Options for Global Warming Mitigation via Space Based Solar Power or a Solar Occulus

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Contents

An **occultation** is an event that occurs when one object is hidden from the observer by another object that passes between them.

--- Wikipedia

Global Warming and Thermal Heat Balances

Summary

The increase in atmospheric CO2 levels over the last century is substantial and caused by the burning of fossil fuels. The exact impact of this increase is up for debate, but the general consensus is that the change in atmospheric CO2 will lead to a gradual increase in global temperatures with negative impacts to the planet and human civilization. Human concerns about Global Warming appear to be high, and hundreds of billions are being spent annually to address, but the efforts are disjointed, frequently in conflict with other priorities, and arguably have led to no decrease in CO2 emissions. The world currently spends a staggering amount on green energy- according to a Bloomberg report $501.3 billion in 2020 alone (Saul & Mathis, 2021). Currently the most optimistic projections are for the rate of CO2 increase to slow down but an actual decrease will not occur for another century.

Thomas Sowell is famous for the quote “There are no solutions, only tradeoffs”. In this article I compare various alternative technologies for reducing the impacts of increased CO2. I will then investigate the merits and tradeoffs of two space-based technologies, Solar Power Stations vs a sun blocking Occulus, that could be developed to combat global warming. I will compare the engineering challenges, risks, and implantation strategies as well as the approximate costs to implement.

Explanation of Global Warming- Heat Balances

Effectively all energy that warms the earth comes from the fusion fire of the sun. It is true that very small amounts of heat come from within the earth, the residual heat of its formation as well as the radioactive decay within the planet, but these quantities are relatively insignificant.

The earth’s surface temperature is kept in balance because the heat it receives via the sun is exactly balanced by the heat emitted from the atmosphere and ground. During the day large quantities of solar radiation add heat to the atmosphere and ground. Some of this is reflected back into space immediately, but some of this heat is retained for a while until discharged. At night the earth continues to radiate the heat accumulated during the day, bringing the atmospheric and surface temperatures down.

At the distance of the earth from the sun, the average amount of energy received is 1360w/m2 for a flat plate directly perpendicular to the sun’s rays. Because the earth is curved, and half the earth is dark at any one time, the actual average energy received over the earth’s surface is about 340w/m2 (Lindsey, 2009).

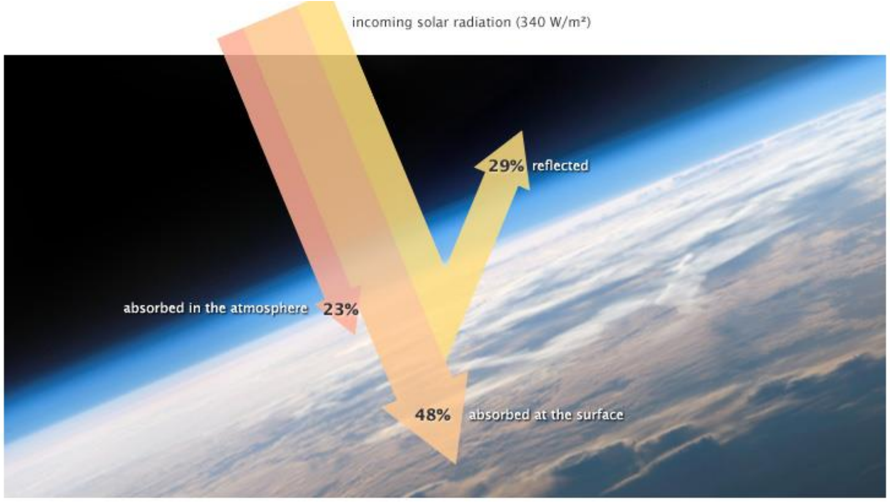
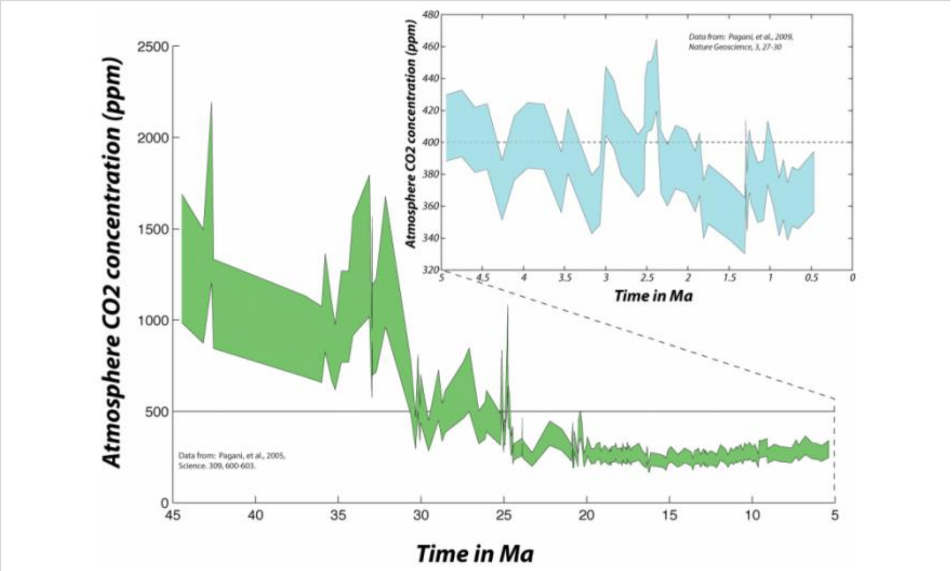


Figure 0-1 (Lindsey, 2009)

Of this quantity, about 29% is directly reflected back into space, either from the atmosphere or from the ground, and plays no role in heating the planet. The rest is retained by the atmosphere or the surface where it warms the planet up. As the atmosphere and ground heat up, they emit more and more infrared radiation until the emitted radiation is sufficient and equivalent to the amount of heat arriving and the earth has reached equilibrium.

Anthropomorphic Climate Change

Almost by definition, the climate changes and always will. Putting aside the question of whether human caused climate change is fundamentally worse than natural climate change, there is widespread agreement that humans are changing the climate- primarily through the tremendous increase in CO2 levels in the atmosphere released through the burning of fossil fuels. Over the history of the earth, CO2 has been scrubbed from the atmosphere through various means so that the CO2 levels have decreased substantially over the eons. Until humans, the primary means for replenishing this lost CO2 was volcanic activity. Over the age of the earth, large quantities of CO2 have been sequestered by living organisms that, when they died, were covered either by the next generations of dead organisms or dirt, silt or volcanic ash, thereby removing the CO2 from the atmosphere. Over millions of years this carbon was driven deeper and deeper into the depths of the earth where they were subject to high temperatures and pressures which converted into items like coal and gas. The drilling for oil and gas or the extraction of coal brings



Data from: Pagani, et al., 2005, Science. 309, 600-603.

Data from: Pagani, et al., 2009, Nature Geoscience, 3, 27-30

Figure 0-2 (Pagini, 2005)

this material back to the surface where, when burned, release this stored CO2 back into the atmosphere.

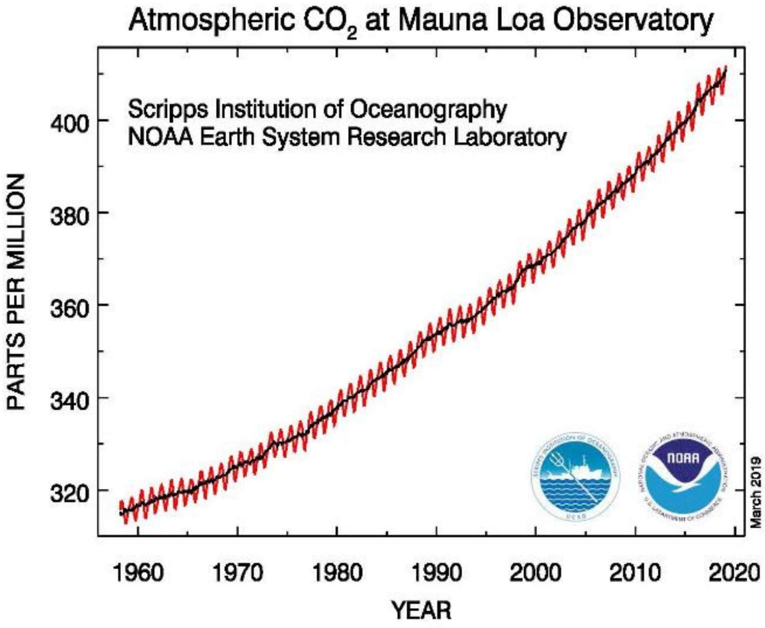


Figure 0-3 Atmospheric CO2 Levels (Courtesy NOAA)

CO2 (or specifically Carbon) in the atmosphere is the primary structural material for plants and trees. As the earth gets older and CO2 gets removed from the atmosphere and buried, the CO2 levels will gradually drop, eventually so low that plants can no longer survive, and all plant life (and all those animals that live off the plants) will die. It is estimated that this will occur within anywhere from a few million to one billion years. The burning of fossil fuels temporarily counteracts the long-term tendency towards reduced CO2 levels.

On the earth, some of the sun's incoming radiation is immediately reflected back into space, and some gets absorbed into the ground and atmosphere. The ground reradiates its heat either directly into space or into the atmosphere where it is re-absorbed. This absorbing layer will emit 50% of this radiation back up into space and 50% back down to the ground. If the make-up of the atmosphere changes through changes in CO2, water vapor, etc., the atmosphere can trap more heat, preventing the ground and lower atmosphere from cooling. The surface warms up, and eventually this increase in temperature will cause the atmosphere to warm up, increasing the heat emitted at the top of the absorbing layer (remember 50% of the heat is sent up). Venus emits exactly as much heat as it receives and maintains its blistering heat because it has to. When Venus originally heated up it was because the greenhouse gases prevented efficient radiation of the surface heat back into space, eventually increasing the temperature of the re-radiating atmosphere. All planets must reach equilibrium temperature with the heat received, but the equilibrium can vary with

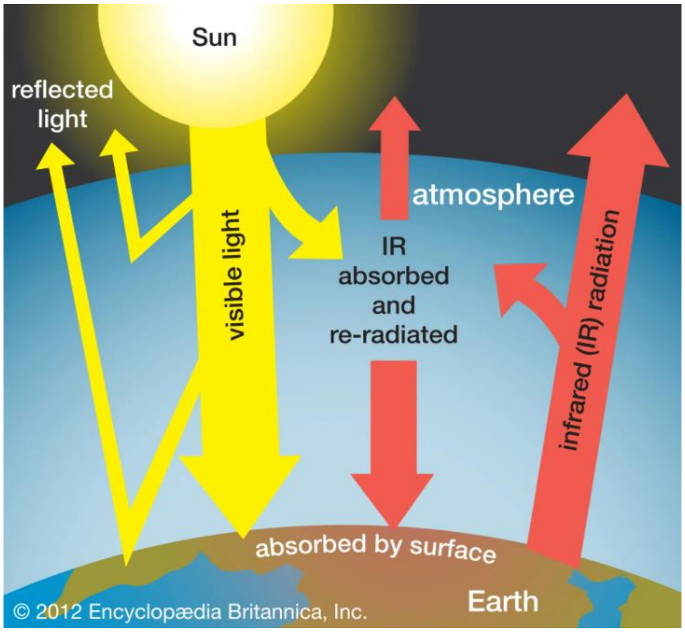


Figure 0-4 Greenhouse Effect (Courtesy Encyclopedia Brittanica)

surface and atmospheric reflection, and ground and atmosphere radiation.

