How Much Nanomachinery Can We Have on Earth?

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Abstract. To avoid melting the polar icecaps or causing any other significant changes to planetary ecology, habitability, or appearance, active nanomachinery deployed on Earth should be restricted to a baseline maximum global power limit of ~1600 TW if no environmental mitigations are undertaken. If the concentration of CO_2 greenhouse gases in Earth's atmosphere is reduced to preindustrial 280 ppm levels and if the solar insolation received by Earth from the Sun is reduced by 6%, then worldwide active nanomachinery could be allowed to release a maximum of ~13,000 TW of waste heat without melting the polar icecaps. A representative nanomachinery specific power of ~10^{-2} MW/kg at the conservative 1600 TW global power limit would imply a global mass limit of ~1.6×10^{11} kg of continuously *active* nanomachinery worldwide, or ~16 kg/person on an Earth inhabited by ~10 billion people who each receive the same allocation. This is just a tiny fraction of the ~2 billion kg/person of all diamondoid nanomachinery or atomically precise infrastructure that is potentially available to every human inhabitant of Earth using only terrestrial carbon resources, with ~100 times more mass available for silicon- or sapphire-based inactive nanomachinery using only terrestrial resources and at least ~10,000 times more inactive nanomachinery mass potentially deployable on Earth using nonterrestrial resources.

Cite as: Robert A. Freitas Jr., "How Much Nanomachinery Can We Have on Earth?" IMM Report No. 54, 21 Jul 2024; http://www.imm.org/Reports/rep054.pdf.

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1. Introduction

After more than four decades of detailed exploratory engineering and related technical studies,[1] it appears that atomically precise manufacturing of both microscale and macroscale products using nanofactories is a realistic prospect that lies “a few decades from now”,[2] given the recent accelerating pace of developments.[3]

In this paper, we wish to envision a future world in which this form of mature nanotechnology is ubiquitous worldwide, then estimate the fundamental limits that may constrain deploying such atomically precise nanomachinery on Earth, an issue first raised by this author in 1999.[4]

Today, Earth is a beautiful terrestrial planet generously endowed with air, water, and a richly complex biosphere. The addition of excessive amounts of waste-heat-producing nanomachinery might alter that. There is some evidence that the widespread deployment of human technology may already be causing some increases in global mean temperatures.[5] How far could this go? In perhaps the most extreme case, we might imagine a scenario in which all of Earth’s mass has been reconfigured into a giant ball of hot computronium,[6] inside which the virtual inhabitants (e.g., uploaded humans) might simulate a perfect copy of Earth that to them appears

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[1] Drexler KE. Molecular engineering: An approach to the development of general capabilities for molecular manipulation. Proc Natl Acad Sci U S A. 1981 Sep;78(9):5275-8; https://www.pnas.org/doi/pdf/10.1073/pnas.78.9.5275. Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.. Freitas RA Jr. Nanomedicine, Volume I: Basic Capabilities. Landes Bioscience, Georgetown, TX, 1999; http://www.nanomedicine.com/NMI.htm. Freitas RA Jr., Merkle RC. Kinematic Self-Replicating Machines. Landes Bioscience, Georgetown, TX, 2004; http://www.MolecularAssembler.com/KSRM.htm. Freitas RA Jr., Merkle RC. A minimal toolset for positional diamond mechanosynthesis. J Comput Theor Nanosci. 2008;5:760-861; http://www.molecularassembler.com/Papers/MinToolset.pdf. Freitas RA Jr. Cryostasis Revival: The Recovery of Cryonics Patients through Nanomedicine. Alcor Life Extension Foundation, Scottsdale AZ, 2022; https://www.alcor.org/cryostasis-revival/. See also http://www.molecularassembler.com/Nanofactory/ and https://en.wikipedia.org/wiki/Molecular_assembler#Nanofactories.

[2] Dr. Marie O’Mahony. The Age of Atomically Precise Manufacturing: Talking Nanotechnology with David Forrest. Intl Fiber J, 30 May 2024; https://www.fiberjournal.com/the-age-of-atomically-precise-manufacturing/.

[3] Kurzweil R. The Singularity is Nearer: When We Merge with AI. Viking Press, 2024; https://www.amazon.com/Singularity-Nearer-Ray-Kurzweil/dp/0399562761.

[4] Freitas RA Jr. Nanomedicine, Volume I: Basic Capabilities. Landes Bioscience, Georgetown, TX, 1999, Section 6.5.7, “Global Hypsithermal Limit”; http://www.nanomedicine.com/NMI/6.5.7.htm.

[5] https://en.wikipedia.org/wiki/Intergovernmental_Panel_on_Climate_Change.

[6] Sandberg A. The Physics of Information Processing Superobjects: Daily Life Among the Jupiter Brains. J Evol Technol 1999 Dec;5(1); https://jetpress.org/volume5/Brains2.pdf.

indistinguishable from the original unmodified planet. Such planetwide transformations are not the subject of this paper. Rather, our main purpose here is to examine the limits of technological deployment that will *not* materially alter the existing Earth. Specifically, the objective is to think about how much nanomachinery our planet could accommodate without suffering any significant changes to its current ecology, habitability, or appearance.

All technology-based activities critically depend upon the availability and application of energy. Therefore, if we wish to think about what a nano-intensive world might look like, we must first ask the question: What are the ultimate limits to power generation on Earth? This is not a limit based on local energy availability. Importation of space-based solar energy, or the development of widespread ground-based nuclear power or other compact energy-producing sources,[7] could theoretically support the power demands of Earthbound atomically precise nanomachinery in virtually any intensity desired. The principal limit to the deployment of nanomachinery on Earth is the impact of its waste heat on the environment.[8]

As a useful analogy, consider a large population of medical nanorobots deployed inside a human body. These devices will generate a certain amount of waste heat, warming the patient's body. Humans normally produce at least **0.1 kW** of basal (resting) metabolic waste heat, but maximum athletic efforts can run this up to ~**1.6 kW**, temporarily raising body temperature by 3.5 °C during the exertion.[9] This observation supported an early recommendation[10] that a population of active nanorobots resident inside a human body for any extended period of time should conservatively seek to release no more than ~100 watts of waste heat to avoid harming the patient.

But the body mainly employs evaporative cooling to carry off internally generated waste heat. For short periods of time, adult humans can produce a maximum of 4 L/hr of sweat.[11] This is mostly liquid water that, if deployed with maximum efficiency, could, in principle, carry off up to **2.7 kW** of waste heat.[12]

The limits of nanorobot waste heat toleration in the human body can be stretched further by employing some form of external refrigeration. For instance, a patient could be submerged in a

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[7] Freitas RA Jr. Energy Density. IMM Report No. 50, 25 June 2019, 516 pp; http://www.imm.org/Reports/rep050.pdf.

[8] https://en.wikipedia.org/wiki/Climate_change.

[9] Freitas RA Jr. Nanomedicine, Volume I: Basic Capabilities. Landes Bioscience, Georgetown, TX, 1999, Table 6.8; http://www.nanomedicine.com/NMI/Tables/6.8.jpg.

[10] Freitas RA Jr. Nanomedicine, Volume I: Basic Capabilities. Landes Bioscience, Georgetown, TX, 1999, Section 6.5.2, "Thermogenic Limits *in vivo*"; http://www.nanomedicine.com/NMI/6.5.2.htm.

[11] Gisolfi CV. 5. Water Requirements During Exercise in the Heat. In: Marriott BM, editor. Nutritional Needs in Hot Environments: Applications for Military Personnel in Field Operations. National Academies Press (US), Washington DC, 1993; https://www.ncbi.nlm.nih.gov/books/NBK236237/.

[12] The heat of vaporization of water at 37 °C is ~2400 kW/kg (https://www.engineeringtoolbox.com/water-properties-d_1573.html), and (2400 kW/kg) (~4 kg/hr) / (3600 sec/hr) ~ 2.7 kW.

bath of continuously recirculating ice-cold water. Unfortunately this noninvasive method would be extremely inefficient because thermal conduction would only occur through the relatively small surface area of the skin. Skin tissue typically vasoconstricts when exposed to cold,[13] greatly reducing the ability of the blood to convey excess internal heat to the outermost body surfaces for disposal.[14]

Most efficiently, a highly invasive vascular-like internal plumbing network such as a vasculoid[15] installed in the vasculature throughout the patient's tissues could circulate chilled water or ice slurries to every part of the body, penetrating even into the capillaries, carrying off supermetabolic waste heat generated by an *in vivo* nanorobot population. For instance, a slurry consisting of submicroscopic water-ice particles suspended in cold liquid propanol[16] might have nearly the highest theoretical heat-carrying capacity of any common refrigerant liquid. The energy required to warm water-ice from, say, 150 K (-123 °C) to 273 K (0 °C), melt it, then warm it from 273 K to 310 K (37 °C), is $E_{thaw,body} \sim \rho_{ice}\ c_{ice}\ (T_{273K} - T_{150K}) + \rho_{ice}\ H_{fusion,water} + C_{V,water}\ (T_{310K} - T_{273K}) = 5.74 \times 10^8\ J/m^3$, taking $\rho_{ice} = 916.7\ kg/m^3$ (the density of ice at 0 °C), $c_{ice} \sim 1400$ J/kg-K (the average specific heat of ice over the indicated temperature range),[17] $H_{fusion,water} = 333{,}550$ J/kg (the heat of fusion of water at 0 °C),[18] and $C_{V,water} \sim 3 \times 10^6\ J/m^3$-K (over the indicated temperature range). The human vascular system circulates blood at $V_{slurry} = 5.4$ L/min. Assigning a similar volumetric capacity for the slurry-transporting vasculoid and assuming the slurry is $f_{water\text{-}ice} = 50\%$ water-ice by volume, this extremely aggressive cooling system might be able to remove a continuous $P_{slurry} \sim f_{water\text{-}ice}\ E_{thaw,body}\ V_{slurry} \sim$ **26 kW** of nanorobot waste heat from the human body.

Even higher power levels may be tolerable for brief periods of time. The highest heat capacity material in a person's body is its water content. A 70 kg adult male body is perhaps 70% water by weight, or $m_{water} \sim 49$ kg. The highest survivable human body temperature ever recorded is 46.5 °C,[19] which is $\Delta T \sim 9.5$ °C above the normal (basal) body temperature of 37 °C. The

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[13] Alba BK, Castellani JW, Charkoudian N. Cold-induced cutaneous vasoconstriction in humans: Function, dysfunction and the distinctly counterproductive. Exp Physiol. 2019 Aug;104(8):1202-1214; https://physoc.onlinelibrary.wiley.com/doi/10.1113/EP087718.

[14] Of course, *in vivo* nanorobots could selectively force the capillary beds in skin tissue to remain open, to allow rapid heat conduction to continue, but this would have to be done carefully to avoid other medical complications.

[15] Freitas RA Jr., Phoenix CJ. Vasculoid: A personal nanomedical appliance to replace human blood. J Evol Technol. 2002 Apr;11:1-139; http://www.jetpress.org/volume11/vasculoid.pdf.

[16] The liquid range of water-miscible 1-propanol is 147-370 K (-126 °C to 97 °C, -195 °F to 206 °F); https://en.wikipedia.org/wiki/1-Propanol.

[17] Robert C. Weast, Handbook of Chemistry and Physics, 49th Edition, CRC, Cleveland OH, 1968; "Specific Heat of Ice," -200 °C to -2.2 °C, p. D-95. See also: https://www.engineeringtoolbox.com/ice-thermal-properties-d_576.html.

[18] https://en.wikipedia.org/wiki/Properties_of_water.

[19] https://en.wikipedia.org/wiki/Human_body_temperature.

specific heat of water at 37 °C is about c_P = 4190 J/kg-K. If the nanorobot waste heat could be distributed perfectly uniformly throughout the watery portions of the human body, this water could absorb up to $E_{body} = m_{water} \Delta T c_P = 1.95 \times 10^6$ J of waste heat before warming to lethal temperatures. At P_{body} = 1.6 kW, the limit would be reached in a maximum of E_{body} / P_{body} ~ 1220 sec or ~20 minutes. In theory, a perfectly uniformly distributed power input of **1950 kW** (~2 megawatts) might be endured for almost ~1 sec by a 70 kg person before causing hyperthermic death. Of course, these upper limits may be greatly reduced if such elevated levels of waste heat are released in localized concentrations, creating damaging hot spots inside critical tissues or organs such as the brain.

In this paper, we apply a similar analysis to the introduction of large amounts of waste-heat-producing nanomachinery to the entire Earth.

Section 2 considers the maximum anthropogenic waste heat that Earth can tolerate without suffering any significant changes in planetary ecology, habitability, or appearance. Perhaps the dominant major impact of excess heating would be polar icecap melting, which would cause major continental flooding and many other ecological impacts. Section 2.1 reviews the worldwide impacts of icecap melting and a range of possible mitigations that could be employed to maintain habitability if such melting was allowed to occur. We then provide an estimate of the maximum global power that could be consumed by active nanomachines without causing icecap melting to occur, based on relevant published simulations.

This baseline maximum global nanomachinery power limit can be increased either by reducing the concentration of greenhouse gases in Earth's atmosphere (Section 2.2) or by reducing the solar insolation received from the Sun (Section 2.3). We also briefly consider the effects of localized heating effects due to geographical concentrations of nanomachine activity, analogous to urban heat islands (Section 2.4), and whether various mitigations might allow Earth's ecology to tolerate significantly higher temperatures than today (Section 2.5), potentially enabling the maximum global nanomachinery power limit to increase still further.

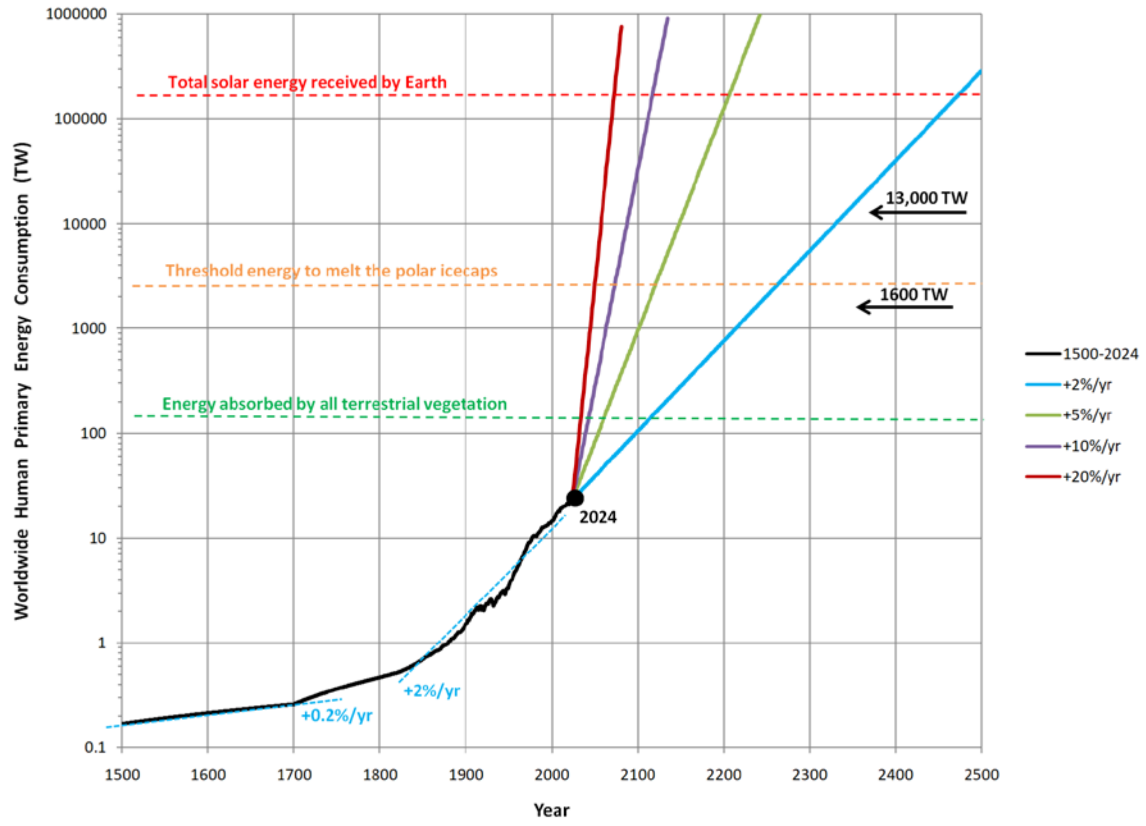
Having established the maximum global nanomachinery power limits, Section 3 summarizes the anticipated specific power (MW/kg) requirements of various classes of proposed nanomachinery (Section 3.1), then provides estimates of the maximum mass of simultaneously active nanomachinery that can be allowed to operate continuously on Earth (Section 3.2).

The total mass of nanomachinery that can be deployed on Earth is considerably larger than the mass of active nanomachinery that can safely be allowed to operate. This total mass is ultimately limited by resource availability because most of it will be passive structure or nanomachinery that is usually inactive, hence not contributing to the global heat load. Section 4.1 estimates the maximum mass of diamondoid nanomachinery that we can deploy on Earth using only materials sourced from Earth. Section 4.2 expands this estimate to include resources available from elsewhere in the Solar System that could be imported to Earth.

The author thanks Ralph Merkle, Tad Hogg, and J. Storrs Hall for helpful comments on an earlier version of this paper.

2. How Much Waste Heat Can Earth Tolerate?

In the future and at the planetary scale, the total mass of nanomachinery extant in the world will generate a certain amount of waste heat, warming the planet. If we initially postpone discussing the problem of localized hot spots such as cities (Section 2.4) and simply assume that all nanorobotic waste heat is uniformly distributed over the entire planet, how much nanomachinery waste heat can Earth tolerate?



The chart above shows the estimated worldwide primary energy consumption of humanity on Earth from the year 1500 AD through 2024 AD,[20] and the projected future energy consumption through the year 2500 AD assuming four different constant growth rates, as measured in terawatts

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[20] Data for 1820-2018 is from Malanima P, World Energy Consumption: A Database (2020 revision); https://histecon.fas.harvard.edu/energyhistory/DATABASE%20World%20Energy%20Consumption.pdf. Pre-1820 and post-2018 figures are interpolated or estimated, then consistency-linked, from "Global primary energy consumption by source," Our World in Data, 2021; https://ourworldindata.org/grapher/global-energy-substitution, and from Malanima P, Energy Consumption in the Roman World, Jan 2013; https://www.researchgate.net/publication/256120824, using data attributed to Morris I, Why the West Rules, 2010, p. 268; https://www.amazon.com/Ian-Morris-Rules-Patterns-History/dp/B004WSV4M4/.

(TW, or 10^{12} W), a unit of power. Human energy use in ancient and medieval times grew at a modest +0.2%/yr rate, but this jumped tenfold to a +2%/yr rate with the advent of the Industrial Revolution during the 1800s. A jump of similar size to a +20%/yr rate cannot be ruled out in an era of rapidly advancing nanotechnology. In such a scenario, the power demands from conventional (non-nano) machines might continue to grow at about +2%/yr (comparable to recent population growth), while the bulk of the +20%/yr increase would be attributable to new generations of nanomachinery coming into widespread use.

One important clarification must be noted. If we replaced existing non-nano machines with nanomachines of equivalent power usage, then there would be no net increase in the terrestrial thermal burden and so the allowable mass of such substitutional nanomachinery could be added to the allowable mass limits for new nanomachinery estimated in Section 3.2. Additionally, the mass of nanomachinery exploiting sunlight that heats the Earth but is not currently used by machines (e.g., sunlight falling on barren desert sand) would generate no net terrestrial heating, thus could also be added to the allowable mass of new nanomachinery estimated in Section 3.2 – although in many cases depriving bare soil, desert sands, or ocean surfaces of normal sunlight could have negative ecological impact, potentially violating the objective of this paper to avoid any significant changes in planetary ecology, habitability, or appearance.

We can see from the chart that humanity consumed ~**23 TW** of power in 2024. For comparison, the energy captured by all vegetation worldwide, via photosynthesis, is estimated at ~**140 TW**; the energy that drives all wind and ocean currents on the planet requires ~**1700 TW**, or ~1% of solar insolation; ~**40,000 TW** runs all the terrestrial hydrologic cycles; and the disk of the Earth as seen from space intercepts P_{Sun} = **174,000 TW** from the Sun (solar insolation).[21] At a +20%/yr growth rate starting in 2025, the power consumption of all human technology on Earth would exceed solar insolation in just 48 years.[22]

2.1 Melting Earth's Polar Icecaps

How much diffusely-distributed power would it take to melt Earth's polar icecaps? Computer simulations[23] of the initial formation of the permanent Antarctic ice sheet ~34 million years ago found that no ice formed until the atmospheric carbon dioxide concentration had fallen below ~1000 ppm. As a crude estimate, a simple formula for the heating effect of CO_2 in Earth's atmosphere is ΔF (W/m^2) = $\alpha_{CO2} \ln(C/C_0) = 4.90$ W/m^2, where the radiative forcing constant α_{CO2}

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[21] "Energy Flows on Earth," https://energyeducation.ca/encyclopedia/Earth%27s_energy_flow.

[22] The chart shows the new rates initiating in the year 2025. If a particular reader expects the new nano-rich usage rate to initiate N years later than 2025 and wishes an updated expectation, they should simply follow the 2% line upwards until the year 2025+N, sliding the faster-growth lines N years to the right but keeping the same slopes.

[23] DeConto RM, Pollard D. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature. 2003 Jan 16;421(6920):245-9; http://www.essc.psu.edu/essc_web/seminars/spring2006/jan18/DeContoPollard.pdf.

= 5.35 W/m^2, C = 1000 ppm CO_2, and C_0 ~ 400 ppm (the CO_2 level in 2023).[24] This suggests that the additional power input necessary to melt the icecaps of today's Earth may be approximated by $P_{Melt} \sim 4\pi R_{Earth}^2 \Delta F$ ~ **2500 TW**, taking Earth's radius $R_{Earth} = 6.37 \times 10^6$ m. This figure is consistent with the basic thermochemical requirements to melt a polar volume of ice in ~117 years,[25] and represents ~1.4% of total solar insolation.

