction, which requires polishing and purification, compression and cooling, adds to the GHG footprint. These steps require significant electricity inputs, which today are almost entirely generated by co-located natural-gas power generation. This adds roughly 5–16% to the carbon intensity of the fuel.[29] Low-carbon electricity (e.g., renewables, nuclear) or application of carbon capture and storage (CCS) could reduce the emissions from this step.
- For rocket fuel, ultra-low sulfur methane is needed, which can add significant cost and energy penalties for purification.[30,31] Given the lack of publicly available information on this step, we assume modest additional capital, operational and associated emissions.
- Incomplete combustion can create soot (black carbon) in the exhaust stream, which adds to radiative forcing. In general, operators ensure high conversion efficiency (>98%) so that relatively little soot is generated. However, black carbon can still be an important issue if it is deposited in the stratosphere (see below).

Assuming conventional production practice, LNG carbon intensities can range between ~3.01 kg CO_2e/kg LNG and ~4.90 kg CO_2e/kg LNG, chiefly as a function of low upstream leakage (see Table 2.4-2).

Table 2.4-2. *Carbon intensity of liquefied natural gas (LNG) rocket fuel for different upstream methane leakage rates, in kg CO_2e/kg LNG. Assumes full conversion of fuel (no soot), and a mean value for emissions from liquefaction and processing. Values using the 20-year global warming potential (GWP) for methane are indicated in italics.*

Component	Low leakage (0.5%)	High leakage (6.0%)
Direct combustion	2.75	2.75
Liquefaction and processing	0.11	0.11
Fugitive methane (100-year GWP)	0.15	1.79
Total: 100-year CO_2e	**3.01**	**4.90**
Fugitive methane (20-year GWP)	*0.41*	*4.95*
Total: 20-year CO_2e	***3.27***	***7.81***

Note: Commodity LNG cannot be used for space flight. Rocket fuel requires ultra-low sulfur distillation (as with kerosene refined into RP-1). Little public information is available regarding the price and energy implications of this process, and it is not included here.

b) Kerosene

Kerosene is the workhorse of rocket engine flight, commonly in the highly refined form of RP-1.[32] Kerosene combines high combined gravimetric and volumetric density and is liquid at the Earth's surface, simplifying fuel-handling logistics (these are also reasons why kerosene constitutes most aviation fuel). Roughly 45% of all launches in 2019 used kerosene and LOX as propellant.[33] Falcon-9 and Falcon-Heavy rockets use kerosene, as do Russia's Roscosmos Soyuz-2 and China's Long March 6. Firefly Aerospace uses kerosene to power its Reaver and Lightning engines.[34]

The carbon intensity of kerosene-based fuels like RP-1 is overwhelmingly from combustion of the fuel itself. There is no significant direct radiative forcing from unburned kerosene, and refining and polishing are small components of the fuel's carbon intensity. We estimate upstream emissions from fuel production between 0.5 to 0.65 gCO_2e/g RP-1.[35,36] However, since RP-1 involves greater refining than jet fuel, true values could be higher.[16]

However, combustion of kerosene produces significant amounts of soot (black carbon), far more than combustion of LNG. This contributes to the overall climate impact. A heavy launch engine using 1000 tons of RP-1 generates roughly 20–40 tons of black carbon, which varies by engine design and launch-cycle parameters. The climate impact of this black carbon varies significantly by the altitude at which it is released:

- Black carbon released in the troposphere (up to roughly 18 km at the equator) has an atmospheric residence time of roughly one week,[37] limiting its overall impact on warming.

- Black carbon released in the stratosphere (above roughly 18 km at the equator) remains in the atmosphere for much longer because it is not washed out by weather processes. The typical lifetime of stratospheric black carbon is 1–2 years, giving it a far higher climate impact. It also has ~5x higher radiative adsorption efficiency than tropospheric black carbon.

A significant percentage of black carbon emissions from kerosene propellants enters the stratosphere. Estimate range from 75% to 85%.[8,38]

In this chapter, we assume 22 g of black carbon emitted per kg of RP-1 (based on the estimate in Barker et al., 2024[8]) and a 25/75% split for black carbon deposition in the troposphere and stratosphere, respectively. These assumptions are conservative, given the potential range and level of confidence today. In this calculation, only the global warming potential (GWP) for tropospheric black carbon,[39] which is reasonably well understood scientifically, is included. The radiative forcing caused by stratospheric black carbon is unclear and potentially very large (see below)

Table 2.4-3: *Carbon intensity of RP-1 rocket fuel in kg CO_2e/kg RP-1. Includes soot (black carbon) emissions, as noted in the text, and a mean value for emissions from upstream refining. Values using the 20-year GWP for methane are indicated in italics. Black carbon GWP100 = 900, GWP20 = 2800 Source: Bond et al., 2013.[39]*

Component	Carbon intensity (kg CO_2e/kg RP-1)
Direct combustion of fuel	3.16
Upstream refining	0.5
Black carbon (tropospheric only, 100-year GWP)	5.0
Total: 100-year GWP	**8.66**
Black carbon (tropospheric only, 20-year GWP)	*15.5*
Total: 20-year GWP	***19.2***

c) Liquid hydrogen

Many rockets use liquid hydrogen[40] as a propellant. NASA's two-stage rockets commonly use liquid hydrogen for the core and upper stages.[41] Blue Origin uses liquid hydrogen for many of its rockets,[17] including the BE-3U, BE-3PM and BE-7, as do the Japanese HE-II series and Chinese Long March 3, 5 and 8.