The CO2 levels currently being experienced are the highest in the last 25 million years (figure 0-2 and 0-3). Historically the earth has had periods where CO2 levels have been much higher than current levels- so high that during certain periods the earth had no major ice sheets. Over the last 45 million years there have been spikes of over 1500ppm. Over the last 600 million years CO2 levels have been even higher- occasionally over 5000ppm (Figure 0-5). Nevertheless, the increase over the last century has been impressive (Figure 0-3). Technically the climatic situation over the last few million years has been defined as an ice age as large ice sheets have covered parts of the globe- primarily Antarctica and Greenland. During periods of higher CO2 levels- say about 30million years ago, it appears that there were no large ice masses and sea levels were 100m higher. (Bice, n.d.)

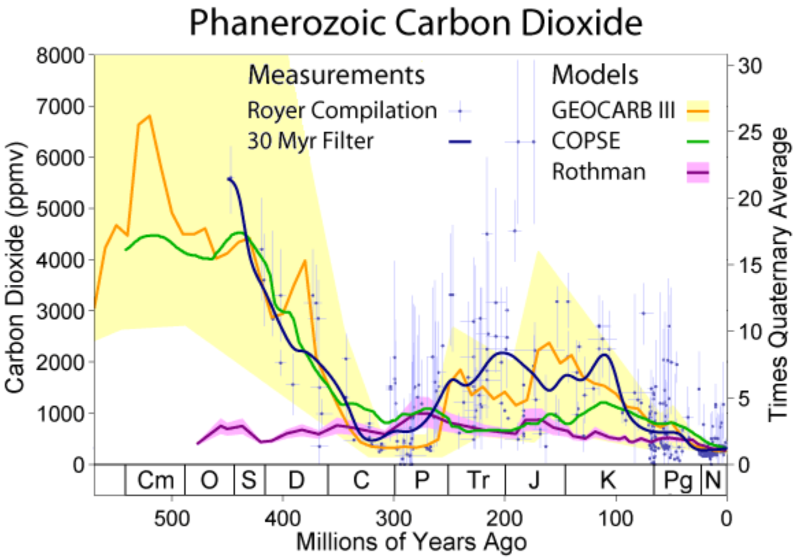


Figure 0-5 (Rohde, Robert A, 2019)

The question for us is if the disadvantages of human caused warming are worse than the natural climate change. In general, the idea that the increase in atmospheric CO2 as well as the impact this has on the climate (warming) is uncontroversial. More controversial are the conclusions- that the disadvantages of human induced climate change are worse than climate changes that would be occurring naturally. If it were not for the current increase in CO2, the world would be colder and likely less habitable. Offsetting this, a cooling planet would not have rising sea levels as a threat. Furthermore, the rate of increase in CO2 levels is extremely rapid and unprecedented over the last 20 million years or so. Historically the few exceptions to this statement were when major volcanic eruptions injected large quantities of CO2 into the atmosphere.

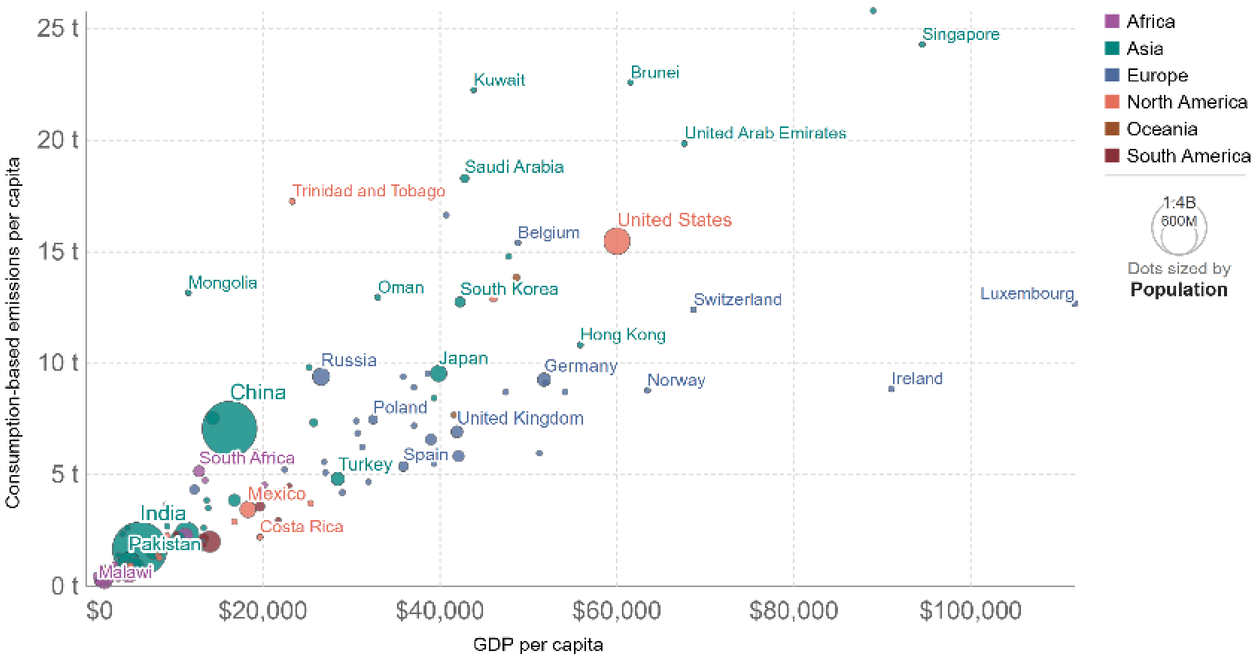
The increase in CO2 levels brings with it the risk of global warming which can be disruptive to human civilization as well as putting stress on natural ecosystems. However, there are two related issues that have two different solutions- is the concern with global warming or more with the concern about raising CO2 levels? If CO2 levels were not causing an increase in temperature, some would argue for the reduction of CO2 levels anyway. However, the public as well as politicians use the specific issue of global warming as the priority and not the increase in CO2. Each of the two space-based solutions in this article address a different aspect of human induced climate change. If global warming is a concern, then a Solar Occulus or SBSP can help- indeed it could likely prevent global warming for centuries. If, however, the concern is increased CO2 then only the SBSP will be an effective solution.

Energy- The Ultimate Resource

Energy usage is one of the primary indicators of wealth. When we say wealth, we mean material wealth which includes things like cars, homes, computers, as well as items that are more intangible but make life more comfortable like lighting, heating and air conditioning as well as travel. It is probably obvious that heating was key to making large parts of the world habitable. In a study looking at worldwide deaths over a 20-year period, about 4,594,098 deaths were caused by cold (Zhao, Guo, Ye, Gasparrini, & Tong, 2021)- or about 230,000 per year. Without heating large parts of the world would not be habitable- and usually colder countries use more energy resources than temperate countries. Heating can be achieved through the direct burning of fossil fuels (diesel, natural gas), burning of biomass (wood) or by electricity via direct resistive heating or the more complicated but efficient heat pumps. In general, it can be assumed that the warming earth has reduced the need for fossil fuels for heating.

Consumption-based CO_2 emissions per capita vs. GDP per capita, 2020

– Consumption-based emissions[1] are national emissions that have been adjusted for trade. It's production-based emissions minus emissions embedded in exports, plus emissions embedded in imports.
– GDP per capita is adjusted for price differences between countries (PPP) and over time (inflation).



Source: Our World in Data based on the Global Carbon Project; Data compiled from multiple sources by World Bank
OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

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1. Consumption-based emissions: Consumption-based emissions are national or regional emissions that have been adjusted for trade. They are calculated as domestic (or 'production-based' emissions) emissions minus the emissions generated in the production of goods and services that are exported to other countries or regions, plus emissions from the production of goods and services that are imported. Consumption-based emissions = Production-based – Exported + Imported emissions

Figure 0-6 Energy Consumption and Wealth- a clear link (Our World In Data, n.d.)

A little less obvious requirement for humans is the need for cooling. Far fewer people die from heat related causes- but excessive heat also has risks. Airconditioning is a truly world changing technology that is far more difficult from a technological and energy point of view than heating but makes living and working in parts of the world more desirable. If it were not for air conditioning, Florida, Texas and most of central America would not have anywhere near their current populations. In general, extensive air conditioning requires large amounts of electricity. Global warming, growing populations, along with increased wealth and the requirement to cool electronics in data centers, will require larger amounts of cooling and hence greater energy production in the future.

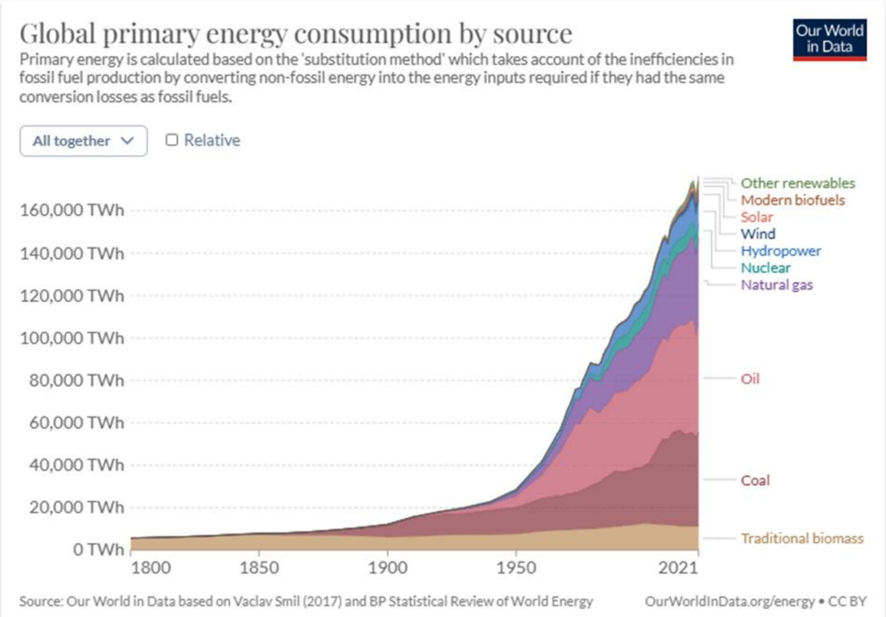


Figure 0-7 Energy Consumption by Source ((Ritchie, Roser, & Rosado, 2017)