How bad could things get at 2500 TW? Melting all of the ice covering Antarctica (South Pole), Greenland (near the North Pole), and all mountain glaciers around the world (~0.6% of all global ice) would have many serious consequences, including:

1. **Global sea level rise.** The melting of all ice would cause a significant rise in sea levels, often estimated as ~68 meters (223 feet).[26] This would result in the inundation of coastal cities, island nations, and low-lying areas worldwide, displacing hundreds of millions of people and causing widespread damage to infrastructure and ecosystems, while shrinking the total land area of Earth by at least 7-10%,[27] and possibly more (image, right).[28]

2. **Altered ocean circulation.** The influx of fresh water from melting ice would change the salinity of the oceans, potentially disrupting ocean circulation patterns such as the Gulf Stream and other major currents.[29] We might expect stronger wind and ocean currents, as the

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[24] Myhre G, Highwood EJ, Shine KP. New estimates of radiative forcing due to well-mixed greenhouse gases. Geophys Res Lett. 1998 Jul 15; 25(14):2715-2718; https://agupubs.onlinelibrary.wiley.com/doi/pdfdirect/10.1029/98GL01908.

[25] If the ice in both of Earth's polar icecaps (~90% in Antarctica) has a volume of ~30 x 10^6 km^3 (https://hypertextbook.com/facts/2000/HannaBerenblit.shtml) with a density of 917 kg/m^3 and a heat of fusion of 334 kJ/kg for water-ice, then the power required to melt the icecaps in ~117 years is (30 x 10^6 km^3) (10^9 m^3/km^3) (917 kg/m^3) (334 kJ/kg) (1000 J/kJ) / [(117 yr) (3.14 x 10^7 sec/yr) (10^{12} W/TW)] ~ 2500 TW.

[26] Church JA, White NJ. Sea-level rise from the late 19th to the early 21st century. Surveys in Geophys 2011; 32(4-5):585-602; http://www.rpgroup.caltech.edu/aph150_human_impacts/assets/pdfs/Church_2011.pdf. See also: IPCC (2019). Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Intergovernmental Panel on Climate Change; https://www.ipcc.ch/srocc/.

[27] About 1.9% of the global land area lies below 5 meters of elevation, and 4.7% lies below 20 meters. Kulp SA, Strauss BH. CoastalDEM: A global coastal digital elevation model improved from SRTM using a neural network. Remote Sensing Environ. 2018 Mar 1; 206:231-239; https://www.sciencedirect.com/science/article/abs/pii/S0034425717306016.

[28] https://www.youtube.com/watch?v=1s5CekC5UZY.

[29] Rahmstorf S. Ocean circulation and climate during the past 120,000 years. Nature. 2002 Sep 12;419(6903):207-14; http://www.ccpo.odu.edu/~klinck/Reprints/PDF/rahmstorfNature2002.pdf. Srokosz MA, Bryden HL. OCEAN CIRCULATION. Observing the Atlantic Meridional Overturning Circulation

~1700 TW now available to drive these flows would more than double. Such changes could have significant impacts on regional climates, marine ecosystems, and global weather patterns.

3. **Climate change acceleration.** Ice reflects a significant amount of solar radiation back into space, helping to regulate Earth's temperature. With less ice cover, more solar radiation would be absorbed by the Earth's surface and oceans, potentially accelerating global warming.[30] The sequelae of increased global warming might include stronger and more destructive storms, more intense wildfires, changes in the distribution of pathogens affecting agriculture, and so forth.

4. **Ecosystem disruption.** Rapid melting of ice would significantly impact polar and alpine ecosystems, leading to the loss of habitat for many species, including iconic animals like polar bears and penguins.[31] Additionally, the loss of ice could release trapped methane (from warming permafrost[32] or oceanic clathrates[33]) and carbon dioxide, further contributing to climate change.[34]

5. **Geopolitical consequences.** The melting of ice would lead to the opening of new shipping routes in the Arctic, potentially creating geopolitical tensions over resource extraction and transportation.[35] Additionally, hundreds of millions of climate refugees might be created due to rising sea levels, putting immense pressure on countries to provide aid and adapt to new migration patterns.[36]

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yields a decade of inevitable surprises. Science. 2015 Jun 19;348(6241):1255575; http://www.ccpo.odu.edu/~klinck/Reprints/PDF/srokoszScience2015.pdf.

[30] Flanner MG, Shell KM, Barlage M, Perovich DK, Tschudi MA. Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. Nature Geosci.2011 Mar; 4(3):151-155; http://www.homepages.ed.ac.uk/shs/Climatechange/Climate%20model%20results/Flanner%20and%20shell.pdf. Stroeve JC, Kattsov V, Barrett A, Serreze M, Pavlova T, Holland M, Meier WN. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. Geophys Res Lett. 2012; 39(16):L16502; https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2012GL052676.

[31] Post E, Bhatt US, Bitz CM, Brodie JF, Fulton TL, Hebblewhite M, Kerby J, Kutz SJ, Stirling I, Walker DA. Ecological consequences of sea-ice decline. Science. 2013 Aug 2;341(6145):519-24; http://ffden-2.phys.uaf.edu/usbhatt/publications/PostetalScience2013.pdf.

[32] https://en.wikipedia.org/wiki/Permafrost#Impact_on_global_temperatures.
[33] https://en.wikipedia.org/wiki/Methane_clathrate#Oceanic.

[34] IPCC (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

[35] Raspotnik A. The European Union and the Geopolitics of the Arctic. Edward Elgar Publ. Ltd., Cheltenham UK, 2018; https://books.google.com/books?hl=en&lr=&id=Rh1HDwAAQBAJ.

[36] McLeman RA, Hunter LM. Migration in the context of vulnerability and adaptation to climate change: insights from analogues. Wiley Interdiscip Rev Clim Change. 2010 May;1(3):450-461; https://www.ncbi.nlm.nih.gov/pmc/articles/pmid/22022342/.

Most of these consequences seem quite undesirable, so 2500 TW may be higher than we'd care to push the maximum limit. Of course, a thrillseeking technophile might point out that in a world of abundant molecular manufacturing that gives humanity efficient access to essentially unlimited material and energy resources, each of the aforementioned problems can be addressed – albeit at the cost of creating a very different, though still potentially habitable, world in which to live.

For example, the negative effects of the predicted 68-meter sea level rise might be offset by constructing dikes surrounding all major continents and islands (image, left), preserving existing dry land and perhaps reclaiming additional land by extending these barriers a bit farther out onto the continental shelf, providing plenty of extra living space for climate refugees.[37] These dikes could take the form of a 100 meter tall triangular-cross-section rock seawall with a 100 meter wide base, positioned ~1 kilometer offshore and surrounding all major continents in the world, in ~20 years using less than 1 TW of power for its construction assuming 50% energy efficiency.[38] Alternatively, we could extract enough CO_2 from the atmosphere to reduce its current 400 ppm concentration down to the pre-industrial 280 ppm level and then separate the carbon from the CO_2 (releasing the oxygen back into the air), liberating enough carbon (~255 x 10^{12} kg) to build a solid diamond seawall 100 meters tall and only ~2 meters average thickness

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[37] A wall separating land from deep ocean could have consequences that would need investigation and further mitigation, such as preventing salmon from returning to rivers.

[38] The coastlines of all Earth's continents, including the mainlands and their islands, measure approximately 26,000 km (Africa) + 17,968 km (Antarctica) + 62,800 km (Asia) + 78,000 km (Europe) + 75,000 km (North America) + 25,760 km (Australia) + 25,427 km (South America) ~ 310,955 km (https://www.cia.gov/the-world-factbook/field/area/country-comparison). (Although strictly speaking, a landmass coastline does not have a well-defined length; https://en.wikipedia.org/wiki/Coastline_paradox.) A triangular berm ~100 m tall with a ~100 m base (average width of 50 m) would be roughly consistent with the dimensions of Hoover Dam, which is 221 m tall and 201 m wide at the base (https://www.nps.gov/articles/-the-greatest-dam-in-the-world-building-hoover-dam-teaching-with-historic-places.htm). This gives a total global seawall volume of (310,955 km) (100 m) (50 m) = 1.55 x 10^{12} m^3 (a cube of rock 11.6 km on a side), having a mass of 4.11 x 10^{15} kg assuming an average rock density of 2650 kg/m^3. The gravitational energy cost of lifting this mass of rock from a hole averaging 11.6 km / 2 = 5.8 km in depth is (4.11 x 10^{15} kg) (9.81 m/sec^2) (5800 m) = 2.34 x 10^{20} J. The power required to supply this energy in ~20 years, assuming a modest ~50% mechanical efficiency, is (2.34 x 10^{20} J) / [(50%) (20 yr) (3.14 x 10^7 sec/yr)] = 0.75 TW.

around all the continents of Earth.[39] More vigorous ocean circulation patterns could be controlled using submerged active seawalls and dams such as the Thames Barrier[40] in London, the MOSE gates[41] in Venice, or the Delta Works in The Netherlands[42] – only vastly larger in scale. The external surfaces of roads and buildings could be made more reflective in order to return more energy back to space, using novel materials that emit light at infrared wavelengths where the atmosphere is transparent while simultaneously reflecting visible and near-infrared light, thereby shifting the infrared wavelengths emitted by the earth to those less affected by greenhouse gases, hence making better use of cold space as a heat sink.

But do we really want to melt the polar icecaps and change the face of the planet? If we're conservative and enjoy the Earth just fine the way it is now,[43] the answer must be no. In that case, the question we should be asking is: How much nanomachinery-produced waste heat can we safely release at the surface of the Earth *without* melting the icecaps?

Referring back to the computer simulations of glaciation by DeConto and Pollard,[44] the Antarctic ice volume did not begin to shrink until the simulated atmospheric CO_2 content rose to 2.6 times the 280 ppm pre-industrial level, or ~728 ppm. Applying the radiative forcing relation described earlier predicts the maximum safe ΔF (W/m^2) = $\alpha_{CO2} \ln(C/C_0) = 3.20$ W/m^2, taking C = 728 ppm CO_2 and C_0 ~ 400 ppm, suggesting that the maximum power input that almost certainly avoids melting the icecaps is $\mathbf{\Psi_{Low}} \sim 4\pi R_{Earth}{}^2\, \Delta F \sim$ **1600 TW**, or ~0.9% of solar total insolation.[45] This becomes our most conservative limit for worldwide nanomachinery power consumption.

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[39] 400 ppm – 280 ppm = 120 ppm of CO_2 has a mass of $M_{CO2\text{-}120} \sim 936 \times 10^{12}$ kg, containing $M_{CO2\text{-}280} \sim$ (12 gm C per mole / 44 gm CO_2 per mole) $M_{CO2\text{-}120} = 255 \times 10^{12}$ kg of carbon having a volume of $M_{CO2\text{-}280} / \rho_{diamond} = 7.27 \times 10^{10}$ m^3 when formed into diamond, enough material to create a 100-meter tall, 310,955 km long seawall of average width (7.27×10^{10} m^3) / [(100 m) (310,955 km)] = 2.34 meters. The 21-fold narrower width of the diamond seawall compared to rock is justified because the failure strength of diamond (~5×10^{10} N/m^2) is ~1000 times higher than the failure strength of rock (~4×10^7 N/m^2 for granite) or reinforced concrete (1-16 x 10^7 N/m^2) as used in dam construction.

[40] https://en.wikipedia.org/wiki/Thames_Barrier.
[41] https://en.wikipedia.org/wiki/MOSE.
[42] https://en.wikipedia.org/wiki/Delta_Works.

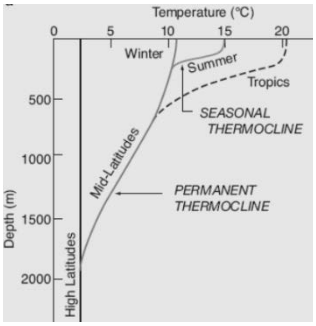
[43] Of course, widespread worldwide deployment of nanofactories and molecular manufacturing will make it possible to create whatever global climate we desire on Earth. Alternatives might include "what it would have been without us" or "whatever gives us the most area of the most enjoyable climate for humans". Or we might mull the desirabilities of something closer to any of various climates and ecologies of the past, such as Jurassic Park (https://en.wikipedia.org/wiki/Jurassic#Climate), Devonian Park (https://en.wikipedia.org/wiki/Devonian#Climate), or Carboniferous Park (https://en.wikipedia.org/wiki/Carboniferous#Climate).

[44] DeConto RM, Pollard D. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature. 2003 Jan 16;421(6920):245-9; http://www.essc.psu.edu/essc_web/seminars/spring2006/jan18/DeContoPollard.pdf.

[45] Note that if global CO_2 levels continue to rise past 400 ppm, the power available for nanomachinery use will decrease from 1600 TW, according to the same formula. For example, at 410 ppm CO_2 in air the new limit for nanomachinery would be ~1570 TW.

If we add 1600 TW of nanomachine waste heat to the environment, how much hotter might Earth become? If we set aside for the moment the greenhouse effect of the atmosphere, the increase in temperature may be crudely estimated using the Stefan-Boltzmann law[46] as $\Delta T_{1600TW} = T_{1600TW} - T_{23TW} = \mathbf{0.637\ K}$, where $T_{1600TW} = (P_{1600TW} / \sigma\ \varepsilon_{Earth}\ A_{Earth})^{1/4} = 282.756$ K and $T_{23TW} = (P_{23TW} / \sigma\ \varepsilon_{Earth}\ A_{Earth})^{1/4} = 282.119$ K, taking $P_{1600TW} = P_{Sun} + 1600$ TW, $P_{23TW} = P_{Sun} + 23$ TW, $P_{Sun} = 174{,}000$ TW, $A_{Earth} = 4\pi R_{Earth}^2 = 5.10 \times 10^{14}\ m^2$, the global average Earth emissivity $\varepsilon_{Earth} \sim 0.95$, and $\sigma = 5.67 \times 10^{-8}$ W/m^2-K^4 (Stefan-Boltzmann constant).[47] A global temperature increase of this magnitude seems fairly modest.

In the absence of a detailed study, as another crude scaling estimate we might imagine a simple scenario in which nanomachinery that is roughly evenly distributed over the surfaces of the continents of Earth initially releases its 1600 TW of waste heat into the atmosphere, after which the warmed atmosphere subsequently heats the oceans without any of the extra heat being radiated away into space. The total heat capacity of Earth's atmosphere is $H_{atmos} \sim C_{p,air}\ M_{atmos} = 5.17 \times 10^{21}$ J/K, taking the specific heat of air at sea-level pressure[48] as $C_{p,air} = 1003.5$ J/kg-K and atmospheric mass as $M_{atmos} = 5.15 \times 10^{18}$ kg.[49] The effective total heat capacity of Earth's oceans is limited by the depth of the seasonal thermocline[50] (the depth at which seawater temperature actively responds to seasonal changes and latitudinal variations in surface temperature) or $d_{thermocline} \sim 500$ m (chart, left),[51] thus is given by $H_{ocean} \sim C_{ocean}\ \rho_{ocean}\ A_{ocean}\ d_{thermocline} = 7.41 \times 10^{23}$ J/K, taking the specific heat $C_{p,ocean} = 4007$ J/kg-K and density $\rho_{ocean} \sim 1025$ kg/m^3 for 20 °C seawater,[52] and $A_{ocean} = 3.61 \times 10^{14}\ m^2$.[53] If surplus atmospheric heat is quickly transferred[54] into the seasonal thermoclinic ocean volume, the temperature rise is $\Delta T_{ocean} \sim \mathbf{\Psi_{Low}} / H_{ocean} = \mathbf{0.068\ K/yr}$, which again seems fairly modest. (The atmospheric temperature increase would be $\mathbf{\Psi_{Low}} / H_{atmos} \sim 9.7$ K/yr in the absence of the large oceanic heat sink.) The heat transfer coefficient from air to water is $h_{transfer} \sim 10\text{-}100$ W/m^2-K,[55] or $H_{transfer} \sim h_{transfer}\ A_{ocean} \sim 3610\text{-}36{,}100$ TW/K over the oceans, indicating an equilibrium atmospheric temperature rise of ΔT_{atmos}



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[46] https://en.wikipedia.org/wiki/Stefan%E2%80%93Boltzmann_law.

[47] Note that $\Delta T_{13000TW} = T_{13000TW} - T_{23TW} = \mathbf{1.023\ K}$ for the scenario described in **Section 2.3** with $\mathbf{\Psi_{High}} \sim 13{,}000$ TW, taking $T_{13000TW} = (P_{13000TW} / \sigma\ \varepsilon_{Earth}\ A_{Earth})^{1/4} = 283.142$ K and $P_{13000TW} = 0.94\ P_{Sun} + \mathbf{\Psi_{High}}$.

[48] https://en.wikipedia.org/wiki/Table_of_specific_heat_capacities.
[49] https://en.wikipedia.org/wiki/Atmosphere_of_Earth.
[50] https://en.wikipedia.org/wiki/Thermocline.
[51] https://en.wikipedia.org/wiki/Thermocline#/media/File:ThermoclineSeasonDepth.png.
[52] https://www.engineeringtoolbox.com/sea-water-properties-d_840.html.
[53] https://en.wikipedia.org/wiki/Ocean.

[54] If the average distance to ocean from any continental emission site is $d_{ToOcean} \sim 2000$ km and the average wind ground speed is $v_{wind} \sim 3.3$ m/sec worldwide (https://www.scientificamerican.com/article/the-worlds-winds-are-speeding-up/), then the average lag time for air-to-water heat transfer is $d_{ToOcean} / v_{wind} \sim 7$ days.

[55] https://en.wikipedia.org/wiki/Heat_transfer_coefficient.

~ $\mathbf{\Psi_{Low}}$ / $H_{transfer}$ = **0.044-0.44 K**. Of course, these are likely significant overestimates of the expected temperature rise, because the calculation neglected radiation of the extra heat into space.

Is it possible to safely release more than $\mathbf{\Psi_{Low}}$ ~ 1600 TW of nanomachinery waste heat on Earth? There are two primary factors that control the temperature of the Earth – the amount of solar energy that reaches the planet, and the presence of greenhouse gases that trap the received energy like a blanket and keep the planet warm. This suggests at least two obvious strategies to increase the maximum global nanomachine power limit. If we can reduce either the solar energy reaching the planet or the concentration of greenhouse gases that retain the received energy on the planet, then the amount of this energy reduction could be utilized by additional nanomachinery without risking icecap melting.

2.2 Greenhouse Gas Reduction

Let's first consider the **greenhouse gas reduction** strategy. Greenhouse gases such as carbon dioxide and methane could be selectively removed from Earth's atmosphere either using nanomachinery-based "diamond tree" tropostats[56] or a global oceanic carbon capture network[57] with seafloor burial of CO_2 (image, right) driven by 2 TW of ground-based solar power (adding no net heat to global warming) that can return Earth's atmosphere to pre-industrial 280 ppm CO_2 levels within 40 years from launch of program and thereafter maintain the atmosphere in this condition indefinitely, according to previously published work. Reducing atmospheric CO_2 from the current 400 ppm back to 280 ppm would offset the heating effect of ΔF ~ 1.91 W/m^2 worth of radiative forcing, or P_{280} ~ 970 TW of new waste heat generation worldwide due to nanomachinery. In other words, nanomachinery worldwide could be allowed to release an estimated total of $\mathbf{\Psi_{Mid}} = \mathbf{\Psi_{Low}} + P_{280}$ ~ **2570 TW** of waste heat without melting the polar icecaps, once atmospheric CO_2 levels have first been reduced to 280 ppm.

If reducing CO_2 to 280 ppm is good, is more reduction better? How far could we push this? Eliminating all CO_2 from the air would have disastrous consequences, including killing all plant life on Earth by shutting down photosynthesis (thus eliminating oxygen production worldwide), changes in ocean chemistry[58] causing drastic changes in marine life and ecosystems (particularly for organisms that rely on the availability of carbonate ions to build their shells or skeletons), disruption of the carbon cycle, and the possibility of hypocapnia[59] in humans and animal life.[60]

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[56] Freitas RA Jr. Diamond Trees (Tropostats): A Molecular Manufacturing Based System for Compositional Atmospheric Homeostasis. IMM Report No. 43, Feb 2010; http://www.imm.org/Reports/rep043.pdf.

[57] Freitas RA Jr. The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture. IMM Report No. 45, Dec 2015; http://www.imm.org/Reports/rep045.pdf.

[58] CO_2 dissolved in seawater helps maintain its pH balance; without CO_2, the ocean would become more alkaline.

[59] https://en.wikipedia.org/wiki/Hypocapnia.

The principal photosynthetic enzyme in plants, RuBisCO,[61] has a specificity and catalytic rate maximum at 200 ppm CO_2.[62] Over the last 23 million years, CO_2 concentrations (to which plants have had to evolutionarily adapt)[63] briefly reached their lowest recorded level of ~170 ppm.[64] The lower limit for efficient photosynthesis varies among plant species, but it is generally accepted that atmospheric CO_2 concentrations below 150 ppm significantly limit the rate of photosynthesis, especially for C_3 plants[65] which make up the majority of plant species on Earth, including many food crops like wheat, rice, and soybeans.[66] Different plant types have varying sensitivities to CO_2 concentration – for example, C_4 plants, such as corn and sugarcane, and CAM plants, such as cacti and succulents, have evolved carbon-concentrating mechanisms that allow them to photosynthesize more efficiently at low CO_2 concentrations compared to C_3 plants, but even these plants would experience reduced photosynthetic rates at extremely low CO_2 concentrations.[67]

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[60] Eliminating all carbon dioxide from the air could cause hypocapnia (low CO_2 levels in the blood) in humans and other animal life, resulting in respiratory alkalosis (with symptoms including dizziness, fainting, and even seizures and coma in extreme cases), since breathing is regulated by chemoreceptors that detect CO_2 levels. Nattie E. CO_2, brainstem chemoreceptors and breathing. Prog Neurobiol. 1999 Nov;59(4):299-331; https://www.sciencedirect.com/science/article/pii/S0301008299000088.

