Downhill and Uphill to Higher Ground: Climate Alteration and Sea-Level Rise

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Slightly Revised and Expanded 4/16 Version of Chit Chat Club Essay for April 9, 2024

I was going to use Bill Gates' phrase, "the hardest challenge humanity has ever faced" [1] as my title, with "the elephant in the room" as a subtitle, with the implication of this phrase as designating an obvious problem or difficult situation that people do not want to talk about. But then I saw the rebroadcast of *Polar Extremes* [2] on PBS NOVA two weeks before the date for this essay. I decided that with this excellent exposition of the polar science available since 2020, I should encourage those who will listen to my essay on April 9 to look it up on PBS and view it. I make the same suggestion to those who may read this essay when it is on the web. I have included other references to available video as well.

The March 18, 2024 cover of *The New Yorker* shows a skier with white snow at the top of the page but grass, flowers, and a pollinating bee where he is skiing. The title is "Downhill" and the reference is clearly to climate alteration. Although the ski resorts in California have plenty of snow this spring, the snowfall in the Alps and Himalayas has been meager as temperatures rise, and precipitation comes as rain rather than snow at elevations where snow has been plentiful in the past.

But I am going to discuss "uphill" in response to sea-level rise. A review in *Science* magazine [3] led me to the book, *California Against the Sea: Visions for Our Vanishing Coastline* [4]. This excellent book by a reporter about the threat of severe storms and sea-level rise for California's coast led me to a book by oceanographer John Englander, *Moving to Higher Ground: Rising Sea Level and the Path Forward* [5]. I was surprised to find this highly informative 2021 book about the science underlying sea-level rise was already out of print. I bought a used copy on Amazon, and it turned out to be autographed by the author. It was to be my main science reference for the talk. But now I can suggest the PBS video [2] as well. I'll use much of my time to discuss my involvement on global climate alteration, and the evolution of my viewpoint.

My Introduction

In the 1980s I was an active member of the Science Advisory Board (SAB) of the US Environmental Protection Agency (EPA). My background in decision and risk analysis allowed me to be an integrating generalist with the multitude of specialists that serve on SAB Committees. I found myself in leadership positions where I was kept busy learning arcane details of the science and drafting report text about the uncertainties on human health and environmental impacts in connection with EPA's statutory responsibilities. I was vice chair of the SAB committee that reviewed EPA's draft report on the ozone hole created by chlorofluorcarbon refrigerant gases. And about that time I was interrogated by several relatively young EPA staff members. They told me they were working on what they considered to be the most important of all environmental threats – global climate alteration from greenhouse gases

(GHGs). But they could not get the attention of those on the building's top floor – The EPA Administrator and his immediate subordinates. They were too busy with the multiplicity of contentious regulatory issues on clean water, clean air, Superfund, etc. I suggested to the young EPA staff that they find someone in Congress (or the Congressional staff) who could arrange a request that EPA prepare a report for Congress on the threat of global climate alteration. It worked! Some months later EPA received this request from Congress. And I was remembered as the one who had made the suggestion. The EPA Policy Office suggested to the SAB leadership that I be made the chair of the SAB review committee! I accepted. I had an intense learning experience, with some of the foremost expert scientists as my committee members and teachers. We got our reviews done for the two reports, one on Adaptation and one on Mitigation. These were the first reports on the subject by EPA to Congress. Much of the methodology in these reports was subsequently picked up and used by the UN Intergovernmental Panel on Climate Change (IPCC). One aspect of this was using averaged global temperature as the main measure of the extent of climate change. The 2015 Paris international meeting set 1.5 degrees Celsius (1.5°C) as a goal – a threshold for increase in global averaged surface temperature not to be exceeded [6].

I shall later argue that this choice of main measure is misleading. The two points that we all should understand are that an enormous amount of heat has already gone into the ocean, and that an enormous amount of carbon dioxide – and other greenhouse gases (GHGs) – have already gone into the atmosphere. Air temperature might be changed by reducing incoming solar radiation. But removing large quantities of heat from the ocean, and carbon dioxide from earth's atmosphere, pose extraordinarily difficult challenges. And reducing the increase of GHGs – and consequent increased ocean heating – appear to be decades away.

