Human Carrying Capacity of the Earth

Benjamin Rubinger

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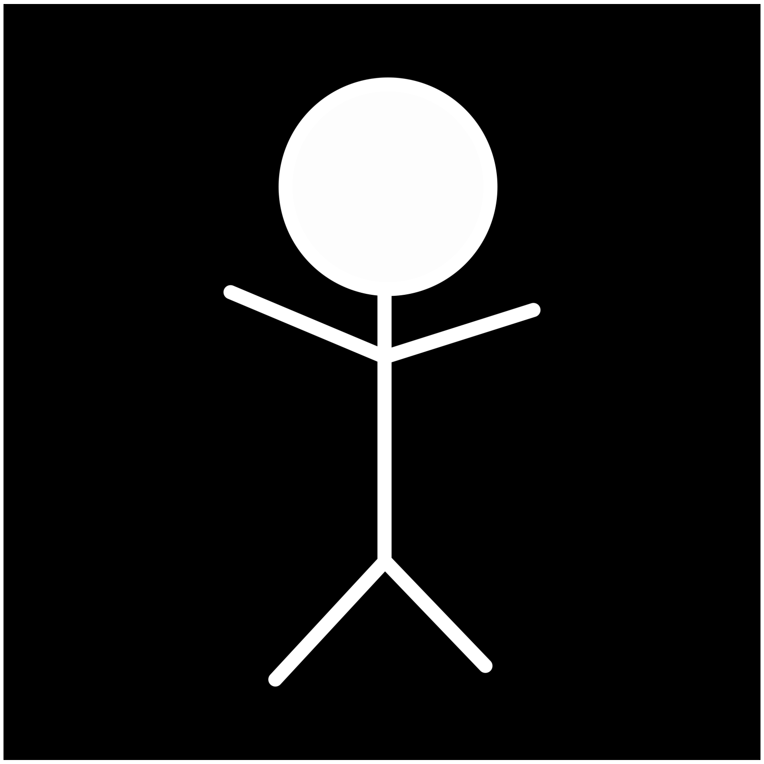


Introduction

The Question

Sustainable Population

How many people can the Earth support? What is the maximum sustainable human population using current technology? The popular answer today is 4 to 10 billion people. My answer is 510 trillion, and this book explains exactly how, so you can improve your own estimate.

Why should you care about this question? Your answer does not directly apply to the problems of your everyday life, but it does affect your views about many of life's larger questions, such as whether you support peace or war, deregulation or regulation, whether you consume more or less, or whether you have children or not. There are many justifiable views about how to live your life. Your views might depend a lot on how you answer the question of Earth's carrying capacity.

The question of carrying capacity is useful because it can be objective. This book explores the physical limits, ignoring politics, ethics, financing, etc. The limits we consider are not a goal or a policy, they serve to illustrate how enormous the actual possibilities are. How many people can sustainably live on Earth at the limit of current technology?

Carrying Capacity

Carrying Capacity

Carrying capacity describes the maximum sustainable utilization of a system. When we talk about the human carrying capacity of the Earth, that is the maximum number of humans that could live here, generation after generation, for a long time. It assumes a steady state, meaning constant population, constant energy use and complete recyling, zero net-new material use. Think of a forest that receives sunshine and recycles the air, water and soil to support a constant population of plants and animals.

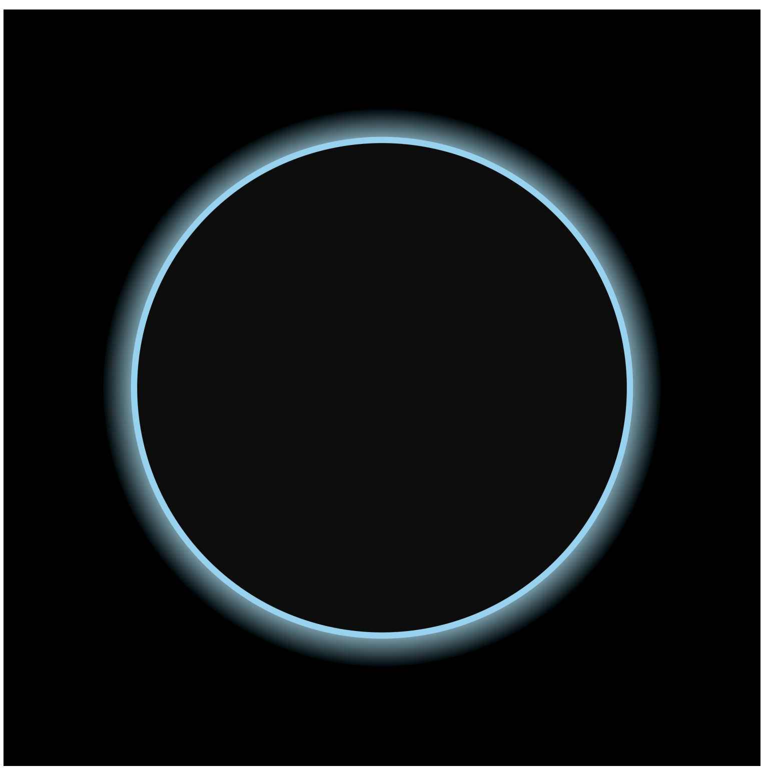
Sustainable

Sustainable processes are closed loop and can continue effectively forever, or can operate for long enough that they can practically be considered forever. For example, digging up fossil fuels for energy production is not sustainable, because the concentration of atmospheric carbon dioxide will increase, and we will eventually run out of fossil fuels to dig up, even if we have enough to last for a long time. On the other hand, solar energy is available to collect every day without altering our atmosphere or the sun running out of energy, at least for a billion years.

Other peoples' incorrect estimates of the human carrying capacity of the Earth

Year	Human Earth carrying capacity estimate	Author	Source	Argument
1964	60 trillion	J H Fremlin	An article in New Scientist magazine titled, How many people can the world support?	Based on 2000 story buildings, nuclear power and synthetic food. Winner of most accurate competitive estimate!
1965	No specific limit	Buckminster Fuller	Series of reports called The World Design Science Decade, and The Operating Manual for Spaceship Earth	Using geodesic domes, hydroponics and recycling
1968	2 billion	Paul Ehrlich	The Population Bomb	Based on the 1960s limits of farming
1976	100 trillion	Gerard O'Neill	The High Frontier	Based on space colony designs, not an estimate of Earth carrying capacity. In my opinion, similar methods could apply to Earth.
1994	1 billion	David Pimentel	Population and Environment	Based on farming sustainability

Year	Human Earth carrying capacity estimate	Author	Source	Argument
1995	4 to 16 billion	Joel E Cohen	How many people can the Earth support?	He did not answer the question, he surveyed people. These were the most common estimates, they often concluded the limit was farming, fresh water, energy or ecosystems.
2002	2 billion	Edward O Wilson	The Future of Life	Biodiversity
2024	10 billion	The United Nations	World Population Prospects	Projection that agriculture will be able to feed that population level, but it may not be sustainable
2024	4 billion	Global Footprint Network	Ecological Footprint Atlas	Based on regenerative biocapacity of food, land and CO_2.



Environmental Conservation

I think I understand the perspectives of environmental conservationists. Humans are only one species of animal on our wonderful planet, it is full of diverse environments, ecosystems and other species. There are two separate arguments to preserve existing ecosystems, human survival and fairness.

Humanity depends on existing ecosystems

Humanity doesn't fully understand or control the world, we depend on it. It is possible that if humanity disrupts ecosystems or creates imbalance, ecological collapse will take humanity out too. Humanity wrongly thinks it can fly, but if it leaps off the cliff, it will fall to its death. The cliff is metaphorically the ecosystems that currently support humanity. Maybe we can survive the jump, maybe we can't, but why risk it? Just live safely and happily within our already functional ecosystems.

My counterargument to concerns about self-destruction from ecological collapse is that humanity should prioritize our safety and security above all else. We should prepare to survive and thrive if there is ecological collapse for any reason, whether it is caused by humanity or not. We should preserve existing ecosystems in the way that we rely on them today, and reduce our reliance on them to zero as soon as possible. After we can survive and thrive without natural ecosystems, then humanity is safe and environmental conservation is optional, not required. Even if we choose to conserve the environment, we should be able to survive in case something happens to it.