[61] https://en.wikipedia.org/wiki/RuBisCO.

[62] Zhu XG, Portis AR, Long SP. Would transformation of C_3 crop plants with foreign Rubisco increase productivity? A computational analysis extrapolating from kinetic properties to canopy photosynthesis. Plant Cell Environ. 2004;27(2):155-165; https://onlinelibrary.wiley.com/doi/pdf/10.1046/j.1365-3040.2004.01142.x.

[63] Leakey AD, Lau JA. Evolutionary context for understanding and manipulating plant responses to past, present and future atmospheric [CO2]. Philos Trans R Soc Lond B Biol Sci. 2012 Feb 19;367(1588):613-29; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3248707/.

[64] Petit J, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Bender M, Chappellaz J, Davisk M, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pepin L, Ritz C, Saltzmank E, Stievenard M. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 1999 Jun 3;399(6735):429-436; https://escholarship.org/content/qt7rx4413n/qt7rx4413n.pdf. Kawamura, K., Nakazawa, T., Aoki, S., Sugawara, S., Fujii, Y., and Watanabe, O., 2007, Dome Fuji ice core 338 kyr wet extraction CO2 data, in International Geosphere-Biosphere Programme (IGBP) PAGES (Past Global Changes)/World Data Center for Paleoclimatology: Boulder Colorado, National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center (NCDC) Paleoclimatology Program, Data Contribution Series #2007-074 (updated Aug 2007).

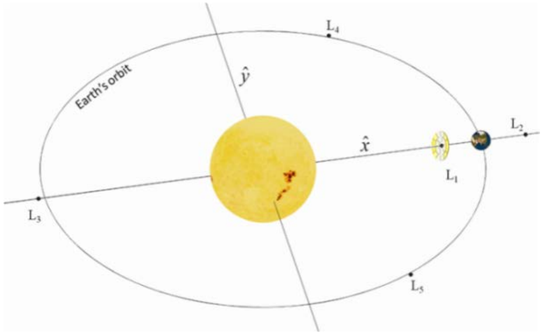
[65] https://en.wikipedia.org/wiki/C3_carbon_fixation.

[66] Sage RF, Coleman JR. Effects of low atmospheric CO(2) on plants: more than a thing of the past. Trends Plant Sci. 2001 Jan;6(1):18-24; https://pubmed.ncbi.nlm.nih.gov/11164373/.

[67] Vogan PJ, Sage RF. Effects of low atmospheric CO_2 and elevated temperature during growth on the gas exchange responses of C_3, C_3-C_4 intermediate, and C_4 species from three evolutionary lineages of C_4 photosynthesis. Oecologia. 2012 Jun;169(2):341-52; https://pubmed.ncbi.nlm.nih.gov/22139428/.

Reducing atmospheric CO_2 from the current C = 400 ppm down to C_0 = 150 ppm (the assumed maximum safe reduction consistent with a long-term viable ecology on Earth) might offset the heating effect of $\Delta F \sim \alpha_{CO2} \ln(C/C_0) = 5.25$ W/m^2 of radiative forcing, or $P_{150} \sim 4\pi R_{Earth}^2 \Delta F \sim$ 2680 TW of additional waste heat generation worldwide. In other words, nanomachinery worldwide could theoretically be allowed to release a total of $\mathbf{\Psi}_{\mathbf{Low}} + P_{150} \sim$ 4280 TW of waste heat without melting the polar icecaps, once atmospheric CO_2 levels had first been reduced to 150 ppm. However, in this scenario there is a serious potential risk if for any reason total nanomachine power usage drops significantly after CO_2 levels have been lowered to 150 ppm, as normal greenhouse warming might then be insufficient to prevent the rapid onset of a new ice age.[68] Note also that atmospheric CO_2 levels were higher, about 180-190 ppm[69] during the Last Glacial Maximum (LGM)[70] around 21,000 years ago, when the Earth experienced widespread glaciation. Additionally, it is unknown whether serious ecological disruptions will occur at 150 ppm CO_2, and the validity of the radiative forcing formula down to 150 ppm is also unknown. Caution suggests sticking with the $\mathbf{\Psi}_{\mathbf{Mid}} = \mathbf{\Psi}_{\mathbf{Low}} + P_{280} \sim$ **2570 TW** figure and assuming a 280 ppm worldwide carbon dioxide target concentration until further studies of these issues can confirm the safety of more extreme carbon reduction targets.

2.3 Solar Insolation Reduction



Next, let's consider the **solar insolation reduction** strategy to enable nanomachinery to release more waste heat without risking icecap melting. A long-standing proposal to accomplish this is space-based solar shades, in which large mirrors or sunshades are interposed between Earth and the Sun in space (image, right) to intercept and reflect away a small percentage of sunlight back into space, thus reducing the amount of solar radiation reaching Earth. One early suggestion[71] was to use a space-based sunshade consisting of a large,

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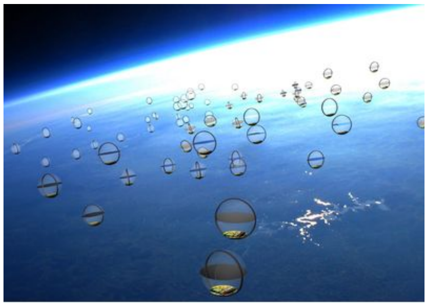
[68] It is difficult to pinpoint an exact CO_2 concentration threshold that would trigger a worldwide ice age, as global climate is influenced by various other factors including solar radiation, Earth's orbit and axial tilt, ocean currents, and albedo (reflectivity of Earth's surface). Ice ages have occurred in the past when CO_2 concentrations were even higher than present-day levels, so it's not solely a matter of CO_2 concentration.

[69] Lüthi D, Le Floch M, Bereiter B, Blunier T, Barnola JM, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K, Stocker TF. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. Nature. 2008 May 15;453(7193):379-82; https://epic.awi.de/id/eprint/18281/1/Lth2008a.pdf.

[70] https://en.wikipedia.org/wiki/Last_Glacial_Maximum.

[71] Early JT. Space-based solar shield to offset greenhouse effect. J Brit Interplanet Soc. 1989 Dec; 42(12):567-569; https://ui.adsabs.harvard.edu/abs/1989JBIS...42..567E/abstract.

thin, wire mesh disc approximately 2,000 kilometers in diameter that would be placed in a stable orbit at the Earth-Sun L1 Lagrange point,[72] a location between Earth and the Sun where gravitational forces balance, allowing the sunshade to easily maintain its position relative to Earth. A later publication[73] recommended launching an array of small, thin spacecraft, each about 60 centimeters in diameter, to form a cloud-like structure at the L1 Lagrange point. These spacecraft would be designed to scatter sunlight away from Earth, reducing the amount of solar radiation reaching the planet's surface. It was estimated that approximately 10 million of these small spacecraft would be required to achieve the desired reduction in solar radiation. More recent analyses[74] have investigated optimal configurations of orbiting occulting disks that not only offset a global temperature increase, but also mitigate regional differences such as latitudinal and seasonal differences in monthly mean temperature.



Another interesting and versatile proposal by J. Storrs Hall is to position a large population of small buoyant nanorobots floating in the stratosphere above Earth’s surface (image, left), each equipped with a radio receiver, a solar power cell, an onboard computer, and a mirror with a sun-tracking sensor.[75] By coordinating the actions of many trillions of these nanoballoons, the amount of sunlight reaching specific areas of the Earth’s surface could be precisely controlled by commanding the devices to position their mirror either to reflect sunlight away or to allow sunlight to pass.

According to one concise description:[76] “The Hall Weather Machine is a thin global cloud consisting of small transparent balloons that can be thought of as a programmable and reversible greenhouse gas because it shades or reflects the amount of sunlight that hits the upper stratosphere. These balloons are each between a millimeter and a centimeter in diameter, made of a few-nanometer thick diamondoid membrane. Each balloon is filled with hydrogen to enable it to float at an altitude of 60,000 to 100,000 feet, high above the clouds. It is bisected by an adjustable sheet, and also includes solar cells, a small computer, a GPS receiver to keep track of its location, and an actuator to occasionally (and relatively slowly) move the bisecting membrane between vertical and horizontal orientations. Just like with a regular high-altitude balloon, the heavier control and energy storage systems would be on the bottom of the balloon to

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[72] https://en.wikipedia.org/wiki/Lagrange_point#Sun%E2%80%93Earth.

[73] Angel R. Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). Proc Natl Acad Sci U S A. 2006 Nov 14;103(46):17184-9; https://www.pnas.org/doi/full/10.1073/pnas.0608163103.

[74] Sánchez JP, McInnes CR. Optimal Sunshade Configurations for Space-Based Geoengineering near the Sun-Earth L1 Point. PLoS One. 2015 Aug 26;10(8):e0136648; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4550401/pdf/pone.0136648.pdf.

[75] https://foresight.org/the-weather-machine/.

[76] Toth-Fejel T. The Politics and Ethics of the Hall Weather Machine. Nanotechnology Now, 17 Sep 2010; https://www.nanotech-now.com/columns/?article=486.

automatically set the vertical axis without requiring any energy. The balloon would also have a water vapor/hydrogen generator system for altitude control, giving it the same directional navigation properties that an ordinary hot-air balloon has when it changes altitudes to take advantage of different wind directions at different altitudes."

Reflecting away just f = 0.1% of total solar insolation would eliminate 174 TW from the global warming process, allowing nanomachines to consume this additional amount of energy at Earth's surface without risking polar icecap melting. The required nanoballoon population for an f = 0.1% reduction would be $N \sim 4\, f\, R_{Earth}{}^2 / R_{balloon}{}^2 = 6.49 \times 10^{17}$, taking $R_{balloon} = 0.5$ mm in radius, assuming negligible occultation by neighboring nanoballoons in flight. This gives a nanoballoon fleet of total volume $V_{fleet} = N\, (4\pi/3)\, R_{balloon}{}^3 = 3.40 \times 10^8\ m^3$ and total mass $M_{fleet} = \rho_{balloon}\, V_{fleet}$ = **2.72×10^7 kg**, taking net nanoballoon density $\rho_{balloon} \sim 0.08\ kg/m^3$ (to permit floating in air).[77] (For comparison, the worldwide production of steel was ~**2×10^{12} kg** in 2022.[78]) If the material comprising the nanoballoons is mostly diamond of density $\rho_{diamond} \sim 3510\ kg/m^3$, then the volume of the material needed to construct the entire fleet of nanoballoons is a fairly modest $V_{material} \sim M_{fleet} / \rho_{diamond} = 7750\ m^3$, which would fit inside a cube ~20 m on a side. Adding more nanoballoons frees up still more TW of power for use by ground-based nanomachinery.

Again, we may wonder: How far can we go with this? At the far extreme, increasing the f = 0.1% nanoballoon population to f ~ 100% would enable us to intercept and reflect away virtually all the radiant energy the Earth receives from the Sun. This would plunge the planet into darkness and eliminate all worldwide photosynthetic activity (and oxygen production) by plants. A global ice age would quickly ensue unless nanomachines operating at Earth's surface could compensate by artificially dissipating ~122,000 TW of additional waste heat. (That's the ~70% of the 174,000 TW of solar insolation that actually warms the atmosphere and surface of Earth; the remaining ~30% is reflected back into space.[79]) In principle, a modest portion of this energy could be employed by chemical synthesis nanomachinery to artificially generate breathable oxygen from atmospheric CO_2 or other sources, supplanting the need for vegetative photosynthesis. (Natural photosynthesis is only 3%-6% efficient[80] and consumes ~140 TW worldwide[81]; nanomachinery should be more efficient and draw less power.) But in the absence of sunlight, terrestrial plant life would likely die off in a fairly short time frame.[82] Clearly this is an outcome to be avoided and would violate the no-ecological-change objective of this paper.

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[77] The density of air at an altitude of 20,000 m (~66,000 feet) is 0.089 kg/m^3; https://www.engineeringtoolbox.com/standard-atmosphere-d_604.html.

[78] https://www.statista.com/statistics/267264/world-crude-steel-production/.
[79] https://energyeducation.ca/encyclopedia/Earth%27s_energy_flow.
[80] https://en.wikipedia.org/wiki/Photosynthesis.
[81] https://energyeducation.ca/encyclopedia/Earth%27s_energy_flow.

[82] The time it would take for all photosynthetic organisms to die after sunlight is fully blocked would vary depending on the species, their energy reserves, and their specific environmental conditions. **Phytoplankton** are microscopic marine algae that form the base of the ocean food chain. They have short lifespans and limited energy reserves, hence would likely start dying within a few days to a week. (Falkowski PG, Raven JA. Aquatic photosynthesis (2nd ed.). Princeton University Press, NJ, 2007; https://www.amazon.com/Aquatic-Photosynthesis-Paul-G-Falkowski/dp/0691115516/.) The time it would take for **terrestrial plants** to die would depend on the species and their energy reserves stored in various tissues (e.g., roots, stems, and leaves), with some plants having smaller energy reserves or higher metabolic

How much sunlight can we block and still maintain a viable global ecosystem? We can provide a conservative estimate based on Earth's historical climate variations and the known adaptability of ecosystems to these changes. For example, we know that solar luminosity has slowly increased over geological time.[83] Solar luminosity[84] was ~7% lower than it is today during the Cambrian explosion ~500 million years ago,[85] and ~**6%** lower than today when the first complete modern land ecosystems appeared about 450-375 million years ago.[86] More recently, during the Last Glacial Maximum[87] (LGM) around 21,000 years ago, Earth experienced significantly cooler temperatures, with global average temperatures 6 °C lower than present-day values. Despite this reduction in temperature, life persisted and ecosystems adapted. Given that the Earth's overall temperature is fundamentally driven by the amount of sunlight it receives, we might use these temperature differences as a rough proxy to estimate the acceptable level of reduced sunlight. A reduction of ~1% of the total solar energy reaching Earth would result in a global average temperature drop of ~1°C.[88] If ecosystems could tolerate 6 °C temperature changes similar to those during the LGM, we might conservatively estimate that a reduction in sunlight of around **6%** should be ecologically sustainable.

Reflecting away f = 6% of total solar insolation would require a fleet of 3.89×10^{19} 1-mm-diameter nanoballoons of total mass $M_{fleet6\%} = 1.63 \times 10^9$ kg, having approximately the same mass as ~50 km of a 4-lane freeway.[89] This nanoballoon fleet would remove $P_{6\%} = 10{,}440$ TW

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rates beginning to die within a few days to a couple of weeks, while others with more substantial energy reserves or slower metabolic rates could survive for a few weeks to a couple of months.

[83] https://en.wikipedia.org/wiki/Solar_luminosity.

[84] Ribas I. The Sun and stars as the primary energy input in planetary atmospheres. In: Kosovichev AG, Andrei AH, Rozelot JP, eds. Solar and Stellar Variability: Impact on Earth and Planets. Proc. IAU Symp No. 264, 2009, pp. 3-18; https://arxiv.org/pdf/0911.4872.

[85] https://en.wikipedia.org/wiki/Cambrian_explosion.
[86] https://en.wikipedia.org/wiki/History_of_life#Colonization_of_land.
[87] https://en.wikipedia.org/wiki/Last_Glacial_Maximum.

[88] The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) estimates a radiative forcing of ~0.18 W/m² during an 11-year solar cycle that involves a ~0.1% change in total solar irradiance, which induces a temperature response of ~0.1 °C. Assuming a roughly linear relationship between radiative forcing and temperature response, a 1% reduction in solar insolation would correspond to a temperature change of around 1 °C. Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H. Anthropogenic and natural radiative forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Doschung J, Nauels A, Xia Y, Bex V, Midgley PM, eds., Cambridge University Press, Cambridge, UK, pp. 659-740; https://www.cambridge.org/core/books/abs/climate-change-2013-the-physical-science-basis/anthropogenic-and-natural-radiative-forcing/63EB1057C36890FEAA4269F771336D4D.

[89] A standard 4-lane freeway with a total width of 24 meters (12 meters per direction, 3 meters per lane) has an area of 24,000 m²/km. Assuming a 0.3 m thick layer of concrete of density 2400 kg/m^3 atop a 0.35 m

from the global warming process, allowing nanomachines to consume this additional amount of energy at Earth's surface without risking polar icecap melting. In other words, nanomachinery worldwide could be allowed to release a total of $\mathbf{\Psi_{High}} = \mathbf{\Psi_{Low}} + P_{280} + P_{6\%}$ ~ **13,000 TW** of waste heat without melting the polar icecaps, once atmospheric CO_2 levels are first reduced and held to 280 ppm and solar insolation is permanently decreased by 6% via the worldwide deployment of a stratospheric nanoballoon fleet, an orbital sunshade, or other similar means.

The proposed 6% reduction seems like a conservative number. If we could survive with a bit less oxygen to breathe,[90] then perhaps we could tolerate even lower levels of sunlight that would further reduce global vegetative photosynthetic activity, making more room in the energy budget for nanomachinery. For example, people can live and function effectively up to 3000 meters above sea level, particularly if they are well acclimatized. A few populations have adapted to living at even higher altitudes, like the Andean people and the Sherpas in the Himalayas[91] – the highest permanently inhabited town in the world is in Peru[92] at 5100 meters.[93] At low-mid latitudes the total air pressure at 3000 meters is 533 torr,[94] or ~70% of the 760 torr pressure at sea level, and 410 torr at 5100 meters, or ~54%. Oxygen content remains ~20.9% up to ~85 km altitude,[95] but at 3000-5100 meters there is 30-46% less oxygen available in every lungful of air,

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thick base course of crushed rock of density 2000 kg/m^3 gives a freeway mass of (24,000 m²/km) [(0.3 m)(2400 kg/m^3) + (0.35 m)(2000 kg/m^3)] = 3.41×10^7 kg/km.

[90] Humanity could tolerate even a complete cessation of oxygen production worldwide for a short while. The total mass of oxygen in Earth's air is $M_{O2} = f_{O2,mass}\ M_{atmos} = 1.19 \times 10^{18}$ kg, taking $M_{atmos} = 5.15 \times 10^{18}$ kg of air on Earth[*] with a mass fraction of oxygen of $f_{O2,mass} = 23.14\%$,[†] and the total biological and nonbiological consumption of oxygen on Earth is $X_{O2} \sim 3 \times 10^{14}$ kg/yr.[‡] OSHA regulations[**] require that a drop in the O_2 mole fraction in air from 20.95% to 19.5% should be considered "immediately dangerous to life or health," a decrease of $\Delta_{O2} \sim (19.5/20.95)\ M_{O2} = 8 \times 10^{16}$ kg, so atmospheric oxygen levels wouldn't drop to dangerous levels for at least $\Delta_{O2} / X_{O2} \sim 267$ yr even if all oxygen production ceased on Earth.
[*] https://en.wikipedia.org/wiki/Atmosphere_of_Earth.
[†] https://www.engineeringtoolbox.com/air-composition-d_212.html.
[‡] https://en.wikipedia.org/wiki/Oxygen_cycle.
[**] https://www.osha.gov/laws-regs/standardinterpretations/2007-04-02-0.

[91] Beall CM. Two routes to functional adaptation: Tibetan and Andean high-altitude natives. Proc Natl Acad Sci U S A. 2007 May 15;104 Suppl 1(Suppl 1):8655-60; https://www.ncbi.nlm.nih.gov/pmc/articles/pmid/17494744/.

[92] https://en.wikipedia.org/wiki/La_Rinconada,_Peru.

[93] Humans have survived for 2 years at 5,950 m (~365 torr, or ~48% of sea level, implying an f = 52%) which appears to be near the limit of the permanently tolerable highest altitude. West JB. Highest permanent human habitation. High Alt Med Biol. 2002 Winter;3(4):401-7; https://pubmed.ncbi.nlm.nih.gov/12631426/.

[94] West JB. Prediction of barometric pressures at high altitude with the use of model atmospheres. J Appl Physiol (1985). 1996 Oct;81(4):1850-4; https://scholar.archive.org/work/755m5l6krbal3jj6j2553mf7f4/access/wayback/https://journals.physiology.org/doi/pdf/10.1152/jappl.1996.81.4.1850.

[95] https://en.wikipedia.org/wiki/Atmospheric_chemistry#Atmospheric_composition.

so f ~ 30%-46% might be a survivable upper limit assuming that photosynthetic production of oxygen responds linearly to solar intensity in this range. (Food production by plants would similarly decrease.) However, as with the 150 ppm CO_2 option discussed earlier (Section 2.2), we shall choose not to adopt a scenario that could heavily impact long-term terrestrial habitability for a significant fraction of the human population.

In all these solar radiation reduction scenarios, safety and the stability of global temperatures depend critically upon the high reliability and rapid response time of the stratospheric nanoballoon or solar shade systems. If for any reason total nanomachine power usage on the planetary surface drops significantly after solar insolation has been reduced by 6%, the solar shades or nanoballoons must quickly adjust to allow more sunlight to reach the Earth or a rapid-onset ice age could be the result. Similarly, if the solar shade or nanoballoon systems are ever destroyed or incapacitated sufficiently to allow excess sunlight to reach the Earth, nanomachine power usage on the ground must be quickly throttled back to avoid rapidly cooking the planet. Any planetary solar insolation reduction system must be continuously operated in precise counterpoint to all major sources of artificial heat generation on the Earth's surface when ground-based nanomachines are generating heat at the $\mathbf{\Psi_{High}}$ ~ **13,000 TW** level.