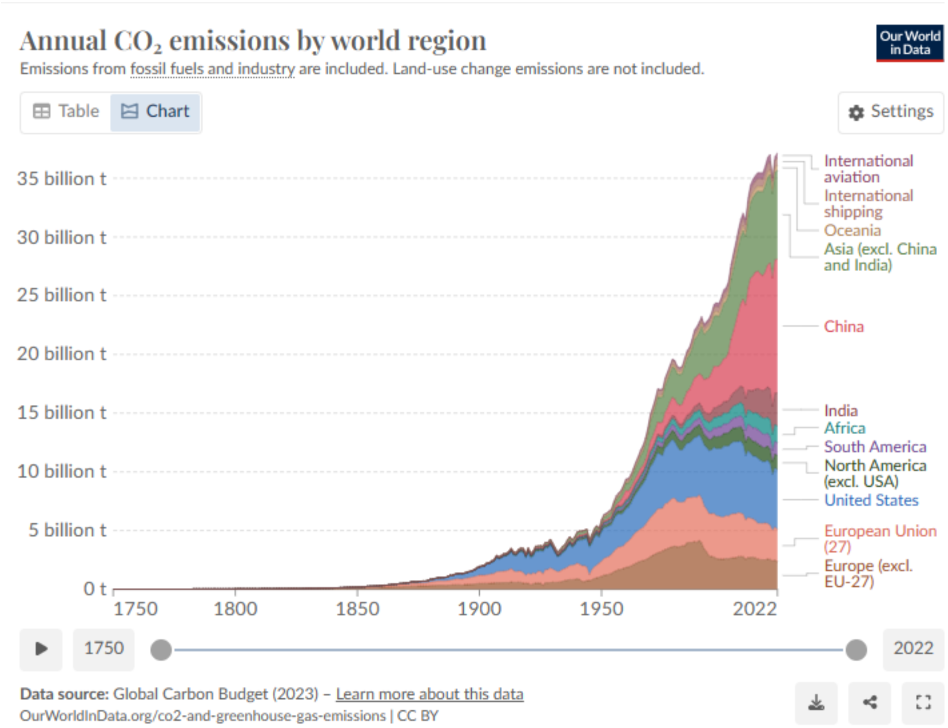
Figure 0-6 shows the link between GDP and energy per capita. Even when energy usage is not as closely linked to GDP (for instance the outliers Luxembourg and Ireland) these are small countries that generate a large amount of their wealth from non-manufacturing jobs like Finance and Tourism. These countries frequently import most or all of their manufactured goods from others. In Figure 0-7 we see the worldwide growth in energy consumption. One thing that becomes obvious is that despite the hundreds of billions spent on green energy every year, almost all the increase in energy usage over the last 30 years was met by coal, oil and natural gas. As we shall see, this is primarily because these energy sources are relatively reliable, cheap, plentiful, and easy to use. Green energy sources frequently cost much more because they are not energy dense, the technology is often more difficult to develop, frequently they require much more land and raw materials and perhaps most importantly, are intermittent, swinging as environmental conditions change and not as demand changes.

Political Will

To be able to determine the practicality of any solution, we need some idea about the cost impacts of global warming as well as the resources that nations and people are willing to spend. Human concern about Global Warming appears to be high, and hundreds of billions are being spent annually to address, but the efforts are disjointed, frequently in conflict with other priorities, and arguably have led to no decrease in CO2 emissions. Despite this substantial dedication of resources, the political and social will to have a meaningful reduction in greenhouse gas emissions is very low. Much of the money spent is on marginal projects designed for patronage rather than meaningful reductions. In the following sections we will go into several examples, but to give a quick illustration over the last thirty years, over 100 nuclear power plants that are essentially emission free have been decommissioned across the world despite this causing a substantial increase in CO2 emissions.

To calculate the impact and costs of global warming on the world's economy and environment is an exercise fraught with uncertainties and a multitude of assumptions. The normal way would be to compare costs of the natural state to the changed state. However, determining the initial state is difficult as the weather changes and always will. Furthermore, few studies address cost/benefits holistically. For example, it could be reasonably assumed that the warmer earth will extend the growing seasons and reduce cold weather deaths in many parts of the world with an accompanying increase in productivity. However, such a holistic and impartial review would be extensive and outside the scope of this article.

Currently the most optimistic projections are for the rate of CO2 increase to slow down but an actual decrease will likely not occur for another century.



Annual CO_2 emissions by world region

Emissions from fossil fuels and industry are included. Land-use change emissions are not included.

Data source: Global Carbon Budget (2023) – Learn more about this data

OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

Figure 0-8 World CO2 emissions; (Our World In Data, n.d.)

Calls for increasing solar and wind electrification have not translated to meaningful policies. Power lines have not been comprehensively constructed to carry the energy from where solar and wind power are generated. In addition, Solar and Wind, because of their intermittent nature, require large energy storage devices- which, if batteries, require large quantities of raw materials including metals. It is estimated that conversion to electric cars alone will require the mining of Lithium to triple by 2026. Cobalt requirements will increase an estimated 20x more than current demand by 2030 (Backhause, 2021). Additional materials including Graphite and Manganese will also see substantial increases. Complicating all of this is that most of these materials are mined in only one country- China. Electric cars are very efficient from an energy perspective but use far more materials (metals, plastics) than comparable internal combustion engine cars (frequently 500-750kgs more per vehicle). The very large mass of batteries is one reason that conversion of aircraft to electrical power is problematic.

Despite the shear amount of materials needed, the countries who have pledged to most to transition to “green power” have not relaxed their regulatory standards and paperwork to permit the expanded mining of resources required to facilitate the conversion to green. In addition to the raw materials used, most of the actual manufacturing of “green” items like batteries and solar panels are done overseas- in particular China which gets a large amount of its electricity from coal.

Additional evidence of public indifference is the fact that the public has not reduced its flying hours even in countries where climate concerns are greatest even though this is a relatively simple and minimally intrusive means of immediately reducing one’s greenhouse gas emissions. The continued strength of shore front property real estate (despite the implied dangers of global warming causing a rise in sea levels) in developed countries is further indication that climate concerns are not acted on by the public at large. Any solution to address climate change will have to recognize that other issues have a higher priority, and the most practical solutions are frequently not the ones chosen.

Per Figure 0-7, over the last 50 years, energy usage has gone up by about 100,000TWh. If the current trends persist, we will continue to increase at the rate of about 2000TWh per year. This is the equivalent of about 228 GW of power coming online annually. Note that this increase is for ALL energy used- electricity, heating, transportation etc.

A typical large nuclear reactor is about 1 GW_e (or 8790GWh annually) so the equivalent of 228 nuclear power plants would need to be built per year[1]. And this is would only stop CO2 emissions from increasing over their current elevated levels. To reduce CO2 emissions to essentially zero, we would need to put even more green energy online and start replacing the current power generation systems that use Coal, Oil and Natural Gas. If we choose a target to reduce our emissions to near zero over the next 50 years, we would need to increase our “green” energy supply by the equivalent of about 450 GW of power per year- or about 450 nuclear powerplants. This would lead to a gradual decrease in CO2 levels to those of a preindustrial world.

To show the challenge that this would be, over the last twenty years or so Hydropower, Wind, Solar, Biofuels, and other renewables generation have increased to about 20,000TWh, or about 2,300GW. Every five years over the next fifty we will need to add this amount more of green energy.

Mitigation Strategies

There are many ways to mitigate the current human induced climate changes. However, the 800 lb gorilla in the room is that there are no major studies that show a reasonable path to reducing CO2 emissions in this century. Most forecast CO2 emissions to continue to increase, albeit at a lower rate, over the balance of the century.

The following is a brief description of all the primary methods that are being considered to assist with lowering the rate of CO2 increase (and eventually lowering the absolute amount of CO2). However, throughout this analysis, I will observe that actual public support is lowest for those items that are most effective at lowering emissions. This implies that whatever solutions are proposed, the cost and inconvenience must be extremely low in order to be acceptable to the public.

Lower Energy Usage

There are two ways to lower energy usage- reduce wealth or increase efficiency.

Reducing wealth is indirectly achieved when usage of energy (or any other material) is taxed to force a lower consumption or in those command economies (Socialist) resources are specifically rationed. With the free market driven countries, governments can direct the tax revenue to other parts of the economy. The problem with reducing either the absolute consumption of energy or reducing its rate of increase is that the burden would come at the expense of the third world. Their lagging development combined with their high populations means that all future increases in power usage will be in poor

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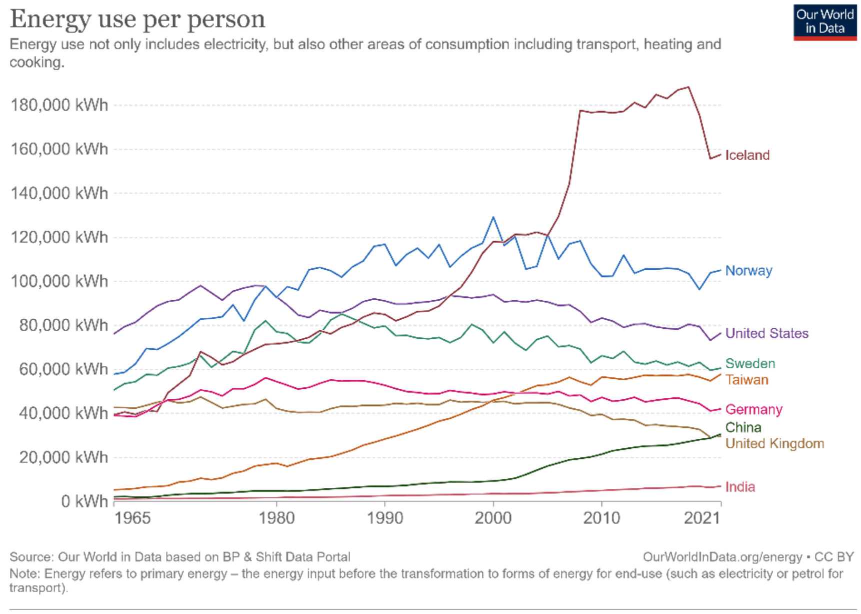
[1] It should be pointed out the most “Nuclear Power Plants” consist of two or three reactors and would therefor produce about $3GW_e$

countries. Most developed countries consume less energy per capita and much less energy per $ of goods produced than they did 30-40 years ago. However, with large parts of the world in relative poverty it would be inhumane to reduce the economic development rates of second and third world countries by insisting they slow or stop their increase in power requirements and hence emissions.

One extreme way of reducing the growth in the need for more energy and other resources is if countries adopted cultural standards that deemphasized material wealth and possessions. Conversely, if countries adopted policies that led to rapid population decreases (as with the former one-child policy in China), substantial reductions in power usage could follow. However, despite the utopian ideals of some communities, few cultures actually want to accept a lifetime of material poverty or would go along with reducing births to below replacement levels that such ideals would require. Indeed, most cultures/communities seek to grow their influence and material wealth which will mean increased energy usage.