Liquid hydrogen creates no GHGs when burned. However, production of liquid hydrogen results in considerable GHG emissions, and leakage of hydrogen to the atmosphere indirectly increases radiative forcing. Two components of production primarily affect the carbon intensity of making liquid hydrogen: the hydrogen production pathway and liquefaction (Table 2.4-4).

- Most hydrogen production (~98%) comes from uncontrolled natural gas conversion, often referred to as gray hydrogen.

  - Emissions can be reduced by CCS, often referred to as blue hydrogen. In this chapter, we assume 95% capture from steam-methane reforming, which would require additional energy input.
  - The carbon intensity of both these pathways is higher if there is significant upstream methane leakage, which must be mitigated, minimized and verified (see below). In this chapter, we assume 1% leakage for methane-sourced liquid hydrogen.

- Hydrogen can also be produced through electrolysis of water using low-carbon electricity, often called green hydrogen. The carbon intensity of the hydrogen is proportional to the carbon intensity of the electricity, which must be used to mitigate direct emissions from production. The reference case analyzed in this chapter assumes hydropower for electrolytic synthesis.
- Liquefaction requires deep cooling to –253 ºC (~20 K), which requires significant amounts of electricity and compression. Again, low-carbon electricity is required to minimize climate impacts. The reference case analyzed in this chapter assumes US-grid average power footprint for gray and blue cases and hydropower for the green case.

Table 2.4-4: *Carbon intensity of liquid hydrogen rocket fuel for different hydrogen production processes, assuming 1% upstream methane leakage rates, in kg CO_2e/kg liquid hydrogen. Additional assumptions are stated in the text. Values using the 20-year GWP for methane are indicated in italics. Natural gas power assumed for conventional liquefaction and processing.*

Component	Gray liquid hydrogen (1% upstream methane leakage)	Blue liquid hydrogen (1% upstream methane leakage)	Green liquid hydrogen
Steam methane reforming process (plus 15% energy penalty for blue liquid hydrogen)	9.40	10.81	N/A
With 95% capture	N/A	0.45	N/A
Fugitive methane (100-year GWP)	1.03	1.03	N/A
Electrolysis (hydro)	N/A	N/A	1.32
Liquefaction (grid or hydro)	4.56	4.65	0.29
Total (kg CO2e/liquid hydrogen produced)	**15.0**	**6.3**	**1.6**
Fugitive methane (20-year GWP)	*2.83*	*3.26*	*N/A*
Total (kg CO2e/kg liquid hydrogen)	***16.8***	***8.4***	***1.6***

These estimates assume minimal hydrogen leakage. Although H_2 is not a GHG, it indirectly increases radiative forcing by scavenging atmospheric radicals,[42] effectively extending the half-life of non-CO_2 GHGs like methane and NOx. If leakage is large enough, hydrogen can significantly affect radiative forcing.

ii. Liquid Oxygen (LOX)

Although much smaller than the footprint of the other three fuels, oxygen separation and liquefaction to LOX can add significantly to the total carbon intensity of a rocket propellant mix. LOX production requires significant amounts of energy, chiefly electricity to operate cryogenic equipment. As such, the carbon intensity of the electricity determines the carbon intensity of the LOX.

The primary means of oxygen separation is cryogenic separation, which pulls oxygen from the air by cooling it below the condensation point using an air-separation unit (ASU). This integrated process of air compression, cryogenic cooling, and final pumping and compression for storage and transport uses 600–800 kWh/ton based on optimization, unit efficiency, etc. A typical commercial cryogenic LOX ASU consumes ~670 kWh/ton. Rockets require very high purities (>99.8%) for propellants, so additional energy is often required. Because specific numbers are hard to find, we use the conservative assessments of commercial carbon intensities for LOX production (Table 2.4-5).

Table 2.4-5: Carbon intensity of different liquid oxygen (LOX) production scenarios (tonnes CO2e per tonne fuel).

Scenario or case	Carbon intensity
Low-carbon case (renewables or nuclear)	0.02
US grid average	0.27
Global average	0.38
Coal-heavy case	0.63

These calculations provide a sense of scale. The estimated US and global average cases would add roughly 10% to the GHG radiative forcing compared to LNG and 5% compared to RP-1. The renewable case would add less than 1% to total radiative forcing.

iii. Known unknowns

In assessing the launch-related emissions of GHGs and black carbon, data gaps and scientific uncertainties are significant. These “known unknowns” include the following:

- Data with respect to emissions of black carbon and water vapor into the stratosphere are poor.
- Understanding of the potential warming impacts of black carbon and water vapor in the stratosphere is limited.
- Data with respect to methane slip in and around launchpads are not publicly available.
- A large-scale deployment of satellites will, unfortunately, likely involve some accidents, but estimating the frequency of such accidents and the fuel leakages associated with them is challenging.

We discuss these topics below.

a) Stratospheric black carbon

Releases of black carbon into the stratosphere during the launch of SBDCs could have very significant warming impacts. Uncertainties are large, the physics are complicated and measurements are scarce.

Importantly, no altitude-dependent characterization factor exists for rocket-emitted black carbon. As a result, uncertainties are extremely large and radiative forcing could be 10s to 100s of times larger than the direct CO_2 emissions from launches.

For RP-1 use, each launch would generate significant tropospheric and stratospheric soot. Tropospheric soot has a residence time of roughly a week and is readily integrated to the fuel CO_2e estimates.

Stratospheric black carbon is a different matter. Key aspects of the science are not settled, leaving significant uncertainty regarding its climatic impact.