Ultraviolet sunscreening is an interesting variant of the aforementioned solar shade system that could further reduce solar insolation with minimal ecological impact, making room in the global energy budget for additional nanomechanical power use on Earth. Since 8%-10% of the solar radiation received by Earth lies in the ultraviolet (UV) wavelengths, selectively eliminating UV would reduce terrestrial warming by this same percentage, creating a cooling effect while eliminating a form of high-energy radiation that is mostly harmful to living organisms without decreasing the amount of planetwide photosynthesis or the production of breathable oxygen and biomass. This could be achieved by interposing a material that is opaque to UV but transparent to visible (40-45% of solar energy) and near-infrared (IR) (45%-50%) radiation between Earth and Sun, perhaps parked near Earth-Sun L1 as described earlier, either using a single large solid disk or a large population of stationkeeping drones or mechanically confined smaller plates of appropriate material. Many materials are known to selectively absorb UV while transmitting visible and IR, including UV-blocking glasses,[96] UV-selective photonic crystals with UV-blocking bandgaps,[97] organic compounds found in sunscreens (e.g., benzophenones[98] and cinnamates[99]), doped semiconductors, and optical filters made from various polymers and oxides. Other materials might be found that can selectively reflect UV while transmitting visible and IR, perhaps including dielectric mirrors,[100] plasmonic metamaterials employing nanoscale structures,

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[96] https://abrisatechnologies.com/coatings-corner/uv-blocking-glass-for-art-protection-2/.

[97] Xie X, Liu YJ, Du WC, Hao JJ, Ma BL, Yang HW. Research of selective UV shielding material based on photonic crystals structure. Optical Mat. 2019 Jun; 92:267-272; https://www.sciencedirect.com/science/article/abs/pii/S0925346719302745.

[98] https://en.wikipedia.org/wiki/Benzophenone#Uses.

[99] Nunes AR, Vieira ÍGP, Queiroz DB, Leal ALAB, Maia Morais S, Muniz DF, Calixto-Junior JT, Coutinho HDM. Use of Flavonoids and Cinnamates, the Main Photoprotectors with Natural Origin. Adv Pharmacol Sci. 2018 Nov 28;2018:5341487; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6304211/.

[100] https://en.wikipedia.org/wiki/Dielectric_mirror.

or multilayer interference coatings.[101] Even with present-day materials, UV absorption is typically in the 90%-99% range while allowing 80%-95% transmittance of visible light. Using such a scheme could potentially free up to ~**10,000 TW** for use by nanomachinery on Earth, nearly doubling $\boldsymbol{\Psi}_{\mathbf{High}}$. Ideally the ultraviolet sunscreen system would be designed to re-radiate any absorbed energy, presumably in the form of waste heat, in any direction except toward the terrestrial disk. This approach deserves further study.

Several other hypothetical methods for reducing solar insolation have been suggested and are mentioned here for completeness, though none appears to provide a sufficient benefit given the large implementation efforts that would be required:

(1) Microwave Beaming. Excess thermal energy on Earth could be collected and converted into electricity via thermoelectric generators, with the electricity used to produce microwaves to which the atmosphere is largely transparent, after which the microwaves are beamed out into space using high-gain parabolic reflectors (where such energy might be collected and recycled). High efficiency components, probably requiring molecular nanotechnology, would be needed to ensure that the amount of energy needed to run the system doesn't exceed the amount of energy exported from the planet. A conventional 1 MW commercial microwave generator[102] probably weighs ~10 tonnes, so a system built with contemporary components that is capable of generating ~1 TW of microwaves for outbeaming might weigh at least ~10 million tonnes – and likely a bit more, taking all of the support equipment into account – roughly equivalent in volume to 10 cubical boxes, each ~100 m on a side, assuming ~1 kg/L density. An improved system using nanomachinery might be more compact, and might allow an additional **1 TW** of waste heat to be generated by nanomachinery on Earth without altering the planet's climate or ecosphere.

(2) Trans-Atmospheric Heat Pipe. Crystalline diamond, sapphire, and silicon are strong enough materials to build towers standing up to ~1500 km, ~520 km, or ~300 km tall,[103] respectively, in the gravity field of Earth. Atomically precise fabrication techniques might allow a heat pipe[104] to be constructed from the ground up to a trans-atmospheric terminus ~100 km high, well below the altitude of orbital satellite traffic which otherwise might collide with the terminus. Classically, a heat pipe uses a working fluid in a closed environment to transfer heat from one end to the other. As heat is applied at one end, the fluid evaporates and the vapor moves to the cooler end where it condenses, releasing the heat. Then, the fluid flows back to the hot end, usually via capillary action in a wick or by gravitational forces, to repeat the cycle. In the present scenario, the heat pipe would extend from the Earth's surface to a point beyond the

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[101] http://www.grayglass.net/glass.cfm/Flat-Lighting-Glass/UV-Blocking/catid/3/conid/60.

[102] https://industrialmicrowave.com/industrial-microwave-generators/915-mhz/1-megawatt-generator/.

[103] Looking only at gravitational compressive loading and taking compressive failure strength $\sigma_{\mathrm{diamond}} \sim 5 \times 10^{10}$ N/m^2, $\sigma_{\mathrm{sapphire}} \sim 2 \times 10^{10}$ N/m^2, and $\sigma_{\mathrm{silicon}} \sim 0.7 \times 10^{10}$ N/m^2,[*] with densities $\rho_{\mathrm{diamond}} = 3510$ kg/m^3, $\rho_{\mathrm{sapphire}} = 3980$ kg/m^3, and $\rho_{\mathrm{silicon}} = 2330$ kg/m^3, then $H_{\mathrm{max}} \sim \sigma / g \rho \sim 1500$ km for diamond, ~520 km for sapphire, and ~300 km for silicon, assuming a solid column of atomically precise flawless crystal.

[*] Freitas RA Jr. Nanomedicine, Volume I: Basic Capabilities. Landes Bioscience, Georgetown, TX, 1999, Table 9.3; http://www.nanomedicine.com/NMI/Tables/9.3.jpg.

[104] https://en.wikipedia.org/wiki/Heat_pipe.

atmosphere. The Earth-end would absorb heat, evaporate the working fluid, and the vapor would rise and release its heat into space using radiators at the terminus, condensing the vapor back into a liquid and returning to the Earth-end to repeat the process. Low boiling point fluids could absorb and release heat more readily across a range of temperatures, and high thermal conductivity fluids might facilitate faster heat transfer. (In principle, mechanical transport of tanks containing hot or cold fluids could occur at much faster velocities than the speed of capillary transport or heat conduction, further facilitating rapid heat transfer.) Assuming for computational simplicity the use of water which has a high heat capacity, transferring P_{heat} = **1 TW** of waste heat from the ground (generating steam) to space (reclaiming water) using the heat of vaporization of water ($H_{vap} = 2.26 \times 10^6$ J/kg) requires the transport of $m_{water} = P_{heat} / H_{vap} = 4.42 \times 10^5$ kg/sec of water from the ground up to an altitude of h = 100 km, which in turn requires at least $P_{lift} \sim m_{water}\ g\ h$ = 0.43 TW (< P_{heat}) of power to lift the water into space. (For context, 4.42×10^5 kg/sec is about one-sixth of the of the ~28×10^5 kg/sec flow rate of water over Niagara Falls.[105]) Note that most of the steam lifting energy can be recovered from the descending liquid water, analogous to gravity-driven hydroelectric power, enabling a potentially energy-efficient system if numerous technical challenges (e.g., thermal insulation) could be solved. Alternative "air conditioner" systems involving heat exchangers and working fluids with compressors and condensers might employ similar geometries.

(3) **Trans-Atmospheric Heat Sink.** Diamond has almost the highest-known thermal conductivity of any solid material, $K_{diam} \sim 2200$ W/m-K.[106] Thermal energy will flow from the hot end of a heated rod toward its cold end, transferring thermal energy from the former to the latter location.[107] Ignoring a plethora of difficult engineering challenges, a column of flawless crystalline diamond held at ~300 K on the surface of the Earth will transfer thermal energy via conduction to the other end of the column in space maintained at ~100 K (temperature differential ΔT = 200 K), cooling the Earth. The lower levels of the column should be cladded with a good thermal insulator to minimize side leakage into the atmosphere. Transferring P_{sink} = **1 TW** from the ground into space along a conductive rod of length L_{column} = 100 km requires a column of cross-sectional area $A_{column} = P_{sink}\ L_{column} / K_{diam}\ \Delta T \sim 230{,}000\ \text{km}^2$ (roughly the land area of Wyoming or Oregon)[108] and mass $M_{column} = L_{column}\ A_{column}\ \rho_{diamond} \sim 9 \times 10^{19}$ kg, excluding the mass of the insulator and support infrastructure. That's more than 4 times the total mass of carbon readily available from terrestrial sources alone (Section 4.1), so non-terrestrial carbon resources would be needed to complete this seemingly impractical structure.

(4) Earth Moving. Reducing the average solar insolation of $P_{Sun} \sim 174{,}000$ TW by ΔP_{heat} = **1 TW** down to 173,999 TW will occur if the Earth's mean orbital radius from the Sun[109] is increased from $r_{Earth} = 1.49598023 \times 10^8$ km to $r_{Earth\text{-}1TW} \sim r_{Earth}\ (P_{Sun} / (P_{Sun} - P_{heat}))^{1/2} = 1.49598453 \times 10^8$ km. This increase of just 430 km in the mean orbital radius can be accomplished by adding $\sim G\ M_{Sun}\ M_{Earth}\ (r_{Earth}^{-1} - r_{Earth\text{-}1TW}^{-1}) = 1.53 \times 10^{28}$ J (~0.0003%) to the orbital energy of the Earth around the Sun, equivalent to ~2800 years' worth of total solar insolation on Earth, taking $M_{Sun} = 1.99 \times 10^{30}$ kg,[110] $M_{Earth} = 5.97 \times 10^{24}$ kg,[111] and the

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[105] https://www.niagaraparks.com/visit-niagara-parks/plan-your-visit/niagara-falls-geology-facts-figures/.
[106] https://en.wikipedia.org/wiki/Material_properties_of_diamond#Thermal_conductivity.
[107] https://en.wikipedia.org/wiki/Thermal_conductivity_and_resistivity.
[108] https://en.wikipedia.org/wiki/List_of_U.S._states_and_territories_by_area.
[109] https://books.google.com/books?id=tp_G85jm6IAC&pg=PA52&lpg=PA52.
[110] https://en.wikipedia.org/wiki/Sun.

gravitational constant $G = 6.67 \times 10^{-11}$ N-m^2/kg^2.[112] The motive force could be gently applied to the Moon which would then act as a gravity tractor,[113] slowly pulling the Earth slightly outward in its orbit with no disruption to the terrestrial environment.

2.4 Geographically Localized Waste Heat

Nanomachine energy consumption might produce localized atmospheric heating if concentrated in a small area such as a city. One well-known example of an analogous phenomenon is the Urban Heat Island effect,[114] wherein an urban area becomes significantly warmer than its surrounding rural areas due to human activities. In cities, anthropogenic heating is a combination of the waste heat released from vehicle fuel combustion, building and industrial energy consumption, and human metabolism. For example, measurements in the city of Philadelphia[115] found a city-averaged anthropogenic heat flux of ~90 W/m^2 produced a net temperature rise of ~3 °C, yielding a thermal heat transfer coefficient of $H = 3 \times 10^7$ (W/km^2)/°C. In the city of Tokyo, another study[116] of anthropocentric heating found citywide heat fluxes of ~200 W/m^2 in summer associated with a 1.5 °C temperature rise, and ~300 W/m^2 in winter with a 1.5 °C rise, giving $H = 6.7 \times 10^7$ (W/km^2)/°C in summer and 1.2×10^8 (W/km^2)/°C in winter. A second study[117] of the effects of urban air conditioning in Tokyo found a thermal heat transfer coefficient of ~3×10^7 (W/km^2)/°C. These studies suggest that an anthropogenic transfer coefficient of H_{nano} ~ **6**(3-12) **x 10^7 (W/km^2)/°C** might be applicable to nanomachine waste heat.[118]

How far might we go with this? In other words, assuming a city is intended to be inhabited by people, how hot of an environment is survivable by humans? A few notable places include:

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[111] https://en.wikipedia.org/wiki/Earth.
[112] https://en.wikipedia.org/wiki/Gravitational_constant.
[113] https://en.wikipedia.org/wiki/Gravity_tractor.
[114] https://en.wikipedia.org/wiki/Urban_heat_island.

[115] Fan HL, Sailor DJ. Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: A comparison of implementations in two PBL schemes. Atmos Environ. 2005 Jan;39(1):73-84; https://www.sciencedirect.com/science/article/abs/pii/S1352231004008866.

[116] Ichinose T, Shimodozono K, Hanaki K. Impact of anthropogenic heat on urban climate in Tokyo. Atmos Environ. 1999 Oct; 33(24-25):3897-3909; https://www.sciencedirect.com/science/article/abs/pii/S1352231099001326.

[117] Ohashi Y, Genchi Y, Kondo H, Kikegawa Y, Yoshikado H, Hirano Y. Influence of air-conditioning waste heat on air temperature in Tokyo during summer: Numerical experiments using an urban canopy model coupled with a building energy model. J Appl Meteorol Climatol. 2007 Jan;46(1):66-81; https://journals.ametsoc.org/downloadpdf/journals/apme/46/1/jam2441.1.xml.

[118] As a sanity check on this number, applying $P_{air} = 6 \times 10^7$ W to a block of air $A_{air} = 1$ km^2 in area and $x_{air} = 10$ m high (the boundary layer nearest the ground), having density $\rho_{air} = 1.29$ kg/m^3 and specific heat of $C_P = 1005$ J/kg-K at constant pressure, should produce a steady temperature rise of $\Delta K_{air} = P_{air} / (\rho_{air}\, x_{air}\, A_{air}\, C_P) = 16.6$ °C/hr. If the local mean wind speed at ground level is $v_{wind} \sim 3.3$ m/sec, then the air in an A_{air} area of city is exchanged every $t_{exch} \sim A_{air}^{1/2} / v_{wind} = 0.084$ hr, which suggests an equilibrium temperature elevation of $T \sim \Delta K_{air}\, t_{exch} = 1.4$ °C – or roughly the anticipated ~1 °C from the urban experimental data.

* Ahvaz, Iran (map, at right),[119] is a city with 1 million inhabitants and has average daily maximum temperatures exceeding 45 °C for several months of the year. The annual average high is 33.0 °C and the average maximum high is 54.0 °C.

* Furnace Creek, California,[120] has a population of 136 and holds the record for the highest recorded air temperature on Earth at 56.7 °C in 1913, and also the highest recorded natural ground surface temperature on Earth at 93.9 °C in 1972. The annual average high is 33.3 °C and the average daily maximum high is 52.6 °C.

* Dallol, Ethiopia, once inhabited but currently only a ghost town (image, right),[121] holds the record for the highest annual average temperature in the world, with temperatures regularly exceeding 34 °C year-round and daily maximum temperatures over 45 °C during the hottest months. The annual average high is 41.2 °C and the average daily maximum high is 49.0 °C.

These examples suggest that ~40 °C may be the maximum mean environmental temperature that is compatible with unaided human residence on the surface of the unaided[122] terrestrial biosphere. Animal wildlife has similar temperature limits. While the Sahara Desert ant, *Cataglyphis bombycina*, can withstand temperatures around 50-55 °C for a few minutes each day,[123] the maximum temperature for survival and reproduction is much lower for most mammals and birds. Such endothermic animals typically cannot tolerate core body temperatures above 40-41°C for prolonged periods,[124] as it can lead to heat stress, organ damage, and even death. In humans,

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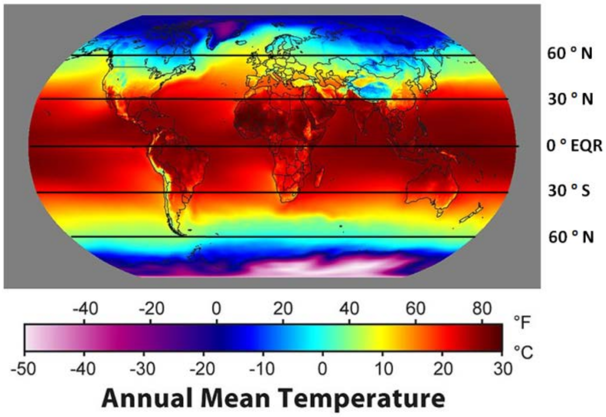
[119] https://en.wikipedia.org/wiki/Ahvaz.
[120] https://en.wikipedia.org/wiki/Furnace_Creek,_California.
[121] https://en.wikipedia.org/wiki/Dallol_(ghost_town).

[122] Of course, living exclusively indoors with the assistance of powerful air conditioning would allow a well-insulated or underground habitat to stay as cool as desired, but this would cost energy, and then create waste heat which if dumped into the local environment would raise the surface temperature above the specified 40 °C maximum limit. And yes, humans could employ even more sophisticated refrigeration systems to comfortably inhabit domiciles in far hotter climes, even ones located on the 464 °C Venusian surface (https://en.wikipedia.org/wiki/Venus). But most external plant and animal species cannot readily survive temperatures exceeding ~50 °C at Earth's surface unless they too are ensconced in the comfortable air conditioned habitat and never venture outside, which would further increase waste heat discharges into the external environment due to the additional refrigeration requirements.

[123] Wehner R, Marsh AC, Wehner S. Desert ants on a thermal tightrope. Nature 1992 Jun 18; 357(6379):586-587; https://www.nature.com/articles/357586a0.

[124] Speakman JR, Król E. Maximal heat dissipation capacity and hyperthermia risk: neglected key factors in the ecology of endotherms. J Anim Ecol. 2010 Jul;79(4):726-46; https://besjournals.onlinelibrary.wiley.com/doi/pdfdirect/10.1111/j.1365-2656.2010.01689.x.

extreme elevation of core body temperature above 40-41 °C (104-106 °F) is called hyperpyrexia and is considered a medical emergency that can lead to severe morbidity, brain damage, or death.[125] Similarly, while a few desert plants such as the creosote bush[126] can survive a peak ground temperature of ~70 °C, most plants also start to experience heat stress at temperatures above 40 °C.[127]



The maximum amount of nanomachine waste heat energy that can safely be released in a given urban location while maintaining basic human habitability depends upon the annual mean temperature (image, right)[128] at that geographic latitude in the absence of the nanomachine activity. For example, in equatorial regions where annual mean temperature is ~**30 °C**, local temperatures can only be raised $\Delta T_{nano} \sim 10$ °C to avoid exceeding our 40 °C maximum, representing a total nanomachine thermal effluent of (10 °C) $(6 \times 10^7 \text{ (W/km}^2)/°\text{C}) \sim 60 \times 10^7 \text{ W/km}^2$. Hence a city[129] with surface area $A_{city} = 100 \text{ km}^2$ that allowed an annual average of ~**0.06 TW** of nanomachine activity within its borders would drive its mean ambient temperature up to the 40 °C maximum tolerable limit. Local temperature naturally varies by time of day and time of year, so the sum total of all energy-consuming nanomachine activities within the city might be carefully regulated hour by hour to ensure that local temperature never exceeds 40 °C. Mid-latitude ~100 km^2 cities with lower annual mean temperature of ~**20 °C** would have $\Delta T_{nano} \sim 20$ °C available to them, so an average nanomachine power usage of ~**0.12 TW** would maintain local temperature near the 40 °C limit, day and night. High-latitude ~100 km^2 cities with annual mean temperature of ~**0 °C** have $\Delta T_{nano} \sim 40$ °C to play with and thus could utilize average nanomachine power usage of ~**0.24 TW** without exceeding the 40 °C limit. Of course, establishing such a huge heat plume within a small geographical area would likely force significant changes in the local weather (e.g., more intense thunderstorms and winds) and ecology.

Would anyone actually want to live in a barely habitable city environment whose local temperature was a constant ~40 °C, day and night, all year long, simply to maximize

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[125] https://en.wikipedia.org/wiki/Fever.

[126] https://en.wikipedia.org/wiki/Larrea_tridentata.

[127] Wahid A, Gelani S, Ashraf M, Foolad MR. Heat tolerance in plants: An overview. Environ Exper Botany 2007; 61(3):199-223; https://sites.google.com/site/drawahid/2007_Heat_tolerance_in_plants_an_ove.pdf.

[128] https://commons.wikimedia.org/wiki/File:Annual_Average_Temperature_Map.jpg.

[129] In 2015, the 123 most populous cities in the world ranged from 181-11,642 km^2 in land area. https://www.worldometers.info/population/largest-cities-in-the-world/.

nanomachine utilization and add a few tenths of a terawatt to capacity? Probably not. Perhaps $\Delta T_{nano} \sim 2$ °C might be a less intrusive and more acceptable target. This is roughly equivalent to the urban heat island effect[130] already experienced in major industrialized cities around the world due to existing non-nanomachine anthropogenic activities, so local weather patterns and ecologies would be only modestly impacted. Such a target would suggest a total urban nanomachine limit of $P_{urban} = \Delta T_{nano} H_{nano} \sim 120$ MW/km^2 (or ~**120 W/m^2**) and an annual average of $P_{100km2} \sim$ **0.01 TW** of total nanomachine activity within the boundaries of a ~100 km^2 city. Note that this citywide limit is at least an order of magnitude larger than the previously recommended maximum global limits (if applied to an $A_{city} = 100$ km^2 city) of $A_{city}\ \boldsymbol{\Psi}_{\mathbf{Low}} / (4\pi R_{Earth}{}^2) \sim$ **0.0003 TW** (intact icecap limit), $A_{city}\ \boldsymbol{\Psi}_{\mathbf{Mid}} / (4\pi R_{Earth}{}^2) \sim$ **0.0005 TW** (reduced greenhouse limit), or $A_{city}\ \boldsymbol{\Psi}_{\mathbf{High}} / (4\pi R_{Earth}{}^2) \sim$ **0.0026 TW** (reduced insolation limit).

2.5 Can Earth Get Hotter Still?

If we were willing to tolerate massive changes to the existing terrestrial environment, ranging from the complete melting of polar icecaps to the overheating and complete extinction of the natural ecology, we could allow nanorobots to release vastly more waste heat at the surface of the Earth.

