

Gigatonne Carbon Dioxide Removal Can Reverse Global Heating Trend

Original Research Article

ABSTRACT

It is a surprising realization to many that a changing temperature *tightly* correlates with the carbon dioxide (CO₂ or CO₂) levels worldwide in a linear, lockstep manner with a reversible but very short temporal feedback loop of only a few decades. A mapping of the past 400,000 years of earth's climate history by Hansen, based on the Vostok ice core sampling, offers a glimpse into this remarkably tight relationship between carbon dioxide (CO₂) and global temperature levels but also the average sea level over four ice ages that are clearly delineated in his historic depiction of all three quantities. As his Table accompanying the graph is analyzed, an equation linking the three variables has now been generated, yielding a fresh view into how soon and how much an atmospheric CO₂ increase can affect the world's temperature rise, also called "global warming." The conclusion that is inescapable from such an analysis is that the present CO₂ levels, far surpassing those present in 1950, need to be drastically reduced by what now amounts to multi-gigatonnes (billions of tonnes) carbon dioxide removal (CDR) by all means available and yet to be invented. (Note: metric tonnes are 0.907 of English tons and both are used in this article.) Research accomplished in this review point to the heat-trapping property of CO₂ as the major contributor to increasing heat worldwide and lead to the prediction of how much higher global temperature will rise if left unchecked, with the level of CO₂ over 40% higher than it has ever been in more than 400,000 years.

Keywords: carbon dioxide, global temperature average, gigatonnes, ice core record

INTRODUCTION

The 2022 summer caused China's heat wave to shatter records, bringing hydropower electricity into question, while in the U.S., it delivered five 1,000-year rain events in five weeks to several Midwest United States.¹ For the first time in history, global population has tripled (3 times = "3x") within less than one 70-year lifetime (mine in particular), with another 50% increase expected by 2100 up to 11 billion (see Fig. 1). Following suit, global annual carbon dioxide emissions *growth rate* has quadrupled (4x) since 1950 and global energy demand has quintupled (5x), all in the same time period. This **3-4-5 triad** has wrecked havoc on the environment, most notably in the past few decades. More importantly, the energy demand at 5x is outstripping the other two and pulling them along, figuratively speaking, to catch up to the leader: the global demand for more and more energy, seen historically in every major society that has grown and declined.

This clearly means that as the population explodes at 3x, those young people also want more than the usual share as fossil fueled generators spread around the globe and modern conveniences including added air conditioner, become more and more desirable. Furthermore, with increasing global warming, Rocky Mountain Institute has predicted that soon, *a billion* new window-mounted air conditioners, each using a kilowatt on the average, will add even more burden to the increasing energy demand by 2050.

IEEE ISTAS 2019 **World Population Growth** – conservative est.

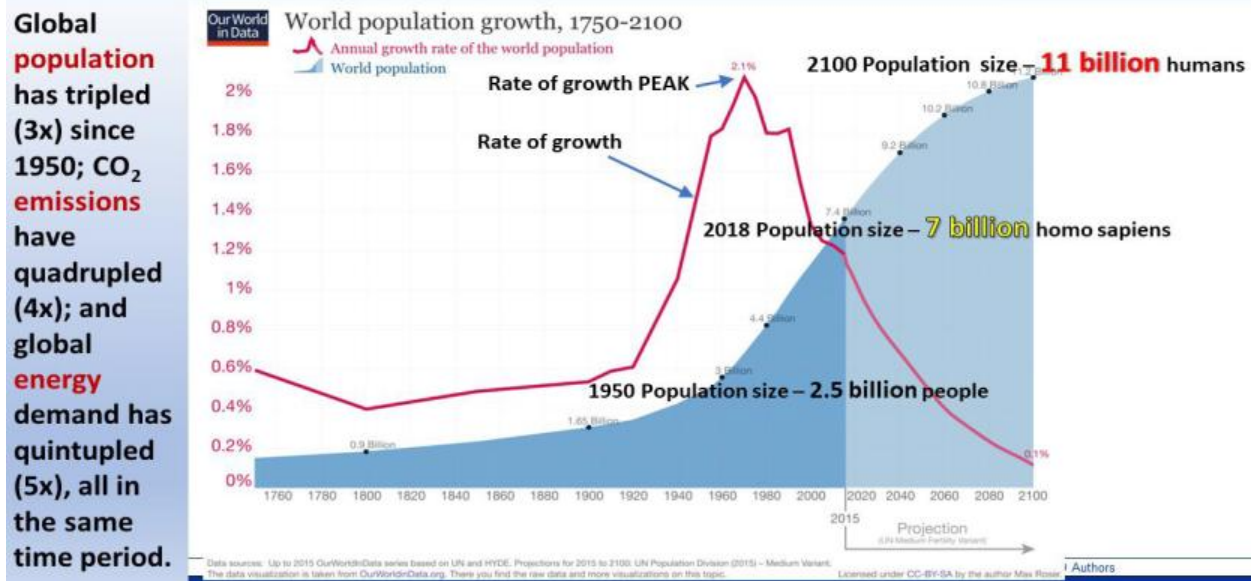


Figure 1. World population growth

Besides all of these inconvenient megafaacts, what really matters to everyone is how it will affect us personally. All of the images in this article are taken from a *slideshow that I gave in November, 2019* at Tufts University for the **IEEE Science and Technology Society conference (ISTAS)**. In the first figure, we see the 3-4-5 triad emphasized on the left and the source of the problem graphically illustrated on the right, which is very revealing. The important takeaway here is the difference between the World Population (say, Quantity “P”) and the RATE of change of that Quantity per Time (this slope = $\Delta P/\Delta T$). What is super valuable to us concerned with climatology in this double illustration graph is that the $\Delta P/\Delta T$ rate for population has reached its peak of growth way back in 1975. However, the World Population Quantity P will not be reaching its subsequent peak until a projected date of around 2100, as the $\Delta P/\Delta T$ rate continues to visibly decline as P slowly levels out over 100 years later. If I was still teaching community college environmental science, I would tell the class at this point: “Remember this unfortunate **one century delay** between the PEAK of a slowly changing growth RATE and the PEAK of the actual Quantity itself, when the number in the set is very large.”

It should be obvious from this image that the 4x CO₂ emission rate since 1950 and the 5x energy demand since 1950 are intimately connected to the 3x global population growth. So, let’s look at the consequential CO₂ emission details to get a feeling for the physics which are somewhat hidden to most of the world at this time. Climatologist **Dr. James Hansen** (from NASA Goddard) predicted in 1988 the one degree C increase in global temperature for 2019, which we are now realizing worldwide. Recently called the most accurate 30-year climate projection that any climatologist has achieved, James Hansen’s famous paper of 1988 was *the first* to contain predictions of a global “greenhouse effect” from a 3-D model developed at the NASA Goddard Institute for Space Studies but using the onerous phrase “climate forcing.”² Since such a concept was not yet accepted by the public, the paper was shunned by academic critics and Hansen was declared to be “wrong” by most of the media at the time.

For that 30-year anniversary of his 1988 article (the first of its kind, using NASA’s computer climate modeling), I wrote a long 32-page article and published it in the *International Journal of Environment and*

Climate Change in 2019. In it I even included a school teacher’s flood lamp experiment and graph of the heating of two soda bottles half filled with water and one with an Alka Selzer tablet dissolved in it. It becomes crystal clear that a little bit of CO₂ added to the air from the dissolved Alka Selzer in the soda bottle drove the final temperature to 44°C, since CO₂ is a “heat-trapping gas”, while the clean air bottle settles down and levels out at 35°C. It provides irrefutable evidence for students that only the carbon dioxide makes the difference in how much heat is retained in a closed system from incoming radiant energy, like the sun.