Fairness

The other reason for environmental conservation is fairness. Other species have no less right to exist than people do, it is just as wrong for people to destroy ecosystems as much as it would be for ecosystems to destroy us, live and let live. Or consider fairness across human generations. Maybe I appreciate ecosystems that are alive today and I can experience them personally, but if humanity destroys ecosystems, then future generations won't be able to experience them. Destroying ecosystems is unfair to future generations of people.

My counterargument to fairness is that life isn't fair, and in many ways life should not be fair. Humanity is natural. Anything that is artificial is not supernatural, it is just man-made. Nature is unfair, nature is red of tooth and claw. Nature made humanity, and humanity can artificially develop the natural environment. Humans don't disrupt ecosystems out of selfish wanton destruction. We don't hate ecosystems or future generations. Humanity wants to live better lives and make more happy lives in the future, but human lives take space and resources. I value human lives over other animals or ecosystems. I am humanist. It is naturally fair that humans take territory from existing ecosystems because we outcompete them totally. This is not a perversion of nature, it is the rule of nature, survival of the fittest. Humans are the fittest. This planet is ours. Now, how many happy people can we keep on it?

If it were possible to both increase human population and preserve our wonderful ecosystems, that would be best. Well, that is possible! As long as humans migrate to space, living either in spaceships or other bodies, such as currently dead planets, we can have both. We could proliferate across the stark and lifeless solar system while preserving the blue jewel of Earth as our human heritage, a whole-planet ecological preserve. If you are an environmentalist, you should support aggressive space colonization. But space colonies are not the subject of this book, the subject is the human carrying capacity of the Earth, if we stay.

Rules of This Game

Seeking Limits

When you consider how many people we can keep on Earth, you naturally change your perspective from the Earth being a fixed, natural rocky home, to the perspective of Earth as a modifiable space ship. Our question is really about the practical potential of Earth's life support system. If we planned to live as hunter gatherers using the natural life support system, we would get one number, perhaps in the hundreds of millions. If we fully apply the technology we already have today, we get a very different number.

Population limit analyses, if they investigate the absolute population limit, require terrible human lifestyles with meagre food, space and other privations, what is called a Malthusian Condition, where people are barely alive, crowded and starving. My analysis is based on the sustainable carrying capacity of happy, healthy people who have plenty of space and everything else they need for a pleasant life. Specifically about food, they eat an adequate, normal, omnivorous human diet without forcing them to eat insects or bacteria spreads. Let them eat steak.

This analysis will rely only on today's technology, nothing speculative. I only propose applying proven technologies that are available today. Geothermal power and lab-grown meat? Yes. Fusion power or self-replicating nanotechnology? No.

Lab-grown meat has been proven, but is it available? Do we feed the world using lab-grown meat today? No, we don't. Is it feasible to feed the world using only lab-grown meat by next year? No. But is it feasible to convert conventional ranching and factory farming to lab-grown meat eventually? Yes. Should we expect the cost to produce lab-grown meat to come down and efficiency to increase as we scale-up the production of lab-grown meat? Yes.

Population Growth

This thought exercise is intended to be realistic, you can apply this model to the real world that we have today, with one fictional assumption. The difference is that this model assumes that the human fertility rate will immediately jump to 4 and stay at that level until we reach Earth's limit. A fertility rate of 4 means that women have on average four surviving children each. Some women would have more than four, some fewer children or none, but the average would be 4. The human population would increase quickly but not explosively, growing and growing until we hit the carrying capacity of the Earth. After we hit the capacity limit, then the fertility rate would fall to replacement, and humanity could live on Earth sustainably, until the sun explodes.

Table describing one possible timeline of population growth at a fertility rate of 4

Year	Population in billions
2025	8
2050	13
2075	24
2100	60
2125	112
2150	198
2175	359
2200	623
2225	1129
2250	1991
2275	3577
2300	6276
2325	10948
2350	18975
2375	32955
2400	57247
2425	99170
2450	172419
2475	299325
2500	510000

Bottlenecks

As the human population grows, we can keep operating society as usual until we hit a bottleneck. A bottleneck is when we run out of something when we need more, requiring us to do something different. For example, if people keep having children, and every person consumes electricity, then if the power companies don't build more power stations, we would run out of power. Or maybe we have enough power, but people need more fresh water, and maybe there isn't enough rainfall in the area to provide fresh water for all the new water demand. How can we get more fresh water? There can be all kinds of different bottlenecks that could limit population growth. We will solve every bottleneck we hit to allow the population to keep growing.

We will consider every significant potential bottleneck in the order that we might hit them, solve that bottleneck, and consider what the upper limit of that resource on Earth could be. For example, people need water, and there is a lot of water on Earth. Considering only water, how many people could Earth support? A lot. We will keep solving bottlenecks until we finally can't solve one and call that the final limit. The limiting factor is the single reason we can't sustainably keep more people on Earth, and that will tell us the approximate human carrying capacity of the Earth.

These are all the significant bottlenecks we will consider.

Space

Water

Food

Elements. We will calculate per-person elemental estimates, check the known abundances on Earth, and then say how many people we can support of each element.

- Oxygen - concrete, atmosphere, biomass
- Silicon - concrete, glass
- Calcium - concrete

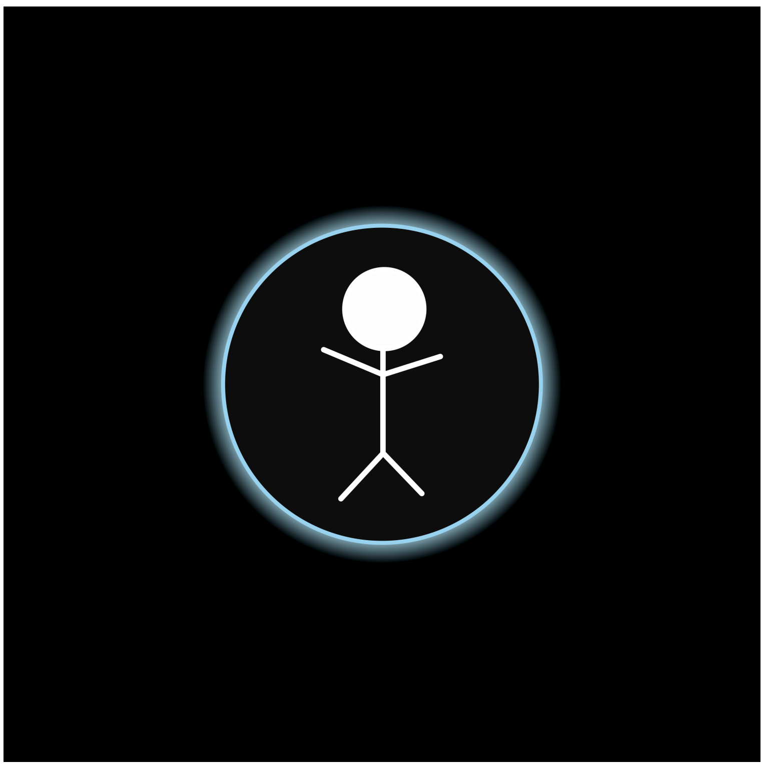
- Iron - steel
- Aluminum - structures, devices
- Nitrogen - atmosphere
- Carbon - plastics, biomass
- Chromium - steel
- Copper - electric infrastructure, devices
- Potassium - biomass
- Phosphorus - biomass

Waste management

Energy

- Geothermal
- Solar

Heat



Space

Square-Cube Law

Square-Cube Law

An essential concept we will rely on to surpass bottlenecks is the Square-Cube Law. In a square area, like a plot of land with an area of one square kilometer, you could place one farm field, or about 440 suburban detached houses. If you don't limit your construction to the ground surface, and use the volume of a cubic kilometer instead, you could fit 44,000 homes in the same land area. People can only crowd together so closely on the surface of the Earth. The way to grow is not to crowd closer together, it's to build vertically. Think in terms of volumes, not areas.

Some things work better with increased density. Compared to houses that are spread far apart, you need less infrastructure such as roads, wires and pipes to connect houses that are grouped close together or stacked on top of each other.

Habitable Space

People need space. With a growing population, we might run out of free land or farmland. The surface of the Earth is vast, but sprawling human settlement could cover the land before we hit other bottlenecks. If we converted the surface of the Earth into a five story building, the floor space would be about five times the surface area of the Earth, we would have five Earths of surface area. We can build higher than five stories, too. How tall is each floor? 4.3 meters per floor is a common building practice today.