Source: Our World in Data based on BP & Shift Data Portal
OurWorldInData.org/energy • CC BY
Note: Energy refers to primary energy – the energy input before the transformation to forms of energy for end-use (such as electricity or petrol for transport).

Figure 0-9 Energy Use Per Person (Our World In Data, n.d.)

The more desirable method of reducing consumption is through increased efficiencies. We have seen this in the increase in mileage efficiencies with cars, or the switching over to LED lighting which are about 10x more efficient than traditional incandescent lights. However, most energy consuming items have a limit in the efficiencies that can be achieved and most of the low hanging fruit have been picked. LED light efficiencies are approaching their theorhetical maximum.

Electric motors and pumps in general are about as efficient as possible with current materials. The Internal Combustion Engine is close to its maximum efficiency. Similarly jet turbines, while having a bit more room for improvement, are also constrained by the rules of thermodynamics which will limit their future efficiency increase to perhaps only 25% or so over the rest of this century. Power generation, whether from a hydroelectric plant, gas turbine or Nuclear Power plant, cannot get much more efficient than they already are. Meanwhile even when achieving greater efficiencies this is often negated by greater usage. Electronics, while getting more efficient, use ever more power as we add additional capabilities. As an example, it is estimated that all the world data storage centers use roughly 205TWh of power (Masanet, Shebhabi, Lei, Smith, & Koomey, 2020). Converting to instantaneous average energy usage this is 23 MW- or 23 nuclear power plants. Not a huge number but if provided by coal then it adds to the emissions.

To substantially increase efficiency frequently will require using a totally different technology- in the case of cars, switching from an internal combustion engine to an electric motor. For motors and pumps high temperature superconductors could allow for substantially increased efficiencies but they have not reached the level of development necessary to be used in most applications.

Greater efficiency can lower the growth rate of power needs- both per capita as well as function of wealth produced. In Figure 0-9, we can see that for industrialized countries like the US, the United Kingdom and Germany, energy usage per person has leveled out or even decreased slightly over the last 40 years. Part of this is illusory however since the United States and the United Kingdom, and to an even greater extent Germany, have achieved much of this improvement by exporting manufacturing and mining to other countries.

From Figure 0-9 we can see that in general (and as you would expect) colder countries consume more power. However no industrialized countries use much less than 40,000kwh per person and with some 75% of the world population using less than 20,000kwh per person, it can be assumed that energy usage in these parts of the world will easily double over the next century- NOT TAKING INTO ACCOUNT THEIR POPULATION GROWTH.

Green Energy- Nuclear Power

An unfortunate problem with climate change ideology is that we could have substantially mitigated current greenhouse gas levels with nuclear power. Beginning in the late 1980’s not only did construction of new nuclear power plants slow down substantially, but several countries elected to shut down their existing power plants. This unfortunate situation wound up substantially increasing the amount of CO2 in the atmosphere. In an ironic twist Germany, ideologically one of the most committed green countries, has increased its greenhouse gases over the last several years, despite spending tens of billions of dollars on wind and solar, because it decided to not only stop building new nuclear plants, but shut down ones that were in operation. One conclusion from this is that fear of non-CO2 emitting nuclear power plants is more powerful than the fear of climate change. Climate change is not perceived as the number one threat even in a very “green” country like Germany which puts a severe limit on how dedicated the public is to resolve the global warming issue and indicates that concerns about climate change may not be as high as the general perception might be. Since 2005 approximately 102 nuclear power plants (Statista Reasearch Department, 2023) have been shut down, removing almost 100 GW_e of green power from the grid. Much of this power was replaced by coal, gas and oil.

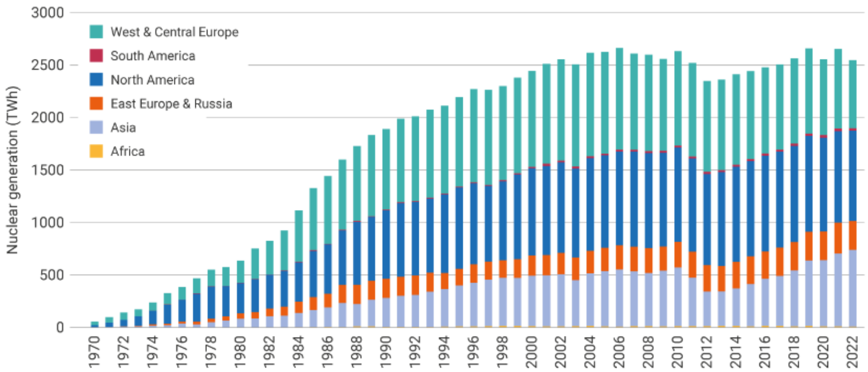


Figure 0-10 Worldwide Nuclear Power Generation by Region (Wold Nuclear Association, 2023)

Nuclear emits the least CO2 emissions for any power source and consumes the least land per watt generated, including when Uranium mining is factored in. Using the target of 450GW of added power every year (3900 TWh) over the next fifty years to eliminate essentially all greenhouse gases, the world would need to build about 450 nuclear reactors per year. The world currently has a total of about 440 reactors in operation- but many of them consist of several reactors together in a single large power plant. These reactors collectively generate approximately 2653 TWh_e in 2021 (Wold Nuclear Association, 2023).

The increase in nuclear power generation slowed down substantially in the 1990's and stagnated since the early 2000's. Nuclear energy, since it is used to generate electrical power, primarily decreases the greenhouse gases emitted by power plants. If the growth of nuclear power generation had continued at the rate witnessed from 1970's to the 1980's nuclear power could now be providing about 6000TWh_e or more annually- or a baseload of about 685GWe. This could have reduced worldwide Coal usage by about 2/3rds. Eventually the Transportation and heating industries would have to be modified to an all-electric basis to permit nuclear to mitigate these greenhouse gas sources.

Green Energy- Renewables

Green energy usually refers to those forms of energy that are renewable (recyclable) and emit no greenhouse gases. By this definition, even though most studies indicate that nuclear power is on balance produces the lowest emissions and has the least impact to the environment, it is not considered green since it cannot be recycled. Green energies include biodiesel, ethanol, solar and wind.

Bio Diesel/Ethanol

The logic of Bio Diesel and Ethanol is that photosynthetic organisms, (algae or plants- usually corn) grow, absorb atmospheric CO2, and then release the same CO2 when burned leading this fuel to be carbon neutral. While technically correct, the reality is that to grow all these crops we either require the cut down of forests, diversion of land that could be making food, or land that was laying fallow. These crops would require water and fertilizer (derived from fossil fuels) etc. Billions have been spent on green fuels; however the biggest motivator is that it increases farm income by creating demand for more crops. Creating fuel from plants is not very efficient and a study by Cornell University said that each acre of land will make only about 7.3 barrels of ethanol per year (Cornell Chronicle , 2001). In this same study it was found that 70% more energy is required to produce ethanol than the actual energy in the ethanol.

Solar

Solar energy is a well-known, and by some measures the ideal environmentally friendly power supply. The problems with solar is the intermittent nature of sunlight over the surface of the earth, the large amount of land required to collect useable power due to its low energy density, and the amount of mining materials needed to fabricate the panels, and even more challenging, the energy storage equipment. The following factors reduce solar effectiveness.

- Solar cells usually convert about 15% of the sun's energy to useable power (though some advanced solar cells have the potential to convert up to 20-25%).
- They generate power episodically.
- The rotation of the earth and the fact that the earth is a sphere reduces the average energy received to 340 w/m2. The actual effectiveness of a solar panel is impacted by the following:
  - They don't work at night (50%of the time)
  - They generate the most power when the sun is directly overhead and, on a yearly basis, will come closest to this peak power generation only once a year (the first day of summer). Because the earth is tilted on an axis and is spherical, solar radiation is highest near the equator, and drops off close to zero at the poles.
  - They can be effected by cloud cover (varies depending on location and season)

- Their episodic nature means that solar frequently doesn't produce power when needed and conversely may produce too much power when not.
- Usually, the best place to put solar (the desert) is where they are least needed.
- Because of its lack of energy density, they require a substantial amount of land.
- Related to their episodic nature, to make solar work as a baseload you need substantial power storage capabilities which increases the land, resources, complexity and cost of the design.

During peak sunlight you may be getting over 1000w/m2 but with the efficiency of solar cells you will be realizing 150-200 wm^2 and this would apply only at the equator at noon. The rest of the time (early morning, late afternoon, nighttime, or during bad weather) you will be generating far less- often zero. Because of the factors above, a reasonable average production number for a solar farm is 75watts/m^2 over the course of a year. To generate 1GW of power you need 13.3million m^2 of panels- or a farm 3.65km on a side. During the peak daytime you will be storing much of your power for night and poor weather. From a technological and engineering point of view how you store this power has not been resolved. Batteries require vast quantities of material and the battery size required for the stable generation of a 1GW solar farm are extremely large. A 1GW solar power facility would generate in the course of a year about 8760GWh. To account for night time and poor weather, a large amount of energy would need to be saved in batteries. Assume we wanted to store the equivalent of 1GWe for 12 hours of power we would need 12GWh of storage. Assume this energy was saved in batteries and assuming a typical car battery with 85kwh storage, you would need on the order of 141,000 car batteries for each 1GW solar farm. It is likely that you would want to store additional power to also handle the power needs on a cloudy day.

The best (cheapest) design for power storage would likely be water storage reservoirs where the excess power generated during the day pumps water up into large, elevated holding ponds. At night the water would be released into a lower pond or river permitting gravity to pull the water down while turning turbines as with hydroelectric power. These artificial reservoirs need to be fairly large and each step of the process (pumping water up to the reservoir and extracting power when draining) would introduce inefficiencies.

Using the 75w/m^2 number, in order to build 450 GW of power per year the world would need to build $6x10^9$ m^2 of panels annually- or the equivalent of 6,000km^2. This works out to a square solar farm 77.45km on a side.

As with Nuclear power, Solar is primarily used to generate electricity, and at least initially, would not be able to address greenhouse emissions caused by transportation or heating.

Wind

Wind has many of the same disadvantages of solar:

- Require large amounts of land.
- Are episodic and require substantial storage capacity.
- Are only practical in certain areas of the globe that experience frequent and consistent winds (typically the ocean)
- The best areas of the globe for wind- the oceans- are expensive to build on, tough on materials and equipment, and generate very expensive power.

- They can look ugly. Hundreds of towers are needed to generate the power that one Nuclear Power plant would generate.

A typical wind turbine produces up to 5MW of power (variable) but typically operate at only 30-40% peak capacity. Using this as an average, a wind turbine might average only about $2MW_e$. Using this number, in order to increase power supply by 450GW per year, we need to build 225,000 large wind turbines per year. As with Solar power the storage capacity issue would need to be addressed with reservoirs or batteries.

As with Nuclear power and Solar, Wind is primarily used to generate electricity, and at least initially, would not be able to address greenhouse emissions caused by transportation or heating.