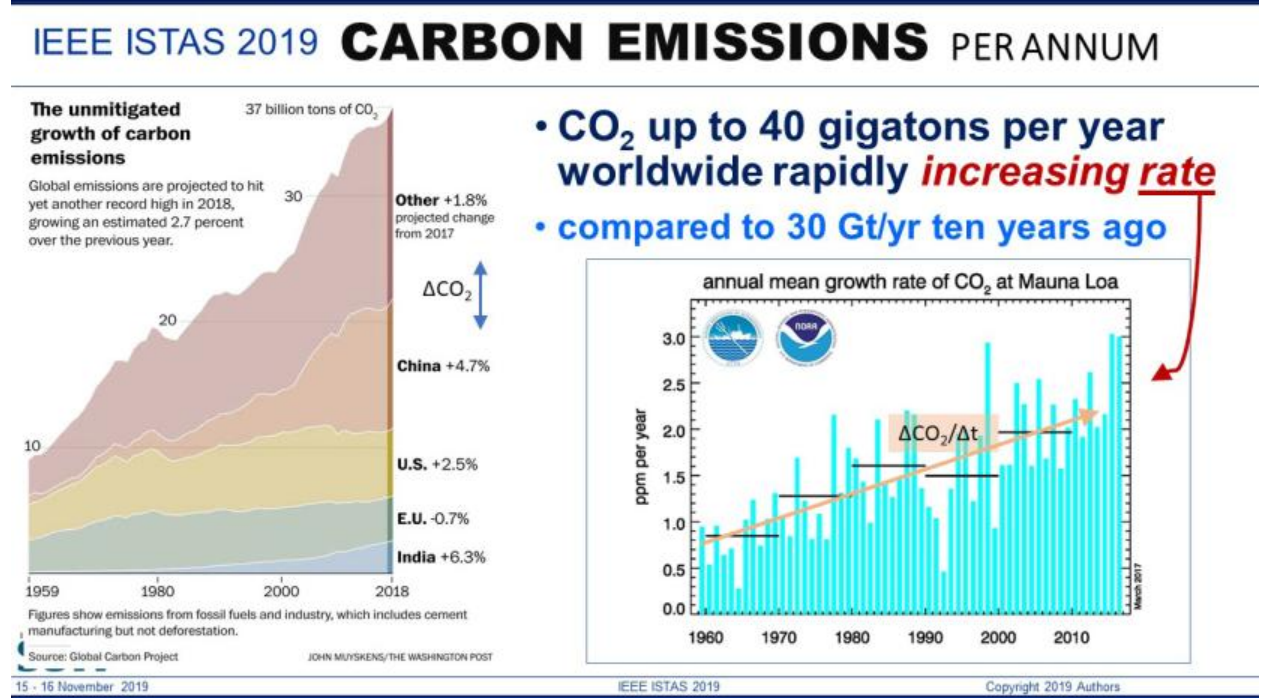


Figure 2 . Carbon ratio rate

Now comparing the first illustration of Figure 1 for World Population Quantity and the Rate of Global Population growth per Time to this second illustration of World CO₂ Emissions Quantity and the Rate of Global CO₂ Emissions growth per Time, it is disturbing to most of environmentalists to see the continually INCREASING rate on the right, which now in 2020 surpasses even the 1975 peak population growth rate of 2.1% with no sign of slowing down or reaching its own peak. From this double graphic illustration, any climatologist can speculate that such a large system will not peak for decades to come, since any change in a global phenomenon is gradual. Furthermore, the CO₂ emissions QUANTITY peak is reasonably projected to be at least 100 to 150 years in the future, from the behavior of the intimately connected population graphs of Figure 1 which actually causes the Figure 2 data. This scientific conclusion of such a systems behavior is a difficult concept to work around or argue against. Everyone in the world is under an apparent misconception that the CO₂ emissions Quantity is immediately controllable with a little more renewable energy adaptation to replace fossil fuel usage, which somehow magically will keep global warming under a tiny one degree or two of change. This brings up the purpose of this article: to explain the actual control for atmospheric CO₂ levels and what can bring global temperature into a stable region of the pre-industrial age.

In that regard, it may be more understandable to the reader what Hansen also discovered in 2006 which he published in MIT’s *Technology Review*. Hansen found a little-known *linear relationship* between CO₂, temperature, and sea level rise in the Vostok ice core data for the past 400,000 years, which can be applied today. He made it clear that the baseline maximum carbon dioxide (CO₂) concentration for almost a half million years or so was 290 ppm, which we got used to up to the Industrial Age. However, now in 2020, we

were experiencing a surprisingly increasing level of CO₂ that surpassed 410 ppm, with its rate of growth ALSO increasing.

What Dr. Hansen did for scientists like me was to tell us the details of the linear relationship between CO₂, temperature, and sea level rise which also gave us quantitative, locked-in estimates of temperature and sea level rise for the coming centuries. While consequential global warming due to the projected doubling and tripling of the greenhouse gas content of the atmosphere is clearly destined, there still are minority numbers of climate deniers controlling major policies in the United States and elsewhere. Recently a 30% drop in the publication rate of the phrase “climate change” has been noted from US government publications, even in the midst of record-breaking heat, fire, and drought.

TEMPERATURE TRACKS CO₂ LEVELS

It is a surprising realization to many that global temperature *tightly* correlates with and tracks the CO₂ levels worldwide, in a “lockstep” with a very short temporal feedback loop. The most convincing for me was to see the Vostok 420,000 year record in Figure 3 of both variables matching each other’s lead on the same graph. It clearly does not matter which appears to change first (which is a really assuring relationship as we will see later in this article), since the other will invariably follow.