On my website is a paper [7] I wrote with my impression of the main insight I learned from our SAB review. The main determinant of the growth of GHGs in the atmosphere was not what we do in the US, but rather what happens elsewhere on the planet, especially the developing nations such as China, India, and other countries moving from rural agriculture to an industrial economy and a large urban population. It was not accepted for publication. The reviewers said it offered nothing new. It reads rather well in retrospect. I think its fault was it did not highlight a need for drastic reductions in US use of fossil fuels and a shift to renewable energy. Instead it emphasized the need for developing countries to limit the increase in GHG emissions from their increased use of fossil fuels.

I was asked to brief the EPA Administrator, William Reilly. He was a friend and classmate from Yale – and a lawyer, not a scientist. He asked me whether it was apparent that increases in GHGs such as carbon dioxide (CO_2) were affecting the climate. I said that because of the natural variability in climate, it might be ten to fifteen years – into the 21st century – before clear evidence of climate change was apparent. An increasing level of CO_2 in the atmosphere was occurring, and scientific theory predicted that more heat from the sun would be retained rather than radiated back out into space. It was clear to me that he wanted evidence now, or much sooner, and not a discussion of scientific theory and uncertainties.

The first Bush Administration organized an international meeting in Washington, D.C. on climate change. I was invited as an observer, along with a distinguished US government scientist, Warren Washington [8]. As various experts in atmospheric science discussed how increased CO2 and other gases might heat the atmosphere, Dr. Washington quietly explained to me that these experts and their models of the atmosphere were missing a very important consideration. Most of the additional retained heat goes into the ocean, rather than air or land. The fraction is more than 90% ([4], p. 17; [9]).

In the following quarter century I had little further involvement besides teaching about climate alteration as a risk problem in my Stanford course. I was surprised that there was much discussion but little action as emissions increased, the level of CO2 and other GHGs in the atmosphere climbed upwards, and the increase in globally-averaged atmospheric surface temperature reached levels above the variability in recorded data.

My 2015 Book Reports

In 2015 I wrote a set of five book reviews [10] for the journal **Risk Analysis**, published by the Society for Risk Analysis. I was president of this society in 1991-92 and was an area editor for many years. Four points stand out in these reviews. First, the infrastructure for obtaining, transporting, and burning fossil fuels in the economies of developed and developing nations is immense and will not be replaced by other technologies without huge costs and decades to make the transition. Second, to stop the increase of greenhouse gases such as CO2 and methane (the main constituent of natural gas), combustion of coal, oil, and natural gas must be reduced by the order of 75% worldwide. Third, cooperation is needed by both developed and developing nations. Fourth, integrated analysis of the costs and benefits of alternative strategies is needed. Among the five books reviewed, the one by Willliam Nordhaus provided the best effort at such integrated analysis, with his DICE model.

The Current Situation

What has been happening since 1990 is that developed countries have achieved a modest transition into renewable energy sources with little change in the extent of nuclear electric generation, which like the renewables wind, solar, and hydroelectric, avoids any GHG emissions from combustion of fossil fuels. Many developing countries such China, India, and others in Asia and Latin America have industrialized and greatly increased their use of fossil fuels. Levels of greenhouse gases in the atmosphere have greatly increased, and alterations in climate such as rising average global air temperature have become quite evident. (As an example from a recent PBS broadcast, see [11], which is about the current industrialization of Vietnam – using coal.)

Three people I greatly respect have recently presented their points of view. John Kerry just ended his position as the Biden Administration's top diplomat on climate alteration. He gave an interview to David Wallace-Wells that ran as an "opinion" piece in *The New York Times* under the headline, "John Kerry: 'I Feel Deeply Frustrated'"[12]. Here is an excerpt:

DW-W: [If it is about survival] … how are we doing?