How much space does one person need? 20 square meters of personal floor space per person means 86 cubic meters personal volume per person. But we need other things to support a person, such as plants to feed them, and pipes and pumps and hallways, so let's allocate 1000 cubic meters per person.

Let's consider a moderate scenario first. We will only use land that people already inhabit. That is all existing human settlements, including urban, suburban and rural villages but excluding sparse rural, farms, pastures, parks or undeveloped land. These current human settlements only cover 2.1% of Earth's land area. Assume we fully use only this already-settled land to house and support people, 1000 m^3 per person, all inclusive. Using mid-rise buildings, they would be 31 stories tall, 132m, their total volume could support 414 billion people. We could return all the sparse rural and farmland to nature, leaving 97.9% of the land area as a nature preserve while greatly expanding our population.

But the real question is, what is the current human limit of habitable space? How high above the surface of the Earth can people live, and how low below the surface of the Earth can people live? We know the answers based on what people already do. The J Hotel in Shanghai Tower has occupied rooms at 556 meters above ground level. How deep can we live underground? At least a kilometer, demonstrated by the staff who work in deep mines. Let's consider a spherical shell, 1 kilometer thick, centered on the surface of the Earth, with floors reaching 500 meters above ground level and basements down to 500 meters below ground level. That will be the habitable volume of the Earth.

How many people can we fit in the habitable volume of the Earth?

The volume of a 1km thick spherical shell centered on the surface of the Earth is 510 quadrillion cubic meters.

The volumetric human carrying capacity of a 1km thick shell around the Earth with 1000 m^3 per person is

The Earth population limit of habitable space is 510 trillion people.

Perhaps future developments would allow us to build taller and dig deeper, if we need more space than that. There is no limit of space, in space.

Water

If we grow the human population, one of the first things that some areas might run out of is fresh water. Running out of fresh water is different from a lack of water overall. Any sailor knows that people and plants can't survive by drinking seawater, as in the expression, water, water everywhere but not a drop to drink. There is a lot of water in general, but there are local limits to fresh water, such as on the ocean, deserts or areas with contaminated water sources.

The water cycle describes the environmental process of heat evaporating water from the surface of the Earth into pure water vapor, forming clouds in the sky, raining fresh water down that humans can use. Running out of local fresh water has nothing to do with running out of water overall, it is about mismanagement of water resources and expecting free fresh water to fall from the sky wherever you are standing. We have the ability to transport water to where it is needed and filter not-fresh water into fresh water. Moving and filtering water are things we can accomplish at scale, they require modest infrastructure and modest energy to create abundant and constant fresh water anywhere on Earth. There is no practical limit to freshwater capacity.

The ultimate question about water is how many people can the water of Earth support at the limit?

Analysis of Water Use Per Person Per Day

This is a simple analysis of the full water involved with a person, during one day in a closed-loop system. Embodied stocks, like the water in plants or that makes up your body, are combined with cycled uses, which are treated and reused. We use these to derive the total amount of water we need per person.

Item	Amount of water required in liters
Production of Plants, Meat, Dairy	1,600
Wastewater processing	100
Drinking, Cleaning	95
Human body	42

Item	Amount of water required in liters
Food, Excreta	5
Humidity	5
Total	1,847

We can estimate

1,850 liters of water / person.

The total water on Earth is 1.372×10^{21} liters

The population limit due to water is the total water on Earth divided by the water per person

$1.372 \times 10^{21} / 1{,}850 = 7.416 \times 10^{17}$ people

The Earth population limit of water is 742 quadrillion people.

Food

The most common assumption of the limiting factor for human population is food, due to limits of farmland and threats like soil erosion and weather. Yes, those are problems if you insist on farming outside in the dirt, but we don't have to produce food that way. Indoor agriculture is a proven technology that is not limited by farmland, soil or weather conditions. Aquaponics is the practice of farming plants in water, often fertilized by fish, and aeroponics is a technique to grow plants without soil, occasionally spraying the roots with a mist of nutrient solution. Indoor agriculture is a revolution in farming efficiency compared to outdoor agriculture. For example, indoor agriculture uses substantially less water to grow the same food. Indoor agriculture, conducted indoors, can prevent water vapor from escaping into the atmosphere, or spreading into the ground away from the roots that need it. Fertilizer applied to plants outdoors can be washed away, becoming environmental pollution, but fertilizer applied to plants indoors can be collected and reapplied until it is fully used.

Indoor agriculture uses artificial lighting to grow the plants instead of sunlight. Plant leaves can only absorb specific colors of light, which is why leaves are green. Leaves reflect green light because they can't absorb it. If leaves absorbed all colors of light, they would appear to be black. The lights used in indoor agriculture are made to emit only the colors of light that the leaves can absorb, saving a lot of energy and reducing waste heat. Not relying on the sun means that plant growth is not limited by day-night cycles, bad growing temperatures, seasons or cloud cover. The plants can grow nearly continuously, significantly increasing production speed and food quality.

What are some of the worst pollutants that harm humans today? Fertilizers, herbicides and pesticides used in outdoor agriculture. Indoor agriculture creates a factory environment that can prevent the invasion of weeds, pests and diseases, so the need for herbicides and pesticides is all but eliminated, or managed far better than outdoor agriculture does today. Indoor agriculture is volumetric and more space efficient, so food production can be located near food consumption. This means fresh, local food with minimal transportation costs even in dense human settlements. Indoor agriculture is much more efficient on all key dimensions, space, energy, inputs, pollution, logistics. All of this is nice and all, but what we really care about is that indoor agriculture is scalable. That means that we can make as much food as we want.

Food production is unlike space or water, it is not a fixed attribute of the Earth. We can decide how much space to devote to farming, which foods to produce and how to optimize the production process. We could minimize space, water use, energy, a combination of the above, or something else. The limits to food production are almost the same as the limits to human carrying capacity, which is why food is popularly recognized as the most prominent limit to sustainable human population. The analysis of food production in space, water, materials and energy are described in those sections instead of analyzing every aspect here.

The important point about food production is that humanity has the technology today to sustainably scale food production without limitation by farmable land, soil conditions, weather, seasons, location, pollution etc.

I also want to emphasize that analyses of maximum population usually compromise on human diet, demanding unhealthy, unpleasant, limited diets such as vegan diets because calories from grains are so much more efficient to produce. Authors tend to rely on efficient grains to calculate the maximum population. I am not interested in a restrictive or unpleasant human carrying capacity, so the food production I am talking about is the full omnivorous diet that humans enjoy, including all the things that people like to eat, including meat, dairy, vegetables, grains, fruits and anything healthy and delicious. But we will produce them using far more efficient methods than conventional farming practices, surprisingly using only technology that is available today, such as indoor agriculture and lab grown meat and dairy.

Elements

When we consider scaling human population to extreme numbers, there is always a possibility that we will run out of a critical material or element such as steel, concrete, glass, plastic or oxygen. Modern steel is an artificial material, so really our concern is about the constituent elements of our materials, such as oxygen, iron, or silicon. Modern materials are so complex and sometimes exotic, maybe we can't make enough high-strength steel to house everyone, because we don't have enough of some rare element. Who knows? Maybe chromium is the limiting factor. Some elements are hard requirements, such as oxygen, while others have acceptable alternatives and substitutes. If we ran out of glass, we could substitute plastic for some applications of glass, or vice versa. Interestingly, some materials are convertible into others. For example, water H_2O, can be split into hydrogen and oxygen, meaning that if we have plenty of water, but not enough oxygen, we could convert some water to oxygen to solve that problem, and vice versa.

The concern about running out of critical materials is reasonable because materials on Earth are limited, but the analysis concludes that we have plenty of every material we need. The human population limit is not a material constraint.

Below are separate analyses of the most critical elements, their allocation per human, how much there is of that element on Earth, their abundance, and the implied human Earth carrying capacity of each element. We assume a one year stored supply of food for resilience.