Hydroelectric

Building Dams are one of the oldest, cheapest, and most reliable methods of storing and generating power. They can be considered “solar” power in that they generate energy through the evaporation and then condensation of water into rivers and lakes. They extract the stored potential energy by creating elevated lakes and then permitting the water to drain from the high location through electric turbines to a lower river or lake. Besides being a familiar technology dams also have the advantage in that they can make artificial lakes that are good public spaces for fishing, boating and recreation. However, they restrict natural river flow, impact fish and wildlife, and alter the landscape. Furthermore, most of the most appropriate rivers have already been dammed. Many environmentalists actively oppose building large dams because of their impact on the natural environment.

How much more power can hydroelectric produce? This varies tremendously depending on the height of the impounded water and the flow volume. The largest dams have multiple generator turbines and can produce 7 GW_e or more. More typical is 2-3 GW_e. To generate our 450 GWe of new power per year would require 180 new dams per year.

As with Solar, Wind and Nuclear, Hydroelectric is used to provide electricity.

Carbon Sequestration

With this technology, the CO2 is removed from the atmosphere. There are many ways of doing this, frequently involving the planting of crops that remove the CO2. The challenge with crop planting is that the earth is already filled with crops, forest and plants. To meaningfully decrease CO2 levels, you would have to convert lands that currently do not have crops or forests on them. The only large unused portions of land remaining on earth are those that are not compatible with growing plants, like desserts or tundra. It is likely that inadvertently, some additional CO2 removal is being done now since the earth is becoming more

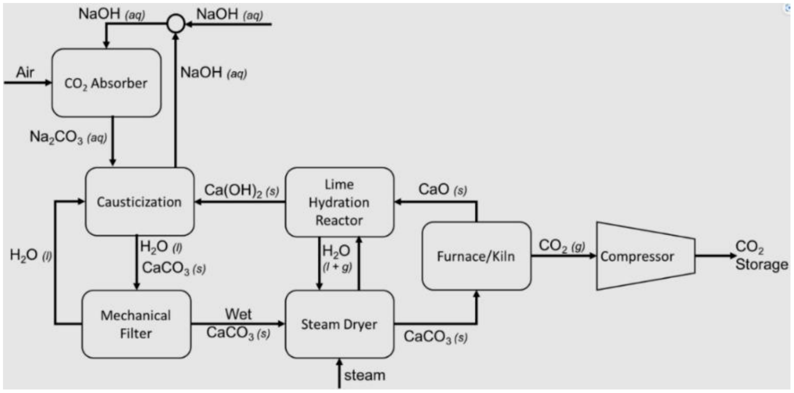


Figure 0-11 Process for removing CO2 from the atmosphere. Several of the steps require substantial power (JoseZZ, 2017).

“green” - with higher CO2 levels, plants tend to grow better and with the increase in temperatures forests and plants can grow in areas previously untenable. However, this contribution is limited.

CO2 can also be removed via human mechanical means, but this involves considerable energy- which unless provided by nuclear or solar/wind, would be generated by fossil fuels. The removed CO2 would be pumped into underground storage.

CO2 can also be released when pumping fossil fuels out of the ground since CO2 is frequently trapped in the ground with oil and gas. As before, CO2 can be captured and injected back into the ground for permanent storage. While helping to reduce this CO2 released during the pumping of fossil fuels, this does not help much as most CO2 is produced by the burning of fossil fuels.

Fusion Power Plants

Before we proceed, it is an article of faith that long term power needs will eventually be fulfilled by large and green Fusion power. However, this technology is still in development and we are likely 40-50 years before Fusion makes a meaningful contribution to reducing greenhouse gas emissions.

Albedo changes

One possible relatively inexpensive solution that has not been pursued except in small scale experiments is changing the earths’ albedo. This would be accomplished by making the earth’s surface or atmosphere more reflective. For instance, farm land is more reflective than forests so it may make sense to cut down forests and replace them with grass. Alternatively, there are means of increasing cloud cover or the reflectivity of the atmosphere through high altitude aerosols. This is an area that requires further research and experimentation before it can be decided on the feasibility and desirability of the various options. An albedo change would primarily address the issue of global warming and would not be of any help in reducing CO2 emissions.

Space Based Solutions- Space Base Solar Power (SBSP)

There are two space-based solutions that can make a meaningful impact to global warming- building large Space Based Solar Power Systems (SBSPs) which will provide greenhouse gas emission free energy, and a Solar Occulus which will serve as a shield to reduce solar radiation and permit a cooler planet.

Beamed Solar, or SBSP, has been widely recognized since the 1970’s as an extremely promising real-world application for the space industry. Its advantages over earth based solar power are substantial and include:

- The Sun’s solar radiation is much stronger in space than on the surface of the earth.
- Depending on the placement of the SBSP, solar radiation may be uninterrupted eliminating the need for power storage devices like batteries or storage reservoirs.
- It moves large infrastructure off earth thereby saving land. (Note the SPSP receiving stations will be quite large but can be placed in remote areas, and like wind turbines, the land beneath the receiving rectennas can be used for limited purposes)

The issue with beamed solar is that to provide meaningful power the power station needs to be extremely large and typically requires all the materials to be launched from Earth. In order to minimize power interruption, they are generally conceived to be placed in geosynchronous orbit. The electricity generated would be converted to microwaves and beamed down to a receiving rectenna station on earth.

For planning purposes, let's assume we would like a 10GW power station- equal to that of ten large earth based nuclear reactors. If we assume a solar panel efficiency of about 24% (the efficiency of current solar cells for spacecraft) and a power transmission efficiency of 85% we will need to have a extremely large SBSP mass (but much smaller than an equivalent earth based plant). To get 10GW of useable power we would need a power plant able to collect the equivalent of nearly 50GW of energy.

Let's assume we receive 1400W/m^2 in our orbit. With 24% solar cell efficiency we will be able to create about 336W$_e$/m2. With 85% beam efficiency we are down to 286W$_e$/m^2. This power would be beamed down to the earth via microwaves. For 10GW we will need 3.4965x10^7 m^2- or a square solar panel 5,913m^2- 5.9km on a side.

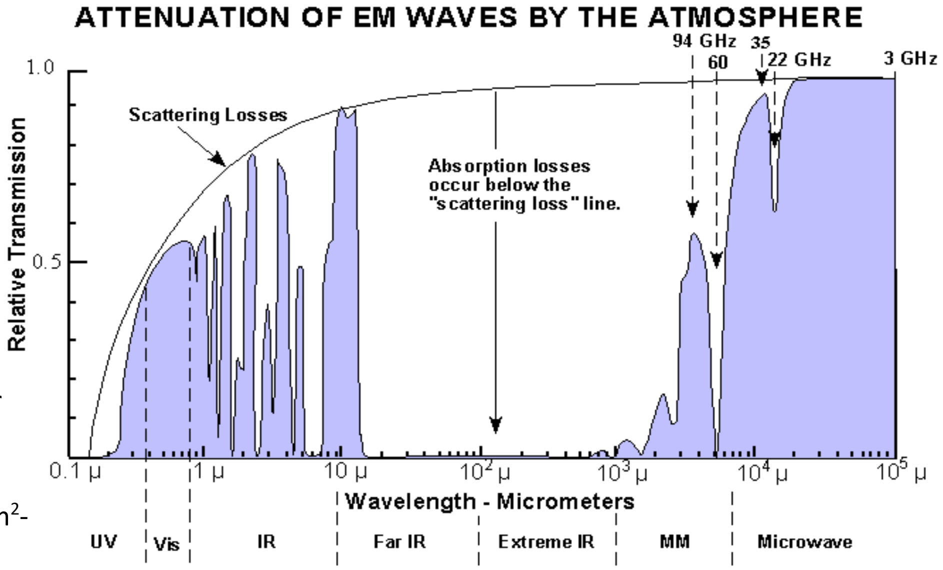


Figure 0-12 Attenuation and Absorption of EM Waves (Courtesy of US Navy via Wikipedia)

The solar arrays on the international Space Station mass around 2400 lbs. (1087kg) and each generate about 31,000 Watts, or 28.5 W/kg (NASA Shuttle Press Kit, 2001). The very efficient Juno Spacecraft generated about 35W/kg for its solar panel. Using this more efficient number we can calculate that our mass will be 2.857x10^{8}kg or 285,714 mt. This would work out to about 8 kg/m^2 for the solar panels.

To launch this from earth would be extremely expensive. Currently the published launch costs for a Falcon 9 are about $67million for up to 22000kg to orbit- this works out to $3050kg. This number is far too expensive to justify constructing a SBSP station. However, Elon Musk has stated that the new fully reusable SpaceX Starship costs will be much lower- target payload in the range of 150mt to orbit for $15million which would only be $100kg. At the ambitious cost of $100per kg our launch costs would be $28.6 billion- large but not unreasonable. Note that Elon Musk has stated that to build the colony on Mars he believes a minimum of a million tons will be required to be launched to orbit so the number of launches for a SBSP station is large but less than that being considered for a Mars colony.

In order to get the all-in costs, we need to add the development costs for the design of the solar power facility as well as the earth receiving station. The receiving station would need to be very large as OSHA regulations limit the amount of microwave exposure for humans to 250w/m^2. The earth's atmosphere is transparent to microwave- per Figure 0-12 it can be seen that at about 30mm (10 GHz) and longer- in what is the microwave range- the atmosphere is transparent and beaming down energy via microwaves with low losses are feasible. A 10GWe ground receiver will require 40 million m^2 (40km^2) or a square receiver 6.3km on a side. The receivers can be built in the desert or may even be able to be built on farm land as with wind turbines, the land below and around the receiving rectennas can still be used.

The development cost burden for this would primarily be absorbed by the design of the first power plant. Let us assume about $20 billion in development costs are required.

SBSP Unit	Launch Costs $B/mt	Development Cost $B	Manufacturing Costs $B	Incremental Costs $B
1	29	20	29	77
2	26	0	26	51
3	23	0	23	46
4	20	0	20	40
5	17	0	17	34
6	14	0	14	29

Table 0-1 SBSP costs sequential 10GW$_e$ units; launch and manufacturing costs are assumed to be $100kg for first Power Station and decrease by $10kg for each subsequent launch until $50kg is hit.

To this we need to add the actual construction of the solar power plant, including the solar panels, structure and microwave transmitters. According to Global Com (Global , n.d.)a weather satellite costs about $290million- or for a 3mt satellite almost $100,000/kg. Conversely, Musk has indicated that a Starlink satellite costs less than $250,000 each (Wang, 2019). The latest version of Starlink, V1.5 weighs 306kg which indicates a cost of $816/kg. Their Starlink system already has many thousands of satellites mass produced at relatively low prices.

Let us assume that for a large power plant we will have additional economies of scale and can get the cost down to $100kg. In this case our first 10GW$_e$ satellite manufacturing costs total would be about $77 billion.