For example, we could erect giant refrigerators enclosing large land areas, fully preserving the local ecology and a comfortable shirtsleeve environment within the protected cooled volume, while disposing the waste heat into the atmosphere outside of the structure. This could cause the air to overheat, the oceans to warm or evaporate, and the biology stranded outside of the protected enclaves to become stressed or even die, while life inside the protected enclaves continues on as normal.

In an even more extreme scenario, up to 6 trillion people[131] could be uploaded as emulations running on thermally-tolerant sapphire-based irreversible[132] mechanical nanocomputers located in large structures on the Earth's surface,[133] perhaps operating as high as ~1200 K in temperature (still well below the ~2300 K melting point of sapphire).[134] In this scenario, much or all of the Earth's surface would have been converted into hot computronium[135] glowing cherry red,[136] the

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[130] https://en.wikipedia.org/wiki/Urban_heat_island.

[131] A metabolome-level emulation of a human brain accompanied by a full virtual environment at the Landauer limit for irreversible-operation nanocomputers operating at T = 1200 K is ~7.35 MW/person, requiring ~44,000,000 TW to emulate ~6×10^{12} people, taking 6.4×10^{26} bits/sec for each brain emulation and $E_{Landauer1200K} \sim k_B T \ln(2) = 1.15 \times 10^{-20}$ J/bit for $k_B = 1.381 \times 10^{-23}$ J/K (Boltzmann's constant).

[132] Fully- or partially-reversible computing can create significantly less waste heat, possibly several orders of magnitude less, which in principle could allow the population of emulations to be several orders of magnitude larger.

[133] e.g., perhaps resembling the "Machine City" depicted in the movie *Matrix Revolutions*; https://en.wikipedia.org/wiki/The_Matrix_Revolutions.

[134] https://en.wikipedia.org/wiki/Sapphire.
[135] https://en.wikipedia.org/wiki/Computronium.

oceans would have boiled away, and all traces of biology and organic matter would have been incinerated. Crustal rock melts at 1000-1600 K,[137] so the excessive power emanations of the sapphire nanocomputers might create localized magma lakes, possibly requiring nanocomputers to have buoyant architectures (e.g., internal voids) to permit flotation on molten rock because sapphire (ρ_{sapphire} = 3980 kg/m^3)[138] is denser than magma (2180-2800 kg/m^3)[139] and would otherwise sink. Areal power density rises as the 4th power of blackbody temperature,[140] so creating a surface temperature of 1200 K by normal solar heating would require solar insolation to rise from $P_{\text{EarthSolar}}$ = 1370 W/m^2 to P_{1200K} ~ $(1200\text{ K} / 300\text{ K})^4\, P_{\text{EarthSolar}}$ ~ 350,000 W/m^2. This would be the equivalent of having active nanocomputers releasing an additional $\pi R_{\text{Earth}}{}^2\, P_{\text{1200K}}$ ~ **44,000,000 TW** at the Earth's surface, assuming an airless planet. If the atmosphere still exists, probably filled with superheated steam from the boiled oceans, the 1200 K surface temperature would likely be reached at much lower global nanocomputer power levels because water vapor is a powerful greenhouse gas.[141]

While these and related scenarios appear technically feasible, there's no obvious advantage to destroying a precious artifact that may be quite rare in the universe – i.e., a planetary surface with a viable and unique ecology, like the Earth – when we can pursue the exact same activities in space where comparatively unlimited amounts of waste heat can be harmlessly released. It seems likely that we will choose not to do these unnecessarily extreme things, on Earth.

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[136] https://en.wikipedia.org/wiki/Red_heat.
[137] https://education.nationalgeographic.org/resource/magma-role-rock-cycle/.
[138] https://en.wikipedia.org/wiki/Sapphire.
[139] https://en.wikipedia.org/wiki/Magma.
[140] https://en.wikipedia.org/wiki/Black-body_radiation.

[141] Water vapor is the most potent greenhouse gas in Earth's current atmosphere, primarily because it absorbs a wide range of infrared radiation wavelengths more effectively than CO_2; https://www.sec.gov/comments/s7-10-22/s71022-20129950-296266.pdf.

3. How Much Active Nanomachinery Can We Operate?

Aside from restrictions imposed by compression loading and materials strength, there are few limits to the total mass of passive atomically precise nanomachinery or diamondoid structure that can be deployed on Earth after it has been manufactured. If installed nanomachinery isn't actively operating, it makes no waste heat and thus contributes nothing to the planetary thermal load, with few specialized exceptions.[142] The thermal limits on waste heat generation apply only to the mass of nanomachinery that is actively consuming energy and generating waste heat.

The amount of active nanomachinery that people can safely operate at one time depends on its average specific power in MW/kg (Section 3.1),[143] which may incorporate the fraction of all nanomachinery that is active and the average duty cycle (%) of the active nanomachinery in normal use. Estimates of the maximum mass of active nanomachinery that we can operate on Earth are briefly summarized in Section 3.2.

It should be noted that thermodynamically reversible mechanical systems can in principle be designed to dissipate arbitrarily little energy for any specific operation, though all well-known systems take twice as long to complete an operation every time the energy dissipated for that operation is cut in half.[144] In this case, running at half speed for twice as long would result in one-quarter of the power consumption. While the cited analyses are for mechanical computation, their results are likely to generalize to some degree to a wider range of reversible mechanical operations. How far reversibility[145] can be employed in practice, particularly in the more general world of mechanical operations outside of computation, remains to be fully explored.

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[142] **Reflectivity:** A particularly dark or shiny planetwide coating of machinery, if not top-surfaced with living biological matter, could significantly impact the planetary albedo, causing greater or lesser amounts of solar energy to be absorbed by the surface, thus increasing or decreasing the amount of local heating. **Thermal insulation:** Diamondoid materials tend to be good thermal conductors (e.g., 2200 W/m-K for diamond, 380 W/m-K for silicon, 20 W/m-K for sapphire) compared to thermal insulators like air (~0.03 W/m-K), wood (0.1 W/m-K), and water (0.6 W/m-K) at room temperature, so diamondoid coatings should not trap heat excessively.

[143] Specific power is the power per unit mass (e.g., W/kg or MW/kg), whereas power density is the power per unit volume (e.g., W/m^3 or MW/L). Freitas RA Jr. Energy Density. IMM Report No. 50, 25 June 2019, 516 pp; http://www.imm.org/Reports/rep050.pdf.

[144] Hogg T, Moses MS, Allis DG. Evaluating the Friction of Rotary Joints in Molecular Machines. Mol Syst Des Eng. 2017; 2:235-252; https://pubs.rsc.org/en/content/articlehtml/2017/me/c7me00021a. Merkle RC, Freitas RA Jr, Hogg T, Moore TE, Moses MS, Ryley J. Mechanical computing systems using only links and rotary joints. J Mechanisms Robotics 2018 Dec;10(6):061006; https://arxiv.org/pdf/1801.03534.pdf.

[145] Landauer R. Irreversibility and heat generation in the computing process. IBM J Res Devel. 1961;5:183-191; http://fab.cba.mit.edu/classes/MAS.862/notes/computation/Landauer-1961.pdf. Bennett C, Landauer R. The fundamental physical limits of computation. Sci Am. 1985 Jul;253(1):48-57; http://web.eecs.umich.edu/~taustin/EECS598-HIC/public/Physical-Limits.pdf.

3.1 Specific Power of Active Nanomachinery

A few types of individual active nanomechanical components, especially electromechanical power conversion devices, can have extraordinarily high specific power. For example, running a disk-shaped electrostatic nanomotor[146] 25 nm thick and 100 nm in diameter at 10 volts with a 110 nanoampere current may produce a rim speed of ~1000 m/sec and deliver ~1.1 μW of power in a motor volume of 2 x 10^{-22} m^3, giving a specific power of ~**1,600,000 MW/kg** (~5,500,000 MW/L) if the device has the density of diamond. (As the designer wryly notes: "Cooling constraints presumably preclude the steady-state operation of a cubic meter of these devices at this power density.") Similarly, a ~1 nN force applied to a ~1000 nm^3 diamondoid mechanical component at a velocity of ~1 m/sec represents a specific power of **280,000 MW/kg** (~1,000,000 MW/L). A single 40 nm^3 rod-based nanocomputer memory register cell operated at 1 GHz with a loss of ~4.5 zJ/cell-cycle dissipates ~**32,000 MW/kg** (~113,000 MW/L).[147]

As extensively reviewed elsewhere,[148] operating nanomechanical and mechanochemical systems that are 10-500 nm in size may dissipate energy in the specific power range of **0.1-1000 MW/kg** (0.1-1000 MW/L). For example, a simple nanosieve[149] for separating molecules based on size and shape may have a specific power of ~**0.02 MW/kg** (~0.08 MW/L) for large molecules (~10 nm molecules, ~5.9 x 10^7 molecules/sec) or ~**0.2 MW/kg** (~0.8 MW/L) for small molecules (~0.64 nm molecules, ~1.5 x 10^9 molecules/sec). Each 150 nm wide unit of a diffusion cascade system,[150] if held to a ~**0.3 MW/kg** (~1 MW/L) limit, can process ~10^6 small molecules/sec. Telescoping nanorobotic manipulators[151] 30 nm wide and 100 nm in length may dissipate ~**0.96 MW/kg** (~1 MW/L) in continuous operation at a ~1 cm/sec arm speed. Classic sorting rotors[152]

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[146] Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 11.7.3, "Motor power and power density"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[147] Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 12.4.2, "Device size and packing", and Section 12.4.3(d), "Summary of losses"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

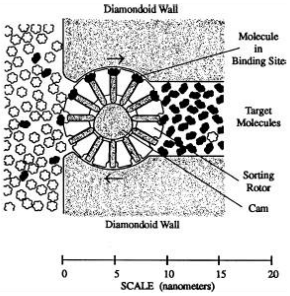
[148] Freitas RA Jr. Energy Density. IMM Report No. 50, 25 June 2019, 516 pp; http://www.imm.org/Reports/rep050.pdf.

[149] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 3.3.1, "Simple Nanosieving"; http://www.nanomedicine.com/NMI/3.3.1.htm.

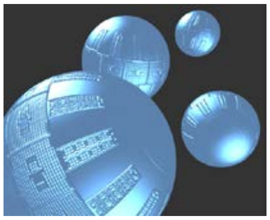
[150] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 3.2.4, "Diffusion Cascade Sortation"; http://www.nanomedicine.com/NMI/3.2.4.htm.

[151] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 9.3.1.4, "Telescoping Manipulators"; http://www.nanomedicine.com/NMI/9.3.1.4.htm. Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 13.4.1(f), "Speed, productivity, and magnitude of power dissipation"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[152] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 3.4.2, "Sorting Rotors"; http://www.nanomedicine.com/NMI/3.4.2.htm.



10-15 nm in size (image, right) will typically dissipate up to ~**6.9 MW/kg** (~10 MW/L) when operated at full speed (~10^5 rev/sec). Transporter pumps[153] ~10 nm in size transporting ~10^6 molecules/sec may draw ~**30 MW/kg** (~45 MW/L), while an 8000 nm^3 positive displacement pump for liquids runs at an estimated ~**500 MW/kg** (~125 MW/L).[154] A ~1 GHz rod-logic-based mechanical nanocomputer[155] may draw ~**640 MW/kg** (~1000 MW/L) of power, although an extremely energy-efficient helical logic-based nanocomputer[156] may be able to achieve specific power levels as low as ~**0.05 MW/kg** (~0.1 MW/L).[157] A 100 nm x 300 nm diamondoid nanocentrifuge[158] dissipates up to ~**1500 MW/kg** (~1200 MW/L) when operated at ~20% of its bursting speed. Specific power is high in these devices because much of their mass consists of active nanomachinery.



Microscale devices in the 0.5-5 μm size range will normally have a relatively small fraction of their mass or volume (perhaps only ~1%) devoted to continuously active nanomachinery, with lots of space devoted to passive hulls, tank walls, solid beams and related structures, internal voids, and bulk storage of compressed gases, liquids, or chemicals. For example, medical nanorobots may have specific power in the ~**0.001-0.1 MW/kg** (0.001-0.1 MW/L) range – e.g., ~**0.009 MW/kg** (~0.0061 MW/L) (resting) to ~**0.18 MW/kg** (~0.12 MW/L) (peak) for respirocytes (artificial red cells; image, above left).[159] Peak specific power for other nanorobot classes generally lies within this

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[153] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 3.4.1, “Transporter Pumps”; http://www.nanomedicine.com/NMI/3.4.1.htm.

[154] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 9.2.7.2, “Positive Displacement Pumps”; http://www.nanomedicine.com/NMI/9.2.7.2.htm.

[155] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 10.2.1, “Nanomechanical Computers”; http://www.nanomedicine.com/NMI/10.2.1.htm. Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 12.8, “Cooling and computational capacity”; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[156] Merkle RC, Drexler KE. Helical Logic. Nanotechnology 1996; 7(4):325-339; https://www.zyvex.com/nanotech/helical.pdf.

[157] An atomically-precise semiconductor logic element with energy dissipation of ~10^{-27} J/logic operation running at ~10^{10} operations/sec (10 GHz) of density ~2000 kg/m^3 and “a few nanometers” in size (e.g., ~100 nm^3) dissipates ~10^{-17} W per logic element with a specific power of ~0.05 MW/kg (~0.1 MW/L).

[158] Freitas RA Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999, Section 3.2.5, “Nanocentrifugal Sortation”; http://www.nanomedicine.com/NMI/3.2.5.htm.

[159] Respirocytes have a dry density of 0.679 kg/L. Freitas RA Jr. Exploratory Design in Medical Nanotechnology: A Mechanical Artificial Red Cell. Artif Cells Blood Subst Immobil Biotech. 1998;26:411-430; http://www.foresight.org/Nanomedicine/Respirocytes.html.

range, including ~**0.031 MW/kg** (~0.032 MW/L) for microbivores or artificial white cells,[160] up to ~**0.0025 MW/kg** (~0.0029 MW/L) for chromallocytes (cell repair machines),[161] and up to ~**0.007 MW/kg** (~0.007 MW/L) for maximally-active "foglet" nanorobots.[162] Biological cells typically operate in the much lower **10^{-3} – 10^{-7} MW/kg** range.[163]

Most macroscale systems and products that might contain atomically precise nanocomponents should have even lower bulk specific power levels because the percentage of active nanomachinery on board may be exceeding small, perhaps ~100-fold less than in the microscale systems, typically giving overall specific powers in the **10^{-2} – 10^{-5} MW/kg** range. For example, specific power may range from ~**0.00010 MW/kg** (~5 x 10^{-7} MW/L) for seagoing nanomachine-based carbon-capture paddleboats[164] to ~**0.00005 MW/kg** (~2.9 x 10^{-5} MW/L) for a desktop whiskey-synthesizing nanofactory,[165] ~**0.0004 MW/kg** (~5 x 10^{-5} MW/L) for a desktop cell mill[166] that fabricates biological components of biological cells including entire living cells, or ~**0.0013 MW/kg** (~2.6 x 10^{-5} MW/L) for a mature desktop nanofactory[167] that incorporates an internal nanomechanical apparatus for performing production-level mechanosynthetic chemical transformations requiring ~**0.0069 MW/kg** (~6.9 x 10^{-4} MW/L).[168] Macroscale biological

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[160] Freitas RA Jr. Microbivores: Artificial Mechanical Phagocytes using Digest and Discharge Protocol. J Evol Technol. 2005 Apr;14:55-106; http://www.jetpress.org/volume14/freitas.pdf.

[161] Freitas RA Jr. The Ideal Gene Delivery Vector: Chromallocytes, Cell Repair Nanorobots for Chromosome Replacement Therapy. J Evol Technol. 2007 Jun;16):1-97; http://jetpress.org/v16/freitas.pdf.

[162] i.e., ~700 kW/cm^3 with dissipative losses in the 10^{-5} range due to regenerative power capture. Hall JS. Utility Fog: The Stuff That Dreams Are Made Of. In: Crandall BC, ed. Nanotechnology: Molecular Speculations on Global Abundance. The MIT Press, Cambridge MA, 1996, Chapter 10, pp. 161-184; https://www.amazon.com/Nanotechnology-Molecular-Speculations-Global-Abundance/dp/0262032376.

[163] Freitas RA Jr. Energy Density. IMM Report No. 50, 25 June 2019; Table 4. Specific power of natural systems; http://www.imm.org/Reports/rep050.pdf.

[164] Freitas RA Jr. The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture. IMM Report No. 45, Dec 2015; http://www.imm.org/Reports/rep045.pdf.

[165] Freitas RA Jr. The Whiskey Machine: Nanofactory-Based Replication of Fine Spirits and Other Alcohol-Based Beverages. IMM Report No. 47, May 2016; http://www.imm.org/Reports/rep047.pdf.

[166] Freitas RA Jr. Cell Mills: Nanofactory Manufacture of Biological Components. IMM Report No. 53, 15 June 2024; http://www.imm.org/Reports/rep053.pdf.

[167] Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 14.4, "An exemplar manufacturing system architecture"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[168] The ~10^{17} Stage 1 mills that perform all of the mechanosynthesis in Drexler's mature desktop nanofactory using ~20 nm mechanisms are estimated to have a total mechanism mass of ~0.06 kg and dissipate ~1.5 x 10^6 J/kg of product with a product throughput of ~1 kg/hr, giving a specific power of [(1.5 x 10^6 J/kg) / (3600 sec/kg)] / (0.06 kg) = 0.0069 MW/kg. Assuming 100 kg/m^3 for the mill mechanisms, the power density is (0.0069 MW/kg) (0.1 kg/L) = 6.9 x 10^{-4} MW/L.

animals ranging from fungi to horses generally operate in the same **10^{-4} – 10^{-7} MW/kg** range, with humans clocking in at **0.14-2.3 x 10^{-5} MW/kg** (0.17-2.7 x 10^{-5} MW/L) depending on exertion level.[169] Of course, high specific-power macroscale systems such as nanocomputer-rich computronium are quite feasible – cooling systems for macroscopic volumes of nanomachinery have been proposed to deal with specific power levels up to ~**100 MW/kg** (~100 MW/L).[170]

What is the specific power of ordinary everyday human artifacts and machines that incorporate no nanomachinery? The specific power of active man-made objects in our ordinary surroundings is normally quite low, ranging from ~**10^{-3} – 10^{-8} MW/kg** (~10^{-3} – 10^{-9} MW/L). For instance, the Empire State Building,[171] a large commercial edifice, draws ~**3 x 10^{-8} MW/kg** (~9 x 10^{-9} MW/L), while the Burj Khalifa,[172] the world's tallest building in 2024, draws ~**7.2 x 10^{-8} MW/kg** (~2 x 10^{-8} MW/L) at peak demand. The average-sized 2000 square-foot U.S. residential house that consumes a continuous annual average of 2 kilowatts of electricity has an overall specific power of ~**1 x 10^{-8} MW/kg** (~3 x 10^{-9} MW/L).[173] Inside the house, a ~1 m^3 (~100 kg) refrigerator drawing 200 watts draws **2 x 10^{-6} MW/kg** (2 x 10^{-7} MW/L), while a single incandescent 100-watt light bulb measuring 6 cm in diameter (~30 gm) consumes **3.3 x 10^{-3} MW/kg** (9 x 10^{-4} MW/L). A 200-horsepower 10 m^3 passenger automobile draws ~**15 x 10^{-5} MW/kg** (~1.5 x 10^{-5} MW/L) when accelerating at maximum load,[174] while its human occupant draws only **1.4 x 10^{-6} MW/kg** (0.17 x 10^{-5} MW/L) at the 100-watt basal metabolic rate.

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[169] Freitas RA Jr. Energy Density. IMM Report No. 50, 25 June 2019; Table 4. Specific power of natural systems; http://www.imm.org/Reports/rep050.pdf.

[170] Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 11.5, "Convective cooling systems"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[171] The Empire State Building draws a peak of 9.5 MW (https://www.scientificamerican.com/article/making-big-apple-green/) with a total volume and mass of 1.04 x 10^6 m^3 and 3.65 x 10^5 tons (https://www.esbnyc.com/sites/default/files/esb_fact_sheet_4_9_14_4.pdf), giving 9.13 x 10^{-9} MW/L and 2.6 x 10^{-8} MW/kg.

[172] The Burj Khalifa draws a peak of 36 MW with a total volume and mass of 1.76 x 10^6 m^3 and 5 x 10^8 kg (https://www.burjkhalifa.ae/img/FACT-SHEET.pdf), giving 2 x 10^{-8} MW/L and 7.2 x 10^{-8} MW/kg.

[173] (2000 W) (10^{-6} MW/W) / [(2000 ft^2) (0.0929 m^2/ft^2) (4 m avg height) (1000 L/m^3)] = 2.69 x 10^{-9} MW/L. The average weight of a one-story house is ~200 lb/ft^2 (https://lovehomedesigns.com/how-much-does-a-house-weigh/), giving a total mass of (2000 ft^2) (200 lb/ft^2) (0.4536 kg/lb) = 181,000 kg and thus a specific power of (2000 W) (10^{-6} MW/W) / (181,000 kg) = 1.1 x 10^{-8} MW/kg.

[174] A 1000 kg, 10 m^3 car with a full 16-gallon gas tank has an overall energy density of E_D ~ (16 gallons)(3.78 L/gallon)(33 MJ/L)/(10,000 L) = 0.2 MJ/L and specific energy E_S ~ E_D / (0.1 kg/L) = 2 MJ/kg. If the car generates 200 horsepower (~0.15 MW), then p_D ~ 1.5 x 10^{-5} MW/L and p_S ~ 15 x 10^{-5} MW/kg.