Oxygen

```
Per Person Analysis of Oxygen

    50,000 kg in concrete

    350 kg in food, 1 year of stored supply

    276 kg in 1000 m³ atmosphere

    106 kg in glass

    105kg in biomass

        45 kg in human body

        60 kg in farming biomass

    30 kg in plastics

50,867 kg total oxygen / person
```

The total oxygen in Earth's crust, water, and atmosphere is ~1.2×10^{22} kg

The population limit due to oxygen is the total available oxygen on Earth divided by the oxygen per person

$1.2 \times 10^{22} / 50{,}867 = 2.36 \times 10^{17}$ people

The Earth population limit of oxygen is 236 quadrillion people.

Silicon

```
Per Person Analysis of Silicon

    29,000 kg in concrete
```

```
    106 kg in glass

    0.2 kg in devices

    0.1 kg in food, 1 year of stored supply

    0.05 kg in biomass

        0.02 kg in human body

        0.03 kg in farming biomass

29,106 kg total silicon / person
```

The total silicon in Earth's crust is ~7×10^{21} kg

The population limit due to silicon is the total available Silicon on Earth divided by the silicon per person

7×10^{21} / 29,106 = 2.4×10^{17} people

The Earth population limit of silicon is 240 quadrillion people.

Calcium

```
Per Person Analysis of Calcium

    20,000 kg in concrete

    1.2 kg in biomass

        1 kg in human body

        0.2 kg in farming biomass

    0.3 kg in food, 1 year of stored supply

    0.1 kg in fertilizer buffers

20,002 kg total calcium / person
```

The total calcium in Earth's crust is ~8.75×10^{20} kg

The population limit due to calcium is the total available calcium on Earth divided by the calcium per person

8.75×10^{20} / 20,002 = 4.37×10^{16} people

The Earth population limit of calcium is 43 quadrillion people.

Iron

```
Per Person Analysis of Iron

4,950 kg in steel

4,950 kg total iron / person
```

The total iron in Earth's crust is ~1.4×10^{21} kg

The population limit due to iron is the total available iron on Earth divided by the iron per person

1.4×10^{21} / 4,950 = 2.83×10^{17} people

The Earth population limit of iron is 283 quadrillion people.

Aluminum

```
Per Person Analysis of Aluminum

    1,000 kg in structures

    100 kg in devices and equipment

1,100 kg total aluminum / person
```

The total aluminum in Earth's crust is ~2×10^{21} kg

The population limit due to aluminum is the total available aluminum on Earth divided by the aluminum per person

2×10^{21} / 1,100 = 1.82×10^{18} people

The Earth population limit of aluminum is 1.82 quintillion people.

Nitrogen

```
Per Person Analysis of Nitrogen

    900 kg in atmosphere

    5.5 kg in food, 1 year of stored supply

    3.6 kg in biomass

        2.1 kg in human body

        1.5 kg in farming biomass

910 kg total nitrogen / person
```

The total nitrogen in Earth's atmosphere and crust is ~4×10^{18} kg

The population limit due to nitrogen is the total available nitrogen on Earth divided by the nitrogen per person

4×10^{18} / 910 = 4.4×10^{15} people

The Earth population limit of nitrogen is 4.4 quadrillion people.

Carbon

```
Per Person Analysis of Carbon

    160 kg in plastics

    120 kg in food, 1 year of stored supply

    43 kg in biomass

        13 kg in human body
```

```
        30 kg in farming biomass

    25 kg in steel

    20 kg in other items

    10 kg in fabrics

378 kg total carbon / person
```

Steel is used in reinforced concrete, structures, infrastructure, devices and equipment.

The total carbon in Earth's crust is ~5×10^{18} kg

The population limit due to carbon is the total available carbon on Earth divided by the carbon per person

$5 \times 10^{18} / 378 = 1.3 \times 10^{16}$ people

The Earth population limit of carbon is 13 quadrillion people.

Chromium

```
Per Person Analysis of Chromium

50 kg in steel alloys

50 kg total chromium / person
```

The total chromium in Earth's crust is ~3.5×10^{18} kg

The population limit due to chromium is the total available chromium on Earth divided by the chromium per person

$3.5 \times 10^{18} / 50 = 7 \times 10^{16}$ people

The Earth population limit of chromium is 70 quadrillion people.

Copper

```
Per Person Analysis of Copper

    10 kg in electrical infrastructure

    5 kg in devices, equipment

15 kg total copper / person
```

The total copper in Earth's crust is ~1.5×10^{18} kg

The population limit due to copper is the total available copper on Earth divided by the copper per person

$1.5 \times 10^{18} / 15 = 1 \times 10^{17}$ people

The Earth population limit of copper is 100 quadrillion people.

Potassium

```
Per Person Analysis of Potassium

    1.1 kg in food, 1 year of stored supply
```

```
    0.75 kg in biomass

        0.25 kg in human body

        0.5 kg in farming biomass

    0.2 kg in fertilizer buffers

2.05 kg total potassium / person
```

The total potassium in Earth's crust is ~6.5×10^{20} kg

The population limit due to potassium is the total available potassium on Earth divided by the potassium per person

$6.5 \times 10^{20} / 2.05 = 3.17 \times 10^{20}$ people

The Earth population limit of potassium is 317 quintillion people.

Phosphorus

```
Per Person Analysis of Phosphorus

    0.9 kg in biomass

        0.7 kg in human body

        0.2 kg in farming biomass

    0.44 kg in food, 1 year of stored supply

    0.1 kg in fertilizer buffers

1.44 kg total phosphorus / person
```

The total phosphorus in Earth's crust is ~2.5×10^{19} kg

The population limit due to phosphorus is the total available phosphorus on Earth divided by the phosphorus per person

$2.5 \times 10^{19} / 1.44 = 1.74 \times 10^{19}$ people

The Earth population limit of phosphorus is 17 quintillion people.

Material Limits

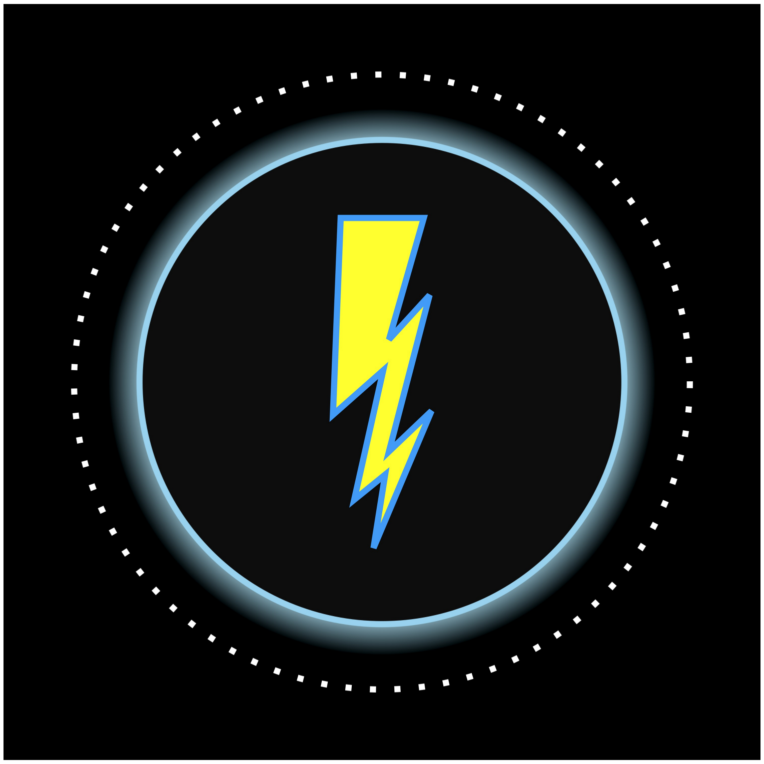
Nitrogen is the bottleneck at 4.4 quadrillion people, but people can comfortably live in lower atmospheric pressures, using less nitrogen. The material limit of the human carrying capacity of the Earth is in the quadrillions.

Waste Management and Recycling

Wastewater management is a problem we are already able to solve today. Conventional wastewater treatment can remove most solids and water contaminants, while reverse osmosis or distillation can convert treated wastewater back into potable water. The materials filtered out from wastewater can be merged into the solid waste treatment.

Solid waste management is mainly resolvable through existing recycling techniques and burning, recapturing the burned gases as well. These are not trivial challenges, but they are manageable through existing technologies with adequate investment, space and energy. Future developments will increase efficiency and reduce costs.

In other words, the primary reason that society does not perfectly recycle today is not a technical limitation. We could recycle everything, but it is more profitable today to discard waste into landfill and extract new materials. When materials are limited but energy is abundant, full recycling will come into practice.