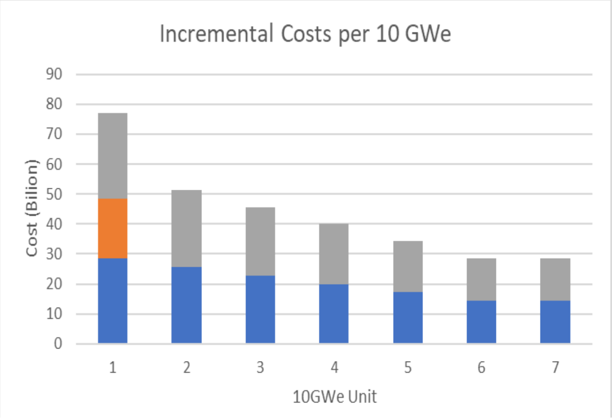


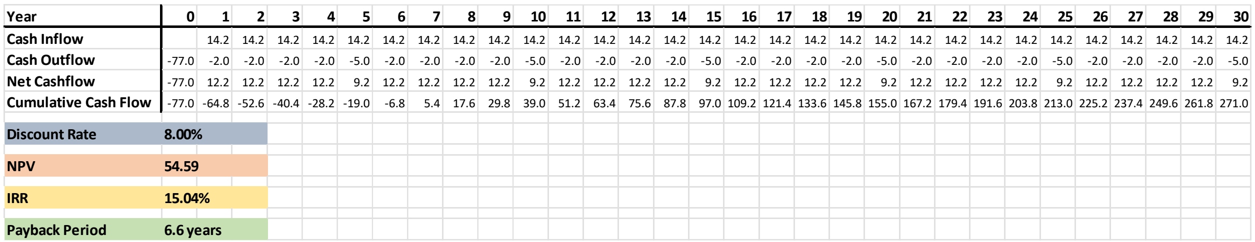
Figure 0-13 Graph of Incremental Costs

After this first unit is built, launch costs are assumed to drop by $10kg for each additional SBSP (or about every 1900 launches) until a final cost of $50kg is reached. For the commercial airline industry, costs vary wildly depending on distance and aircraft type, but a typical aircraft may fly a 100kg person for a $500 ticket which implies a cost of only $5 per kg. While this seems unrealistic for a rocket, I do believe that if we were launching thousands of ships per year, additional savings of on launch costs could be achieved. Elon Musk, in 2020, stated his goal would be to eventually launch a Starship for $1.5 million which equates to only $10kg. Table 0-1 lays out the unit price for the first 6 10GW$_e$ units.

After the first article is built, development costs would go to near zero. Furthermore, I assume that the manufacturing costs will drop, as we get additional efficiencies with each additional power plant constructed by implementing lessons learned, economies of scale and manufacturing improvements. As with the launch costs, I show manufacturing costs drop linearly by $10 kg for each SBSP plant produced until a final cost of $50kg is reached by the sixth unit. A 50% reduction should be reasonable. The F-35 aircraft programs initial articles were reported to be in excess of $160million per aircraft in the initial lots but the latest contracts indicate a price of about $80 million (Harper, 2019) per aircraft.

This will drive the sixth and subsequent unit price down to about $29 billion a piece. After this, fixed costs, the launch fuel, normal maintenance costs and diminishing returns will level out the price reductions.

In 2024 the average cost of electricity in the US was 16.2 cents per kwh (US Energy Information Administration, 2023). Assuming a SBSP station generated an average of $10GW_e$ (or 87.6 TWh annually), this equates to about $14.2 billion in revenue. The ground station is low tech and should be relatively inexpensive to operate and the SBSP platform, if designed for 30-year operation with minimal repair costs, will have moderate reoccurring operating costs- assumed for our purposes of only $2 billion per year. Further, let's assume that we incur additional planned maintenance expenses requiring launches to the SBSP station for programmed repairs every five years that cost an additional $3billion. Assuming a discount rate of 8% for a 30-year life and calculating NPV, IRR and Payback we come up with the following:



Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Inflow		14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
Cash Outflow	-77.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0
Net Cashflow	-77.0	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2
Cumulative Cash Flow	-77.0	-64.8	-52.6	-40.4	-28.2	-19.0	-6.8	5.4	17.6	29.8	39.0	51.2	63.4	75.6	87.8	97.0	109.2	121.4	133.6	145.8	155.0	167.2	179.4	191.6	203.8	213.0	225.2	237.4	249.6	261.8	271.0

Discount Rate	**8.00%**
NPV	**54.59**
IRR	**15.04%**
Payback Period	**6.6 years**

Table 0-2 NPV, IRR Payback Period for 10GWe $77 billion first article

Follow up units will be cheaper and have payback periods even faster. Based on this rough analysis it would appear that large SBSP stations can be economically viable once launch costs and manufacturing costs come down to the range of $100kg.

Comparisons With Ground Based Solar

Installing a square meter of SBSP panel will be much more expensive than an equivalently sized ground-based panel. However, it is much more efficient and generates far more power per meter of panel. On average a SBSP station will receive about 5x more power per square meter than a ground station ($1366w/m^2$ vs $250\ w/m^2$). There will be some power transmission losses on SPSP so we can adjust down to about 4x more power. Unfortunately, published reports on the costs of land based solar power do not list a constant baseload cost so as to compare to other forms of power (SBSP, Nuclear, Gas, Oil and Coal). A large solar ground station will need to have substantial storage capacity to save a portion of its energy to provide power at night and on cloudy days- easily doubling the installed cost. Published reports indicate that installed solar roof panels generate power for $.07 kwh, or half the average price of electricity generated in the US. If this were true, all power would be generated by rooftop solar panels and subsidies would not be needed. However, the truth is that these prices do not include power storage but only the instantaneous peak power generated for the house consumption or is fed back into the grid. To compare Solar to other forms of power generation we would need to include power storage in our total costs which will likely triple costs to about $.21 per kwh.

An SBSP does not need this storage capability- therefore to generate the same returns a space-based solution can be about 12x more expensive to build than a ground solution for each square meter of generating power.

I also wanted to look at the energy required to launch the SBSP. If it takes more energy to launch the 286k mt into orbit than the energy produced over the lifespan, then it will not be advantageous to build an SBSP. Using the SpaceX Starship as a template, the Starship will put about 150mt into orbit for each launch. To put this much into orbit requires about 5000mt of methane and oxidizer. Over 1900 launches, this equates to 9.5million mt of fuel and oxidizer. This assumes (overoptimistically) no additional fuel is required to transfer the SBSP from low earth orbit to geosynchronous orbit. The specific impulse of the methane fueled rockets are about 380seconds, so the exhaust velocity would be about 3800mps. Using our equation of Kinetic Energy,

$KE= ½ mv^2= ½ (9.5x10^9)3800^2$

$KE=6.859x10^{16}$Joules

This works out to 68.59 Petawatt sec or about 19TWh. Our 10GWe SBSP generates about 88TWh annually so within about 2.6months it would generate more power than is required for launch.

Space Based Solutions- Solar Flux Reduction-The Solar Occulus

The continued growth in energy usage in the third world combined with limitations of each of the “green” solutions discussed means it will likely be nearer to the end of the century before CO2 levels even out and start decreasing. It is likely that all of the options discussed will be part of the solution to meet the long-term goal of significantly reducing CO2 emissions.

For these reasons I wanted to look at the feasibility of a quick, lower-tech, shorter term fix. Like the proposal for increasing the earth’s albedo, this fix would not address the increasing CO2 levels but would address the global warming issue and would be able to address it quickly- within the next twenty years. Instead of trying to create greener power or increase the earths’ albedo we would instead reduce the solar flux impacting the earth in order to reduce the earth’s temperature.

Suppose we blocked 2% of the sun’s energy with a large solar shade (which I will refer to as an Occulus because it sounds better than a solar shade)- how would that effect our temperature? Using the so-called Stefan Boltzmann equation, we can calculate the temperature change. The Equation for calculating temperature for a body at the earth’s distance from the sun is:

EQUATION 0-1 $\boldsymbol{T_T = T_\odot \surd(\frac{R_\odot}{2R_T})}$

σ is the Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^2K^4)

R_Θ is the radius of the sun in meters. This is 696 x 10^6 m

T_Θ is the temperature of the sun in Kelvin. The surface temperature of the sun at R_Θ is 5780K

R_T is the distance of the earth from the sun- or about $1.496x10^{11}$ m. CC

$$\boldsymbol{T_T = 5780\surd(\frac{696x10^6}{2(1.496x10^{11})})}$$

Or a temperature of around 278.8K. This is called the effective temperature and assumes all energy hits the ground, that the earth is a perfect absorber, and there is no atmosphere. In reality the earth reflects about 30% of the energy and the actual temperature would be 255k.

For our calculation we can assume the effective temperature of a perfect absorber without atmosphere. For an Occulus that reduced the solar flux by 2% (the equivalent of approximately increasing our planets orbital distance by about 2% or 1.523x10^{11}km) our planet's temperature would be 276.3K or a decrease of 2.5C. This comfortably spans the projected temperature increase over the next century.

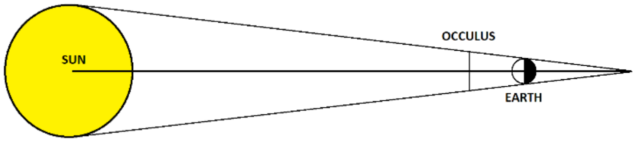


Figure 0-14 Sun Earth Occulus Geometry (Not to Scale) for a 100% occultation

To accomplish this reduction, a large Occulus would be placed just inside the L1 Lagrange point which is about 1.5million km inside the earth orbit, or about 1% of the distance between the earth and sun (Figure 0-15). At this distance, to fully oculate the sun a shade would need to be considerably larger than the sun's diameter. A similar effect can be observed during a total solar eclipse… where those in the so-called umbra see a total eclipse but anyone outside in the penumbra see only a partial eclipse. This is because, even though the moons apparent diameter is about the same as the sun it fully blocks the sun over only a very small part of the earth's surface along a narrow path of totality. The geometry of the Earth and L1 position mean that to fully block out the sun everywhere on earth the diameter of the Occulus would need to be much larger than the apparent diameter of the sun- or about 28,000km- appearing from Earth about twice the apparent diameter of the sun when positioned at L1. This would ensure a complete shadow of the earth even at the poles. The actual geometry for a fully eclipsing Occulus is shown in Figure 0-14 and would have an incredible area of 615,752,160 km^2 (6.1575x10^8 km)

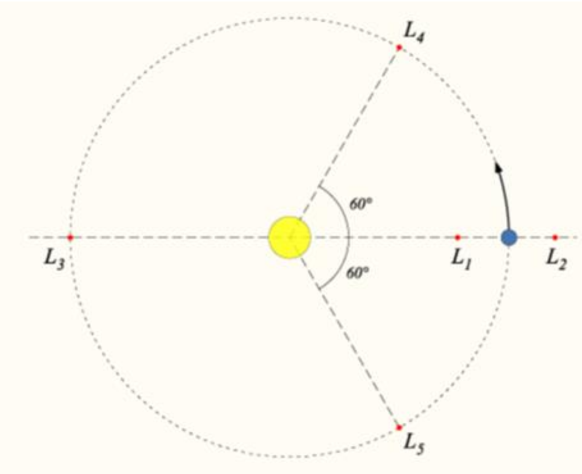


Figure 0-15 Occulus would be located just inside the L1 position

Fortunately, we need only to block 2% of the sun's radiation and would require a more manageable but still huge area of 1.2315x10^7 sq km. The diameter for such a device would be 3,960 km. At dawn such an Occulus would appear as a black chip off the sun's edge. As the day advanced the chip would gradually move across the sun's face, until it appeared as a large dark mote on the sun's face (see Fig 0-16). In the course of the day, it would continue to migrate across the sun until by dusk it would appear as a chip at the side opposite of the dawn position. From a place directly below the shadow of the Occulus the shadow would be quite large- however, as with the change in the time of day, depending on the latitude, the Occulus will appear either above or below the solar equator.