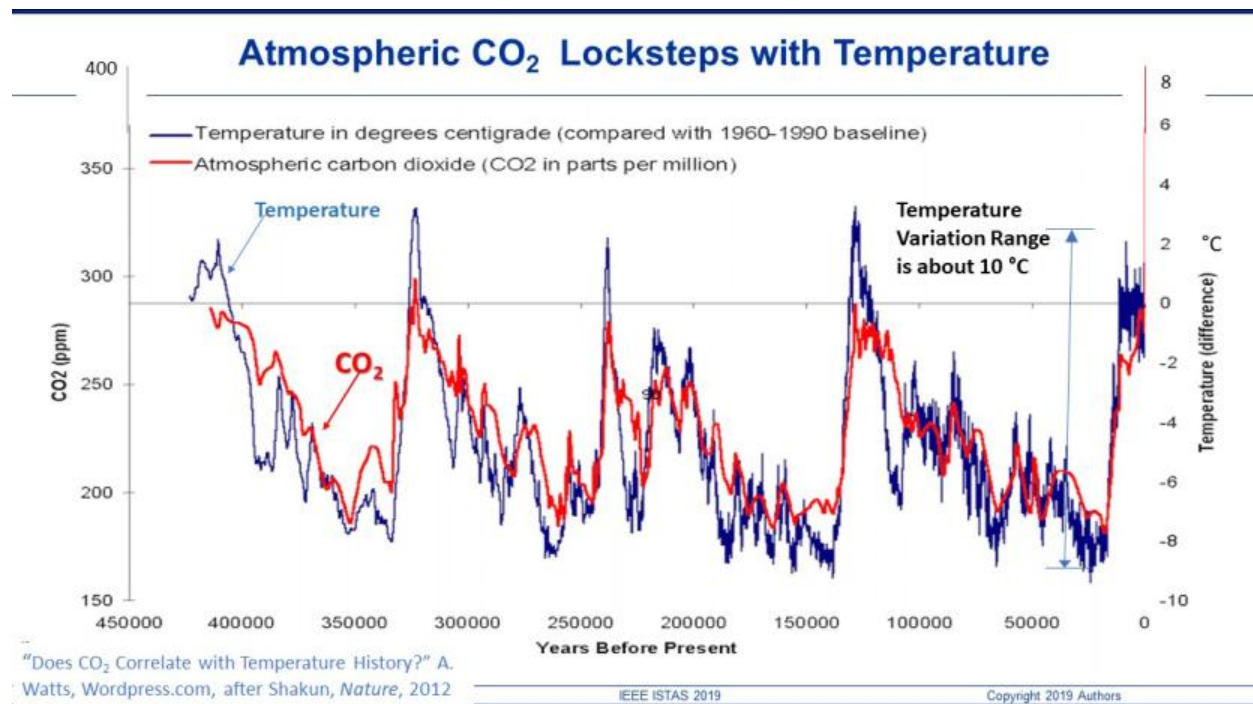


Figure 3. Temperature Tracks CO₂ Levels

In Figure 3 is a plot of the world average temperature and CO₂ data from air bubble analysis of the Vostok Station Antarctica ice core. In 1999, the Vostok ice core 420,000-year record of carbon dioxide was published by Petit et al.³ *Exhibiting great stability, the CO₂ levels clearly have never exceeded 290 ppm worldwide even through four ice ages.* However, in the isolated monitoring station cited above for our modern, with our wanton fossil fuel carnage, the latest global carbon dioxide levels have now exceeded 410 ppm, with apparent disregard for the consequences. Notice in Figure 3 the important clearly tight correlation of temperature (blue graph) and carbon dioxide (red graph) for the past 420,000 years, which leads us to the obvious problem of the red line at the end (present time). If we are forced to admit the historic red and blue data lines don’t lie, then the axis label of CO₂ concentration on the left necessarily correlate to the axis label of global temperature on the right. This is, to me, the most important realization and conclusion for the reader to grasp from this article. While climatologists know this relationship exists,

the United Nations Environmental Program (UNEP) and the International Panel on Climate Change (IPCC) among others are clueless or simply choose to ignore the consequences of the present CO₂ excess, which now surpasses 40% of the maximum 290 ppm the earth has ever experienced in over 420,000 years. It is vital that the reader comprehends the blatant fact that we are indebted for at least 8 degrees C increase in temperature, which will manifest approximately by 2100, unless something drastic is done to reduce the amount of carbon dioxide in the atmosphere globally. Before we explore those possibilities, let's look at the corroborating evidence that Jim Hansen brought to the table in 2006.

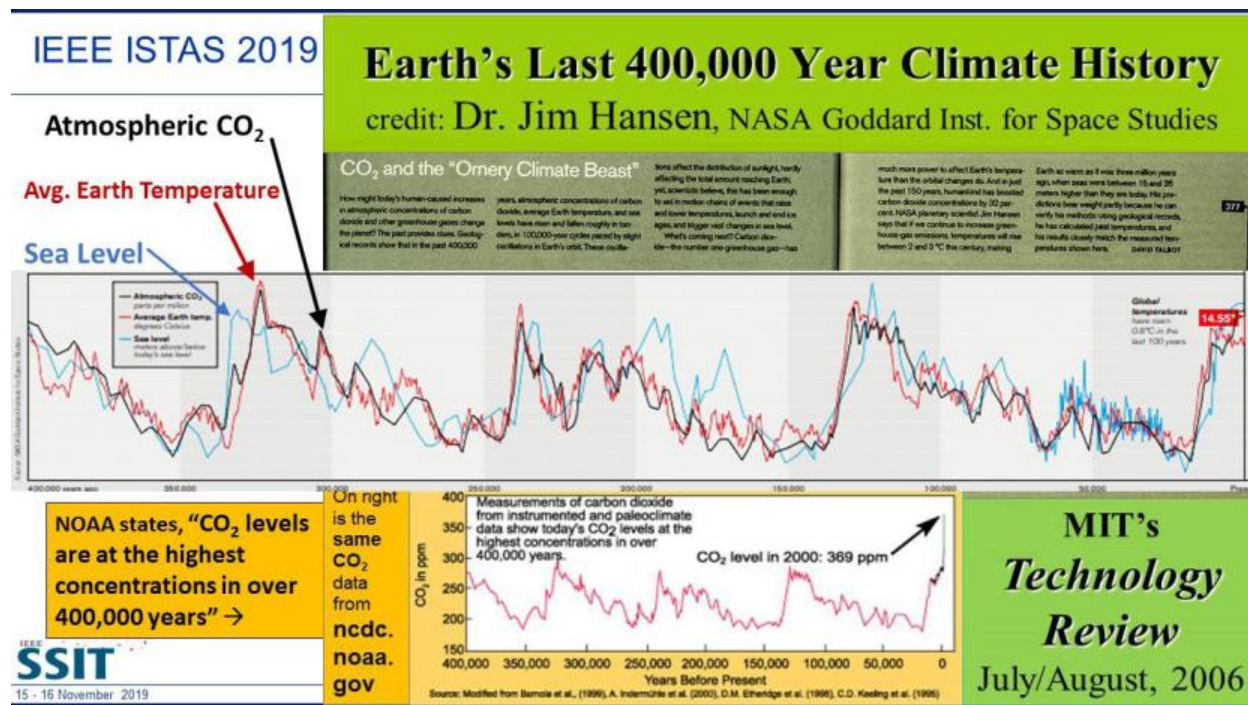


Figure 4 Correlation for CO₂ and temperature

While Petit et al. show us the correlation for CO₂ and temperature, Hansen brings in the sea level data as well in Figure 4. You can also see that even in 2006, the CO₂ value of 377 ppm was already shooting way above the millennial maximum of 290 ppm (regarded as the baseline). I have inserted the similar graph from the National Oceanic and Atmospheric Administration (NOAA) as well to show that they are all speaking the same language. While sea level also tracks the other two variables of CO₂ and temperature, it has a longer temporal feedback loop. In other words, it takes hundreds or even a thousand years for sea level to reach the correlated value that climate forcing dictates. And what is the "correlated value" for sea level that even the present 410 ppm of CO₂ dictates, you might ask? I usually hesitate to even mention it during interviews or lectures. The reason is that most people, including me (for over ten years), don't believe the number. To prepare the reader for a shock, let me introduce the next figure first, to reinforce the LINEAR relationship between all three (3) variables that Dr. Hansen discovered and published in 2006.