Energy

Electric power is the magical force of the modern age. Indoor agriculture avoids depending on the sun, but it requires energy for the lights, water pumps, monitoring systems etc. We are going to need a lot of power to sustain so many people. Will we run out of energy? No. There is a lot of energy available, and the amount of energy necessary to sustain a person is moderate. How we generate and manage the power to sustain people is still a critical choice that can affect the human carrying capacity of the Earth.

There are many power generation technologies, but they derive from the fundamental forces of physics, the strong nuclear force, the weak nuclear force, and gravity. I will propose which currently available power generation technologies we should use.

I also distinguish between active and passive. Active production of, for example fresh water, requires pumping seawater to where it is needed, filtering seawater into freshwater, using the freshwater, collecting and treating the wastewater. This is an active process, artificial, people have to intervene and control every step. Compare this active process to passive water management, where people depend on the natural water cycle to move the water around, collect freshwater from wells and rain barrels, use the freshwater and dump the wastewater in the street or into rivers. The natural water cycle manages most aspects of dealing with water in this more passive approach, but it leaves people vulnerable to droughts or water contamination.

Energy Generation Technologies

Nuclear

Nuclear power generation has two available mechanisms, nuclear fission and nuclear fusion.

Active Fission

Conventional nuclear power. Find and extract uranium or thorium ore, refine it, manufacture fuel rods, manage the fuel with the reactor to generate energy, breed more fuel, treat the nuclear waste, dispose and store the nuclear waste. Complex and has risks.

Passive Fission

Decay of radioactive materials underground generates heat that contributes to the overall heat of the interior of the Earth, usable by geothermal power generators. No mining, refinement, manufacturing, treatment, disposal or storage of nuclear materials. Total utilization of all radioactive materials, except for breeding.

Active Fusion

Artificial fusion power. Not an operational technology today, excluded from this analysis.

Passive Fusion

Solar power. The Sun generates so much power, we don't know what do to with it, yet. Solar panels and batteries can easily collect enough energy from the surface of the Earth for current human energy demand. Energy is lost if we have to transmit it over long distances, and seasons and cloud cover can significantly reduce the practicality of solar panels on parts of the Earth's surface, terrestrial solar. These problems do not exist in Earth orbit. A satellite with solar panels orbiting the Earth can collect strong solar energy half the time or even all the time, depending on its orbit. Solar power collecting satellites can beam the energy down to the surface of the Earth using microwaves, where a special receiver called a rectenna can safely collect the microwaves and convert them to electricity we can use. This method works at all times and all locations on Earth. Space-based solar panels are not visible from the ground, don't take up space on the surface of the Earth, and are scalable to collect an almost unlimited amount of power. There is effectively unlimited power from the sun, we can beam it to Earth's surface and have effectively free, unlimited energy. Furthermore, this is not a theoretical energy source, this is a proven and demonstrated technology, it just hasn't been necessary to apply it, yet.

Gravity

Heat of formation of the Earth

Geothermal energy is a passive power generation technology that uses the temperature difference between the hot center of the Earth and the cold crust to generate energy. Geothermal energy technology has been developed and operational for a long time, but conventional geothermal is limited to active geological areas, for example volcanic areas like Iceland. There have been recent significant improvements to geothermal energy technology, called enhanced geothermal. Enhanced geothermal energy generation can work almost anywhere on Earth. The enhancement refers to two improvements over conventional geothermal, new drilling technologies and hydraulic fracturing. These techniques allow wells to be drilled better faster cheaper, and the hydraulic fracturing uses pure water to crack open the rocks underground. Operators then pump water into the well and the hot rock boils the water into pressurized steam, which can be used to generate electricity. Enhanced geothermal can cause small Earthquakes. The amount of power available with geothermal is significant but limited, it is an ideal form of energy generation for sustainability because it makes use of the waste heat of the Earth that humanity has to live with anyway.

Tidal forces on the Earth from the Moon

Tidal energy is a passive energy source, but is limited to oceans and does not generate as much energy as geothermal or solar, so excluded from this analysis.

Sustainable Energy Generation

My analysis relies on geothermal and Space-Based Solar Power, SBSP. Starting today, sunny areas could adopt terrestrial solar and batteries to meet their energy needs, and areas without enough sun can drill geothermal wells. Both of these technologies can provide consistent, sustainable energy as the population grows. Using existing space launch and satellite technologies, we can introduce global SBSP and continuously increase capacity. As long as the production, delivery and maintenance of SBSP meets or exceeds the energy demands of the growing population, there is effectively no limit to the amount of energy available on Earth to support human population. SBSP is not outside of Earth's area of influence, it is just outside of Earth's atmosphere. For efficient transmission of the energy, the satellites can't be too far away, so the SBSP satellites would be in medium Earth orbit, firmly within Earth's influence and legitimately contributing to the human carrying capacity of the Earth.

Analysis of Energy Use Per Person

Category	Energy use in Kilowatt Hours Per Day
Food	7.81
Industry	5.17
Life support	3.34
Climate control	3.08
Transport	1
Personal care	1
Backup	1
Lighting	0.7
Entertainment	0.5
Medical	0.5
Maintenance	0.5
Communications	0.4
Education	0.2
Water treatment	0.1
Total	25.25 Kilowatt Hours / Day

1052 Watts Per Person

Geothermal Power

Total available geothermal energy is 100 terawatts.

The Earth population limit of geothermal energy is 95 billion people.

Terrestrial Solar Power

The total amount of incoming solar energy, insolation, at the surface of the Earth is 89 petawatts.

If the entire surface of the earth was completely covered with solar panels at 20% conversion efficiency, we could collect 18 petawatts.

We do not currently have the technology to cover and maintain solar panels over the entire surface of the Earth. For example, we cannot currently cover the deep oceans with floating solar panels, but we can manage solar arrays in the ocean at depths under 200 meters, the ocean shelf.

Let's consider covering only 25% of Earth's surface with solar panels to estimate the maximum practical amount of terrestrial solar energy.

In this analysis, covering a land area with solar panels assumes a 20% effective coverage in practice. The land area covered by the solar panels is five times the active panel area.

Land use category	Area with solar panels, in millions of square kilometers	Power produced in terawatts
Dry land	28.75	195
Desert	8.25	82.5
Ocean	7	56
Rooftops	0.25	1.7
Total	44.25	336

Total available terrestrial solar energy is 336 terawatts.

The Earth population limit of terrestrial solar energy is 319 billion people.

Launching and Maintaining a SBSP Constellation

Space-based solar power is practically unlimited, because of the incomprehensible amount of energy produced by the Sun. We already have the technologies necessary to collect and transmit solar power from space to Earth. Scaling SBSP requires solving many different problems. Many of the problems are already individually solved, some solutions are partially proven, and some are certainly feasible, but not developed yet.

The design of the satellites should emphasize efficacy, simplicity and durability. My proposed design consists of a three-dimensional cross of structural beams, with solar panels extending from the beams. The beams all connect to a central core with the batteries, computers, antennas, etc. All of the beams extending from the core can rotate to orient the panels. The solar panels are triple use. On one side of the panels are the solar cells that capture solar radiation and convert it to electricity, the primary purpose of a solar satellite. The other side of the panels can be radiators to keep the satellite cool. The third use of the solar panels is as solar sails to gently shift the rotation and position of the satellite by rotating the panels to face, redirect or cut through the solar wind.

Terrestrial solar panels are often backed with plastic, but these solar panels will be backed with glass, because glass is more durable than plastic in space. Solar panels can operate for a long time in space, but experience about ~2% annual degradation in performance, caused by high energy particles damaging the electronics and micrometeorite impacts. While the panels and satellite can continue to operate for decades, it is safer and more efficient to recycle the original satellite every period of time, such as every 20 years. Recycling the satellite involves capture, disassembly, melt, refine, and manufacture. The satellites are composed of materials that are simple to recycle and manufacture, aluminum for structure, wiring and radiators, glass for the front and back of panels and electric insulation, and pure silicon with dopants for the active layer of the solar panels. Each satellite would have ~3 km² of solar panels and weigh about 1.9 million kilograms. The constellation would require in-orbit satellite production facilities that could receive materials or components launched from Earth, or collect existing satellites at end-of-life to produce new satellites to build or maintain the constellation. The constellation could be built up over a long period of time, for example between 2025 and 2500 AD, until the carrying capacity is hit and the constellation could remain fixed in size.