> JK: … When Biden came in, the credibility of the United States was in the crapper, and we were viewed with suspicion if not derision. Our job was to go out and create credibility for our nation and for the president. At the time, the US didn't really have a global strategy, and so we laid out "keep 1.5 alive."
>
> DW-W. Do you think the goal is still alive today?
>
> JK: If we did the things we could do – that we know how to do and have the technology for – we could actually do it. We're just not. We're not doing it on a global basis. Emissions are going up in too many countries. Oil and gas are still on a binge and their profits are obscene. I mean, they're just shocking. And everybody seems to be locked into a place of indifference. … Our biggest problem is the amount of coal that is still being spewed into the atmosphere, unmitigated.

Granger Morgan is a professor at Carnegie-Mellon University (CMU) who has been a close professional colleague of mine in the field of risk analysis for about 50 years. He and a CMU colleague just co-authored an editorial [13] for *Science*, perhaps the leading scientific journal in English, with the title, "Stop arguing and cut emissions." Here are two sentences illustrating the content:

> Given the urgency of the climate problem, everyone should be focused on reducing the concentration of GHGs in the atmosphere as rapidly as possible, using a broad portfolio of affordable and achievable strategies. … Let's not allow the perfect to become the enemy of the good in responding to the climate emergency.

A paper [14] from Nobel Laureate in economics William Nordhaus and a colleague was just published in the *Proceedings of the National Academy of Sciences*. It presents the latest results from an updated version of planetary-wide integrated analysis using the DICE-2023 model, an update from the 2016 version. The paper provides an analytical basis for the frustration with inaction expressed above by Kerry and Morgan. First, the analysis indicates the 1.5° C goal will not be met:

> To meet the 1.5 °C target, emissions would be required to fall virtually to zero in the next 5 years. This would entail either a deep depression (output declining by around 75%) or an implausibly sharp increase in emissions reductions (by at least 50% within a decade). The scenario is so far from what any economic model can hope to capture realistically that it is best thought of as infeasible.

The paper states that even a limit to 2.0° C will be very difficult to attain. The base case of weak reductions, representing current emissions reduction policy, leads to a near-doubling of CO2 level and an estimated temperature increase over 3° C by 2100. Compared to policies of sharply ramping up emissions reductions to achieve 2.0°C or close to it, the gain in planetary wealth less damage and emissions reduction cost compared to the base case is on the order of $100 trillion dollars.

> The 2 °C target will require stabilization of CO_2 concentrations at slightly more than 10% above current levels. Note that the Paris Accord will reduce concentrations about one-third of the way to the 2°C target.

To achieve the required ramping-up of emissions, the value of reducing a ton of CO2 emissions (the "social cost" of carbon, an estimate of negative benefits (or damage) would need to be increased by more than an order of magnitude from values now in use. The incentives to make the reductions by shifting from fossil fuels to alternative technologies are nowhere near the levels that would make these shifts seem beneficial. A problem is that the cost of developing and deploying these technologies is incurred in the near future, compared to the later time when the severe damages will take place. The discount rate used for calculating net present value is therefore an important consideration, as discussed in the books I reviewed in 2015 ([10] as well as the discussion in [14]).

Another reference, from 2019, is the BBC television program narrated by David Attenborough [15]. It is similar to [2] but even more, "a call to arms."

The Tipping Point for Sea-Level Rise: Melting of Sea Ice in the Polar Regions

Over the 8,000 years of recorded human history following the end of the last ice age, sea level has remained approximately constant. We are used to sea level as a reference point, with cities such as Denver ("the mile-high city") listing their elevation above sea level with no reference to a date. And why is there a need to have a date? In the past 100 years, despite industrialization and greatly increased use of fossil fuels, sea level has changed little – by less than 9 inches on the California coast ([4], p. 15).

Most discussions of damage from climate alteration have had little about sea-level rise. If it is mentioned it has been described as uncertain and occurring slowly, well into the future. These descriptions rarely mentioned that massive changes have occurred in sea level in earth's geological history as polar ice has expanded and contracted, and that melting of polar ice can occur again. Further, the trigger for such melting is additional heat into the oceans, particularly in the Polar Regions. Earth was once a snowball, with ice covering the entire planet. And about 50 million years ago, earth was ice-free at the poles. Three million years ago, the fossil records show a sea level 60 feet above the present level [2]. This sea level coincided with less ice in the Arctic.