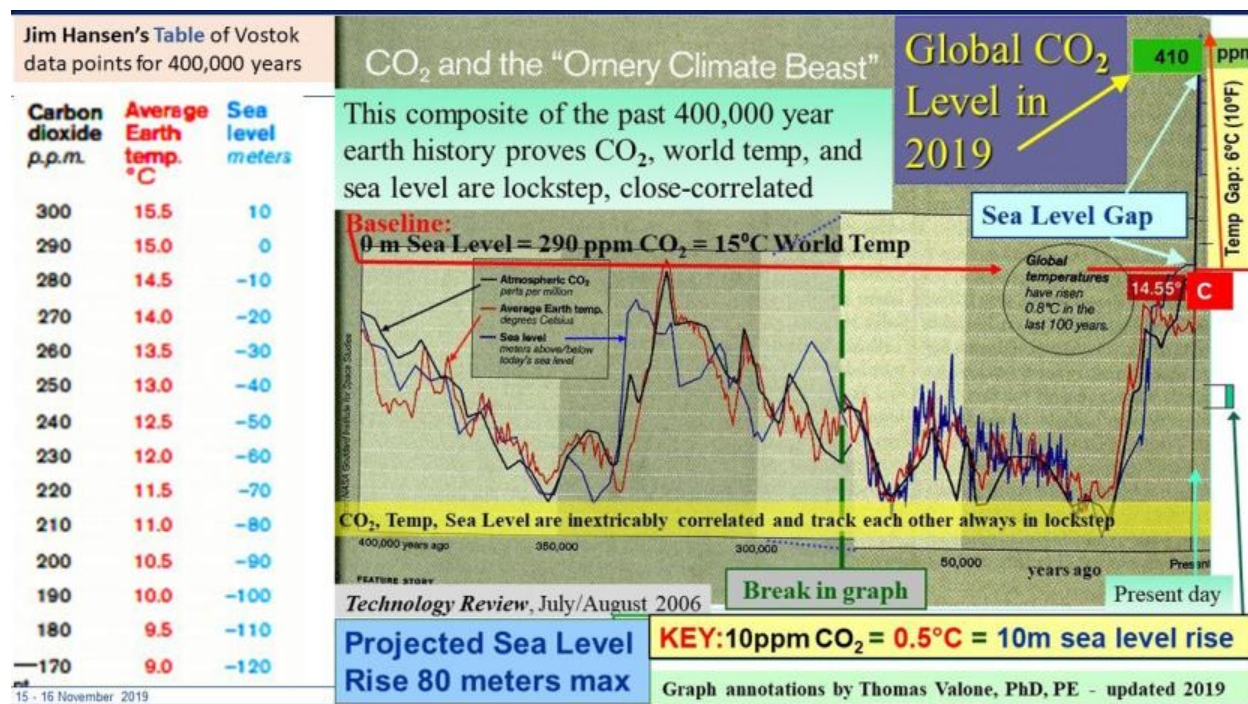


Figure 5 . Hansen’s data showing climate beast

Here in Figure 5, all of the facts are laid bare for the reader to contemplate and absorb fully. The Table on the left is Hansen’s data which comes from his Figure 4, with the zero (0) value of sea level corresponding to the maximum 290 ppm and 15 degrees C which we experienced recently as the average global values up until around 1960.

However, the sea level data is clearly shown in the Table which I translated into a simple equation seen in Figure 5. The equation (double of the KEY in Figure 5 for convenience) is designed to allow anyone to compress the Table data into a formula that is easy to memorize:

$$\pm 20 \text{ ppm} = 1^\circ\text{C} = 20 \text{ meters}$$

What may be the most reassuring part of the formula here is the +/- sign. As clearly seen in Figures 4 and 5, the response of the earth (I like to call it “Gaia” after James Lovelock) system to any change in global CO2 levels entrains the other two to follow, with a corresponding delay. In other words, as humans wantonly pushed the CO2 level rapidly above the 290 ppm baseline only in the past few decades with very little delay in the rising temperature response to the heat-trapping gas increase, I am confident that we will learn in the very near future to bring down the global level to 290 ppm or below, by CCS on the gigaton (gigatonne) level, as renewable energy is gradually brought online.

GLACIERS ARE MELTING FAST

Now we can disclose the sea level rise that the world is indebted for, just from the 370 ppm of CO2 we saw in the air around the year 2000. We can take the rounded number 370-290 (zero value) = 80 ppm and divide by the 20 ppm from the formula into 80 ppm to get the disturbing number of 4 to multiply by 20 meters. Or we can just simply note that the numerical values of CO2 and sea level change are the same, so sea level increase destined by Gaia is 80 meters, which is probably the maximum sea level increase possible. Any CO2 value above the 30% increase from baseline, or about 370 ppm of that year, is hitting the ceiling of globally available ice since the major contributors to sea level rise, as I found out, are

Antarctica and Greenland. These huge glaciated island continents are the only two main landlocked glacier ice of frozen water on earth. Antarctica will contribute about 60 meters of sea level rise and Greenland is estimated to contribute about 10 meters which equals 70 meters, so even the 80 meter result may an overestimate.


This brings us to the unavoidable conclusion which is a real shocker:

Around the turn of the millennium (year 2000) the human race as a whole threw in all of its chips of the earth’s reservoir of frozen water in exchange for the freedom of emitting a few more gigatons of CO2 (as seen in previous figures). As a consequence, we quickly maxed out ALL of the earth’s glacier ice, which now is equivalent to a “dead man walking.” They are already gone, in the Gaia Ledger Book, and will continue to melt for the next thousand years without a letup UNLESS the amount of CO2 in the atmosphere is brought back down to equal the pre-industrial value of 290 ppm or lower. Look at Figure 6 for visible evidence of the melting speed already happening.

Such an observation renders all other arguments moot since the only cause and driver for the sea level and the global warming of the atmosphere is the incremental amounts of CO2 above the baseline of 290 ppm. The best climate estimates of the trendlines for temperature increase is **about 1°C every decade or so**, reaching the 6 to 8°C increase of Figure 3 by 2100. There are already pockets of 1.5°C and even 2°C average increase occurring in geographically suitable regions already. Next is an example of the speed of the warming trends that are happening and expected to happen.


IEEE ISTAS 2019 ALASKA Columbia Glacier ONLY SIX Years Apart

Columbia Bay, Alaska – Photographer James Balog, Nat. Geo. magazine: **Extreme Ice Survey of 18 Glaciers**
The most extreme: Columbia Glacier is losing one mile every three years – so two miles of loss are shown below.
Since 1980, this glacier has lost height equal to the Empire State Building!



2006

2006 When James Balog first photographed the debris-covered Columbia Glacier, it had advanced 1.5 miles since 1980. That year compelled him to launch the Extreme Ice Survey, recording cameras at 18 glaciers to witness climate change.



2012

2012 Looking about three "William Conrad" records that the retreat of the Columbia Glacier is accelerating. It has now more miles of ice in six years. And since 1980, it has lost an amount equal to the height of New York's Empire State Building.

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Figure 6 . Extreme climatic event

This record of a glacier melting at a record speed is surprising, since we often think these things happen very slowly. Not anymore! Below is NOAA climatologist Solomon’s prediction of how long a temperature increase will last, along with the convenient form of the Hansen equation recited earlier. Note that Dr. Solomon made her estimate about ten years ago, when we were pumping only 30 gigatons of CO2 into the atmosphere annually. Now that the amount has risen to 40 gigatons annually, the peak amount of temperature increase has to be updated. Regarding Figure 7, Solomon explains, “After emissions cease, the temperature change approaches equilibrium with respect to the slowly decreasing carbon dioxide concentrations” which she calls “irreversible climate change.”⁴ This is based on a 7 billion ton carbon (25

gigatons of CO₂) annual emissions in 2009 which has now increased to a 40 gigaton CO₂ level annually a decade later, so the leveling off long term temperature is more realistically projected to be around 6°C, as seen elsewhere in this review, and expected to last thousands of years before decreasing to present day levels.

IEEE ISTAS 2019 Hansen Formula for CO₂, Temperature, and Sea Rise

+/- (20 ppm CO₂ = 1 °C = 20 m sea rise)