- Little is known about the residence time of soot in the stratosphere. Estimates range from 1 to 2 years or roughly 50–100x more than tropospheric soot.
- Current studies suggest significant potential impact from regular launches. Ryan et al. (2022) estimated that the 100 launches in 2019 produced ~8 MW/m2 radiative forcing—much greater than all other direct or indirect emissions combined.[33]
- The effects of stratospheric soot on tropospheric weather are also poorly understood. While black carbon heats the stratosphere, the consequences in the upper troposphere are uncertain. The impacts on cloud formation and associated optical depth are complicated and could potentially include both short-term cooling and long-term warming.[43,44]
- The specific chemistry of the soot45 affects its radiative forcing and possibly its residence time, which in turn can lead to significant climate impacts.
- Since the soot would be deposited chiefly along launch paths, this could lead to local patches of very high black carbon concentration.
    - The transport and diffusion times of this black carbon are unknown.
    - Similarly, the consequences of patches of high-density stratospheric soot are unclear.
    - Studies show[46] significant variability of impact based on latitude, longitude and season of black carbon emissions and that patches of black carbon can have outsized impacts on regional climate.[45]
- Although the black carbon from RP-1 is well understood, soot produced from LNG/LOX propellants is essentially unmeasured.[47] Methane combustion produces roughly 80% less soot than kerosene combustion, including cleaner burning and afterburn effects.[8] Direct observations are important to understand structure, volume and atmospheric disposition.

Studies show that the majority of soot would enter the stratosphere between 15 and 50 km (Figure 2.4-1), although the ranges vary significantly between scholars.[8,38,48] Current studies suggest that black carbon at this elevation could represent peak radiative forcing of over 400% increase (5x), although again the consequences are unclear.[43] The longer residence time and higher radiative forcing produce 250–500x greater estimated radiative forcing than for tropospheric ozone. Estimates for a 100-year GWP exceed 6000 tons CO_2e per ton of RP-1, roughly 2000x larger than the direct CO_2 emissions. However, these estimates are highly uncertain and would vary significantly with LNG or liquid hydrogen fuels. Similarly, the consequences of stratospheric forcing are poorly constrained and could be modest or lead to cooling (see above).

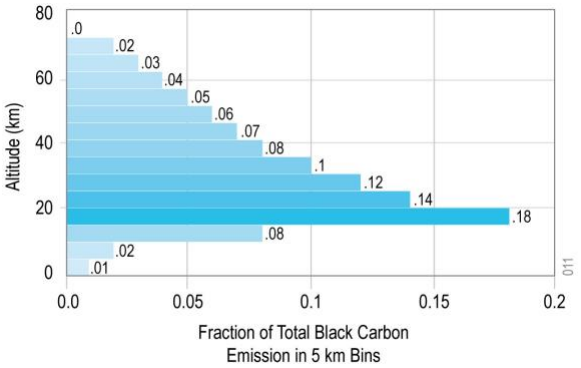


Figure 2.4-1: *Deposition of black carbon into the atmosphere. The stratosphere is 10–60-km elevation and receives ~85% of total black carbon from launch, significantly different than the 25/75% split used in this chapter. Source: Maloney et al., 2022.[38]*

Ryan et al. (2022) found that 100 launches with conventional propellants in 2019 may have produced significant climate consequences.[33] It is reasonable to assume that thousands of launches in the next few years could have a dramatically greater consequence, with unknown effects on weather patterns and climate, both regional and global. Data collection and further scientific analysis of this topic should be a high priority. In combination with other safety risks related to SBDCs, the risks related to black carbon emissions in the stratosphere provide a compelling basis for a slow SBDC launch cadence in the years ahead until risks are better understood and managed.

b) Stratospheric water vapor

Water vapor is a powerful GHG. While the radiative forcing of water vapor in the lower atmosphere (troposphere) is well understood, much less is known about water vapor in the stratosphere. The lower atmosphere is effectively saturated with water vapor; consequently, the water cycle of evaporation and precipitation fully exchanges atmospheric water volume 40 times a year. Concentration of water vapor depends on average temperature, so higher average tropospheric temperatures allow increased saturation of water vapor, which multiplies radiative forcing.

In contrast, water vapor enters the stratosphere rarely, driven largely by rare events that entrain water. The 2022 Hunga Tonga volcanic eruption brought mostly water vapor into the stratosphere—an estimated volume of 100–150 million tons—providing an opportunity to better calibrate its effects.[49] Studies of the eruption estimate the residence time of stratospheric water vapor to be 5–10 years, and the radiative forcing of the event to be ~0.05 W/m^2 (pretty small).[50] While these studies are important, they do not address all uncertainties associated with radiative forcing of stratospheric water vapor. They also do not address the potential for stratospheric ice formation, which directly increases risks to the ozone layer.

Based on the stoichiometry of combustion, a single Falcon-9 launch would deposit ~150 tons of water vapor in the stratosphere, 500,000x smaller than the small effect of the Hunga Tonga eruption. A Starship Super Heavy configuration would deposit ~1500 tons of water vapor in the stratosphere, roughly 50,000x smaller than the eruption. Based on these results, stratospheric water vapor appears to be a very small GHG warming factor. However, the science is incomplete, and more study is required to rule out stratospheric water vapor risks and impacts.

c) Methane releases

Some amount of methane is accidentally or operationally released in connection with launches, independent of upstream leakage. This includes slip (e.g., release from fueling or boil-off), incomplete fuel combustion and venting of unused fuel after launch. These methane releases could add significant GHG emissions from direct release. (Catastrophic release of LNG from accidents is covered separately below.)

Text Box: UNCOMBUSTED PROPELLANT

An important unknown term is the amount of LNG and LOX vented by returning spacecraft.