Can this happen again? And how quickly might it happen? And can it be prevented by actions humanity might take, such as taking carbon out of the atmosphere or ocean, or geoengineering methods to reduce incident solar radiation, such as by adding sulfate particles in the stratosphere [16], placing a giant parasol in space [17], or using fine aerosols of salt particles for marine cloud brightening [18]?

In the remainder of this essay I am going to argue that a sea-level rise of tens of feet can happen again, that it is highly likely, and it may be unstoppable by any technology we have or are likely to develop. I have come to this conclusion reflecting on what I learned in 1990 from Warren Washington [8]. I wish he had been on my review committee, but I met him and learned from him just after my committee had finished its work. Only recently has the evidence accumulated, which I have learned about by seeking out summaries and interpretations such as in [2], [4], and [5] plus publications in the past year.

Let's start with the extent of sea ice in the Arctic Ocean, and then learn why this measure is much more significant than global averaged surface air temperature. More than 90% of the additional heat from the change in energy balance from increased GHGs goes into the ocean. How much heat is that? An almost inconceivable amount, 14 zeta joules (1.4×10^{22} joules) in a year. As an aid to understanding this number from [4], it is the equivalent of seven Hiroshima-sized nuclear bombs going off every second. In [5] a lower number, five Hiroshima sized bombs every second, is given for the energy gain for the year 2019. (The source is [19]). But [19] notes the rate of energy gain in the ocean is increasing every year.)

Why is the rate so big and increasing? Consider an area in the Arctic Ocean. When covered with sea ice, the sun's rays are reflected. When the sea ice has melted, the sun's rays hit dark ocean and the energy is absorbed. And the area in question is immense. This year's maximum extent of Arctic Sea ice was just reached [20]. The decline in sea ice area since 1979 when the satellite records began is 691,000 square miles, about the size of Alaska.

How about sea ice near Antarctica ? Is that area declining as well? The area has been highly variable since 1979, with no long-term trend [21]. There was a record summer minimum in 2023, which was 405,000 square miles below the average. That's about half the size of Alaska.

Has Antarctica been firmly locked up in ice for many millions of years? Evidence from the genome of a little octopus indicates the ice shelves near the Antarctic Peninsula may have melted as recently as about 125,000 years ago [22]. The authors conclude with sentences that I would happily use were I still teaching about decision and risk analysis at Stanford University:

> Understanding the past nature of ice loss informs future sea-level rise projections, which are of fundamental importance to coastal planners.
>
> The problem, perhaps, runs even deeper than these specific, scientific questions. The challenge in identifying a precise tipping point – is that the tipping point will likely not be apparent until it has been passed. Policy-makers will always have to make decisions in the face of uncertainty about the future, and this latest piece of evidence from octopus DNA stacks one more card on an already unstable house of cards. ([22], p. 1357.)

Can we reverse the process of heating the polar oceans? Not without reducing GHG levels drastically and then waiting for the added heat to be radiated out into space. That's the problem that makes melting of sea ice the indicator of a tipping point.

Recall that 32°Fahrenheit (F) is the temperature below which fresh water freezes and above which it melts. Seawater freezes at a lower temperature, about 28.4° F [23]. The ice contains little salt because only the water part freezes. Sea ice can build up from snowfall, but ice floe movement and seasonal melting cause the thickness of sea ice to be much less than for glaciers on land. About ten feet is the usual maximum.

Consider a glacier that is in contact with seawater. If the seawater temperature is below about 28.4° F no melting of glacial ice or sea ice will take place. But when the seawater gets up to 28.4° F where sea ice melts, only a small additional increase takes it above 32° F where glacial (freshwater) ice will melt. It should not surprise us that when the sea ice is melting, seawater near the sea surface may get warm enough to melt glacial ice in contact with seawater, especially when the warmed seawater gets under the glacial ice.