How massive would such a structure be? With high performance solar sails engineers are looking at materials that mass less than what the local solar gravity force is- about 1.53 g/m^2 (or 1.53x10^{-3} kg/m^2). This is also called the sail loading. This very ambitious requirement is one of the reasons solar sailing has not been seriously applied for space travel. Some of the best materials currently available and considered for solar sails mass about 7g/m^2 (mylar). For our Occulus, let's assume an even less ambitious material that when combined with a rigid structure masses 10g/m^2. For a 1km shade we would mass 10mt/km^2. Using this our Occulus would mass 12.315x10^8 mt.

With the planned Starship Launch payload of 150mt and goal of $100kg, we would require 821,000 launches at a total cost of 12.315 trillion dollars! Note that this seems to be unrealistic as the world GDP in 2021 was on the order of $100 trillion. Nevertheless in 2019 there were about 38.9 million commercial flights worldwide (Statista Reasearch Department, 2023) so it is not impossible to envision that over the next few decades that the number of rocket launches will grow significantly. If, as with the SBSP scenario, we drop launch costs by $10kg every 1900 launches, we will reach our target cost of $50kg very quickly and early on in the program.

Total Reduction	Launch Costs $B/mt	Development Cost $B	Manufacturing Costs $B	Cost per incremental .1%	Total Cost
0.10%	278	10	28	316	316
0.20%	278	0	28	306	621

Table 0-3 Occulus Costs costs for initial .1% increments; launch and manufacturing costs are assumed to quikly be reduced during the first increment to $50kg for launch and $5kg for manufacturing, and with the intial development costs hitting the first .1% increment

To the cost of launches, we would add the cost of development. The solar Occulus is fairly low tech (compared to the SBSP system) so I assigned a cost of $10billion.

Finally, the manufacturing cost of the Occulus needs to be considered. As opposed to the solar power facility, I originally proposed that the simpler design of the Occulus should lead to a much lower initial cost- 1/10th the SBSP manufacturing costs per kg or about $10kg. For comparison, a typical 2mt $50,000 car costs $25/kg. Furthermore, with increased manufacturing efficiencies as thousands of square kilometers of the Occulus are built, manufacturing prices would likely drop further- to a final estimated $5kg.

We can compare the costs of various Occulus configurations in Table 0-3 to the SBSP satellites of various sizes shown in Table 0-2. For the SBSP station I reduced manufacturing and launch costs for every 1900 launches. Because of the sheer number of launches needed for the Occulus, I use the mature launch and manufacturing costs right at the start- $50kg for launch and $5kg manufacturing. The Occulus, since it is scalable, will start out relatively small- and intercept only .1% of the radiation. The first .1% Occulator will cost $316 billion, and each follow up unit $306billion. To build an occulator that intercepts a full 2% of solar energy would cost 6.123 trillion. I believe that this would be achievable if spread out over a 20-year implementation plan of about $310 billion per year.

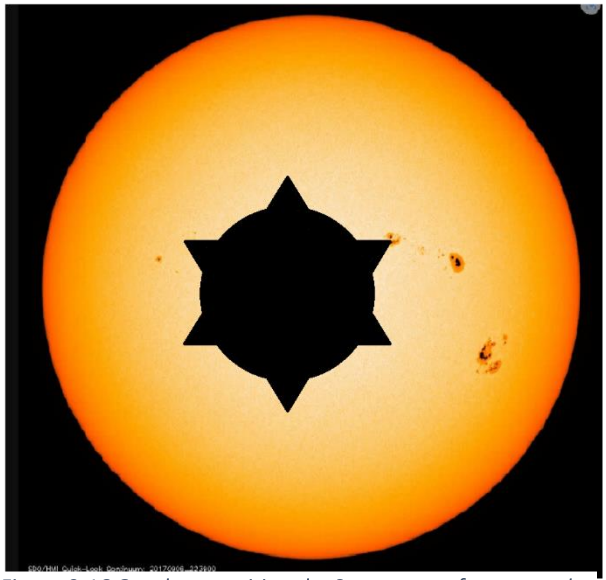


Figure 0-16 Occulus transiting the Sun as seen from near the equator and near noon. Note the triangular vanes used for tacking and manuevering.

The primary cost driver for a relatively low-tech solution like the Solar Occulus is its huge mass and associated launch costs. If we could significantly lighten the Occulus with a mass of only 5g/m2 we would half our costs. Furthermore, it may be possible to reduce launch costs even further-perhaps by supplying the required materials from the moon and launching them with a mass driver. Unfortunately, some of the raw materials that might be considered for the Occulus are various carbon rich fibers and the moon is very poor in carbon.

Note that when comparing alternatives, cheaper launch costs would similarly lower the cost of a SPSP system. However, with the SPSP system less than half the total costs are related to launch prices whereas over 90% of the Occulus costs are. Similarly, if the manufacturing cost of the SBSP were higher than $100kg but the Occulus costs achieved their target of $5kg, this would shift cost benefits to the Occulus sooner.

Despite the high cost, it may still be advantageous to build an Occulus. The Occulus is scalable- we may start out with one that intercepts only .1% of the solar flux. We could gradually expand it over several decades as needed and as other technologies evolve that reduce greenhouse gas emissions. As mentioned, expanding it to 2% would negate the next 100 years of temperature increases, buying additional time to develop SBSP, and Fusion/Fission. One way of looking at it is that the cost of a $6 trillion Occulus is equivalent to building 2070 GW_e of SBSPs (or about 10 years of projected worldwide annual growth in electricity usage) but buys us 100 years of time!

Alternate Designs

The proposed design has the simplicity of a single large structure able to be adjusted and moved as needed to vary the desired effect. Alternate designs are available that may be preferred. However, for several reasons I doubt that these would be an acceptable solution.

The simplest alternate design is to place multiple large "Occulators" closer to the earth that block the sun's rays periodically. These could be placed in any orbit but perhaps be easiest to maintain would be a geosynchronous one. Since this orbit is only 1/42nd as far as L1 our Occulus would only need to be about 1/42nd the diameter for the same amount of shade and its area only about 6301 km^2. This area would work out to only about 1/764th the size of our L1 Occulator. Unfortunately, at this distance from the earth the Occulator satellite would transit the sun in only about 2 minutes. To keep a continuous progression of such transits, we would need a total of about 720 satellites in a circular band around the earth- negating a large portion of the size advantage.

We could even consider building a line of these stations connected into a continuous large band that would girdle the earth- a configuration that would look like a ring around the planet- though because of its orientation the thick part would be along its axis so it would bear some resemblance to a ringworld. The stability of such a system would be difficult to maintain as the incoming solar radiation pressure as well as the gravitational effects of the moon would tend to push these around and distort the ring and possibly tear the structure unless we engage in continuous active adjustment. All of these alternate designs are dynamically much more complicated and not as mass efficient as you would imagine… only a portion of the band or a few of the large orbiting shields would actually be intercepting the sunlight headed for the earth at any particular time. Perhaps even more importantly, these hundreds of large shades or this ring would be visible at night, each brighter than the full moon. Nighttime would be effectively eliminated- not a very green solution.

Occulus Design, Station Keeping, Orientation and Positioning

Effectively the Occulus will be a large (though poorly performing) solar sail. Like a solar sail, it will have various moveable flaps or panels for attitude adjustments (see Fig 0-13) and will be maneuverable enough for station keeping as the L1 point is not completely stable especially because of the effects of the moon's gravity. It may be cost effective to build several large sections of the Occulus in earth orbit and then, using their intrinsic solar sail capabilities, gradually raise their orbit until they get to the L1 point.

The proposed Occulus would be positioned just inside the L1 point nearer the sun where the suns gravitational and solar radiation pressure will be balanced by the earth/moon gravitational forces. Keeping the Occulus in the correct position will require continuous orbital correction achieved by light pressure from the sun (as with a solar sail) with large moveable flaps that can be extended or retracted so as to give the appropriate orientation and course correction.

To determine the Occulus performance and material temperature we will assume a reflectivity of 80%. Using the equation for the force a solar sail generates we have the equation:

$$\boldsymbol{F_{Sail} = \frac{(1+k)I}{c}}$$

Where:

k: Sail reflectivity between 0 and 1. A perfectly reflective sail would be 1.

I: Intensity per m2. At earth this is about 1366w/m2. At the L1 point it would be slightly more-1408w/m2.

Filling in for c, and setting k=.8 we calculate:

F=.0000085 newtons per m^2

This force from the sun would counteract the net gravitational forces that our solar sail would experience since it is just inside the L1 point.

To calculate the temperature of our Occulus we need to use the following equation:

EQUATION 0-2 $\boldsymbol{L_\odot = 4\pi R_\odot^2 \sigma T_\odot^4}$

Where:

$L_\odot$ is the suns luminosity.

σ is the Stefan-Boltzmann constant (5.67*10^{-8} W/m^{2}K^4)

R_Θ is the radius of the sun in meters. This is 696 x 10^6 m

T_Θ is the temperature of the sun in Kelvin. The surface temperature of the sun at R_Θ is 5780K

To determine the temperature at a different distance from the sun we can use the equation:

EQUATION 0-3 $\boldsymbol{T_T^4 = (\frac{R_\odot^2 T_\odot^4}{4R_T^2})}$

Where T_T = temperature of our Target and R_t is the radial distance to our target.

Rearranging and simplifying:

EQUATION 0-4 $T_T = T_\odot\sqrt{(\frac{R_\odot}{2R_T})}$

For our Solar Occulus at L1 R_T distance from the sun will be about 148,500,000 km. Substituting

$$T_T = 5780K\sqrt{(\frac{6.96x10^8}{2 * 1.485x10^{11}})}$$

T_T= 279.8K

We are actually even cooler than this. If we assume 80% reflectivity (20% absorption) we have:

$(.2)^{.25} = .56$

or only 56% of the temperature. Our Occulus temperature will now be only 157.33K. Temperature will not be a problem.

The Occulus could be built in many configurations similar to the designs for large solar sails. It would likely be a tension structure where the tension is caused by a slow rotation rate- perhaps on the order of once every 10 hours. The benefit of the Occulus over a solar sail is that its performance is pretty much mass independent. As opposed to a solar sail that needs to be large but feather light to achieve high performance, our Occulus does not need to be very light. The only reason mass is important is the substantial costs associated with earth launch or launching the required material from the moon with a mass driver delivering the mass to L1.