- The Falcon-9 booster uses RP-1, which is readily regathered.
- The Starship LNG is different: current practice is that any remaining fuel on the Starship Heavy is vented upon landing due to cryogenic boil-off.
- This practice is likely to be the same for BE-4, Long March 10 and other LNG-powered spacecraft.

Data are not available regarding the tonnage typically vented. If remaining fuel is gathered and reused, the fugitive emissions with this practice are also unknown. Assuming 100 tons of residual LNG/LOX propellant and 100-year GWP, each return would add 625 tons of CO_2e to the atmosphere, roughly an additional 15–20% beyond that from the launch. In contrast, 100 tonnes of vented LNG would add ~3000 tons CO_2e, or roughly 70% more radiative forcing. This topic requires additional research.

No data are available on operational slip from fueling or boil-off—a significant point of uncertainty. There are also no available data on uncombusted fuel from launch. In general, Falcon rocket engines burn lean and are highly efficient, suggesting minimal release of unused methane. There are no reliable data regarding methane slip or uncombusted fuel from Starship launches, nor from BE-4 or Long March 10. This is another point of significant uncertainty.

Absent direct information from operators and governments, this study is reasonable to assume no more than 2% slip and uncombusted fuel, which would contribute roughly 0.6 tons of CO_2e per ton of LNG fuel (assuming a 100-year GWP). For a Falcon Heavy booster plus Starship, 2% methane release from the 1278 tons of fuel would be ~25 tons of fuel, or ~750 tons CO_2e per launch.

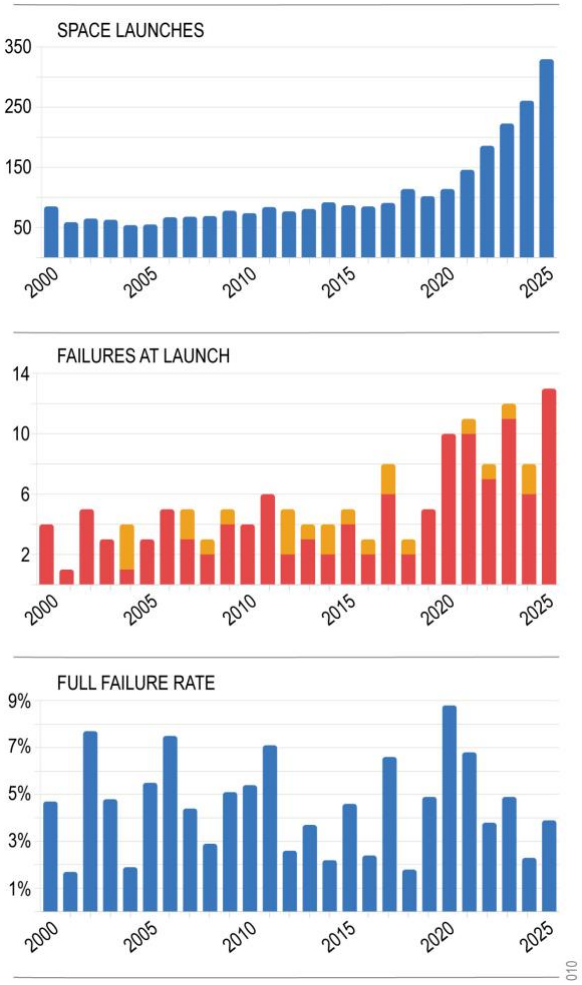


Figure 2.4-2: *Upper chart: Time series of annual number of space launches. Middle chart: Failures at launch (red are full failures, which do not reach orbit; yellow are partial failures, which do not deliver full payload). Lower chart: Full failure rate (full failures vs. total annual launches) by year. All figures are global. SOURCES: Wikipedia annual spaceflight summaries (e.g., 2024[52] and 2025[53] and statistical analysis pages from Jonathan McDowell Space Report[51])*

d) Accidents

An accidental release of fuel, by explosion or jettison, is in effect a 100% fuel leak into the atmosphere. Hydrogen's radiative forcing is caused by scavenging free radicals (e.g., hydroxyl ions) from the atmosphere, thereby extending the life of shorter-lived non-CO_2 gases like methane and nitrous oxides. In contrast, LNG is pure methane, which is a strong direct GHG.

The radiative forcing of uncombusted fuel can be significant—commonly ~20% of fuel is consumed in explosion, while the remainder is dispersed by shock waves. Assuming 80% of fuel is uncombusted due to explosion, a Starship explosion would vent ~1025 tons of methane, with a 100-year GWP of ~32,000 tons CO_2e. In contrast, the radiative forcing of 61 tons of uncombusted hydrogen from a modified Falcon-9 system would be ~670–2100 tons CO_2e using a 100-year GWP.

The consequence of accidents, rare though they are, could prove significant in terms of GHG warning and radiative forcing. In 2025, the failure rate was about 4% (13 out of 330 launches globally) (Figure 2.4-2 The majority of these were full failures, in which the rocket and payload did not reach orbit. Of the 124 failures this century, roughly 20% appear to be explosions,[51] which vent propellants to the atmosphere. This is another potential focus for better characterization.

Naturally, operators seek to avoid all accidental explosions and venting. The data below suggest there is no improvement over time. One interpretation: we are still at the early phase of deployment for advanced rocket technologies, so learnings have not yet materialized from experience.

iv. Sample launches

Based on the analysis above, we now estimate emissions from several sample launches of SBDCs. Our Reference SBDC, used for analysis in this Roadmap, weighs 2.5 tons (see Text Box 1-1). Based on this weight, we estimate the fuel used and, by extension, GHG and black carbon emissions for a Starship/Super Heavy configuration.