Often what keeps a glacier from moving faster is a large tongue of ice (an "ice shelf") extending into the ocean, or a submerged rock outcropping (a ridge of hard rock) that the bottom of the glacier hits. Then the glacier tends to break off or "calve" icebergs, because the mass of ice behind pushes the ice in the front forward, while the rock below holds the bottom. Either the ice shelf or the submerged rock is said to "pin" the glacier (see the diagram, Figure 2, p. 25, of [5]).

The Arctic area is warming, as vividly illustrated in [2], [15], and [24]. Glaciers have begun to melt in Greenland. And as they melt, sea level rises. This will "unpin" glaciers, first in Greenland, and then, as sea level rises further, some of the much larger glaciers in Antarctica. When these glaciers are "unpinned," they are expected to move about twice as fast, bringing more fresh water to the sea, which causes the sea level to rise. Warmer sea water contributes to sea-level rise from thermal expansion of ocean water, but by a much smaller amount than the potential rise from melting of the massive glaciers in Greenland and Antarctica.

If all the ice melts on Greenland, the estimated sea-level rise is about 24 feet, but if all the ice melts in Antarctica, the rise is 186 feet. All other glaciers are minor by comparison, with a potential to cause a rise of only 2 feet. (The source of these estimates is [5], page 33, from a 2009 publication [25]. The 24 foot figure is repeated in [24].) Recent research suggests two of the large glaciers in Antarctica may have become "unpinned" [26].

How fast and how far will the sea rise? During the melting phase of the last ice age, the sea rose 65 feet over a 500 year period, an average of 13 feet per century ([5], p. 33; diagram, p. 35). At this time scientists are uncertain about the potential timing, especially for the glaciers in Antarctica. The Department of Defense in 2016 estimated that the rise could be as high as 2 meters (7 feet) by 2100. This estimate has been used in planning the rebuilding of the Embarcadero Sea Wall in San Francisco [27],[28]. But the melting process does not stop at 2100. It should be expected to continue, and it may accelerate ([5], chapter 3, pp. 36-58). An estimate of the level at which it might stop is "roughly 70 feet (20 meters) above present" … for "the new equilibrium with the planet at its current temperature." ([5], p. 53.) But the temperature of the planet continues to rise.

Three articles in the same February 2024 issue of *Science* add to the evidence that sea ice and CO2 levels may be the key determinants of temperature change and the melting of ice. [29] reports on the close relationship found between recent melting of sea ice in the Arctic and the advance of boreal forests into areas that were previously frozen tundra. [30] and [31] examine data indicating that sea ice and CO_2 levels in the Southern Ocean surrounding Antarctica may explain why the climate cooled and ice ages became longer about a million years ago. The sensitivity of sea ice and climate to CO_2 levels may be greater than scientists have previously believed. Research in this area is progressing. But what has emerged from recent research is that the melting of sea ice is a strong indicator of more heat going into the ocean near the poles, and of potential acceleration in glacier movement and consequent sea-level rise.

There is good news. Sea-level rise is limited by the amount of ice, and if it all melts the estimate is 212 feet ([5], p. 33). Sea-level rise should not go significantly higher. Polar ice will not be restored for centuries, and ice ages such as earth has experienced in the last 3 million years may not come for perhaps millions of years with future GHGs at or above the mildly elevated levels of the 20th century.

The bad news is that humanity may need to move to higher ground starting with a sea-level rise of perhaps three to ten feet in the next hundred years, similar or somewhat larger increases over subsequent centuries, with uncertainty about how far this process will go. The greater the buildup of GHGs in the next hundred years, the higher is the probability of a larger melting of the polar ice.

The added CO_2 stays in the atmosphere more than a century, perhaps 300 to a thousand years [32]. The ocean takes more than two decades to adjust to the altered heat balance as GHGs have increased. The historical data from ice age cycles is that ice melts over a period only a fifth as long as the time needed for heat to dissipate and ice to build up again. Ocean heat may take from centuries to millennia to dissipate after GHG levels are reduced. There may be thousands of years with a hotter climate, altered ecosystems and agriculture, and loss of species.