Table 1. Specific power in conventional contemporary engineered systems

Macroscale Engineered System	**Specific Power** (MW/kg)
Closed cell batteries[175]	0.2-2140 x 10^{-5}
Steam-, diesel-, and electric locomotives[176]	0.4-5.1 x 10^{-5}
Batteries and fuel cells	0.4-632 x 10^{-5}
Electrostatic, electrolytic and electrochemical capacitors[177]	0.5-804 x 10^{-5}
Vestas V164 8 MW wind turbine[178]	0.62 x 10^{-5}
Fuel cell stacks and flow cell batteries[179]	0.6-150 x 10^{-5}
Photovoltaics[180]	0.6-200 x 10^{-5}
Modern cell phone	1.2-6.2 x 10^{-5}
Abrams battle tank[181]	2 x 10^{-5}
Heat engines and heat pumps[182]	3-15300 x 10^{-5}
Fluid engines and fluid pumps[183]	4.7-570 x 10^{-5}
Common passenger automobiles[184]	5.3-11.4 x 10^{-5}
800 kW diesel generator[185]	5.7 x 10^{-5}
Aircraft (propeller)[186]	11.7-36.1 x 10^{-5}
Performance luxury, roadster, and mild sports automobiles[187]	12.4-17.4 x 10^{-5}
Sports vehicles (automobiles)[188]	17.9-76.3 x 10^{-5}
Modern cell phone's CPU, GPU, and modem chips	20-67 x 10^{-5}
Electric motors and electromotive generators[189]	29-1010 x 10^{-5}
Sports vehicles (race cars and racing motorcycles)[190]	50-572 x 10^{-5}
Aircraft (jet fighters, max load),[191] using $p_S \sim$ (200 m/sec)(thrust)/(mass)	114-176 x 10^{-5}
Jet and rocket engines,[192] using $p_S \sim$ (200 m/sec)(thrust)/(mass)	352-3530 x 10^{-5}
Thermoelectric generators and electrothermal actuators[193]	509-16500 x 10^{-5}
Nuclear reactor fission core[194]	770 x 10^{-5}

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[175] https://en.wikipedia.org/wiki/Power-to-weight_ratio#(Closed_cell)_batteries.

[176] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Notable_low_ratio.

[177] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Electrostatic,_electrolytic_and_electrochemical_capacitors.

[178] https://en.wikipedia.org/wiki/Vestas_V164.

[179] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Fuel_cell_stacks_and_flow_cell_batteries.

[180] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Photovoltaics.

[181] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Notable_low_ratio.

[182] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Heat_engines_and_heat_pumps.

[183] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Fluid_engines_and_fluid_pumps.

[184] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Common_power.

[185] http://www.generac.com/Industrial/products/diesel-generators/configured/800kw-diesel-generator.

[186] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Aircraft.

[187] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Performance_luxury,_roadsters_and_mild_sports.

[188] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Sports_vehicles.

[189] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Electric_motors_and_electromotive_generators.

[190] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Sports_vehicles.

[191] https://en.wikipedia.org/wiki/Thrust-to-weight_ratio#Fighter_aircraft.

[192] https://en.wikipedia.org/wiki/Thrust-to-weight_ratio#Jet_and_rocket_engines.

[193] https://en.wikipedia.org/wiki/Power-to-weight_ratio#Thermoelectric_generators_and_electrothermal_actuators.

Table 1 above shows the typical specific power ranges for a variety of conventional contemporary engineered systems, reported in MW/kg.[195] The specific power for most "high-power" macroscale systems seems surprisingly low, such as ~**0.0015 MW/kg** for fighter jets and **0.00423 MW/kg** for the Saturn V moon rocket (whose average output power of 12.6 GW could only be maintained for 1028 sec).[196]

3.2 Maximum Mass of Active Nanomachinery on Earth

If we take $\boldsymbol{\Psi}_{\mathbf{Low}}$ ~ **1600 TW**, $\boldsymbol{\Psi}_{\mathbf{Mid}}$ ~ **2570 TW**, or $\boldsymbol{\Psi}_{\mathbf{High}}$ ~ **13,000 TW** as our maximum nanomachinery waste heat emission limits on Earth, consistent with full biosphere preservation, an equal allocation to each of our planet's N_{people} ~ 10 billion inhabitants would represent a maximum per capita global power budget of ~**0.16 MW/person**, ~**0.257 MW/person**, or ~**1.3 MW/person**, respectively. These figures assume that non-nanomachinery power demand continues to grow at the existing ~2%/yr rate (Section 2) or even declines, so that virtually all of the above power limits are available for nanomachinery. These future per capita allocations are ~100-1000 times higher than the current worldwide average of 0.0029 MW/person on Earth.[197]

Table 2, below, shows the global total active nanomachinery mass limit for a variety of mean nanomachinery specific power levels. For example, a representative nanomachinery specific power of ~$\mathbf{10^{-2}}$ **MW/kg** at the conservative $\boldsymbol{\Psi}_{\mathbf{Low}}$ = 1600 TW global power limit would imply a global mass limit of ~1.6×10^{11} kg of continuously *active* nanomachinery worldwide,[198] or ~**16 kg/person** on an Earth inhabited by ~10 billion people who each receive the same allocation.

Note that this is just a tiny fraction of the $m_{diamond} / N_{people}$ ~ **2 billion kg/person** of all diamond nanomachinery or atomically precise infrastructure that's potentially available to every human

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[194] Sun H, Wang C, Liu X, Tian W, Qiu S, Su G. Reactor core design and analysis for a micronuclear power source. Front Energy Res 2018 Mar 22; 6:14; https://www.frontiersin.org/articles/10.3389/fenrg.2018.00014/full.

[195] Freitas RA Jr. Energy Density. IMM Report No. 50, 25 June 2019; Table 5. Specific power in conventional contemporary engineered systems; http://www.imm.org/Reports/rep050.pdf.

[196] Saturn V data (https://en.wikipedia.org/wiki/Saturn_V), whole rocket with payload: mass 2.97×10^6 kg, volume 6129 m^3, density 0.485 kg/L, burn time 1028 sec, total energy 1.29×10^7 MJ, average thrust power 1.26×10^4 MW, E_S = 4.34 MJ/kg, E_D = 2.10 MJ/L, $p_S = 4.23 \times 10^{-3}$ MW/kg, $p_D = 2.05 \times 10^{-3}$ MW/L. The fueled rocket carried 770 m^3 of kerosene at 820 kg/m^3, 1576 m^3 of LOX at 1141 kg/m^3, and 1237 m^3 of LH2 at 71 kg/m^3 (https://www.space.com/18422-apollo-saturn-v-moon-rocket-nasa-infographic.html), or 2.52×10^6 kg of fuel, giving a mass density for the fueled rocket of 485 kg/m^3 but only 73 kg/m^3 for the unfueled rocket.

[197] In 2024, a world population of 8.02 billion people (https://www.commerce.gov/news/blog/2024/01/census-bureau-projects-us-and-world-populations-new-years-day) consumed ~23 TW of power (**Section 2**), a per capita power allocation of 0.0029 MW/person.

[198] The ~10^{15} kg global biological mass (~83% is plant life, ~17% microorganisms) generates ~140 TW of photosynthetic power, consistent with an average specific power of ~$\mathbf{10^{-7}}$ **MW/kg** for terrestrial biology on Earth.

inhabitant of Earth using accessible terrestrial carbon resources (Section 4.1), with ~100 times more mass available with silicon- or sapphire-based nanomachinery using only terrestrial resources and at least ~10,000 times more diamondoid inactive nanomachinery mass available using nonterrestrial resources (Section 4.2).

Such quantities of nanomachinery are sufficient to substantially impact human civilization. For example, a previous study[199] published in 2015 estimated that an advanced ocean-based system of atomically precise diamondoid nanomachinery could establish and indefinitely maintain comprehensive terrestrial atmospheric homeostasis at a global energy cost of ~4 TW,[200] holding carbon dioxide levels at pre-industrial ~300 ppm levels thus **entirely eliminating the ecological threat of global climate change**. This energy cost represents just **0.25%** of the conservative ~1600 TW global power limit and just 0.03% of the maximum ~13,000 TW global power limit for worldwide active nanomachinery deployments. The proposed ocean-borne system would employ carbon-capture devices having a specific power of **~10^{-4} MW/kg**, giving a total diamondoid nanomachinery mass requirement of ~4 x 10^{10} kg.[201] This is only about one-billionth of the ~2 x 10^{19} kg of carbon potentially available for diamond nanomachinery on Earth using terrestrial resources alone (Section 4.1).

Table 2. Global total mass limit on continuously active nanomachinery (and per-capita mass limit, assuming ~10 billion people on Earth) as a function of specific power

Specific Power of Active Nanomachinery (MW/kg)	**Global Mass Limit at Ψ_{Low} ~ 1600 TW**	**Global Mass Limit at Ψ_{Mid} ~ 2570 TW**	**Global Mass Limit at Ψ_{High} ~ 13,000 TW**
10^{-6}	1.6 x 10^{15} kg *(160,000 kg/capita)*	2.6 x 10^{15} kg *(260,000 kg/capita)*	1.3 x 10^{16} kg *(1,300,000 kg/capita)*
10^{-4}	1.6 x 10^{13} kg *(1600 kg/capita)*	2.6 x 10^{13} kg *(2600 kg/capita)*	1.3 x 10^{14} kg *(13,000 kg/capita)*
10^{-2}	1.6 x 10^{11} kg *(16 kg/capita)*	2.6 x 10^{11} kg *(26 kg/capita)*	1.3 x 10^{12} kg *(130 kg/capita)*
1	1.6 x 10^{9} kg *(0.16 kg/capita)*	2.6 x 10^{9} kg *(0.26 kg/capita)*	1.3 x 10^{10} kg *(1.3 kg/capita)*
100	1.6 x 10^{7} kg *(0.0016 kg/capita)*	2.6 x 10^{7} kg *(0.0026 kg/capita)*	1.3 x 10^{8} kg *(0.013 kg/capita)*

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[199] Freitas RA Jr. The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture. IMM Report No. 45, Dec 2015; http://www.imm.org/Reports/rep045.pdf.

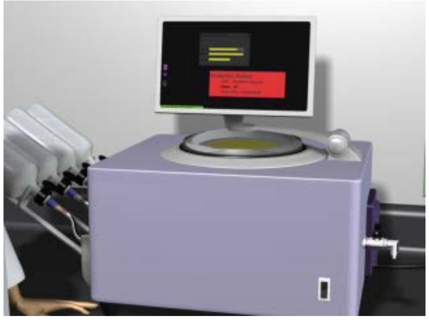
[200] $N_{golfcarts} P_{golfcart}$ ~ 4.04 TW, taking $N_{golfcarts}$ = 4.04 x 10^{10} golfcarts at $P_{golfcart}$ = 100 W/golfcart to achieve the targeted atmospheric CO_2 removal rate of ~50 gigatonnes/year.

[201] $N_{golfcarts} M_{golfcart}$ ~ 4.04 x 10^{10} kg, taking $N_{golfcarts}$ = 4.04 x 10^{10} golfcarts at $M_{golfcart}$ = 1 kg/golfcart to achieve the targeted atmospheric CO_2 removal rate of ~50 gigatonnes/year.

4. How Much Nanomachinery Can We Build?

In a future era of ubiquitous mature nanofactories, what is the maximum mass of atomically precise diamondoid[202] structure or product that we could manufacture and then deploy on Earth?

4.1 Using Only Terrestrial Resources



The estimated power density for a ~1 kg mature desktop nanofactory[203] (image, right),[204] measuring roughly 50 cm x 50 cm x 20 cm with device volume ~0.05 m^3 (50 L), that can manufacture ~1 kg/hr of a wide variety of atomically precise nanomachinery and diamondoid products, including more nanofactories, is $p_D \sim 2.6 \times 10^{-5}$ MW/L, or a specific power of $p_S \sim$ **0.00130 MW/kg**.

At the <u>most restrictive</u> $P_{max} = \mathbf{\Psi_{Low}}$ (1600 TW) limit, the world could continuously operate $M_{1600TWNF} = P_{max} / p_S = 1.23 \times 10^{12}$ kg of such nanofactories worldwide. Operating at a manufacturing rate of $\alpha_{NF} \sim 1$ kg/hr per kg of nanofactory, this fleet of nanofactories could produce $r_{1600} \sim 1.23 \times 10^{12}$ kg/hr, ~3.42×10^8 kg/sec, or ~**$\mathbf{1.07 \times 10^{16}}$ kg/yr** of atomically precise carbon-rich diamondoid product.[205]

The ability to process this much carbon gives us planetary-scale leverage over our environment. For example, recall our earlier estimate (Section 2.1) that 120 ppm of CO_2 has a mass of ~936 x

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[202] Most diamondoid materials resemble ceramics. First and foremost, diamondoid materials include pure diamond, the crystalline allotrope of carbon. Among other exceptional properties, diamond has extreme hardness, high thermal conductivity, low frictional coefficient, chemical inertness, a wide electronic bandgap, and is the strongest and stiffest material presently known at ordinary pressures. Diamondoid materials also may include any stiff covalent solid that is similar to diamond in strength, chemical inertness, or other important material properties, and that possesses a dense three-dimensional network of bonds, e.g., carbon nanotubes, fullerenes, several strong covalent ceramics such as silicon carbide, silicon nitride, and boron nitride, and a few very stiff ionic ceramics such as sapphire (monocrystalline aluminum oxide) that can be bonded to purely covalent structures such as diamond.

[203] Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 14.4, "An exemplar manufacturing system architecture"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[204] https://web.archive.org/web/20110716171312/http://www.lizardfire.com/html_nano/themovies.html.

[205] In principle, that's enough to coat the entire $f_{land} \sim 29\%$ of the land surface area on Earth ($A_{Earthland} = f_{land}\, 4\pi R_{Earth}^2 = 1.48 \times 10^{14}$ m^2; https://www.nationsonline.org/oneworld/earth.htm) with solid diamond product of density $\rho_{diamond} = 3510$ kg/m^3 to a depth of $r_{1600} / \rho_{diamond}\, f_{land}\, 4\pi R_{Earth}^2 = 2$ cm/yr. At the <u>least restrictive</u> $P_{max} = \mathbf{\Psi_{High}}$ (13,000 TW) limit, we would have a $M_{13,000TWNF} = 9.99 \times 10^{12}$ kg fleet of nanofactories worldwide, manufacturing $r_{13,000} \sim$ **$\mathbf{8.72 \times 10^{16}}$ kg/yr** of diamond product, enough to add a $r_{13,000} / \rho_{diamond}\, f_{land}\, 4\pi R_{Earth}^2 = 16.8$ cm/yr diamond coating to Earth's land surface area.

10^{12} kg and contains $M_{CO2\text{-}280}$ ~ 255 x 10^{12} kg of carbon that would have a volume of $V_{CO2\text{-}280}$ ~ 7.27 x 10^{10} m^3 if formed into diamond. Working at the $\boldsymbol{\Psi}_{\mathbf{Low}}$ (1600 TW) limit, an $M_{1600TWNF}$ = 1.23 x 10^{12} kg worldwide fleet of nanofactories able to metabolize carbon directly from atmospheric CO_2 to produce diamond product at the rate of r_{1600} ~ 3.42 x 10^8 kg/sec could drop the global CO_2 content of our present-day atmosphere from 400 ppm to 280 ppm in just $M_{CO2\text{-}280}$ / r_{1600} ~ 8.6 days.

Once we've stripped the maximum safe amount of carbon (2.55 x 10^{14} kg) from the air, reducing CO_2 content to just 280 ppm, how much of this key element might be available in other places on Earth, and where?

1. **Biomass.** The carbon content of all life on Earth is **5.45 x 10^{14} kg C**, consisting of 450 Gt in plants; 70 Gt in bacteria; 23.2 Gt in fungi, archaea, protists, and viruses; and 2 Gt in animals, including 0.06 Gt in humans.[206] We wish to avoid disturbing the ecology, so this carbon is considered off-limits for human nanotechnological use.

2. **Atmosphere.** 280 ppm equates to (280 ppm / 120 ppm) $M_{CO2\text{-}120}$ = 2.18 x 10^{15} kg of CO_2 that contains (280 ppm / 120 ppm) $M_{CO2\text{-}280}$ = **5.95 x 10^{14} kg C** having a volume of (280 ppm / 120 ppm) $V_{CO2\text{-}280}$ = 1.70 x 10^{11} m^3 when formed into diamond. But the ecology will be stressed or may perish if we extract too much of this carbon (Section 2.2), so as previously noted we will conservatively regard the remaining atmospheric carbon as off-limits for human nanotechnological use.

3. **Fossil Organic.** As of the year 2021,[207] the total carbon content of global fossil organics was estimated as **1.22 x 10^{15} kg C**. This derives from the following three primary sources: (1) Coal reserves were 1.0741 x 10^{15} kg; typical bituminous coal is 84.4% carbon by weight,[208] giving a carbon content of $\underline{9.07 \text{ x } 10^{14} \text{ kg}}$. (2) Proven petroleum reserves were 2.444 x 10^{14} kg; oil is typically 82%-85% carbon by weight,[209] giving a carbon content of $\underline{2.04 \text{ x } 10^{14} \text{ kg}}$. (3) Proven natural gas reserves were 188.1 trillion cubic meters, or 1.43 x 10^{14} kg taking density as 0.76 kg/m^3 at atmospheric pressure;[210] the carbon content of methane (CH_4), the principal component of natural gas, is 75% carbon by weight, giving a net carbon content of $\underline{1.07 \text{ x } 10^{14} \text{ kg}}$. Fossil organic carbon is potentially available for manufacturing diamondoid products, though significant underground extraction resources will be needed to obtain it. Interestingly, the

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[206] Bar-On YM, Phillips R, Milo R. The biomass distribution on Earth. Proc Natl Acad Sci U S A. 2018 Jun 19;115(25):6506-6511; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6016768/pdf/pnas.201711842.pdf. The unit of measurement "Gt" signifies a Gigaton, which is 10^9 tonnes or 10^{12} kg.

[207] Statistical Review of World Energy 2021, 70th Edition, British Petroleum; https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf.

[208] https://en.wikipedia.org/wiki/Coal#Composition.

[209] Gordon D. The carbon contained in global oils. Carnegie Endowment for Intl. Peace, 18 Dec 2012; https://carnegieendowment.org/2012/12/18/carbon-contained-in-global-oils-pub-50398.

[210] https://www.gov.uk/hmrc-internal-manuals/gas-for-road-fuel-use/hcogas400350.

estimated mass of all human-made buildings and other technology infrastructure extant on Earth in 2020, or ~1.3 x 10^{15} kg, was of similar size to the carbon content of all fossil organics but dominated by concrete, aggregates (e.g., gravel), bricks, asphalt, and metals.[211]

4. **Ocean.** The oceans contain about 63 times more carbon in the form of dissolved inorganic carbon than in the atmosphere, representing the largest inorganic carbon reservoir at ~3.8 x 10^{16} kg of carbon. Dissolved carbon dioxide occurs mainly in three inorganic forms: free aqueous carbon dioxide ($CO_2(aq)$), bicarbonate (HCO_3^{-}), and carbonate ion (CO_3^{2-}). The CO_2 concentration of this reservoir is in equilibrium with the much lower CO_2 content of the air over timescales of 10^3-10^5 years.[212] All else equal, extracting significant amounts of CO_2 from the ocean will disturb this equilibrium, causing atmospheric CO_2 to slowly leave the air and dissolve in the water to re-establish the equilibrium. The most CO_2 we might be able to permanently and safely extract from 280 ppm pre-industrial air without disrupting the terrestrial ecosystem is ~130 ppm (Section 2.2), eventually lowering the air concentration from 280 ppm to 150 ppm, a ~53% reduction.[213] If it was true that a 53% reduction in oceanic CO_2 would ultimately result in a ~53% atmospheric reduction, this might imply a long-term safely-extractable carbon resource of (53%) (3.8 x 10^{16} kg) ~ **2 x 10^{16} kg C** from the oceans. Because of the long time constant, a sudden reduction of oceanic CO_2 might produce only a few percent decrease in atmospheric concentration on ~century timescales.

5. **Fossil Inorganic**. Carbonate mineral deposits are the primary mineral store of carbon on Earth's surface, including limestone ($CaCO_3$) which is 12% carbon by weight, and dolomite ($CaMg(CO_3)_2$) which is 13% carbon by weight. One source[214] estimates that the total mass of all carbonate rocks is ~6 x 10^{19} kg comprising ~4% of Earth's crust, with a carbon content of 7.2 x 10^{18} kg. Another source[215] estimates a total of ~**2 x 10^{19} kg C** in Earth's crust, lying only 6 km below the ocean beds but up to 70 km below the highest mountain ranges like the Himalayas. Accessing this carbon store would require massive subsurface mining extending many tens of kilometers deep into Earth's crust, plus a significant amount of chemical processing to selectively extract elemental carbon from the carbonate materials. Since temperature rises ~30 °C/km of

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[211] Elhacham E, Ben-Uri L, Grozovski J, Bar-On YM, Milo R. Global human-made mass exceeds all living biomass. Nature. 2020 Dec;588(7838):442-444; https://www.nature.com/articles/s41586-020-3010-5 or https://fisherp.mit.edu/wp-content/uploads/2021/01/s41586-020-3010-5.pdf.

[212] https://www.soest.hawaii.edu/oceanography/faculty/zeebe_files/Publications/ZeebeWolfEnclp07.pdf.

[213] While the current CO_2 content of the air is ~400 ppm, changes in the ocean concentration that operate on a ~10^5 yr time frame are still mostly in equilibrium with the ~190-260 ppm air CO_2 concentration that prevailed for most of that historical time period.* Therefore, reducing atmospheric levels from 400 ppm to 280 ppm as recommended in **Section 2.2** should not cause extensive CO_2 outgassing from oceanic stores.
* https://en.wikipedia.org/wiki/Carbon_dioxide_in_Earth%27s_atmosphere#/media/File:CO2_40k.png.

[214] Meybeck M. Global chemical weathering of surficial rocks estimated from river dissolved loads. Amer J Sci 1987 May; 287(5):401-428; https://ajsonline.org/article/60410.pdf.