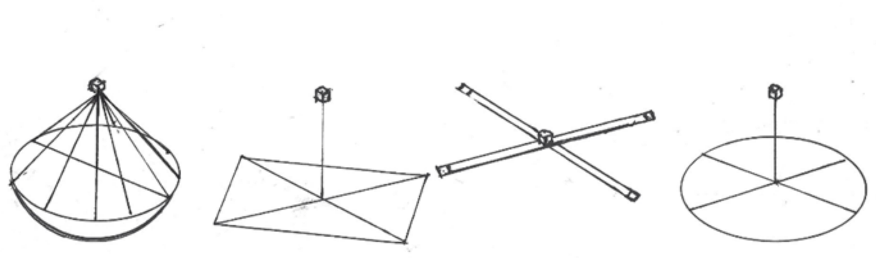


Figure 0-17 Similar in design to Solar Sails, here are some possible Occulus configurations.

Advantages and Disadvantages of an Occulus Station over a Geosynchronous Power Station

The Occulus has several advantages over a Geosynchronous Power Station:

- Much lighter per square meter.
- Much simpler design, manufacture and assemble. Low Tech. Most of the mass will be a thin, lightweight material or fabric in tension.
- Cheaper (per m^2 and kg of mass) to build due to its simple design.
- Low risk- no new technology. Even though the engineering of physics of large Solar Power stations is well known, the construction of such massive stations with Gigawatts of power that also can beam down this power via Microwaves is a substantial, though achievable, technological challenge. The Occulus is a lightweight membrane stretched out over many kilometers and can be designed with minimal engineering.
- Scalable. The Occulus, as currently proposed, can, through appropriate positioning, intercept anywhere from 0%-2% of the solar radiation. By nature of its design, it can be enlarged or shrunk as needed.
- Requires no land for power receiver.

- Can easily offset global warming anticipated over the next 100 years.

These advantages mean that the Occulus could be designed, built and launched relatively quickly as long as space launch capabilities are expanded, and launch costs decrease to $100kg or lower. It is not much of an extrapolation to believe these capabilities will be achieved within the next decade.

The disadvantages of an Occulus that blocks 2% of the suns energy over SBSPs plant are:

- Much higher total mass and therefore much higher launch costs
- Even though the Occulus is much lighter per square meter than the SBSP facility, the area is so much larger that the total manufacturing costs will be higher.
- Unlike the SBSP it does not generate any revenue. For the price of a $6 trillion Solar Occulus you could build the equivalent of more than 200 10GWe SPSP plants that would collectively generate (at 16.2cents per kWh) $2.8 trillion in electricity per year.
- The Occulus does not reduce Greenhouse gas emissions.

Additional Uses for an Occulus

The Occulus and its associated technology have even more exciting applications further into the future. A very large Occulus placed at the Venusian L1 point could make this planet habitable- though it would need to be much larger in order to block most or all of the sunlight to quickly lower the planet's temperature. Extremely large quantities of hydrogen would be imported to convert a portion of the CO2 atmosphere into water and large quantities of carbon (note some of the carbon may be useable to build the Solar Occulus).

The British Interplanetary Society proposed a fully occulting shade for Venus that would be about 4.5x the diameter of Venus itself- or $2.5 \times 10^8 km^2$ (Birch, 1991, p. 158). In this scenario, the sun is totally blocked and the temperature of Venus drops rapidly over a timespan estimated as 87.2-200 years. In this scenario the CO2 precipitates out first as rain, creating CO2 oceans, and then snow as the temperature continues to drop (Birch, 1991, p. 159). Besides the extremely large quantities of hydrogen that would need to be imported to create water, the BIS study also postulated an extremely light sunshade material only massing .4g/m2. If such a light material were ever developed the Occulus as well as solar sails become eminently viable.

We could also use a modified version of an Occulus as a large reflector or mirror which if placed in either a large orbit or perhaps at a planets L2 point and appropriately focused, can add energy (heat) to a planet (Mars for example) to help raise its temperature. One challenge with Venus is the extremely slow rotation which makes a day its synodic day last for 116.75 days. Once the temperature of Venus was reduced to where we could introduce plants and animals, a duel system of Occulator and solar mirror may be needed to provide a more reasonable day/night cycle.

Summary of Alternatives

Determining the actual costs to build and operate these various power alternatives is difficult and outside the scope of this article. Part of the reason for this is that certain tax and rule advantages are in place in many countries to encourage certain energy resources and discourage others. Nuclear in particular has been restricted in construction due to hostile regulations and low rate of production (i.e., in the US only one new power plant is currently under construction). This will tend to drive the cost of Nuclear Power higher. Furthermore, nuclear reprocessing and breeder facilities have been shut down for political reasons, further driving up costs. Conversely, there are favorable rules and tax breaks in place to encourage wind and solar. The rapid expansion of these technologies has reduced their apparent prices to the customer. However, since these are artificial price distortions, they are subject to changing policies and do not reflect the true costs. Because of this I have concentrated on only some broad aspects of the characteristics of the various energy sources in Table 0-2 and the engineering challenges of building 450GW$_e$ Worldwide of green power each year. Changing the Earths Albedo and the Solar Occulus do not address increased CO2 emissions nor power requirements and have no cash flow so are not included in this table.

Source	Plant Size	Number Needed	Comments
Nuclear Power	1 GW	450 Nuclear Reactors	Least Emissions, Least Land. Most regulated. Large potential for economies of scale. Most Nuclear plants consist of 2-3 Reactors of 1 GWe each.
Renewables			
Bio Diesel			Not likely or practical. Frequently create more greenhouse gases than they prevent. Will be useful for aircraft and vehicles.
Solar	75 W$_e$/m2	6000km^2 per year	Land intensive if dedicated power plant. No inexpensive solution to power storage. Distributed rooftop installation will use less land, but costs are several times higher
Wind	2 MW$_e$ Average	225,000 turbines per year	Larger Turbines can be installed at sea and can reduce this quantity by 50%. Sea installation and maintenance costs will be higher. No inexpensive solution to power storage.
Hydroelectric	2.5 GW$_e$ Average	180 Dams per year	Not many undeveloped large rivers remain. Environmental regulations make new dam construction difficult to get approved.
Space Based Solar	286 W$_e$/m^2; 250 W$_e$/m^2 Ground	45 10GW facilities per year requiring a total of 1573km^2 space 1800km^2 ground	Space based area and ground receiver-based area. Substantial and efficient launch capabilities required.

Table 0-4 Requirements to build 450GWe per year

Summary and Conclusions

If greenhouse gas emissions and their implied increase in global temperatures are determined to be a real issue that needs to be addressed, we as a species are currently failing. Increased emissions by third world countries along with little or no expansion in the use of nuclear power in advanced countries has led to a substantial increase in CO2 emissions over the last twenty years despite large subsidies on "green" energy items like wind and solar. Because of their variable power generation, wind and solar are not suitable for base loads without substantial investments in storage systems. The increase in raw materials for batteries alone will require a substantial expansion of mining industries which has heretofore not occurred in advanced industrial countries.

Space-based solutions are primarily limited because of the high costs of launch services. It is unlikely that any space-based solution would be economically viable unless launch costs are driven down to the

$100kg range. Solar Based Power Stations, while requiring large upfront costs, look to provide a viable and green alternative to other technologies and would address the biggest shortfall with most green energy sources- providing baseload power. However, if launch costs were driven down to $100kg and the SBSP facility could be manufactured for as low as $100kg, then a 10GWe plant could generate $14billion of electricity per year and, assuming annual operating costs are low, could be paid off in less than 7 years.

The Occulus is an expensive but technologically viable device that, while not addressing the CO2 rise, would address the primary concern of increasing temperatures forecast over the next century. The construction of the Occulus would serve to buy time until better solutions (SBSP, Fusion, Fission) can be developed and become available. If launch costs could be reduced to $25 kg and we could develop a lighter design massing 5g/m^2 its cost would be in the neighborhood of $1-$1.5 trillion which is the approximate amount currently spent every 2-3 years on green energy initiatives.

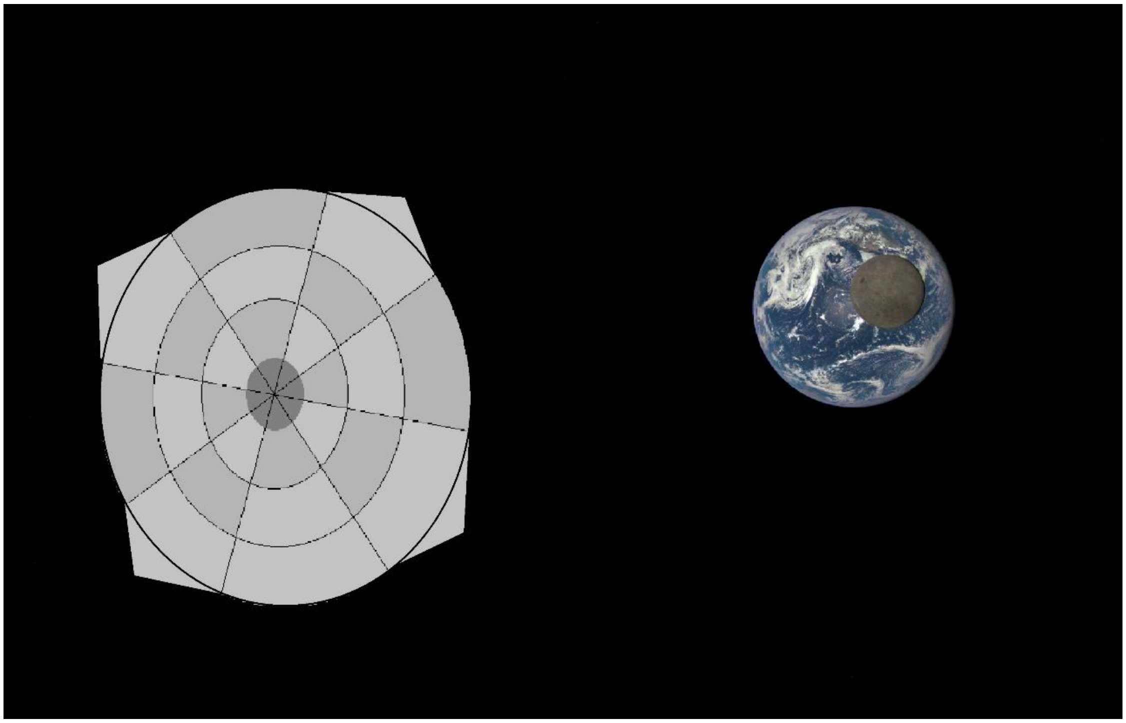


Figure 0-18 The Occulus 1.5million km in front of the Earth/Moon system

Additional Space Based Articles are available at https://www.allthingsspace.info

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