Can humans alter this prospect? It seems unlikely. Geoengineering may be able to reduce the incident radiation from the sun, but it can't remove the added heat from the ocean. And removal of the added CO_2 from the atmosphere will be an enormous task. The nations of the world are still adding CO_2 and other GHGs. Curtailing these increases to achieve a planetary Net Zero – no further increases – requires truly massive changes.

It will take many decades for a transition to a greatly reduced level of emissions from the use of fossil fuels. Only baby steps such as development of electric vehicles have been taken so far despite the international meetings such as Paris in 2015 and Dubai in 2023. One of our US political parties still denies there is a climate alteration problem. An expansion of nuclear, hydro, wind, and solar power by a factor of ten to a hundred is needed to meet world energy demands (including the aspirations of non-OECD countries). Some of the technologies for energy production, transportation, distribution, and meeting end uses will require extensive further research and development. Cement and steel manufacture pose similar massive challenges.

As one energy conversion example, Yale University has committed to phasing out use of fossil fuels for its campus by 2050 [33]. Campus buildings are to use heat pumps and geothermal energy, by using pipes set into the granite bedrock for heating and cooling of campus buildings. Research is beginning on a few buildings. The cost could be high, and many more years may be needed for such heat pump technology to be installed in buildings, worldwide.

Adaptation

San Francisco's Embarcadero Sea Wall proposed project [27],[28] is held up in [4] as an example of enlightened planning and cooperation between local, state and federal authorities to plan for sea level rise by as much as 7 feet by 2100. Aaron Peskin, who has just announced his candidacy for San Francisco's mayor, is described sympathetically in [4], pp. 119-121, for his advocacy of planning for the threat of sea-level rise. He is quoted as follows: "Everybody knows this is real. Nobody is in denial about climate change. "

Would that this was true, that nobody is in denial about climate change! The San Francisco Sea Wall is still a draft project. While supported by the Army Corps of Engineers, San Francisco will have to raise its share of the projected $13.5 billion cost.

Moving to Higher Ground [4] describes an alternative to the words in this book's title: Dam the ocean to keep the rising sea from flooding valued land. That might be done in many places besides San Francisco for a rise of 3 to 7 feet, but where might it make sense against a much higher rise? The entrance to the Baltic Sea between Denmark and Sweden at the Kattegat is narrow. Pages 159-160 of [5] discuss maintaining the present level of the Baltic Sea by building what would be the world's largest dam to protect the low-lying land of the nine bordering nations.

Similarly, it may be worthwhile to consider a dam on San Francisco Bay, perhaps between the Carquinez Heights and Crockett, to protect the Delta and the Central Valley. (Building dams on the Bay has been considered before [34] for the purpose of turning large portions of the Bay into freshwater lakes.)

Carbon Capture

Let's now consider putting the carbon back under the ground, where the coal, oil, and gas used to be. Technologies for carbon capture and geologic emplacement are nearing the stage of large-scale demonstration [35],[36],[37].

First let's get an idea of the enormity of the carbon dioxide already in the atmosphere. The PBS NOVA *Polar Extremes* [2] started with 1 gallon of gasoline, which has five pounds of carbon, represented by a small pile of charcoal briquettes. The host then scales the pile up to a tank of gasoline (say, 20 gallons = 100 lbs), then a year's worth, say 18,000 miles at 30 miles/gallon = 600 gallons = 3000 lbs = 1.5 tons. Converting to metric tonnes and multiplying by 3.67, this is about 5 metric tonnes of CO2 for a year's worth of driving for one car. Extend it to all US vehicles, then to the world and to all sources of CO2. [2] showed a giant pile next to a very small car. Current CO2 emissions are about 36 billion metric tonnes per year [35],[38].