[215] https://www.andrew.cmu.edu/course/09-106/Chapters/08.Carbonates%20in%20the%20earth.

depth in Earth's upper crust,[216] digging deeper than ~30 km could expose excavation machinery to temperatures exceeding the maximum operating temperature of diamond machines unless adequate heat transfer or refrigeration is provided for the mining equipment, or sapphire is used.

6. **Crustal Silicon and Aluminum.**[217] We can also make strong atomically precise diamondoid products out of silicon, which in crystalline form has a failure strength of ~0.7 x 10^{10} N/m^2 or ~14% of the ~5 x 10^{10} N/m^2 failure strength of diamond; silicon carbide failure strength is intermediate at ~1.8 x 10^{10} N/m^2. The average thickness of Earth's crust is 15-20 km with an estimated mass of 2.5 x 10^{22} kg, of which 27.7% is silicon by weight,[218] giving a total silicon content of **6.9 x 10^{21} kg Si**. The crust also includes 8.1% aluminum by weight, or **2 x 10^{21} kg Al**, which can be combined with plentiful crustal oxygen to make crystalline sapphire (Al_2O_3) having a failure strength of ~2 x 10^{10} N/m^2, or ~40% as strong as diamond. As with the carbonate rocks, accessing this elemental storehouse will require massive subsurface mining and large amounts of energy for chemical processing (see below) to extract pure silicon, aluminum, and oxygen from the several other elements with which they are normally compounded in crustal rocks.

Utilizing all of the potentially exploitable terrestrial diamondoid resources (**Table 3**), we could produce on Earth approximately $m_{diamond}$ ~ **2 x 10^{19} kg of diamond** nanomachinery (from C), $m_{silicon}$ ~ **6.9 x 10^{21} kg of silicon** nanomachinery (from Si), and $m_{sapphire}$ ~ **3.8 x 10^{21} kg of sapphire** nanomachinery (from available aluminum, also requiring the acquisition of 1.8 x 10^{21} kg of oxygen from Earth's crust). This is enough to manufacture $V_{diamond} = m_{diamond} / \rho_{diamond}$ = **5.70 x 10^6 km^3 of diamond**, $V_{silicon} = m_{silicon} / \rho_{silicon}$ = **2.96 x 10^9 km^3 of silicon**, and $V_{sapphire} = m_{sapphire} / \rho_{sapphire}$ = **9.55 x 10^8 km^3 of sapphire**, taking $\rho_{diamond}$ = 3510 kg/m^3, $\rho_{silicon}$ = 2330 kg/m^3, and $\rho_{sapphire}$ = 3980 kg/m^3. The total useful (diamondoid) nanoconstruction materials mass of $m_T = m_{diamond} + m_{silicon} + m_{sapphire}$ ~ 1.072 x 10^{22} kg, having a total solid volume of $V_T = V_{diamond} + V_{silicon} + V_{sapphire}$ = 3.92 x 10^9 km^3, represents ~0.18% of the entire 5.97 x 10^{24} kg mass of Earth.[219]

Note that a diamond construction mass limit of $m_{diamond}$ ~ 2 x 10^{19} kg should be enough to build a single Trantor-sized planetary city,[220] assuming the fictional Trantor covers ~194 million km^2 (about the surface area of Mars) and is ~3 km deep with a total habitable volume of 5.82 x 10^8 km^3 and a mass density of ~34 kg/m^3.[221]

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[216] https://www.encyclopedie-environnement.org/en/zoom/pressures-and-temperatures-in-underground-storage/.

[217] Silicon, aluminum and oxygen are the three most plentiful elements in Earth's crust, comprising 82.5% of the total by weight. Of the most common remaining elements, titanium has strength similar to silicon but is only 0.6% of the crust (https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust). Iron and magnesium are slightly more plentiful but generally lack silicon's structural strength in both elemental and compounded forms.

[218] https://en.wikipedia.org/wiki/Earth%27s_crust.
[219] https://en.wikipedia.org/wiki/Planetary_mass.
[220] https://en.wikipedia.org/wiki/Galactic_Empire_(Asimov)#Trantor.

[221] This is similar to the ~29 kg/m^3 mass density for an atomically precise ~22,000 SF diamondoid mansion (design details to be published elsewhere). Typical mass densities of contemporary conventional habitable

Table 3. Total mass and volume of exploitable diamond (carbon), silicon, and sapphire (Al_2O_3) materials available solely from terrestrial Sources

Terrestrial Source	Diamond	Silicon	Sapphire
Biomass (regarded as off-limits)	(5.45 x 10^{14} kg)		
Atmospheric CO_2			
400 ppm → 280 ppm	2.55 x 10^{14} kg		
280 ppm → 0 ppm (regarded as off-limits)	(5.95 x 10^{14} kg)		
Fossil Organic	1.22 x 10^{15} kg		
Ocean	2 x 10^{16} kg		
Fossil Inorganic	2 x 10^{19} kg		
Crustal Silicon and Aluminum		6.9 x 10^{21} kg	3.8 x 10^{21} kg
Total MASS	***2.00 x 10^{19} kg***	***6.9 x 10^{21} kg***	***3.8 x 10^{21} kg***
Total VOLUME	***5.70 x 10^{15} m^3***	***2.96 x 10^{18} m^3***	***9.55 x 10^{17} m^3***

How long would it take for Earthbound nanofactories to exhaust all terrestrial diamondoid resources?

First, we have to build the nanofactory fleet on Earth. To initiate this effort, we must develop the first 1 kg mature nanofactory[222] that can make 1 kg/hr of additional nanofactory structure. After that, the nanofactory is employed to replicate itself again and again, and its offspring nanofactories are similarly used. Assuming each nanofactory produces one daughter device per cycle, then $\log_{10}(M_{1600TWNF}) / \log_{10}(2) \sim 40$ generations are needed to build out the entire maximum global nanofactory fleet at the $\mathbf{\Psi_{Low}} = 1600$ TW limit, or $\log_{10}(M_{13,000TWNF}) / \log_{10}(2) \sim 43$ generations at the $\mathbf{\Psi_{High}} = 13,000$ TW limit. Since the doubling time[223] is nominally ~1 hr, the replication of the global fleet starting from the first nanofactory could in principle be completed in just 40-43 hrs. However, in practice it will take considerably longer than this because numerous logistics issues must be addressed including (1) resource mining, (2) chemical conversion to feedstock, (3) transportation of feedstock, nanofactories, and finished product around the world, and so forth, all of which become more challenging as the total mass of working nanofactories gets larger. Depending on circumstances, the buildout could take from a few weeks to a few years.

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structures include ~240 kg/m^3 for the average ~2000 SF American wood-frame house, ~280 kg/m^3 for the Burj Khalifa (the world's tallest building), and ~350 kg/m^3 for the Empire State Building.

[222] Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 14.4, "An exemplar manufacturing system architecture"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[223] A "doubling time" is the time required for a ~1 kg mature nanofactory to manufacture its own mass of product, where that product is a duplicate nanofactory.

Once we've built out the entire terrestrial nanofactory fleet, how much time may be required to complete the fabrication of atomically precise diamondoid products using all remaining terrestrial diamondoid resources? Running at maximum output, a full terrestrial nanofactory fleet operating at the $\mathbf{\Psi_{Low}}$ = 1600 TW limit could convert all available terrestrial resources into diamond structure in $t_{best\text{-}C} \sim m_{diamond} / r_{1600} \sim 1870$ years, silicon structure in $t_{best\text{-}Si} \sim m_{silicon} / r_{1600} \sim 645{,}000$ years, and sapphire structure in $t_{best\text{-}Saph} \sim m_{sapphire} / r_{1600} \sim 355{,}000$ years. A larger nanofactory fleet operating at the $\mathbf{\Psi_{High}}$ = 13,000 TW limit could produce all manufacturable diamond product in $m_{diamond} / r_{13{,}000} \sim 230$ years, silicon in $m_{silicon} / r_{13{,}000} \sim 79{,}000$ years, and sapphire in $m_{sapphire} / r_{13{,}000} \sim 44{,}000$ years using only terrestrial resources.

The above time estimates assume that the nanofactories are presented with the ideal hydrocarbon, silicon, or aluminum feedstock. This ignores the additional energy that is required to convert the heavily oxidized liquids, gases and minerals found in nature into the ideal C, Si, Al and O feedstocks for the nanofactories. In the worst case, the reverse enthalpy of formation of atmospheric carbon dioxide from the elements at room temperature is 393.5 kJ/mole,[224] or 3.28×10^7 J/kg C. Extracting carbon from the largest terrestrial fossil inorganic sources would be several times more expensive, costing 1207 kJ/mole (1×10^8 J/kg C) for limestone[225] ($CaCO_3$) or 2325 kJ/mole (9.69×10^7 J/kg C) for dolomite[226] ($CaMg(CO_3)_2$). Extracting the entire 2×10^{19} kg of carbon from these two minerals would require an additional ~39,000 yr at the $\mathbf{\Psi_{Low}}$ = 1600 TW limit or ~4800 yr at the $\mathbf{\Psi_{High}}$ = 13,000 TW limit, both of which dominate the ~1870 years (for $\mathbf{\Psi_{Low}}$) or 230 years (for $\mathbf{\Psi_{High}}$) previously estimated for nanofactory production once the raw materials are available. Similarly, extracting the entire 6.9×10^{21} kg of silicon from the energetically cheapest sources – solid quartz, silica, or other forms of silicon dioxide (SiO_2, 911 kJ/mole,[227] 3.25×10^7 J/kg) – would take 4.5 million years at $\mathbf{\Psi_{Low}}$ = 1600 TW and 550,000 years at the $\mathbf{\Psi_{High}}$ = 13,000 TW limit. Extraction of silicon (or all available aluminum) from other more complex terrestrial mineral sources would take even longer.

It may be possible to recover much of the feedstock preprocessing energy depending on the exact inorganic catabolic[228] and anabolic[229] processes used to extract certain atoms from minerals and then rebuild different minerals containing only the surplus atoms for disposal. It has been pointed out that synthesizing diamond from simple organic molecules is actually exoergic – e.g.,

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[224] https://en.wikipedia.org/wiki/Standard_enthalpy_of_formation.

[225] https://en.wikipedia.org/wiki/Standard_enthalpy_of_formation.

[226] Hemingway BS, Robie RA. Enthalpy and Gibbs energy of formation of dolomite, $CaMg(CO_3)_2$, at 298.15 K from HCl solution calorimetry. U.S. Geological Survey, Report 94-575; https://pubs.usgs.gov/of/1994/0575/report.pdf.

[227] https://en.wikipedia.org/wiki/Standard_enthalpy_of_formation.

[228] i.e., breaking complex minerals into simple molecules or atoms; https://en.wikipedia.org/wiki/Catabolism.

[229] i.e., bonding atoms or simple molecules back into complex minerals after removal of some or all of the C, Si, Al and O atoms; https://en.wikipedia.org/wiki/Anabolism.

converting acetone feedstock into diamond actually generates ~1.7 x 10^7 J/kg of useful energy.[230] This is certainly the ideal feedstock scenario. On the other hand, converting carbon dioxide, limestone or dolomite to diamond is endoergic, generating waste heat rather than surplus energy. Specifying the precise chemical pathways that may be used to metabolize minerals is beyond the scope of this paper, but we can be fairly certain that it will be difficult or impossible to achieve faster diamondoid fabrication times than t_{best-C}, $t_{best-Si}$, or $t_{best-Saph}$, for $\mathbf{\Psi_{Low}}$ = 1600 TW, or their slightly faster equivalents at $\mathbf{\Psi_{High}}$ = 13,000 TW.

All of these time frames can be significantly accelerated by making full use of nonterrestrial diamondoid materials and nonterrestrial nanofactories, as described below in Section 4.2.

4.2 Using Nonterrestrial Solar System Resources

If we want the job done faster, we must manufacture in space and export the finished diamondoid products to Earth's surface. While it's possible to export terrestrial raw materials to space, process them there, and then return the finished products to Earth, it will probably be more economical to exclusively employ nonterrestrial[231] materials for space-based manufacturing.

A thriving space economy would have access to vastly larger power supplies, theoretically up to the full P_{solar} = 3.84 x 10^{26} W limit of total solar output,[232] and even beyond.[233] The increased

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[230] Drexler KE. Nanosystems: Molecular Machinery, Manufacturing, and Computation, John Wiley & Sons, New York, 1992; Section 14.4.8, "Energy output and dissipation"; http://e-drexler.com/d/09/00/Drexler_MIT_dissertation.pdf.

[231] For convenience, we assume only material resources located in our Solar System, no further than ~100 a.u. from the Sun. We also tentatively assume no concerted effort is made to increase the supply of carbon, silicon, or other heavy elements via large-scale nuclear fusion of available H and He atoms.

[232] Dyson FJ. Search for Artificial Stellar Sources of Infrared Radiation. Science. 1960 Jun 3;131(3414):1667-8; https://pubmed.ncbi.nlm.nih.gov/17780673/. See also: https://en.wikipedia.org/wiki/Dyson_sphere.

[233] "Some alien cultures may choose to use up their total energy reserves in a manner which is far more efficient than a stellar furnace normally permits. In other words, by tampering with the normal processes within its sun a technical civilization can increase the total amount of energy that is available to it. Over its normal lifespan the typical star will convert its hydrogen to energy with a net lifetime efficiency of perhaps 0.06% – a far cry from the 1% efficiency that may be had if the aliens turn off their sun and use their own fusion plants to burn the fuel. Furthermore, ETs may elect to burn their hydrogen legacy at a faster rate than natural processes would normally allow. This will inevitably result in a shorter lifetime for the civilization, but this penalty is offset by the grander technological feats which may be accomplished with the vastly greater power expenditure. To take a simple example: **By accepting a lifetime of only one million years, and by tampering with its sun, a Type II civilization should be able to boost its useful power output to 6 x $\mathbf{10^{31}}$ watts** – an increase of nearly six orders of magnitude over the nominal value. The situation is rather like a suicide mission. Since shortened life has been accepted, one is free to devote more resources to the present. There is much less future to save for. While this may be viewed as irresponsible by some, it may also be argued that it is better to experience a brief but glorious career than a drawn-out bland existence." Freitas RA Jr. Xenology: An Introduction to the Scientific Study of

energy availability allows a much larger fleet of nonterrestrial nanofactories to be fielded, with full access to space-derived materials nearly 100 times larger in mass than those available on Earth. Some significant fraction of the diamondoid product output of this much larger spaceborne nanofactory fleet could then make its way to Earth for on-planet use.

How much C, Si, and Al might be available from a vibrant space economy, elsewhere in the Solar System, that could be imported to Earth? The following is an informal inventory of the reasonably available carbon, silicon, and aluminum atoms that would be the most useful for the manufacture of nanomachinery within our Solar System and might be accessible given a significant effort at nonterrestrial resource extraction focused on the top several tens of kilometers of crust and atmospheres of various bodies in the Solar System (while falling considerably short of full planetary disassembly):

1. **Mercury** – surface composition of the ~30 km thick crust[234] (volume ~ 2.24 x 10^{18} m^3, density ~ 3380 kg/m^3, mass ~ 7.6 x 10^{21} kg) is ~1% C, ~25% Si (~55% SiO_2), and~3% Al (~5% Al_2O_3),[235] giving elemental masses of **7.6 x 10^{19} kg C**, **1.9 x 10^{21} kg Si**, and **2.3 x 10^{20} kg Al**, respectively.

2. **Venus** – the 4.8 x 10^{20} kg mass of Venus' atmosphere[236] is 96.5% CO_2 which is 27.3% carbon by weight, giving a carbon content of **1.26 x 10^{20} kg C**. The 50 km deep[237] surface crust of Venus (volume ~ 2.28 x 10^{19} m^3, basalt density ~ 2900 kg/m^3, mass ~ 6.61 x 10^{22} kg) is mostly basalt[238] which is typically ~22.6% Si and ~7.41% Al by weight,[239] giving a total silicon and aluminum content of **1.5 x 10^{22} kg Si** and **4.9 x 10^{21} kg Al**, respectively.

3. **Moon** – the average chemical composition of the ~40 km thick lunar crust (volume ~ 1.5 x 10^{18} m^3, density ~ 2550 kg/m^3, mass ~ 3.8 x 10^{21} kg)[240] is 20% Si and 3% Al,[241] giving a total silicon and aluminum content of **7.6 x 10^{20} kg Si** and **1.1 x 10^{20} kg Al**, respectively. Carbon

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Extraterrestrial Life, Intelligence, and Civilization. Xenology Research Institute, Sacramento CA, 1979; Section 19.2, "Extraterrestrial Habitat Engineering"; http://www.xenology.info/Xeno/19.2.htm.

[234] https://en.wikipedia.org/wiki/Mercury_(planet).

[235] Nittler LR, Chabot NL, Grove TL, Peplowski PN. The chemical composition of Mercury. ArXiv, 6 Dec 2017; https://arxiv.org/pdf/1712.02187.

[236] https://en.wikipedia.org/wiki/Atmosphere_of_Venus.
[237] https://www.universetoday.com/36155/composition-of-venus/.
[238] https://www.britannica.com/place/Venus-planet/Surface-composition.
[239] https://en.wikipedia.org/wiki/Basalt.

[240] Wieczorek MA, Neumann GA, Nimmo F, Kiefer WS, Taylor GJ, Melosh HJ, Phillips RJ, Solomon SC, Andrews-Hanna JC, Asmar SW, Konopliv AS, Lemoine FG, Smith DE, Watkins MM, Williams JG, Zuber MT. The crust of the Moon as seen by GRAIL. Science. 2013 Feb 8;339(6120):671-5; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6693503/.

[241] https://www.space.com/55-earths-moon-formation-composition-and-orbit.html.

is present in the ~10 m thick lunar regolith only in trace amounts (~82 ppm),[242] a cache of just **~8 x 10^{13} kg C**.

4. **Mars** – the 2.5 x 10^{16} kg mass of Mars' atmosphere[243] is 95% CO_2 which is 27.3% carbon by weight, giving a carbon content of **6.48 x 10^{15} kg C**. A presently unknown mass of carbonate minerals are present in the crust, which is mostly basalt and 10-50 km thick (volume ~ 1.4-7.2 x 10^{18} m^3, basalt density ~ 2900 kg/m^3, mass ~ 1 x 10^{22} kg), giving a total silicon and aluminum content of **2 x 10^{21} kg Si** and **7 x 10^{20} kg Al**, respectively.

5. **Asteroids** – the ~2.39 x 10^{21} kg of mass in the Asteroid Belt[244] includes 75% carbon-rich asteroids containing ~3% carbon,[245] or **5.4 x 10^{19} kg C**, and 17% silicon-rich asteroids containing ~18% Si and ~1.5% Al,[246] or **7.3 x 10^{19} kg Si** and **6.1 x 10^{18} kg Al**.

6. **Jupiter** – the 3000 km thick atmosphere (volume ~ 1.8 x 10^{23} m^3, density ~ 1330 kg/m^3, mass ~ 2.4 x 10^{26} kg) includes 0.1%-0.3% C,[247] mostly present as methane, giving an approximate carbon content of **4.8 x 10^{23} kg C**. There might also be traces of atmospheric silicon-based compounds, mostly SiO_2 (~47% silicon by weight) at an estimated concentration of ~10^{-6} kg/L,[248] giving a total atmospheric silicon content of **~8 x 10^{19} kg Si**.

7. **Jovian Moons** – Ganymede has a rocky mantle that's inaccessibly buried ~1000 km beneath a crust of hexagonal ice, a deep subsurface saltwater ocean, and a thick shell of tetragonal ice.[249] Callisto has a submantle of rock and cubical ice below a mantle of rock and tetragonal ice, but these are inaccessibly buried ~400 km below a crust of hexagonal ice, a deep subsurface saltwater ocean, and a shell of monoclinic ice.[250] Europa also has a rocky interior buried beneath a 10-30 km thick layer of cold surface ice atop a 100 km deep subsurface saltwater ocean.[251] Io has a ~12 km thick crust of 2900 kg/m^3 basalt that is ~22.6% Si (~**3.3 x 10^{20} kg Si**) and ~7.41% Al (~**1.1 x 10^{20} kg Al**) by weight, and a silicate-rich mantle that is 75% forsterite (Mg_2SiO_4, 20% silicon by weight, ~3270 kg/m^3) that transitions to a 50 km deep magma ocean located 50 km beneath the surface,[252] giving ~**1.0 x 10^{21} kg Si** assuming a ~38 km accessible (mineable) solid thickness. None of these moons has significant carbon content.

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[242] https://en.wikipedia.org/wiki/Lunar_resources.
[243] https://en.wikipedia.org/wiki/Atmosphere_of_Mars.
[244] https://en.wikipedia.org/wiki/Asteroid_belt.
[245] https://en.wikipedia.org/wiki/Carbonaceous_chondrite.
[246] https://www.space.com/3126-asteroids-data-sheet.html.
[247] https://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html.

[248] Howland G, Harteck P, Reeves RR Jr. Silicon compounds in the Jupiter atmosphere. Z Naturforsch 1979; 34(12):1541-1543; https://www.degruyter.com/document/doi/10.1515/zna-1979-1224/pdf.

[249] https://en.wikipedia.org/wiki/Ganymede_(moon).
[250] https://en.wikipedia.org/wiki/Callisto_(moon).
[251] https://en.wikipedia.org/wiki/Europa_(moon).
[252] https://en.wikipedia.org/wiki/Io_(moon).

8. **Saturn** – the ~1000 km thick atmosphere (volume ~ 4.3 x 10^{22} m^3, density ~ 687 kg/m^3, mass ~ 2.9 x 10^{25} kg) includes 0.34% C,[253] mostly present as methane, giving an approximate carbon content of **9.9 x 10^{22} kg C**.