One Starship/Super Heavy is capable of carrying a 100-tonne payload. This translates to a maximum payload of 40 reference satellites of 100 kW each (4 MW). Rockets rarely operate with a full payload to ensure adequate system performance. The average capacity for rockets launched to LEO in the past year was roughly 85%[54] (although SpaceX has filled its Falcon 9 launches for Starlink to 96% capacity).[55] We assume a slightly smaller number of satellites: 36 per launch, or 90 tons of payload. As discussed in Text Box 1-1, 100-kW satellites will likely be heavier than 2.5 tons, in which case a smaller number of units could enter orbit per launch, requiring more launches to achieve the same computational capacity, with higher total emissions.

Direct and indirect estimates of GHG and black carbon emissions are set forth in Table 2.4-6. Scope 3 (upstream) emissions include liquefaction of LNG and LOX, assuming 1% upstream emissions of methane. We assume 2% operational slip and 100-year GWP. We list potential contributions from soot separately (assuming 80% less soot that RP-1) and assume zero effective radiative forcing from water vapor.

Table 2.4-6: *High-likelihood direct and indirect GHG emissions for a single launch (100-year GWP). Units are tonnes CO2e.*

Propellant	Tonnes CO_2e
Total LNG + LOX	1278 + 4600
Methane (1% upstream leakage)	13
Methane (2% slip)	25
Black carbon produced	6.4
GHG emissions	**CO_2e**
From combustion (CO_2 produced)	3444
From fuel production (Scope 3)	1726 (478 + 1248)
From 1% upstream leakage (100-year GWP)	375
From 2% operational slip + venting (100-year GWP)	750
Stratospheric water vapor (100-year GWP)	~0
Subtotal	**6297**
Black carbon	
Tropospheric black carbon (100-year GWP)	2939
Stratospheric black carbon (100-year GWP)	0 to 1,380,000
Total	**9,236 + possible 1,380,000**

This estimate is similar to Osoro et al. (2026)[4] and Aili et al. (2026)[56] but on the low end of some estimates. For example, Andrew Wilson[57] at Glasgow Caledonia University estimates a single Starship/Super Heavy launch "worst case" scenario to emit ~76,000 tonnes CO_2e—roughly 8.5 times larger than our estimate.[58]

D. Emissions from Manufacturing and Production

Manufacturing SBDCs and the rockets required to launch them results in GHG emissions (often called "embodied emissions"). We discuss the embodied emissions of SBDCs below.

i. Servers

Key components of the servers used in SBDCs (chips and memory, lithium batteries[59]) are largely similar to terrestrial servers, although they have radiation shielding and modified heat exchangers.

The embodied emissions of a single terrestrial 100-kW rack are roughly 135 tons.[60,61] Assuming these are equivalent in a satellite and each satellite serves a 5-year mission, this yields an estimate of 27 tonnes/year CO_2e. If 10,000 terrestrial racks constituted a 1-GW constellation, that would sum to roughly 270,000 tonnes/year CO_2e.

ii. Satellites

Satellites have typically used gallium arsenide (GaAs) solar photovoltaic (PV) cells because of efficiency and radiation resistance, but recent innovations in radiation protection and manufacturing have led to modified silicon-based PV cells being used.[62] Radiators are specially designed for space, with material types ranging from aluminum to carbon polymer composites for more recent missions.[63] Finally, some components are unique to space missions, including propulsion (e.g., Hall thrusters[64]) and optical communication terminals.[65]

Based on a crude bottom-up materials estimate, the carbon footprint of the 1-GW reference constellation described in Textbox 1-1 could be 300–700 tonnes CO_2e per reference satellite, compared to the 27 tons for just the IT equipment (chips, memory, etc.)[56] A constellation of 10,000 SBDCs would have a GHG footprint on the order of millions of tonnes CO_2e, which may be similar to the carbon intensity of their terrestrial equivalents when terrestrial solar panels, concrete, steel and aluminum housings are included. This comparison requires further research.

iii. Rockets

Very little information with respect to rockets' embodied GHG emissions is publicly available. Some researchers have used the restricted Strathclyde Space Systems Database[1] (for example, Osoro et al., 2026 estimates for the Falcon-9 Block 5 system[4]). Since space-grade materials (metals, components) often involve significant refining and fabrication, simple estimates based on typical carbon intensities for steel or aluminum are likely underestimated.

The footprint of the rockets themselves is sensitive to the number of times they are used. A key term is the number of uses per booster. While Osoro et al. (2026)[4] assume the Falcon booster system returns 10 flights, the system now has on average greater than 25 return flights[66] and has recently

exceeded 35 return flights for a vehicle.[67] (However, the Falcon-9's second stage system does not return and should be considered single use). Several other companies are also beginning to demonstrate re-usability across multiple launches.[68,69] Based on these improvements, it appears likely that return-flight vehicles like the Super Heavy booster will achieve similar levels of performance, exceeding 25 return flights per vehicle.

Osoro et al. (2026) estimate a carbon footprint for the Falcon 9 of ~22,000 tons CO_2e per launch, assuming 10 launches.[4] Removing the contributions from fuel, the embodied carbon would be roughly 20,000 tons/launch, again assuming 10 launches. Since key terms in this analysis are not publicly available, it is unclear if this is accurate and representative. Assuming 30 returns for the Falcon booster system would reduce the per-launch embodied emissions estimates to about 6600 tons, not including the one-time costs for the booster or second stage.