Technology	Proven scale	Required scale
Solar panel production	Global solar panel production of ~3,000 km² / year, no solar panel production in space	In-space solar panel production of 3.54 million km² / year

Technology	Proven scale	Required scale
Satellite production	Global terrestrial satellite production of ~2,781 satellites / year, occasional in-space satellite assembly	In-space production of ~1.18 million satellites / year
Space launch capacity	2.6 million kg to orbit / year	~68 billion kg to orbit / year
Rocket reuse	First stage reuse of a single booster x30. No second stage reuse, but second stage recovery is proven. Turnaround time of 9 days.	Reuse of both stages in the hundreds, turnaround times within hours
Satellite constellation management	8,475 satellites in a constellation	~22 million satellites in a constellation
Solar satellites	0.24 megawatts of solar capacity per satellite	478 megawatts of solar capacity per satellite
Solar sails	196 m^2 per satellite	~3,000,000 m^2 per satellite
Solar power transmission from orbit to Earth's surface	~0.01 watts per satellite	~382,000,000 watts per satellite
Satellite recycling in space	Small scale demonstration of cutting or melting metals ~1kg	Industrial-scale, ~2.2 trillion kgs / year of materials such as aluminum, glass and silicon
Space manufacturing	Small scale metal 3d printing	Industrial-scale manufacturing of satellite components such as aluminum beams and solar panels

Analysis of SBSP Scaling

Solar radiation is constant at 1 AU, the orbital distance of the Earth from the Sun: 1,366 W/m^2

Effective radius of SBSP constellation at Medium Earth Orbit, MEO, altitude of 2,000 km: 8,371 km

Cross-sectional collection area of solar radiation: $\pi * (8{,}371 \text{ km})^2 = 220.1$ million km^2

Total interceptable solar power at MEO: 1,366 W/m^2 * 220.1 million km^2 = 300.8 petawatts

Areal coverage of satellites in an orbital constellation, using multiple shells for collision avoidance: 10%

Solar panel efficiency, using specialized multijunction cells: 35%

Conversion and transmission efficiency from panel to ground, DC-RF, beam, atmospheric, rectenna: 80%

Overall system collection efficiency: 35% × 80% = 28%

Power delivered to ground: 300.8 petawatts × 0.1 × 0.28 = 8.42 petawatts

Earth carrying capacity due to energy from SBSP: 8.42 petawatts / 1,052 W/person = 8 trillion people

This is only an example calculation of a 10% coverage SBSP constellation at 2000 km. This is not the actual limit of Earthly SBSP. We can add additional shells of satellites outward, collecting more solar radiation and beaming it to Earth at about ~1 petawatt / trillion people.

Heat

The Final Boss

Life requires energy. More people require more energy. More energy means more waste heat. More waste heat means higher temperatures. People can only live within a specific temperature range, and solids melt, sublimate or burn if they get too hot. The human habitat will be climate-controlled, it will maintain comfortable human temperatures. The outside will become much hotter than the inside of the habitat, but heat wants to distribute itself evenly. How do we keep the habitat cool? Two methods. The first method is thermal insulation, to reduce the rate that heat enters the habitat. The second method is active cooling of the inside of the habitat, using heat pumps. Heat pumps use energy to move heat, they can cool things. But heat pumps also require energy to operate, so we are generating heat to try to get rid of heat, proving the saying that heat is the final boss. Thermal insulation is very effective, and heat pumps with today's technology are very efficient, and can operate in a wide range of temperatures. We can consume a lot of energy to support a lot of people and still keep them cool. Even though we can support a lot of people, as we add more energy to the system, managing the heat would eventually reach the limits of current technology and become a bottleneck.

Reaching the Current Limit

This book explains, as simple as possible, the fundamental physical limitations to human population on Earth. This analysis is not a prediction, wish, or policy proposal. If you want to perfectly preserve the natural environment of Earth without people, then promote a policy of space habitats and colonizing other planets. If you want to share the planet, we can preserve large areas of the Earth and still vastly increase our sustainable population without significant environmental changes, aka geoengineering. There are countless tradeoffs we could consider. Never say that Earth can only support 8 billion people. These tradeoffs are useless to answer our central question, what is the absolute limit of comfortable human Earth carrying capacity using current technology? To reach the absolute thermodynamic limit, we have to make the surface of the Earth uninhabitable. The human habitats will be comfortable, and we can have indoor zoos and aquariums that preserve various species and ecologies, but the planet overall will be geoengineered to support the maximum number of humans. The appearance and function of the Earth will change substantially, to massively increase its thermodynamic carrying capacity to the current technical limit.

Outgoing Longwave Radiation, OLR

Outgoing Longwave Radiation

If the sun constantly delivers energy to the Earth and that energy turns into heat, why doesn't the Earth just get hotter and hotter? Space is a vacuum, there is no material outside of Earth's atmosphere to conduct the heat to. But how does the heat from the sun reach the Earth in the first place? Solar radiation, light. We can convert that light to electricity, use the electricity, and that becomes waste heat. The waste heat makes the Earth hotter. What happens when something gets hot? It glows. The way that Earth dissipates the heat from the sun is with thermal radiation away from the sun. The sun glows and heats the Earth, the Earth glows and cools off. But the Earth doesn't look like it is glowing at night. The light that you can see from the sun during the day is in the spectrum of light visible to humans, which you can also see when an object gets red hot, or white hot. But before a hot object glows red, it glows in the infrared, it emits light at a wavelength longer than your eyes can see, longwave radiation.

Invisible infrared radiation is how the Earth cools itself into space, which is the same thing that spacecraft do. Any human-made artificial spacecraft has to control its temperature in space within an acceptable range, or else it will break or melt. Human spacecraft have special radiators that are designed to collect the waste heat from the spacecraft and convert it to infrared radiation that points away from the spacecraft, so it doesn't reheat itself. Radiators have special shapes with ridges to increase their surface area and radiate more heat.

In order for the spacecraft to maintain the same temperature, the incoming heat produced by the spacecraft has to balance with the outgoing radiation. The amount of heat that a spacecraft radiates is called Outgoing Longwave Radiation, OLR. If a spacecraft is already at its maximum temperature, and the spacecraft wants to use more energy and produce more waste heat, it has to increase the OLR to dissipate the additional waste heat to prevent the spacecraft from melting. You can often use more energy, as long as you equally increase the OLR.

Eliminate the Greenhouse Effect

The first step in increasing the thermal budget of the Earth is reducing the greenhouse effect of the atmosphere. The greenhouse gases in the atmosphere trap heat by being transparent to visible light but they absorb and re-emit OLR, trapping heat in Earth's atmosphere and the ground. We want to reduce or eliminate the greenhouse effect of the atmosphere by reducing greenhouse gases such as water vapor, carbon dioxide and methane down to almost zero. This will allow us to use much more energy, without overheating.

The first step is reducing atmospheric CO_2, and the first step to reducing CO_2 is to stop burning fossil fuels. We should replace fossil fuel burning with terrestrial solar with batteries, geothermal, and synthetic fuels where needed. The next step is carbon capture to pull the CO_2 out of the atmosphere. Permanently storing CO_2 gas is difficult, so we should convert the low density CO_2 gas into a dense, stable solid to keep it out of the atmosphere. We want to turn the CO_2 gas back into something like the coal that the CO_2 came from.

To reduce the greenhouse effect as much as possible, we want to pull all the CO_2 out of the atmosphere, which would make plant life impossible outside of the human habitat, as plants need CO_2 for photosynthesis. Plants are necessary for animals to survive, and life is the primary source of methane, so if the plants die, so do the animals and the primary sources of carbon dioxide and methane. Methane is not chemically stable in Earth's atmosphere, if we eliminate most of the methane sources, the atmospheric methane will naturally reduce on its own.

Water vapor is the final, major greenhouse gas. Water vapor reduces OLR and clouds and rain can disrupt SBSP radio-frequency beams. The solution to water vapor is to sequester all of the water outside of the habitats. We can turn water into rock. In fact, it happens every day, both naturally and artificially, and we explore how in the next section.

Without greenhouse gases, there is no greenhouse effect, and the Earth will radiate heat with a much higher efficiency, more like artificial spacecraft in space.