9. **Titan** – Saturn's largest moon has a 6.13 x 10^{18} kg atmosphere containing 2.7% methane by weight, giving a carbon content of **1.24 x 10^{17} kg C**. In addition, Titan has two large open lakes of liquid hydrocarbon, including Kraken Mare (5 x 10^{13} m^3, 638 kg/m^3 (70% methane at 657 kg/m^3 and 14% ethane at 544 kg/m^3), 2.7 x 10^{16} kg)[254] and Ligeia Mare (2 x 10^{13} m^3, 657 kg/m^3 (assumed to be pure methane), ~1.3 x 10^{16} kg),[255] giving a carbon content of ~**3 x 10^{16} kg C**. A rocky core is buried deeply under a crust of ice and is relatively inaccessible without planetary disassembly.

10. **Uranus** and **Neptune** – Uranus' ~3 x 10^{24} kg upper atmosphere is 2.3% methane by weight,[256] giving a carbon content of **5 x 10^{22} kg C**. Neptune's ~5 x 10^{24} kg upper atmosphere is 1.5% methane by weight,[257] also giving a carbon content of **5 x 10^{22} kg C**. These figures exclude several Earth-masses of methane in each planetary mantle and silicon in each rocky core, as these resources are considered inaccessible in any scenario short of planetary disassembly. It has also been speculated[258] that on Neptune at a depth of 7000 km, methane may be crushed into diamond crystals that rain downwards like hailstones. This kind of diamond rain might also occur on Uranus, and very-high-pressure experiments at the Lawrence Livermore National Laboratory suggest that the top of the mantles might be an ocean of liquid carbon with floating solid diamonds.[259]

11. **Triton** – The surface of Neptune's largest moon is a ~1 km thick layer of annealed frozen nitrogen,[260] atop a crust consisting of ~55% nitrogen ice with other ices mixed in, including ~15% CO_2 dry ice (1560 kg/m^3, 27% C) and ~0.1% methane ice (522 kg/m^3, 75% C), below which may exist a subsurface ocean above a deeper core that may be 55%-70% rocky material.[261] A 10 km thick crust[262] would imply ~**1.5 x 10^{19} kg C** from the CO_2 and ~**9 x 10^{16} kg C** from the CH_4. The deeper silicon is relatively inaccessible without planetary disassembly.

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[253] https://en.wikipedia.org/wiki/Saturn.
[254] https://en.wikipedia.org/wiki/Kraken_Mare.
[255] https://en.wikipedia.org/wiki/Ligeia_Mare.
[256] https://en.wikipedia.org/wiki/Uranus.
[257] https://en.wikipedia.org/wiki/Neptune.

[258] Kerr RA. Neptune may crush methane into diamonds. Science. 1999 Oct 1;286(5437):25; https://www.science.org/doi/10.1126/science.286.5437.25a. Benedetti LR, Nguyen JH, Caldwell WA, Liu H, Kruger M, Jeanloz R. Dissociation of CH4 at high pressures and temperatures: diamond formation in giant planet interiors? Science. 1999 Oct 1;286(5437):100-2; https://scholar.archive.org/work/pmm36chombcvxpc76xkl3xndpm/access/wayback/http://cas.umkc.edu/physics/kruger/papers/science_10_99.pdf.

[259] https://en.wikipedia.org/wiki/Extraterrestrial_diamonds.

[260] Sori MM. Can Triton's internal heat be inferred from its ice cap? Geophys Res Lett 2021 Jan 19;48(5):e2020GL090518; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020GL090518.

[261] https://en.wikipedia.org/wiki/Triton_(moon).

12. **Minor Moons** and **Trans-Neptunian Dwarf Planets** – The known objects in this category with a radius >200 km have a total mass of ~6.4 x 10^{22} kg,[263] with the 9 largest trans-Neptunian objects (including Pluto, Eris, and Sedna) comprising ~4.16 x 10^{22} kg of the total and the smaller moons not already listed comprising another 1.7 x 10^{22} kg.[264] If these rocky and icy bodies are ~10% silicon by weight, this gives an additional ~**6.4 x 10^{21} kg Si** if fully consumed.

This inventory (**Table 4**) of the readily accessible carbon, silicon, and aluminum atoms that would be the most useful for the manufacture of conventional nanomachinery[265] within our Solar System suggests than an additional $m_{diamondNT}$ ~ **6.793 x 10^{23} kg C**, $m_{siliconNT}$ ~ **2.75 x 10^{22} kg Si**, and $m_{sapphireNT}$ ~ **1.15 x 10^{22} kg sapphire** (derived from 6.06 x 10^{21} kg Al and 5.39 x 10^{21} kg of oxygen, which is plentiful in the Solar System, to make the Al_2O_3) may be available from nonterrestrial sources without resorting to full planetary[266] or solar[267] disassembly (which would increase available diamondoid construction resource mass by roughly 100-fold and 10,000-fold, respectively). This would be enough to manufacture $V_{diamondNT} = m_{diamondNT} / \rho_{diamond}$ = **1.94 x 10^{11} km^3 of diamond**, $V_{siliconNT} = m_{siliconNT} / \rho_{silicon}$ = **1.18 x 10^{10} km^3 of silicon**, and $V_{sapphireNT} = m_{sapphireNT} / \rho_{sapphire}$ = **2.89 x 10^9 km^3 of sapphire**. The aforementioned total useful (diamondoid) nanoconstruction materials mass of $m_{NT} = m_{diamondNT} + m_{siliconNT} + m_{sapphireNT}$ ~ **7.18 x 10^{23} kg** represents just 0.028% of the 2.54 x 10^{27} kg of non-solar mass in the Solar System.[268]

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[262] https://www.cronodon.com/PlanetTech/triton.html.
[263] https://en.wikipedia.org/wiki/List_of_Solar_System_objects_by_size.
[264] https://en.wikipedia.org/wiki/List_of_gravitationally_rounded_objects_of_the_Solar_System#Planets.

[265] We ignore here the theoretical possibility of building non-conventional nanomachinery using alternative non-ceramic atoms, metals, hard-frozen water-ice, metallic hydrogen and other forms of highly compressed matter, and so forth, because it is not immediately clear how to employ these materials at scale. If a way could be found, this might open the path to still larger available masses of deployable nanomachinery in the Solar System.

[266] Full disassembly of all the planets and moons in the Solar System, excluding Earth, would yield an estimated additional ~2.54 x 10^{27} kg of raw mass, including ~2.69 x 10^{25} kg of C, ~3.22 x 10^{25} kg of Si, and ~2.98 x 10^{24} kg of Al from which ~5.61 x 10^{24} kg of sapphire could be produced using 4.1% of the ~6.40 x 10^{25} kg of O that would also be liberated. Available Fe (~6.82 x 10^{25} kg) and Mg (~2.95 x 10^{25} kg) lack silicon's structural strength in both elemental and compounded forms. About 90.7% of Solar System planetary mass is H and He, both of which are useless as structural atoms unless converted to heavier elements via artificial nucleosynthesis; https://en.wikipedia.org/wiki/Stellar_nucleosynthesis. (Including Earth in the disassembly program would add only 2.8% more Si and 2.8% more sapphire to the total.)

[267] Full disassembly of the entire 1.9885 x 10^{30} kg Sun would yield an estimated additional ~4.73 x 10^{27} kg of C, ~1.33 x 10^{27} kg of Si, and 1.11 x 10^{26} kg of Al from which ~2.09 x 10^{26} kg of sapphire could be produced using 0.86% of the ~1.15 x 10^{28} kg of O that would also be liberated. Available Fe (~2.59 x 10^{27} kg) and Mg (~1.40 x 10^{27} kg) lack silicon's structural strength in both elemental and compounded forms, and there is only ~6.26 x 10^{24} kg of Ti (which has strength similar to silicon). About 98.7% of the Sun's mass is H and He, neither of which is directly useful as structural atoms but both of which could be employed as fusion energy fuels. Asplund M, Grevesse N, Sauval AJ, Scott P. The chemical composition of the Sun. Annu Rev Astron Astrophys 2009 Sep 22; 47:481-522; http://astro.uni-tuebingen.de/~rauch/TMAP/asplundgrevessesauvalscott2009.pdf.

[268] https://en.wikipedia.org/wiki/Planetary_mass.

Some of this manufactured nanomachinery mass can be exported and deployed to Earth, if desired.

Table 4. Total mass and volume of exploitable diamond (carbon), silicon, and sapphire (Al_2O_3) materials available from nonterrestrial sources

Nonterrestrial Source	Diamond	Silicon	Sapphire
Mercury	7.6×10^{19} kg	1.9×10^{21} kg	4.36×10^{20} kg
Venus	1.26×10^{20} kg	1.5×10^{22} kg	9.30×10^{21} kg
Moon	8×10^{13} kg	7.6×10^{20} kg	2.09×10^{20} kg
Mars	6.48×10^{15} kg	2×10^{21} kg	1.33×10^{21} kg
Asteroids	5.4×10^{19} kg	7.3×10^{19} kg	1.16×10^{19} kg
Jupiter	4.8×10^{23} kg	8×10^{19} kg	inaccessible
Jovian Moons	n/a	1.33×10^{21} kg	2.09×10^{20} kg
Saturn	9.9×10^{22} kg	inaccessible	inaccessible
Titan	1.54×10^{17} kg	inaccessible	inaccessible
Uranus and Neptune	1.0×10^{23} kg	inaccessible	inaccessible
Triton	1.509×10^{19} kg	inaccessible	inaccessible
Minor Moons and Dwarf Planets	n/a	6.4×10^{21} kg	n/a
Total MASS	***6.793×10^{23} kg***	***2.75×10^{22} kg***	***1.15×10^{22} kg***
Total VOLUME	***1.94×10^{20} m^3***	***1.18×10^{19} m^3***	***2.89×10^{18} m^3***

How fast can such huge volumes of atomically precise diamondoid structures be manufactured? If we initially ignore the time and energy required to acquire and transport the raw materials and process them into proper nanofactory feedstocks (see estimates below), and also the time and energy needed to build out the fleet of nanofactories, the time required just for manufacturing will be dominated by the available power input. Assuming a solar energy resource (i.e., sunlight) from an intact Sun, this time will be approximated by $t_{manuf} = m_{NT}\, p_S / P_{max}\, \alpha_{NF} = m_{NT}\, p_S / f_{solar}\, P_{solar}\, \alpha_{NF}$, where m_{NT} is the mass of nonterrestrial feedstock materials, $p_S \sim 0.00130$ MW/kg is the assumed specific power demand of a mature nanofactory, $\alpha_{NF} \sim 1$ kg/hr per kg of nanofactory is the productivity per unit mass of a mature nanofactory, and P_{max} is the power input to the manufacturing process. Taking P_{max} as the fraction f_{solar} of the total power output of the Sun ($P_{solar} = 3.84 \times 10^{26}$ W), the total manufacturing time is $t_{manuf} \sim 2.43$ hr / $f_{solar} \sim 2.43$ hr (2.79×10^{-4} yr) using the entire solar output (i.e., $f_{solar} \sim 1$), which would require a space nanofactory fleet of mass $M_{SSNF} = f_{solar}\, P_{solar} / p_S = 2.95 \times 10^{23}$ kg or ~41% of the available construction mass.[269] Even leaving practicalities aside, this seems excessive.

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[269] If each nanofactory produces one daughter device per cycle, then $\log_{10}(2.95 \times 10^{23}\ \mathrm{kg}) / \log_{10}(2) \sim 78$ generations of nanofactory replication are needed, starting from the first 1 kg nanofactory, to build out a nanofactory fleet capable of converting all Solar System diamondoid resources into diamond in 2.43 hr.

A very relaxed buildout time of t_{manuf} = 1000 yr to produce the entire $V_{NT} = V_{diamondNT} + V_{siliconNT} + V_{sapphireNT}$ = **2.09 x 10^{11} km^3** of atomically precise diamondoid product would only require f_{solar} ~ 2.79 x 10^{-4} yr / t_{manuf} (yr) = 2.79 x 10^{-7} of total solar output using a space nanofactory fleet of mass $M_{sNF} = f_{solar}\ P_{solar}\ /\ p_S$ = 8.24 x 10^{16} kg, needing just ~0.00001% of the available Solar System diamondoid construction mass to build the fleet. A circumstellar shell of diamondoid solar power collectors of a generously-estimated average thickness[270] of $x_{collector}$ ~ 100 µm and density $\rho_{collector}$ ~ 1000 kg/m^3 orbiting at Earth's distance from the Sun intercepting $P_{EarthSolar}$ ~ 1370 W/m^2 of solar power and converting it to useful energy at an efficiency[271] of ε ~ 0.5 could produce the required $f_{solar}\ P_{solar}$ power input using a solar collector diamondoid mass of $M_{collector} = f_{solar}\ P_{solar}\ x_{collector}\ \rho_{collector}\ /\ \varepsilon\ P_{EarthSolar}$ ~ 1.56 x 10^{16} kg, which could itself be manufactured by the space nanofactory fleet in $t_{collector}$ ~ $M_{collector}\ /\ \alpha_{NF}\ M_{sNF}$ ~ 680 sec.

What's the scale of the feedstock processing energy cost for this 1000-yr project? Almost all (99.96%) of the accessible carbon in the Solar System is methane (CH_4), sourceable from the four gas giant planets, with a reverse enthalpy of formation of 74.9 kJ/mole (~6.24 x 10^6 J/kg C).[272] Extraction of 6.79 x 10^{23} kg of carbon from the methane in ~1000 yr requires a continuous energy input of 1.35 x 10^{20} W, or f_{solar} ~ 3.5 x 10^{-7} of total solar output, which is roughly the same energy input as required by the entire nanofactory fleet. As for the feedstock transportation cost, efficiently vertically lifting ~7 x 10^{23} kg of methane ~1000 km in the ~1 g surface gravity field of a giant planet in ~1000 yr similarly costs ~2 x 10^{20} W, or f_{solar} ~ 6 x 10^{-7} of total solar output, or roughly double the feedstock processing cost.

A total diamondoid nanoconstruction material mass of m_{NT} ~ 7.18 x 10^{23} kg in the Solar System would be enough to build ~36,000 Trantor-sized planetary cities (at ~2 x 10^{19} kg each), ~10 billion Island Three O'Neill Cylinder space colonies,[273] or a single giant diamondoid space city of ρ_{city} ~ 400 kg/m^3 construction density that could occupy a cubical volume measuring ~12,000 km on a side.[274]

The P_{solar} power draw of the last generation of nanofactories could be collected by a circumstellar shell of power collectors of total mass $M_{collector}$ ~ 2.8 x 10^{22} kg, or another ~4% of the available construction mass.

[270] https://en.wikipedia.org/wiki/Thin-film_solar_cell.
[271] https://en.wikipedia.org/wiki/Solar-cell_efficiency and https://en.wikipedia.org/wiki/Optical_rectenna.
[272] https://en.wikipedia.org/wiki/Standard_enthalpy_of_formation.

[273] Each space colony consists of two counter-rotating hollow cylinders assumed to be 32 km in length, 8 km in diameter, with a 10 m thick outer shell and another ~8 m thickness of internal structure of density ~2000 kg/m^3, and an interior filled with 1.29 kg/m^3 density air, giving a total colony mass of ~7 x 10^{13} kg. O'Neill GK. The High Frontier: Human Colonies in Space. William Morrow & Company, NY, 1977; https://en.wikipedia.org/wiki/O%27Neill_cylinder.

[274] Gravitational compression loading[*] restricts a spherical diamondoid structure of mass m_{NT} ~ 7.18 x 10^{23} kg, failure strength $\sigma_{diamond}$ ~ 5 x 10^{10} N/m^2, and construction density ρ_{city} ~ 400 kg/m^3 to a maximum radius of $R_{max} \sim (3\ \sigma_{diamond}\ /\ 2\pi\ G\ \rho_{city}^2)^{1/2}$ ~ 47,000 km, taking gravitational constant G = 6.67 x 10^{-11} N-m^2/kg^2.
[*] de Pater I, Lissauer JJ. Planetary Sciences. Cambridge University Press, 2015; https://www.amazon.com/dp/1107091616/.

5. Conclusions

The principle objective of this paper is to estimate how much nanomachinery could be deployed on Earth without causing any significant changes to planetary ecology, habitability, or appearance. Actively operating nanomachinery generates waste heat, hence the mass of active nanomachinery is limited by the Earth's heat tolerance. Inactive nanomachinery generates no waste heat, hence is limited in total mass primarily by resource availability.

As the amount of waste heat from deployed active nanomachinery increases and Earth's temperature slowly rises, the dominant major impact of excess heating would be polar icecap melting, causing major continental flooding and many other harmful ecological impacts (Section 2.1). Some of this damage could be mitigated by deploying major geoengineering projects (some of which involve nanomachinery) such as continental-scale seawalls and other adaptations to a hotter and more humid Earth. Future research might explore the limits of nanomachine power generation if we were willing to tolerate the loss of all polar ice worldwide.

Based on relevant published simulations of the effects of atmospheric carbon dioxide concentration on the formation of the permanent Antarctic ice sheet, we can estimate that geographically-uniformly adding $\mathbf{\Psi_{Low}}$ ~ **1600 TW** of nanomachine waste heat into the terrestrial environment would be just insufficient to melt the polar icecaps, but adding P_{Melt} ~ 2500 TW would be highly likely to melt the icecaps (Section 2.1). Thus we conservatively set 1600 TW as the baseline maximum global nanomachinery power limit for Earth.

This baseline limit can be increased, allowing a bit more active nanomachinery to be deployed on Earth, by at least two methods that could be employed singly or simultaneously.

First, greenhouse gases such as carbon dioxide could be selectively removed from Earth's atmosphere using carbon capture and sequestration nanomachinery to reduce the level of Earth's atmospheric CO_2 from over 400 ppm today to the pre-industrial 280 ppm concentration within a few decades of deployment (Section 2.2). Nanomachinery waste heat generation worldwide could be allowed to rise to $\mathbf{\Psi_{Mid}}$ ~ **2570 TW** without melting the polar icecaps once atmospheric CO_2 levels have first been reduced to 280 ppm. This power limit could be slightly increased by reducing global atmospheric CO_2 levels below 280 ppm, but the primary plant enzyme that produces oxygen via photosynthesis has a catalytic maximum at 200 ppm and there is evidence that photosynthesis would be materially impaired below 150 ppm. In the interest of keeping the current planetary ecology largely intact, we conservatively opt for the 2570 TW limit at 280 ppm.

Second, we could reduce the solar insolation received by the Earth from the Sun, making room for additional waste heat generation by nanomachinery without risking icecap melting (Section 2.3). Various technological methods have been proposed for accomplishing this, such as mirrors or sunshades interposed between Earth and Sun orbiting near the dynamically semi-stable Earth-Sun L1 Lagrangian point in space, or by deploying mirror-containing buoyant nanoballoons in Earth's stratosphere that can be remotely-controlled to reflect more or less of the incoming solar radiation back into space. Worldwide nanomachinery could be allowed to release a total of $\mathbf{\Psi_{High}}$ ~ **13,000 TW** of waste heat without melting the polar icecaps, once atmospheric CO_2 levels have first been reduced to 280 ppm *and* solar insolation has been permanently reduced by 6% via the worldwide deployment of a stratospheric nanoballoon fleet, an orbital sunshade, or other means. Reducing insolation by more than 6% may similarly reduce global oxygen production, and hence the oxygen content of the air. Humans can survive permanent reductions in oxygen partial pressures up to at least 30% at high altitudes, but again, in the interest of keeping the current planetary ecology and habitability largely unchanged, we conservatively opt for the 13,000 TW maximum limit at 280 ppm CO_2 and 6% insolation reduction.

Having established the maximum global active nanomachinery power limits, there is a wide range of anticipated specific power (MW/kg) requirements for various classes of active nanomachinery (Section 3.1). For example, a representative nanomachinery specific power of ~**10^{-2} MW/kg** at the conservative $\mathbf{\Psi_{Low}}$ = 1600 TW global power limit would imply a global mass limit of ~1.6 x 10^{11} kg of continuously *active* nanomachinery worldwide, or ~**16 kg/person** on an Earth inhabited by ~10 billion people who each receive the same allocation (Section 3.2).

The total mass of nanomachinery that can be deployed on Earth is considerably larger than the mass of active nanomachinery that can safely be allowed to operate. That's because this total mass can be mostly passive nanostructure or nanomachinery that is usually inactive, hence not contributing to the global heat load. Utilizing all of the readily exploitable terrestrial diamondoid resources, we could produce on Earth ~**2 x 10^{19} kg of diamond** nanomachinery, ~**6.9 x 10^{21} kg of silicon** nanomachinery, and ~**3.8 x 10^{21} kg of sapphire** nanomachinery (Section 4.1). Running at maximum output, a full terrestrial nanofactory fleet operating at the $\mathbf{\Psi_{Low}}$ = 1600 TW limit could convert all available terrestrial resources into diamond structure in ~1870 years, silicon structure in ~645,000 years, and sapphire structure in ~355,000 years. A larger terrestrial nanofactory fleet operating at the $\mathbf{\Psi_{High}}$ = 13,000 TW limit could produce the above nanomachinery ~8 times faster.

The aforementioned time frames can be significantly accelerated, and the total mass of nanomachinery potentially deployable on Earth markedly increased, by utilizing nonterrestrial diamondoid materials and nonterrestrial nanofactories. For example, making use of the readily accessible carbon, silicon, and aluminum atoms within our Solar System would allow the off-planet fabrication and subsequent deployment to Earth of an additional ~**6.793 x 10^{23} kg** (~1.94 x 10^{11} km^3) **of diamond** nanomachinery, ~**2.75 x 10^{22} kg** (~1.18 x 10^{10} km^3) **of silicon** nanomachinery, and ~**1.15 x 10^{22} kg** (~2.89 x 10^9 km^3) **of sapphire** nanomachinery (Section 4.2) without resorting to full planetary or solar disassembly (which would increase available diamondoid construction resource mass by roughly 100-fold and 10,000-fold, respectively).

The question of what we might do with all this nanomachinery is an interesting topic that will be explored in future discussions.