The reusable Starship Super-Heavy booster is still in development and does not yet have sufficient field data to definitively estimate weight, composition and the number of likely flights. Like the Falcon second stage, the upper stage of the Starship (the "Ship") will not be re-flown. Osoro et al. (2026) did not analyze a Starship Super-Heavy system, providing no estimates.[4] In large part because the Starship Super-Heavy is a new vehicle, there is no current literature on its embodied emissions. Importantly, the Starship Super-Heavy uses steel as the primary dry material input, in contrast the Falcon systems, which are chiefly made of aluminum-lithium composites. For either steel or aluminum, the range of potential carbon intensities is very large, with a factor of 10 or greater variance based on the carbon intensity of electricity input, choice of primary versus recycled feedstocks, and manufacturing pathway. Again, data-rich, robust, independent analysis is needed.

Robust, reliable information from supply chains is necessary to generate accurate LCAs. The discussion of rocket embodied carbon in this chapter is intended to serve as a starting point or point of comparison for future analyses.

E. Summary Scenarios

i. Reference Scenario for 1 GW

Given the speed and scale of terrestrial data center construction, we chose to estimate emissions for a 1-GW SBDC reference scenario. This would require a constellation of 10,000 satellites (each requiring 100-kW power) in LEO.

- Vehicle: Given the speed of the advancing field, we selected the SpaceX Starship Super-Heavy configuration, in part due the likelihood of rapid advances on this vehicle and the announced reduction in service of the Falcon 9.
- Fuel: A single Starship Super-Heavy launch uses ~1278 tons of LNG, or 62.4 million standard cubic feet (scf) (about a week of gas for a small state, like Hawaii) and 4600 tons of LOX. We assumed 1% upstream fugitive emissions and 2% operational methane release.

- **Payload**: Assuming each launch would bring ~36 satellites carrying 100-kW racks (85% payload capacity), ~295 launches would be needed to place 10,000 satellites in LEO using Starship Super-Heavy vehicles. We use 300 launches to simplify, or 82% of payload capacity.
- **Accidents**: As a conservative assumption, we selected 1 catastrophic accident per 300 launches.
- **Service life**: Assuming a five-year service life for the satellite constellation divides the annual carbon intensity by five. We assume a 100% compute capacity factor.
- **Other terms**: Given the high uncertainty in stratospheric black carbon and stratospheric water vapor, we chose not to include them in the reference 1-GW constellation emissions scenario.

Estimating embodied emissions is especially challenging, in light of the lack of available data. We provide a very rough estimate as as follows:

- Embodied CO_2e missions for the Falcon 9 are roughly 200k tonnes embodied CO_2e/rocket.[4] Based on conversations with one of the authors of the paper, we believe this is a deliberately conservative estimate that serves as an upper-bound.
- The Starship Super-Heavy weighs roughly 16x more than the Falcon 9[3,4] but is made of a material (stainless steel)[70] with roughly one-third the carbon intensity of the material used in the Falcon 9 (space-grade aluminum).[71] Accordingly, we estimate that embodied CO_2e emissions for each Starship Super Heavy is roughly 5.3 times the embodied CO_2e emissions for a Falcon 9.
- Multiplying 200k × 5.3, we estimate the embodied CO_2e emissions per Starship Super-Heavy Rocket to be 1,060,000 tonnes—an upper-bound.
- Assuming 30 launches per Starship Super-Heavy rocket, we estimate roughly 35,000 tonnes embodied CO_2e/Starship Super-Heavy launch.
- Assuming 300 launches/1-GW constellation, 35,000 tonnes CO_2e × 300 launches = 10,500,000 embodied CO_2e/1-GW constellation.
- We assume each constellation lasts for 5 years, so 10,500,000 tonnes of embodied CO_2e divided by 5 years of launches = 2,100,000 tons of embodied CO_2e/year for a 1-GW constellation, again as an upper bound.

In light of the considerable uncertainties and suggestion that the 200K tonnes of embodied CO_2e/Falcon 9 rocket is an upper bound, we selected a range of 1,000,000–2,000,000 tonnes embodied CO_2e/year for a 1-GW constellation as a very rough estimate in the text that follows. We reiterate that more data and research are needed to more precisely estimate these values. We also recognize there are ways in which the carbon intensities of the Starship Super-Heavy might be improved.

Using the estimate from Table 2.4-6 (~9200 tonnes CO2e/launch) together with the above assumptions yields a scenario with ~558,000 tonnes CO2e without embodied emissions and ~1.5 million–2.5 million CO2e including embodied emissions.

ii. Comparison with emissions from terrestrial data centers

Insight on the risks and impacts from SBDC emissions and radiative forcing requires the context and understanding provided by comparison with their terrestrial counterparts. The direct, indirect and embodied emissions from terrestrial data centers vary significantly as a function of energy source,[72] material fabrication, use, cooling method and local climate. SBDCs appear to show roughly the same GHG footprint as terrestrial data centers powered by clean energy sources and a significantly better footprint than those powered by uncontrolled fossil power or mixed grids.

Table 2.4-7 and Figure 2.4-3 below show the 1-GW orbital data center calculation and compare it with several terrestrial cases. Importantly, the full embodied emissions (Scope 3) are included in these estimates to ensure better parity between examples.