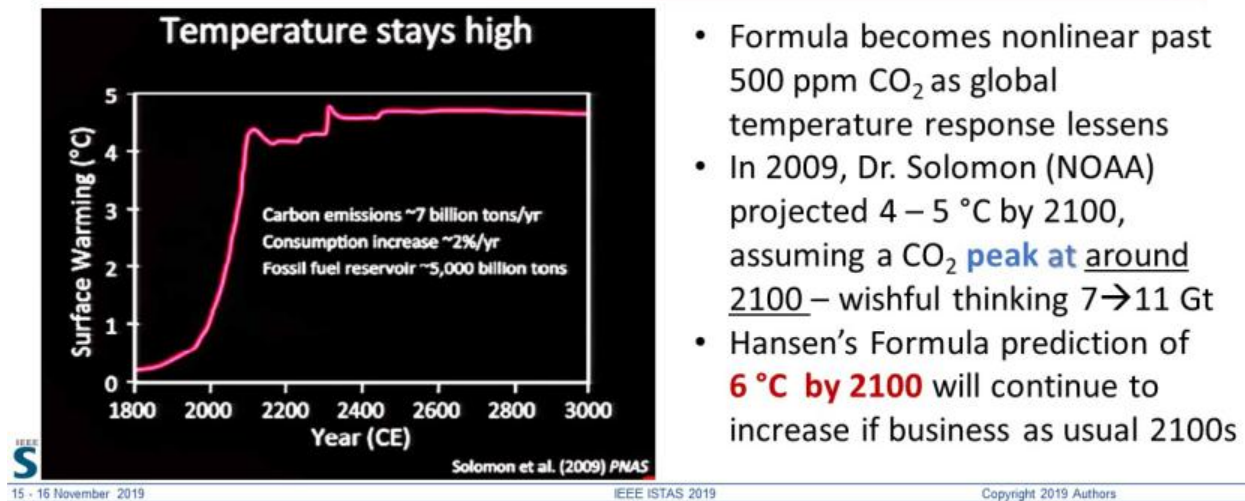


Figure 7 . hansen Formula for CO₂, temperature and sea level rise

Probably the most provocative and disturbing for any audience is a composite temperature trend graph which “reduces uncertainty” (says *Nature* magazine’s editorial introduction) in Figure 8. The best performing models are shown in dark red, projecting above 5°C. Climate models generally agree that greenhouse-gas emissions will continue to raise global temperatures, but the amount of warming predicted varies considerably. To narrow the field of probability, Patrick Brown and Ken Caldeira at the Carnegie Institution for Science in Stanford, California, assessed a plethora of current climate models. They found that some models more accurately simulate the amount of radiation entering and leaving the atmosphere, a flow known as Earth’s energy budget, than others.⁵

The team combined a number of models but reduced the influence of those that less realistically represent the energy budget. It predicts at least a *five degree (5°C) increase by 2100* (red line) with an uncertainty range that reaches 6°C. Much is known about the present exponential trend in temperature up to 2020 but with Brown and Caldeira’s integrated approach, the climate models are merged to include “observationally-informed projections” of *global temperature to 2100*.⁶

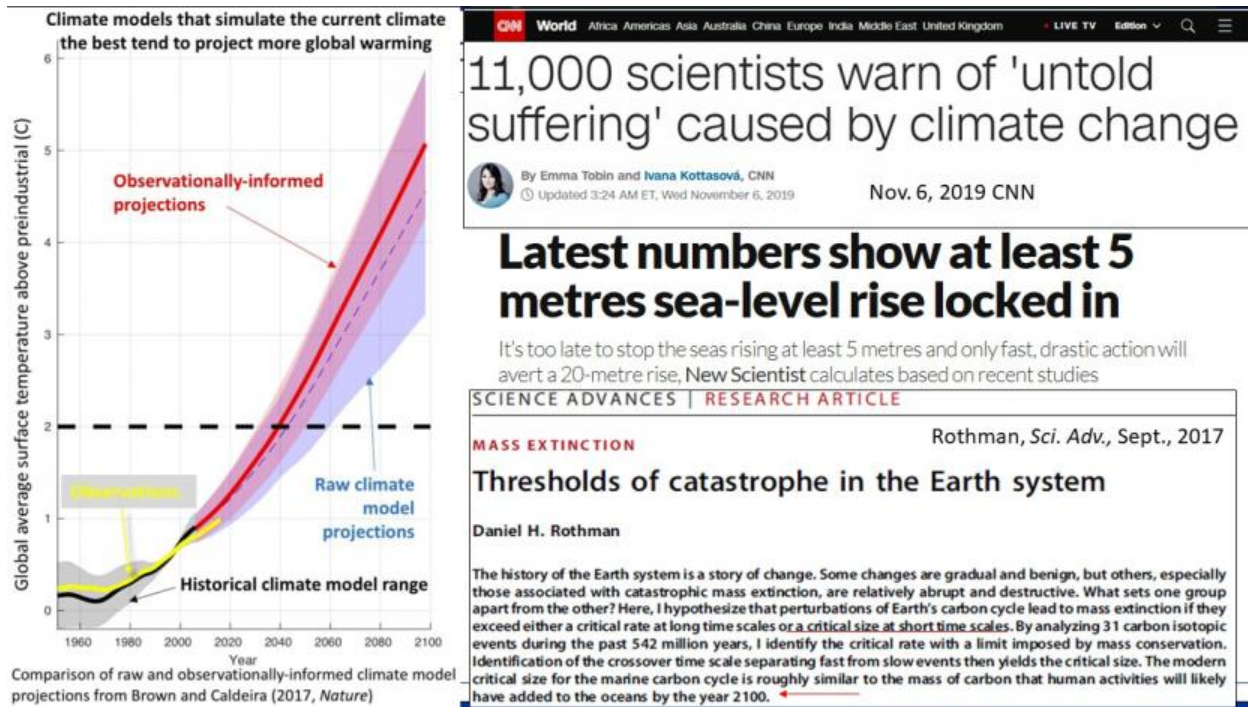


Figure 8. Climate model simulation

The question is often asked by the public if CO₂ is going to level out or 'peak' soon? The 9th UN Emissions Gap Report (ref. 3) states there is "no sign of peaking" and emphatically issues a warning that carbon emissions are *actually increasing*. In Figure 9, the A2 line for CO₂ levels is "business as usual" and most likely by economists and policy makers, according to the University of Washington.⁷ It is estimated that humans have emitted about 550 gigatonnes of carbon (multiply by 3.67 for CO₂ gas amount) from 1870 – 2013.⁸ In addition to this global atmospheric volume of human-created CO₂, the world adds about 40 gigatons of CO₂ emissions each year to the atmosphere, which stays there.⁹ All three recent climate reports cited earlier (ref. 3) acknowledge the Paris limits *are not happening*. No major country is willing to reverse its long-standing use of fossil fuels with a carbon tax, *even if the entire tax goes to funding more renewable energy*.

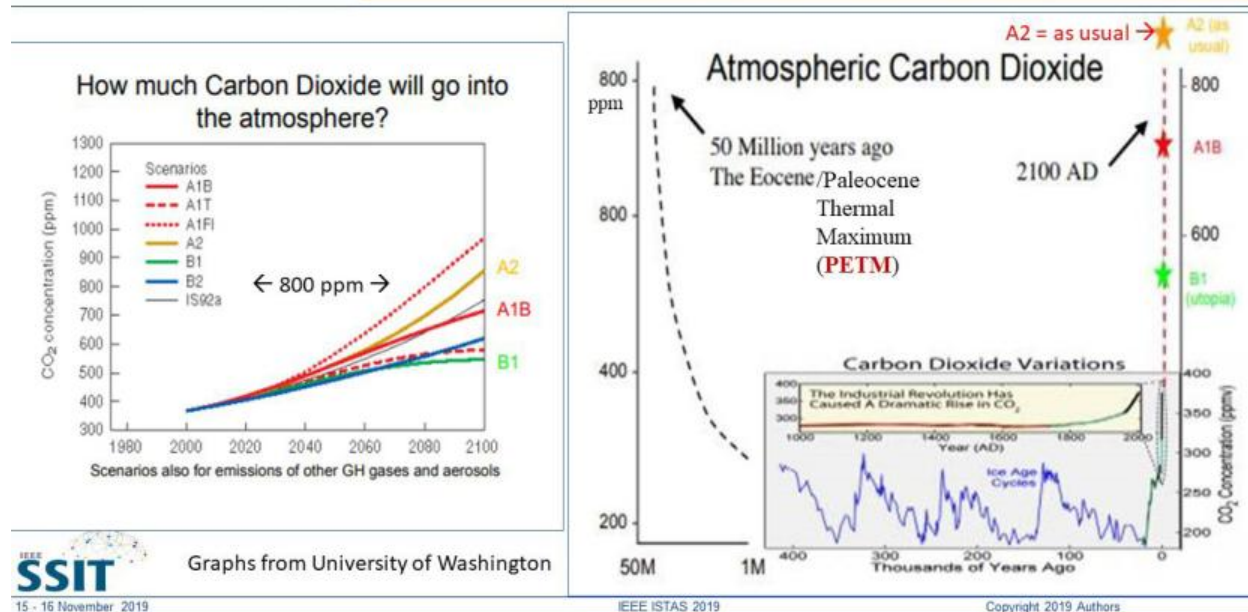


Figure 9. paleoclimatology

There are numerous educational videos with detailed reviews of the PETM on YouTube, such as from BBC Radio¹⁰ and a very popular, ten-minute PBS-TV summary (with 2.5 million views)¹¹. Referring to Fig. 9, one can see the PETM peak and to note that during the geologically short PETM period of about 200,000 years, the earth's atmosphere was gaining CO₂ at a rate of about 1.7 billion tons (1.5 gigatonnes) per year by the best estimates, compared to about 40 billion tons (36 gigatonnes) worldwide per year at our present rate. The vital point though is the estimate of the CO₂ concentration in the atmosphere at that time and the corresponding average temperature, which seems to parallel the University of Washington's most likely estimate of the CO₂ concentration for 2100.