My friend Don Alvarez would have been my guest but he had to be out of town April 9. He did a calculation of the volume of solid carbon from CO2 emissions since 1980 as a pile 5000 feet wide and 5000 feet high – and 100 miles long. Why is the pile so surprisingly big? Consider all the coal, oil, and gas taken out of the ground and used, emitting CO_2. CO_2 is a colorless, odorless gas, so we do not perceive that it is now in our atmosphere in a far greater quantity.

David Wallace-Wells, the journalist who interviewed John Kerry in [12], has written: “We’re adding carbon to the atmosphere at record levels, and the stuff we’ve put up there weighs more than the total of everything we’ve built on the earth’s surface.” [39]. That is the “elephant,” not “in the room,” but in our planet’s atmosphere.

The March 31 Sunday *New York Times*, had the front-page story, "Can We Engineer Our Way Out of a Climate Crisis?" [35]. It is about two projects, Climeworks in Iceland, and Occidental Petroleum's Odessa, Texas plant. Iceland's will capture "up to 36,000 metric tonnes of CO_2 per year and the Occidental plant, up to 500,000 metric tonnes. The CO_2 will be put underground in a location where it will combine with minerals to become solid, rather than gas or gas dissolved in water. The article notes that 36,000 metric tonnes/year is one millionth of today's annual global emissions of 36 billion metric tonnes of CO_2. Occidental intends to build 100 plants each capable of a million metric tonnes per year. 100 such plants would capture up to 0.3% of annual emissions, and on the order of 0.001% of emissions since the beginning of the industrial revolution. “Engineering our way out of the climate crisis” with carbon capture and re-placement underground is a really big job!

Let’s see how big it is. About half of the CO_2 emitted each year goes into vegetation and the ocean. Consider what it would take now to remove the other half, 18 billion metric tonnes per year: 180 times Occidental’s 100 plants to stop the annual increase in CO_2 level. How much to get the level back down? The level of CO_2 has risen about 25 ppm in the last ten years [40]. (The increase over preindustrial level has been going up nearly 2% per year.) With 25,000 million-metric-ton-per-year size plants operating ten years, a net decrease of 7 billion metric tonnes per year would in 30 years offset the net increase of about 18 billion metric tonnes added to the atmosphere each year over the past decade – assuming emissions stayed at today’s level of 36 billion metric tonnes. To reduce CO_2 in the atmosphere by 10% of the increase from preindustrial to today's level of about 420 parts per million, that is, by about 25 ppm from 420 to 395 ppm, 250 times Occidental's planned capacity of 100 plants is needed to be operating for about 30 years. And 25 ppm might be a small reduction compared to what is needed to eventually restore the climate that we have enjoyed during the first quarter of the 21st century. The engineering required is mind-bogglingly gigantic, comparable to the size of our planet’s entire current coal, oil, and gas infrastructure.

On the day I delivered my essay, *The New York Times* had a lengthy discussion of the plans by the Italian energy company ENI to collect CO_2 emissions from the factories in and around the industrial city of Ravenna and dispose of this CO_2 in depleted natural gas reservoirs using the company’s existing infrastructure of pipelines and gas wells [41]. Like Occidental, ENI is starting with a single modest size project: injection of CO_2 from a gas processing plant into an undersea gas field at a depth of 10,000 feet. And like Occidental, ENI has plans to expand, to as much as 16 million metric tonnes of CO_2 per year. ENI is negotiating with the British government as well as the Italian government.

A motivation mentioned in the article is that "some analysts forecast that the European Union's carbon tax will soar well above €100 a metric tonne in future years." ENI believes that using its existing infrastructure, it can dispose of CO_2 at €80 a metric tonne, and therefore make a good profit. Energy company leaders like the idea of establishing carbon-pricing mechanisms, even if these make fossil energy much more expensive [42]. These carbon-pricing mechanisms allow alternative energy projects to be compared on a consistent basis. I hope the idea might become established in the European Union, spread to the United States, and then onto China, India, and other nations now using coal because they consider it to be "cheaper" than energy alternatives. Carbon pricing at the social cost ascribed to future environmental damage by national governments and international bodies might motivate agreement among all nations to pay consistent higher costs for reducing emissions of CO_2 and other GHGs. Of course, governments and richer countries may have to put up the funds when those that are poorer do not have them. While there is agreement in principle for richer nations to do this, so far the actual amounts have been relatively small relative to the assistance that has been promised.