Table 2.4-7: *Estimated total annualized emissions and electricity carbon intensity for different 1-GW compute cases, assuming Starship Super-Heavy launches, low Earth orbit (LEO) and a 5-year satellite life.*

Compute power source	Annualized CO2 equivalent (CO2e) emissions (tonnes)	Carbon intensity, CO2e/kWh	Key assumptions
1-GW scenario: low Earth orbit (LEO) compute, 5-year satellite life, using 10 Starship Super-Heavy vehicles over 300 launches	1,558,000–2,558,000 total 558,000 (direct & indirect) plus 1,000,000 to 2,000,000 (embodied)	~178 total ~64 (direct & indirect) plus 68 (embodied)	~300 launches (roughly 82 tons per launch or 82% of payload capacity); 1 catastrophic accident per 300 launches; 2% methane operational leakage and 1% upstream. Excludes black carbon and water vapor due to uncertainty
US Average Grid	3,329,000	380	
Natural Gas Combined Cycle (NGCC), uncontrolled	2,297,000	262.3	1% upstream leakage, 65% capacity factor, 60% efficiency
NGCC + 90% carbon capture and storage (CCS)	473,000	51.9	1% upstream leakage, 65% capacity factor, 60% efficiency, 25% energy penalty
Solar + 12 hrs Li-ion (10-year amortization)	484,000	55.3	Includes Scope 3 from panels and batteries
Hydropower	210,240	24	Intergovernmental Panel on Climate Change (IPCC) median life-cycle assessment (LCA)

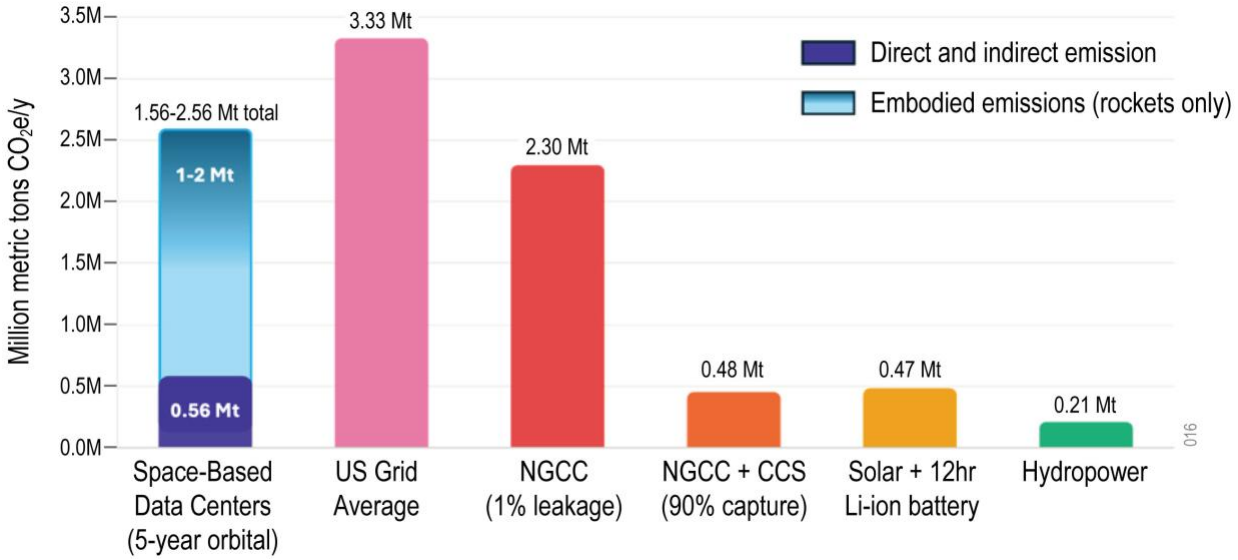


Figure 2.4-3: *Life-cycle annualized greenhouse gas (GHG) emissions for space-based data centers (SBDC) and terrestrial data centers. Assumes 1-GW continuous electricity supply (tonnes CO_2e). Embodied emissions for SBDC include only launch vehicles (rockets). The embodied emissions for information technology (IT) devices and power generation are not included in any data center calculation. (CO_2e = CO_2 equivalent; NGCC = natural gas combined cycle; CCS= carbon capture and storage; Li = lithium)*

Based on the foregoing assumptions, the estimated launch plus embodied emissions from SBDCs are between roughly 60% and 120% of uncontrolled natural gas combined cycle (NGCC), ½-¾ of the US average grid, and more than 3 to 10 times higher than clean options. Said differently, the apparent GHG and black carbon emissions for a 1-GW SBDC are likely more than 1-GW clean options on Earth. If only direct and indirect GHG emissions are included (i.e., excluding embodied emissions), then the direct + indirect GHG emissions would be close to most terrestrial clean options.

Finally, SpaceX has said that it hopes to execute 10,000 launches per year or more, not 300.[73-75] These launches would not all be for data centers, so the fraction of launches for SBDCs versus other SpaceX applications remains another uncertainty. Since other nations and companies might add launches for their own purposes, there is a potential to add significantly to launch-related emissions.

F. Significant Uncertainties

Estimating the potential climate impacts of satellite fabrication and launch with precision relies on scenarios, forecasts, and incomplete data and science. Reducing the uncertainties around a few key terms would greatly enhance the ability to make accurate and precise estimates of current and potential future impacts.

In the near term, one important point for added clarity is number of launches and type of propellant. There is a huge difference between 250 launches (roughly 1-GW compute) and 10,000 launches (announced SpaceX plans) in terms of total emissions. There is a huge difference between kerosene-

and LNG-fueled rockets. A smaller but easier uncertainty to resolve is around the energy and carbon costs of refining LOX and LNG to rocket-fuel specs.

As discussed above, the apparent venting of LNG from returning spacecraft would represent a significant GHG contribution. This is not an uncertainty of physics or chemistry, but an uncertainty of operational practice. Resolving this uncertainty requires transparency from operators and focus from regulators.

Much larger uncertainties surround the climate and environmental impacts of stratospheric black carbon and aluminum oxides. These will take longer to resolve but are potentially of greater consequence.