But how could we sequester all of the carbon dioxide and water?

Sequestration

Sequestration of all greenhouse gases first requires stopping burning fossil fuels, replacing them with renewable energy generated from geothermal and terrestrial solar. Applications that are not yet electrified or cannot be eletrified can use synthetic fuels, made renewably, turning CO_2 to fuel, burning the fuel to return to CO_2 in a sustainable process.

The least disruptive way to reduce greenhouse gases is by sequestering carbon dioxide, turning the CO_2 back into something like coal, a durable high-carbon material we can bury. A material like that will remain stable underground and stay out of the atmosphere. One method to do this is to grow grasses such as bamboo, napier grass or switchgrass, which convert CO_2 into woody biomass. Wood is mostly cellulose, which is made from glucose, which is made from CO_2 and H_2O. It is possible to preserve the wood for a long time if you keep it somewhere without water or oxygen, but the carbon is always vulnerable to decomposition back into CO_2 in that form. A more durable form of carbon for long term storage is called biochar, formed when you heat wood without oxygen in a process called pyrolysis. Biochar is more of a pure carbon material that doesn't easily decompose further, even with water or oxygen, so you can bury biochar and leave it in the ground indefinitely, like coal. Farming bamboo takes no additional energy input beyond sunlight, and making biochar takes modest amounts of energy for pyrolysis but that simplifies the storage significantly. Where could we put all of this biochar? Fill up the mining pits with it, or bury and cover it, it is a fairly safe and inert material. Sequestering CO_2 is the easier challenge. The greater challenge is transforming the oceans into rocks.

Water is a potent greenhouse gas, and the Earth has a lot of it. The Earth surface is 71% covered by ocean. The salty ocean is a chemically aggressive environment, most materials are eroded or degraded by the ocean over time, which is why even modern boats must receive regular maintenence such as repairing coatings in order to survive operating in the ocean. Creating human habitats in the ocean would face a significant challenge if they had to withstand the waves and corrosion.

We could separate out all the salt from the ocean, but where could we keep the salt so that it would never get wet and dissolve back into the water? And the salt isn't the central problem, the greenhouse gas called water vapor is the problem.

The way to turn water into rock is to chemically bind the water with certain very common metals, Aluminum, Calcium and Magnesium, into stable compounds called metal hydroxides. These metals are some of the most common materials in the Earth's crust, and if you keep digging, there are enough of them available to bind with all the water, transforming all the lakes and oceans into stone. The metal-hydroxide compounds I propose to use are stable up to temperatures above 150 °C. It is possible to bind water with iron, the most common element in Earth, but that compound is not stable above 150 °C. Metal hydroxides are naturally occuring and sequester water in a natural process that happens every day, called weathering. To sequester significant amounts of water quickly, we would need to create and scale up industrial processes for sequestering water. Practically speaking, what would that look like?

We would use three of the most common metals in the Earth's crust, Aluminum, Calcium, Magnesium.

In the entire crust of the Earth, there is 3 - 4 times as much of these metals as we need to bind all the surface water on Earth.

That means we do not need to mine out the entire crust.

We need to access most of the metal from the surface down to a depth of about 10km.

Current bulk mining operations reach 4km depth, but that isn't the technical limit for mining.

Drilling for boreholes and oil wells already extend to 12km.

As we dig deeper, the ground gets hotter and hotter, making mining more difficult.

Bulk mining at 10km requires substantial cooling because the rocks at that depth are at 300 °C or even hotter.

Geothermal energy is actually a form of mining and a form of cooling.

Sustainable geothermal energy extraction drills geothermal wells and extracts thermal energy at a rate close to the rate that heat enters the rocks from below

Extraction at the sustainable rate allows us to use the same well to generate energy for a long time

Unsustainable geothermal energy over-extracts heat from the rocks at a rate much faster than the heat from below heats them up, causing the rocks to cool

An overextracted geothermal well can take hundreds of years to warm up again

We can use over-extractive geothermal energy to cool mineral veins in advance of deep mining

We can reuse the geothermal wells as mining pilot holes to speed up and simplify the extraction

Some ores are practical to extract in bulk, leaving mining shafts that can be refilled with metal-hydroxides.

Some ores are better extracted using leaching, where acid is used to dissolve and extract just the metal you want, leaving the rest of the material in place.

Bulk mining has not been proven at depths of 10km, but should be technically achievable using active cooling and remote operation.

All of these processes, mining, transport, refinement, conversion, storage are complex and require significant energy, time, materials and equipment.

To complete the process of removing all greenhouse gases, mostly the water, it would take hundreds of years at least, using current technology pushed to its limits.

The Earth surface would become cool and dry, without a cloud in the sky, after all the water is bound in metal-hydroxides.

Magnesium is especially useful in the form of hydromagnesite, a compound that sequesters both carbon dioxide and water, stable to 350 °C. There is enough magnesium to sequester all of the atmospheric carbon dioxide in hydromagnesite, leaving the remaining water to be bound by magnesium hydroxide.

Calcium and water are two of the three components in cement, which is used to make concrete. Silicon is the third component, and silicon is much more abundant than calcium. Concrete requires more energy to produce, but is also more thermally stable than calcium hydroxide. Cement is a more efficient use of calcium to sequester water than calcium hydroxide, and we need a lot of cement to make structures for human use. Using calcium for cement, over calcium hydroxide, would slightly reduce the amount of mining required to sequester all the surface water, and would produce all the cement we need, with excess, for human structures.

White and Black

Spacecraft often have a white side and a black side. When the spacecraft is receiving sunlight, it turns the white side to face the sun, so the sunlight reflects off of the white part of the spacecraft and isn't absorbed to turn into heat. This reduces the effective incoming heat to the spacecraft from the sun. The side of the spacecraft facing away from the sun is often black, because black surfaces can both absorb and emit heat as OLR. The white side reflects the incoming heat away, and the black side emits the heat as OLR away from the spacecraft.

Increasing the Thermal Budget of the Earth

One bottleneck of sustainable human Earth population is heat, thermodynamic. There are a few things we can do to maximize our available thermodynamic budget.

- Decrease thermal insulation of the Earth, e.g. reduce the greenhouse effect
- Decrease incoming solar radiation
- Increase OLR

We could decrease incoming solar radiation with a sun shade in space, but the technology for such a project is speculative. Instead, I propose to make the surface of the Earth more reflective, using durable white tiles, and more emissive, using durable black tiles.

Increase Earth OLR

We already want to sequester greenhouse gases, keeping the atmosphere clear for OLR. We also want to reflect as much solar radiation as possible, so that when looking at the Earth from the position of the sun, the Earth should appear bright white. We simultaneously want the surface of the Earth to be black, because white does not emit OLR as much as black does. We want the day side to look white, and the night side to look black. We could make tiles that have a white side and a black side and flip them twice a day, but that would only expose the black tiles half the time, only at night. Instead, imagine a pure black radiator base layer, with thin white north-south ridges. During the evening and the morning, the sunlight hits the surface of the Earth at an angle, and the white ridges reflect the sunlight away, preventing almost all absoption of solar radiation. Only during a brief period around midday would the solar radiation reach the radiator layer and get absorbed. This design passively presents a white surface to the sun for almost the entire day while always emitting OLR to space, a win win for reducing heat.

Heat Sources and Insulation

There are three sources of heat in this model of Earth. The first is the heat of the Earth itself, from the formation of the Earth and radioactive decay of materials in the Earth. Today, this energy warms the surface of the Earth and eventually radiates to space. The human habitat creates a new problem with dissipating this heat, because we plan to create a habitat that is a 1 kilometer thick spherical shell around the entire Earth, and maintain that shell at a comfortable temperature. To achieve this, we will use thermal insulation below the habitat, to block the heat from below, and thermal insulation above the habitat, to block the heat from above. The method I recommend to insulate the habitat is thermally insulating concrete, specifically aerogel-enhanced concrete with fiberglass reinforcement. But if we thermally insulate the surface of the Earth, how will the heat from inside the Earth escape? The heat would build up under the habitat. That is why we would need to collect the heat under the habitat, then transmit the heat using heat pipes in insulated channels through the habitat, to transmit and emit the heat from above the habitat. This geothermal energy can be used for energy generation, and used to boil and distill water for water purification.