Of course, the projection of sea level rise, even by a few meters by 2100, is also a disturbing problem that has not been adequately addressed by any government or municipality in the world. The next Fig. 10 gives us a graphic image of the extend of this problem, to help us prepare for the inevitable encroachment of the sea as it continues to rise for the next few millennia.

IEEE ISTAS 2019 Sea Encroachment After 2100 in Major Cities



Figure 10. Best estimates of a moderate increase in sea level

What we see in Figure 10 are the best estimates of a moderate increase in sea level of only a few meters by 2100. However, it has a major effect on coastal cities that are already at sea level to begin with. When I see high rise hotels right on the coast of many cities around the world, including Miami Florida, I think of how unsustainable that property will be in less than a century.

While the global increase in average temperature has reached 1 degree Celsius, an analysis of more than a century of National Oceanic and Atmospheric Administration temperature data across the lower 48 U.S. states and 3,107 U.S. counties has found that major areas are nearing or have already crossed 2-degree Celsius increase in average temperature, thus representing “hot spots.” Today, more than 10% of Americans, or about 34 million people, are living in rapidly heating regions, including New York City and Los Angeles. Alaska is the fastest-warming state in the country, but Rhode Island is the first state in the Lower 48 whose average temperature rise eclipsed 2 degrees Celsius. Scientists do not completely understand the Northeast hot spot. But fading winters and very warm water offshore are the most likely culprits, experts say. That’s because climate change is a cycle that feeds on itself. Daniel Pauly, an influential marine scientist at the University of British Columbia, says the 2-degree Celsius hot spots are early warning sirens of a climate shift. “Basically,” he said, “these hot spots are chunks of the future in the present.”¹²

An ice-free Iceland is not an isolated phenomenon. Glaciers are melting all across the world, contributing enormously to rising sea levels. [Himalayan glaciers](#) help regulate the water supply of a quarter of humankind. Natural systems will be disrupted. The great thaw will also unfreeze vast areas of permafrost, releasing methane, a potent greenhouse gas. The melting of ice sheets in Greenland and Antarctica will, in the long term, result in [dozens of feet](#) of sea-level rise. Scientists cannot pinpoint at what level the melting of Greenland or the West Antarctica ice sheets becomes irreversible.¹³

Greenland holds the second largest store of land-locked ice in the world, after Antarctica. A major reason for including Greenland’s ice loss is that upon comparison to Antarctica, it becomes abundantly clear that [Greenland is losing twice as much ice mass as Antarctica, in the same time frame](#).¹⁴ Such a major influx of fresh water from Greenland into the Atlantic ocean, with less density than salt water, has also been connected to the decrease in flow of the North Atlantic Conveyor System (NACS) by about 20% in the past

few decades. This has major implications for Scandinavia which, along with the UK, receives returning NACS warm sea water current northward from the Mediterranean. Ironically, if the NACS slows down much more, which in all probability it will with present GHG emission trends, the Scandinavian countries may experience a short term cooling trend as the rest of the world continues to rise in average temperature, since there will be a deprivation of the warm northward NACS current to Scandinavia, until global temperature rise dominates. Greenland has also made the news recently because rain-associated melting became twice as frequent in summer and three times as frequent in winter, for the past several years. "Rain now seems to account for 28 per cent of the [Greenland's] ice sheet melt."¹⁵

There are generally foreseen and widely accepted consequences of the extreme conditions outlined above as 4 degrees to even 10 degrees Celsius are anticipated in various areas of the globe, whether "hot spots" or "cool spots," accompanying the projected average global increase of about 6 degrees C in the next several decades.¹⁶ These include the inundation of coastal cities; increasing risks for food production potentially leading to higher malnutrition rates; many dry regions becoming dryer and wet regions wetter; unprecedented heat waves in many regions, especially in the tropics; substantially exacerbated water scarcity in many regions; increased frequency of high-intensity tropical cyclones and hurricanes; irreversible loss of biodiversity, including coral reef systems, as carbonic acidity decreases oceanic pH. Increasing aridity and drought are likely to increase substantially in many developing country regions located in tropical and subtropical areas, as well as in the central and midwestern United States. Although it is often difficult to make comparisons across individual assessments, there are a number of extremely severe risks for vital human support systems. Large-scale and disruptive changes in the earth system are generally not included in climate models, and rarely in impact assessments. One example of such a change would be the collapse of the West Antarctic Ice Sheet, which would lead to much larger sea level rise than projected in the present analysis for the next few decades. Extreme temperatures and new invading pests and diseases that can take over in areas where it was too cold for them to thrive in the past are to be expected, especially in the northern latitudes. Projections of damage costs for climate change impacts typically assess the costs of local damages, including infrastructure of national and regional scales.

Thus, given that uncertainties remain about the full nature and scale of impacts, there is also no certainty that adaptation even to a 4°C temperature increase is possible. A 4°C world is likely to be one in which communities, cities and countries would experience severe disruptions, damage, and dislocation, and civil unrest, with many of these risks spread unequally. It is likely that the poor will suffer the most and the global community could become more fractured with a dramatic increase in border wars and migration. The largest warming will occur over land and range from 4°C to 10°C. Increases of 6°C or more in average monthly summer temperatures would be expected in large regions of the world, including the Mediterranean, North Africa, the Middle East. Almost all summer months are likely to be warmer than the most extreme heat waves presently experienced and, for example, the warmest July in the Mediterranean region could be 9°C warmer than today's warmest July. With pressures increasing as warming progresses toward 4°C, and combining with social, economic, and population stresses, the risk of crossing critical social system thresholds will grow.¹⁷ At such tipping points, the existing global governments would likely become much less effective at supporting the needed social remedies or could even collapse. Similarly, stresses on human health, such as heat waves, malnutrition, and decreasing quality of drinking water or complete loss of available water as presently persisting in over a dozen countries worldwide, have the potential to overburden health-care systems to a point where adaptation is no longer possible, and dislocation is forced.