Figure 2.4-4: *Artist's conception of stratospheric drone fleets collecting data from a SpaceX Starship launch. Image generated by Shutterstock*

- The size of the uncertainty, even the sign of the signal, is not fully resolved. This likely affects both climate and weather.[76]
- The impact sensitives to clustering, altitude, seasonality and latitude are poorly understood.
- The amount of deposition of stratospheric black carbon and aluminum oxides are poorly quantified. The implications for surface chemistry are also poorly understood and could directly affect radiative forcing and ozone depletion risk.

Given these uncertainties, data gathering becomes a critical undertaking. Given the fixed location and LEO orbital trajectories of most launches, both ground-based and stratospheric monitoring campaigns would be straightforward. Such programs may already exist in a limited way in nations with significant space programs (e.g., the Lufthansa-CARIBIC program).[45] If such programs are already collecting these data, federating and sharing this information would be extremely valuable in reducing uncertainties and developing mitigation plans (e.g., through novel rocket designs).

Ongoing uncertainties include our ability to produce clean propellants and the trade-off associated with them. Some of this relates to access to low-carbon electricity and its price, which will dramatically affect green hydrogen production readiness and cost, as well as LOX and liquefaction of LNG. The many modern demands for clean power are complicated by infrastructure limits, permitting debates and green-premium buyer willingness. The technical readiness of solutions like e-methane remains an open question. There may be additional questions around the ability of supply chains to scale up and the associated trade implications. These may all affect the total footprint of SBDCs and rocket launches, as well as the rate of scale up.

Roughly 13 GW of new terrestrial data centers were added in the US in 2025, reaching ~65 GW total load.[77,78] Estimates for annual growth of terrestrial compute worldwide is 20–27%[79,80]—a doubling of total data center compute by 2030. During this time, it is possible that SBDCs would achieve 1 GW of compute. This would involve significant investment in new infrastructure -- including launch, manufacturing and fuel production. Whether that infrastructure would have a lower environmental footprint than for terrestrial data centers is uncertain.

Finally, there are important "no-regret" strategies that would benefit both terrestrial data centers and SBDCs. For example, fugitive methane from natural gas production and infrastructure adds to the carbon intensity of LNG/LOX and liquid hydrogen/LOX propellants, as well as natural gas power for compute, manufacturing and liquefaction. Reducing upstream emissions would improve the environmental performance of all actors in the market. Reducing the carbon intensity of the grid through infrastructure upgrades, increased renewable power generation and grid storage, and CCS retrofits would similarly help all participants achieve commercial and sustainability goals.

G. Findings and Recommendations

FINDINGS

Finding 1: The climate impacts of SBDCs could range from very negative to positive. The range of uncertainty is large, due in significant part to lack of both data and scientific assessments on key topics.

Finding 2: In the best-case scenario, lifecycle GHG emissions of SBDCs might be somewhat less than lifecycle GHG emissions of terrestrial data centers powered by uncontrolled natural gas. Lifecycle emissions of SBDCs would likely be more than those from terrestrial data centers powered by renewable power or by natural gas power with carbon capture and storage.

Finding 3: However, in the worst case, emissions from SBDCs could be substantially higher than their terrestrial counterparts. The chief uncertainties involve stratospheric black carbon. There are strong scientific reasons to believe that the radiative forcing from stratospheric back carbon could multiply the emissions impacts of launches—perhaps modestly or perhaps as much as 500x. The potential impact from 10,000 launches using a relatively clean fuel like LNG could exceed 13 gigatons CO_2e (roughly 25% of global annual GHG emissions). Similarly, uncertainties around stratospheric water vapor are large. In addition, little is known about the volumes of methane slip during fueling and operations pre-flight or what is commonplace for venting uncombusted LNG after flight. Any of these three factors could have very large climate impacts when scaled.

Finding 4: Key data related to the climate change impacts of SBDCs are unavailable. Stratospheric black carbon from rocket launches presents enormous risks, yet there are almost no data on this topic. Other topics on which data are lacking include the embodied emissions of rockets and the volume and fate of vented propellant. Serious and sustained multi-stakeholder work on life-cycle carbon assessments is needed.

Finding 5: The potential climate benefits of SBDCs could be achieved on Earth. Terrestrial data centers powered by low-carbon electricity from renewables (including hydropower, geothermal and solar/wind plus batteries), nuclear, or natural gas + CCS generation would deliver compute with lower GHG emissions than the best-case scenarios with respect to SBDCs.

RECOMMENDATIONS

Recommendation 1: Governments, companies and other stakeholders should launch comprehensive, multi-stakeholder analyses of the GHG and black carbon emissions impacts of SBDCs. Data on stratospheric black carbon is an especially high priority. Other priority topics include methane slip for launch operations and embodied emissions of rockets and fuels.

- Key efforts should include (a) direct observation and data collection from launches, (b) federating and sharing these data and (c) analysis of results, including climate modeling, to better understand risks and impacts.
- Companies should provide governments and other stakeholders with data needed to assess likely GHG and black carbon emissions impacts of launch operations and the production of fuels and rockets. Governments should treat this information as business confidential where appropriate to encourage better data provision.

Recommendation 2: Governments should not authorize and companies should not launch large numbers of SBDC launches until uncertainties with respect to the significant potential impacts of black carbon in the stratosphere and other risks related to SBDCs are better understood.

Recommendation 3: Companies should continually reduce life-cycle GHG emissions from SBDCs, including by using cleaner fuels, cleaner rockets and cleaner engines, reducing methane slip in connection with launches and using clean electricity in production of fuels and rockets.

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