The second source of heat is solar radiation, sunlight. Almost all sunlight is reflected by the white ridges above the habitat. The reflection works better than today, because the scrubbed atmosphere will be much more transparent.

The third source of heat is the energy delivered to the Earth by the SBSP constellation. After the energy is used, it becomes waste heat. The design of the habitat ensures that all of the most heat-producing activities happen in the machine layer above the climate-controlled interior of the habitat. The habitat is a thermodynamic sandwich, that looks like this.

Sun

Outer space

SBSP constellation

Clear atmosphere

Rectennas

White reflector ridges

Black tile radiator layer

Machine layer, heat pumps, water pumps, batteries, fans, incinerators, hot industrial processes

Thermally insulated habitat roof

Human habitat with insulated heat pipes, 1km tall

Thermally insulated foundation

Geothermal heat exchangers

Earth interior

All of the heat is concentrated and collected above the habitat, into the black tile radiator layer. There is still an atmosphere, and it conducts and convects the heat around, above the sealed and insulated habitat.

Aerogel-Enhanced Concrete

The habitat will use aerogel-enhanced contrete as both a structural material and as thermal insulation. I will briefly describe the modern miracle material of aerogel-enhanced concrete. Concrete is structurally strong, heavy, fairly thermally conductive, and is mostly made of random rocks. Aerogel is structurally weak, lightweight, and a thermal insulator. Aerogel is primarily composed of silicon dioxide, aka glass. Fiberglass reinforcement is also made of glass, and is used inside the concrete instead of steel reinforcement, aka rebar, to enhance the strength of the concrete without increasing its thermal conductivity. How do you make aerogel-enhanced concrete? Mix standard concrete with aerogel granules at ~20-50% volume, adding a mesh of fiberglass of 2% volume, achieving the combined properties below.

Name	Density (kg/m^3)	Strength (MPa)	Thermal conductivity (W/m·K)
Standard concrete	2,500	10-30 (compressive)	1.5
Aerogel granules	50-150	0.1-1 (compressive)	0.01-0.02
Fiberglass rebar	1,800-2,200	500 (tensile)	0.04
Aerogel-enhanced concrete	1,500-2,000	10-20 (compressive)	0.05-0.1

The human habitat foundation will be 50m thick, composed of aerogel-enhanced concrete with a thermal conductivity of 0.05 W/m·K, achieving a thermal resistance, R-value, of 1,000 $m^2 \cdot K/W$. The habitat roof needs similar insulation but supports less weight, and can be 40m thick.

The Thermodynamic Limit

Finding the thermodynamic limit is fairly simple. Assuming we can collect almost unlimited SBSP, which will produce a huge amount of waste heat, we can insulate the habitat from high temperatures. We only need to know how much OLR we can emit to determine the maximum outgoing thermal energy. Once we determine the OLR budget, the system is in balance, so the outgoing heat will equal the incoming energy. The incoming energy, divided by the energy use per person, determines the maximum population due to heat.

How do we determine the maximum OLR? The OLR depends on two things, the emission rate per unit area, and the total area. The total area is fixed by the size of the Earth. But the emission rate is highly variable. OLR has an amazing property. The OLR increases with temperature. The higher the temperature, the higher the emission rate. But the relationship is not linear! If you double the temperature, you do not just get double the OLR, you get a lot more than that. The power output of OLR goes by the temperature to the fourth power! If you double the temperature, you multiply the OLR by 16. So the Earth can emit an incredible amount of power at higher temperatures, like the sun does. But heat pumps are physical devices, made of materials that have a melting point. Heat pumps have a limited range of operating temperatures, so there is a conflict. We want higher temperatures to increase OLR, but heat pumps have a temperature limit. However, the entire heat pump doesn't have to operate in an environment at the highest temperature. Different parts of the heat pump can operate in separate, thermally isolated temperature zones, allowing the hot end of the heat pump to become much hotter than the pumps and seals could tolerate. The maximum operating temperature of the hot end of the heat pumps of today are 200 °C. Other parts of the heat pump operate in 150 °C, and the cold end can be as cool as 20 °C. This means that at the limit of current technology, the surface of the Earth could become as hot as 200 °C, and we could still cool the inside of the habitat, but their efficiency is lower at these temperature limits. There are other thermal limitations, such as the maximum temperature of rectennas and the metal hydroxides used to sequester water and CO_2. The highest safe temperature for all these materials and processes appear to be around 150 °C currently, which will be our target maximum Earth surface temperature.

Interestingly, the temperatures both above and below the habitat will be similar, because they will be connected by heat pipes and the heat from both will be dissipated by the radiator layer.

Analysis of the Thermodynamic Human Carrying Capacity of the Earth

Incoming solar: 340 W/m^2 on average

Albedo: 0.9 (white ridges reflect 90% solar energy back to space, 10% absorbed)

Earth surface area: $(5.1 * 10^{14})\ m^2$

Absorbed solar: $340\ W/m^2 * 0.1 * (5.1 * 10^{14}) = 17.34$ petawatts

Radiator temperature: 150 °C = 423 Kelvin

OLR per square meter: $(5.67 * 10^{□8}) * 423^4 = 1815\ W/m^2$ (a constant times the temperature to the fourth power determines the OLR)

Radiator area: $(5.1 * 10^{14}) * 4 = 2.04 * 10^{15}$ m^2 (surface area of the Earth multiplied by four because of radiator fins)

Total OLR: $1815 * (2.04 * 10^{15}) = 3.707 * 10^{18}$ W = 3707 petawatts

Waste heat cap: 3707 petawatts - 17.34 petawatts = 3686 petawatts (OLR minus absorbed solar)

Usable power: 3686 petawatts * 0.85 = 3133 petawatts (loss from rectenna conversion)

Thermodynamic limit: $(3.133 * 10^{18})$ W / 1052 W / person = $2.98 * 10^{15}$ people

The Earth population limit of heat is 3 quadrillion people.

Thermodynamic Bottlenecks

The following table reviews several heat bottlenecks we would face along the way to the current thermodynamic limit. I will offer solutions to each problem in principle, but you can reject any solution as impractical, or independently conclude that a problem is intractable, making that bottleneck your own absolute limit. These bottlenecks are all related to problems caused by increasing Earth ground temperatures. Increasing ground temperatures are caused by increasing energy use to support more people. The temperature increases listed in the table are the simple heating caused by increased energy use, they ignore the greenhouse effect, because one of the solutions to our heat problems is to eliminate the greenhouse gases from our atmosphere. The first two cases are perfectly moderate, without geoengineering, they do not substantially increase the surface temperature of the Earth, and can be achieved within the current areas of human habitation or even less, for those who are more interested in scenarios with environmental preservation.

SBSP energy input in petawatts	Human population limit from energy	Ground temperature in celcius	Bottleneck	Solution
0	95 billion from geothermal + 319 billion from terrestrial solar = 414 billion	15	Zero SBSP energy input causes zero additional ground heating, population limited by available energy	Collect additional solar energy and beam it to Earth using SBSP
0.2	414 billion from terrestrial sources + 190 billion from SBSP = 604 billion	~15.1	SBSP energy input « solar energy input, causing negligible heating over baseline	Collect additional SBSP and use active cooling
8.42	~8 trillion	19.6	Significant energy input over baseline causing significant heating, and the temperature could rise by double this amount due to the greenhouse effect	Sequester greenhouse gases to reduce the greenhouse effect

SBSP energy input in petawatts	Human population limit from energy	Ground temperature in celcius	Bottleneck	Solution
122	~115 trillion	63.4	SBSP energy input == solar energy input, causing massive heating, killing ~all surface life, extreme greenhouse effect from water vapor	Greenhouse effect would cause thermal runaway unless countered. Sequester all the CO_2 and water to eliminate the greenhouse effect
3686	3 quadrillion	150	This temperature is around the thermal limit of rectennas, heat pumps and some sequestration materials	No current technical solution, this is the current thermodynamic limit

Conclusion

The human carrying capacity of the Earth is much higher than current popular estimates. The resource requirements per person and the limits can both be improved with technological development, allowing the carrying capacity to rise even higher. There are various reasons to have more or fewer people, but this book describes the current hard, physical limits. With generous assumptions of resources per person, using only proven technologies and their predictable developments, the current bottleneck is living space, and the current limit of the human carrying capacity of the Earth is 510 trillion people.

The End of Human Carrying Capacity of the Earth

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