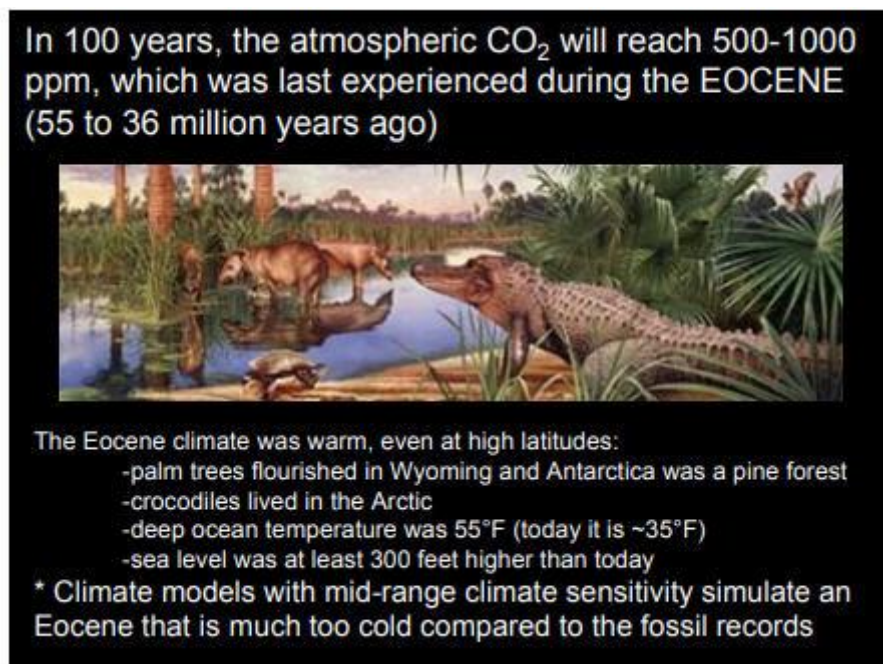


Figure 11. Extreme potential of the facts shown in graphic form

In Figure 11 we see the extreme potential of the facts shown in graphic form in Figure 9. The Eocene-Paleocene Thermal Maximum (PETM), which reached 800 ppm at its peak, is exactly what the experts predict for us even by the end of this century (2100). This is because of the clear trend in the exponential growth of CO₂ emissions worldwide, instead of a slowing down, which is reflected in our Figure 2 CO₂ emissions graph with the rate of CO₂ emissions reaching about 3% presently in 2020, as well as the shocking Figure 9 projection of 800 ppm by 2100 as the “business as usual” most likely scenario for planet earth. Note that we are experiencing a very short temporal feedback loop between CO₂ average levels and global temperature: every report indicates hotter seasons than the previous ones as each year goes by. It can be estimated that there may be only a 20-year gap in the response curve of an increased (or decreased) global average level of CO₂ and the increase (or decrease) in worldwide average temperature.

CARBON DIOXIDE REMOVAL

Therefore, more and more the primary recommendation of informed climatologists is that carbon capture and storage (CCS) also called “carbon sequestration” or more recently carbon dioxide removal (CDR), are the only hope for controlling the world’s average temperature for the immediate and long-term future. This is a new, powerful insight gained from study of the Hansen graph, as well as reviewing Figure 2 and Figure 9. The amount of CO₂ CDR or CCS needed is indeed staggering but not impossible, if a multination, international consortium is formed immediately, if not sooner. At the present global emissions rate, every year we wait adds another 35 gigatonnes (40 gigatons) to the total stored in our thin blue blanket above our heads.

In recent years, there has been a growing interest in carbon dioxide removal (CDR) methods that can help mitigate the impacts of climate change. There are several CDR methods, but not all are effective, affordable, or sustainable. Here are some of the best carbon dioxide removal methods from air:

1. Afforestation and reforestation: Planting trees is one of the most effective, short term ways to remove carbon dioxide from the atmosphere. Trees absorb carbon dioxide during photosynthesis and store it in their trunks, branches, and roots. Forests also provide other benefits like preventing soil erosion, regulating water cycles, and supporting biodiversity. However, after about a century, most of the trees will give the sequestered CO₂ back to the environment as they die and decay.

2. Direct air capture (DAC): Direct air capture technology uses machines to capture carbon dioxide from the atmosphere. The captured carbon dioxide can then be stored underground or used for industrial purposes. DAC technology is still in its early stages and is expensive, but it has the potential to remove large amounts into the gigaton range of carbon dioxide from the atmosphere.
3. Ocean fertilization: Ocean fertilization involves adding nutrients to the ocean to stimulate the growth of phytoplankton. These tiny organisms absorb carbon dioxide during photosynthesis and sink to the bottom of the ocean, where the carbon dioxide is stored. However, there are concerns about gigatonne levels of algae bloom capture of CO₂ and the environmental impacts of such high levels of ocean fertilization, so it is not a widely recommended method but nicely proven in the megatonne range.
4. Soil carbon sequestration: Soil carbon sequestration involves storing carbon in the soil through agricultural practices like crop rotation, conservation tillage, and cover cropping. These practices increase the amount of organic matter in the soil, which helps store carbon. Soil carbon sequestration is a low-cost method and has other benefits like improving soil health and increasing crop yields.
5. Bioenergy with carbon capture and storage (BECCS): BECCS is a combination of bioenergy production and carbon capture and storage. Biomass is burned to generate energy, and the carbon dioxide produced is captured and stored underground. BECCS is a relatively new technology, but it has the potential to remove large amounts of carbon dioxide from the atmosphere while also producing energy.

Such carbon dioxide removal methods are important in mitigating the impacts of climate change. Afforestation and reforestation, direct air capture, ocean fertilization, soil carbon sequestration, and BECCS are some of the best methods for removing carbon dioxide from the atmosphere. Each method has its benefits and drawbacks, and the choice of method will depend on factors like cost, effectiveness, and sustainability. CarbonBrief.org also has a free report on CDR released 2023: <https://www.stateofcdr.org/>.

Recently another leading company has emerged for gigaton carbon capture called Project Vesta, which has as its website motto, "Harnessing the power of the oceans to remove excess CO₂ from the atmosphere." Visit <https://www.vesta.earth/> for their exciting gigaton carbon capture technique under evaluation in the environment at this moment. Carbon-removing sand made of the mineral olivine is added to the ocean. There, the sand dissolves, countering ocean acidification and permanently removing carbon dioxide from the atmosphere.¹⁸



Scaling to Billions of Tons of Carbon Capture & Management Infrastructure

Effective decarbonization requires that carbon capture, management and disposition infrastructure and systems be planned and implemented at "GT scale" (Giga Tonne scale), and not through a piecemeal project-based approach.

Enabling GT scale carbon capture and management requires common, scalable and seamless carbon disposition infrastructure; commoditized cost of carbon capture, storage and disposition; mechanisms for risk transfer & arbitrage for CO₂; mechanisms for net-back and utilization of carbon credits; and enabling policy design.

Figure 12 .Carbon capture

Capturing gigatonnes of CO₂ is a vision of Dastur Energy <https://www.dasturenergy.com/> which is summarized in Fig. 12. Dastur seeks to implement carbon capture technologies as well as decarbonizing industrial activity as well, aiming for a net zero world.

“Pulling CO₂ out of the air and using it could be a trillion-dollar business”

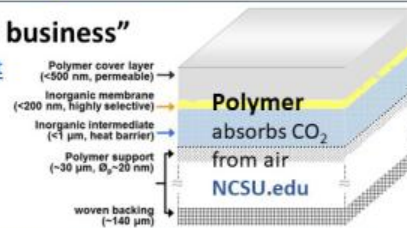
Put CO₂ to work making valuable products. www.vox.com/energy-and-environment

$$1 \text{ ppm CO}_2 = 2 \text{ Gt Carbon} = 7.77 \text{ Gt CO}_2$$

THE HANSEN CHALLENGE

Can we REDUCE the CO₂ level to lower temperature? YES, it is reversible!