Possibly building and operating those 25,000 big and expensive carbon removal plants for many decades, perhaps for centuries, is doable, worldwide. The current cost of $500 to $1000/ton might come down a bit, optimistically to say, $100/metric tonne ([36], p.7). Then taking 25 billion metric tonnes out per year would cost $2.5 trillion a year.

World CO_2 emissions might increase considerably before the increase of 25 ppm per decade in CO_2 level each year is halted. Then double or quadruple the cost figure above might be needed over many decades to lower the CO_2 level back down to below 400 ppm. Such a reduction would be a truly heroic improvement over the peak atmospheric CO_2 level that might be reached by 2050 - or 2075. The associated cost numbers are roughly of the same $100 trillion magnitude in net present value as in the recent Nordhaus paper [14] discussed above. The benefits of such a reduction might be judged to be much greater.

The day after I presented my essay, *The New York Times* had a lengthy discussion on reforestation as a means of removing carbon dioxide from the atmosphere [43]. It seems like an excellent idea, but it ought to be kept in perspective. According to a source [44] citing the US Forest Service, trees in the US remove over 800 million tons of carbon per year, roughly 12% of US emissions. This amount is equivalent to about 3 billion tons of carbon dioxide. Forests also emit CO_2 as vegetation burns or decays. The World Resources Institute estimates [45] that twice as much is removed as is emitted by forests, and that forests provided a net reduction of 7.6 billion metric tonnes per year during the period 2001-2019. Many of the world's forests are being cleared or degraded. Replanting of previously forested lands, planting street trees, and adding more trees in urban parks are all desirable actions for reducing atmospheric CO_2, but it takes many years for mature trees to grow from seedlings. Expanded tree planting would be required on a vast scale to balance the increase in emissions that has been occurring over the last 35 years.

Concluding Thoughts

I hope that a large reduction in the annual emissions could be accomplished by 2050 or so from 36 billion tons of CO_2 annually to a number at least half that size, and another factor-of-two reduction by 2075. Perhaps with these reductions, CO_2 capture and geologic emplacement, plus removal into expanded forests and other vegetation and the ocean, Net Zero worldwide for GHGs might be achieved by 2075 or a bit earlier, but I am not optimistic. I think much of the ice at the poles may melt, which will put San Francisco and a lot of other coastal cities and low-lying land partially or wholly underwater.

In the same issue of the Sunday *New York Times* as [35] is "The Secret to Surviving a Climate Apocalypse," the cover story in the Sunday Opinion section [46]. It is about a small community living on the edge of what remains of the Salton Sea. I've been there. My wife lived nearby in Indio when she was going to high school, and we drove over to the Salton Sea during her 50th high school reunion. Yes, it's REALLY HOT there much of the year, the environment has become toxic, and only a few very hardy people are left. But humans are extremely adaptable and manage to survive - and even have fun - under extreme conditions. And our mammalian ancestors survived the period 50 million years ago when the poles were ice-free.

What might humanity think about the melting of mountain glaciers now, and polar ice beginning now, and continuing for centuries as sea levels rise from tens to perhaps a little over 200 feet? There will be benefits. Melting the glaciers on Greenland will uncover large deposits of valuable minerals, and the same will be true on a much larger scale as the ice melts on Antarctica, a land mass roughly equal to the size of the United States plus Mexico.

On the same Easter Day as the Sunday *New York Times*, I found in my mail a copy of *The Magazine of the National Parks Conservation Association* with a cover story called "The Long Goodbye" [47]. It is about artists paying tribute through their art to the melting glaciers on the Olympic Peninsula. I expect the human race may remember fondly and celebrate in its art and literature the time when Greenland and Antarctica, as well as mountain ranges on the other six continents, had snow-capped peaks and vast glaciers -- and the planet had the ecosystems and temperate climate we are enjoying now.

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