- Choose 350 ppm (+3 °C) as the target CO₂ level just to lower temperature
- Calculate gigatons (Gt) to remove in total if done today
- Take present 410 ppm – 350 ppm = 60 ppm which is equal to **466 Gt CO₂**
- However, every year an average of 5 ppm CO₂ or **+40 Gt/yr** will be added (in A2)
- Therefore, any **Global Carbon Reduction Program** will require CCS-CCU to invest enough to remove say, **100 Gt/yr for 10 years and 50 Gt/yr after**, until the hoped-for carbon emission rate peaks and **a century later**, the emissions slow down, level off, as population has done globally



Carbon Engineering out of Calgary, Canada → Tested Direct Air Capture (DAC) for CCU, CCS

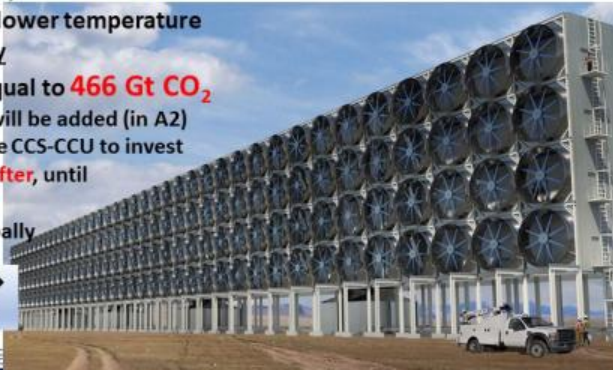


Figure 13 . Carbon capture and utilization ratio

Note the challenging calculation in Figure 13 of the numbers resulting from an attempt to sequester 50 gigatons (45 gigatonnes) every year if the world is fortunate enough to discover a very inexpensive means to capture CO₂ in that quantity reliably. A possible process for doing this is reflected in Figure 13, though the cost estimated in the trillion-dollar range is a present barrier to its realization. The equivalent formula in Figure 13 is given for converting the parts-per-million (ppm) amount of CO₂ to gigatons (Gt) of CO₂ helps to determine the appropriate capture mode and we can multiply by 0.907 to get gigatonnes if needed.

In 2022, the International Energy Agency released a report entitled, “Direct Air Capture--A key technology for net zero” with a full report but also an Executive Summary available online: <https://www.iea.org/reports/direct-air-capture-2022/executive-summary>. Almost all of IEA’s findings result in megaton (MtCO₂) removal as seen in the first paragraph from the Executive Summary below:

Direct air capture (DAC) plays an important and growing role in net zero pathways. Capturing CO₂ directly from the air and permanently storing it removes the CO₂ from the atmosphere, providing a way to balance emissions that are difficult to avoid, including from long-distance transport and heavy industry, as well as offering a solution for legacy emissions. In the IEA Net Zero Emissions by 2050 Scenario, DAC technologies capture more than 85 Mt of CO₂ in 2030 and around 980 MtCO₂ in 2050, requiring a large and accelerated scale-up from almost 0.01 MtCO₂ today.

To its credit, the IEA report does focus on the geological CO₂ storage where the chemical reaction underground forms a carbonate rock permanently and “has several advantages as a CDR approach, including a relatively small land and water footprint, and high degree of assurance in both the permanence of the storage and the quantification of CO₂ removed.”

Besides the basic CDR findings of the IPCC and other agencies like the IEA, more detailed research findings on CDR are presented in Figures 14 and 15.

IEEE ISTAS 2019 Transformative Zero or Negative Emissions Tech

“A Process for Capturing CO₂ from the Atmosphere”

DAVID KEITH ET AL., JOULE, VOLUME 2, ISSUE 8, P1573-1594, AUGUST 15, 2018

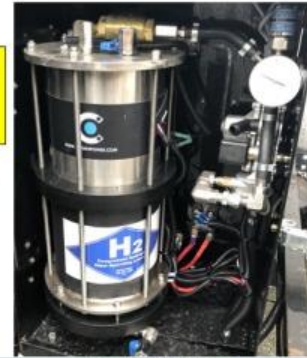
→ Estimates low cost can be around
\$100/ton of CO₂ presently
→ \$50 billion/yr for 50 Gt/yr @\$1/t

Carbon Engineering – very low-carbon fuels, powered by renewables, using CO₂ from the air, drawing **hydrogen** from electrolysis to produce hydrocarbons. The company calls the process “**air to fuels**,” or **A2F**, and it is targeting wide commercialization in 2021.

HyTech is targeting a big market – diesel engines – the source of 50% of urban smog, especially in winter

Onboard electrolyzers are the game plan for turning existing → diesel engine fleet into **zero-emissions vehicles (ZEV)** by making them run on pure hydrogen.

-- **HyTech Power**, based in Redmond, Washington



15 - 16 November 2019

end of slideshow

IEEE ISTAS 2019

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Figure 14 . Transformative zero or negative emission technology

IEEE ISTAS 2019 Solutions, Suggestions, Adaptations besides renewables

Phase Change Materials

Absorb and release energy naturally - without consuming energy.

Phase change insulation is a vital adaptation technique for the immediate future and beyond. **InsolCorp** leads the industry with **InfiniteR** insulation only one centimeter thick has 100 BTU/ft² of energy storage, 314 Watts/m² of energy.



24" - 21C M100 24" - 23C M100 24" - 25C M100 24" - 29C M100



Choose you preferred TEMPERATURE for the phase change. It will **maintain that temperature INDOORS (+/- 2 °F)** while the outdoors swings wildly with 100 °F hot and 20 °F cold.

Like ICE, it freezes and thaws at the chosen TEMPERATURE above.

Western Colloid Fluid – Cool Roof System

- High Reflectivity
- Reduces energy costs by 30%

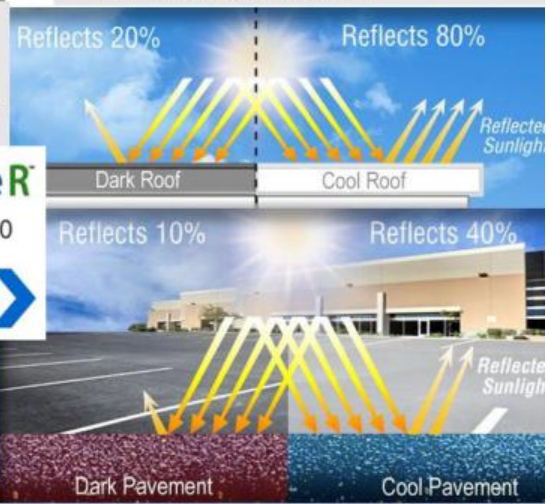


Figure 15 .Adaptation to the impending hot climate

A very good guide for personal adaptation to the impending hot climate is in Figure 15. I met the CEO of the InsolCorp at a recent World Energy Engineering Conference in Washington DC. They have proven their very thin phase change insulation *outperforms any other much thicker insulation* and in many cases, can replace the need for air conditioning. This is because the temperature variation inside any enclosure or building will be very stable with such a material absorbing and releasing heat energy next to the walls or simply under the ceiling or roof.

CONCLUSION

It is hoped that the simple, inextricably tight connection between global CO₂ values and global temperature, delineated and publicized by James Hansen and others, will finally create an urgency in the minds and hearts of all people, so that global atmospheric carbon capture by the gigaton can begin in earnest and in parallel with carbon-free fuels, zero carbon emissions, renewable energy, and even negative carbon emissions, implemented worldwide. One ray of hope, among many suggested climate solutions, which can comprise another separate article, is the recent discovery of an alloy of gallium, indium, and tin that is liquid at room temperature and conducts electricity. By spiking the silvery mixture with a sprinkling of catalytically active cerium and placing it inside a glass tube, along with a splash of water, scientists have now proven a room temperature method to convert CO₂ to carbon, instead of the usual high temperature procedure. Chemists Dorna Esrafilzadeh and Torben Daeneke at RMIT University in Melbourne, Australia, turned to a new class of catalysts made from metal alloys that are liquid at room temperature.¹⁹ This is a process that can be scaled up and may someday offer a novel and inexpensive method for capturing billions of tons of atmospheric carbon that can immediately begin the reversal of the temperature and CO₂ relationship that is so tightly correlated. In that way, more time could be allowed for the world to convert to 100% renewable energy and thus begin to drastically reduce its carbon emissions.

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