# Case H: Global Warming, Climate Change and Energy

*Global warming and global energy supplies are subjects of such complexity and importance that to consider the following as a case study would be inappropriate. Instead, it may be more apposite to view it as an essay prompted by despair at our human inability to look problems squarely in the face.*

## Energy, Demands, Resources and Reserves

Energy demands in an industrialized society rise inexorably. Societies that meet energy demands from fossil reserves must inevitably consume those reserves. Since demand is continually accelerating, the time horizon at which reserves run out is continually foreshortening. Discovery of more fossil reserves merely postpones the evil day.

Burning fossil reserves pollutes the atmosphere. The fossil reserves stored up carbon as hydrocarbons, carbonates, carbohydrates, etc., during their periods of growth as living flora and fauna millions of years ago: burning the fossil fuels releases carbon back into the atmosphere as carbon dioxide ($CO_2$), methane ($CH_4$), and other gases. Some $CO_2$ is reabsorbed by photosynthesis into present day flora, but not enough to prevent an abundance of $CO_2$ in the atmosphere from burning fossil fuels, which deposited their carbon content progressively over hundreds of millions of years, only to have it released in hundreds of years.

Rising $CO_2$ levels have been observed over the last 5000 years. It may be that the levels have risen partly as a result of widespread agriculture, since that also started some 5000 year ago. The rate of rising has accelerated alarmingly in recent years, suggesting that natural mechanisms for reabsorbing $CO_2$ are being swamped.

*Systems Engineering: A 21st Century Systems Methodology* Derek K. Hitchins

# Global Warming and Climate Change

The mean temperature of Earth appears to be rising. This is not unusual: on the contrary, it fluctuates continually, due to a number of different effects, including predictable variation in the Earth's relationship with the Sun's radiation. The eccentricity, axial tilt, and precession of the Earth's orbit vary. The Earth's axis completes one full cycle of precession approximately every 26 000 years. At the same time, the elliptical orbit rotates, more slowly, leading to a 22 000-year cycle in the equinoxes. In addition, the angle between Earth's rotational axis and the normal to the plane of its orbit changes from 21.5 to 24.5° and back again on a 41 000-year cycle.

Moreover, there is reason to believe that, like other stars in its class, the Sun's output is variable, sometimes increasing and sometimes decreasing. Indicators of this variability are not well understood, but may be associated with sunspot activity. The solar system also passes from time to time through interstellar dust clouds — spirals of dust from the center of our galaxy — that can reduce the solar radiation reaching the Earth.

Taking the predictable variations, the less well-understood variability in the Sun's output and the interstellar dust clouds into consideration should lead us to the conclusion that we do not really know if the Earth is heating up through insolation, or for some other reason. Indeed, for all we know, the Earth may be on the cusp of a period of Earth cooling. Or so various climatologists were agreeing some 20 years ago.

Of course, this does not take account of the so-called greenhouse effect, in which re-radiation from the Earth's surface is trapped inside the Earth's atmosphere. As every schoolchild will be aware, $CO_2$ is a so-called 'greenhouse gas,' and has been identified as one of the culprits in global warming.

Latest estimates suggest that the mean temperature of the globe will rise by some 3 °C over the next 100 years. Some climatologists insist that it will be much more — perhaps 5 °C, or even 7 °C. Ice caps will melt, and the climate will change: just how it will change is difficult to predict.

Climatologists have created sophisticated models that purport to show the likely outcomes, none of which looks comforting. But even without such plausible simulations, it seems reasonable to suppose that global warming will put more energy into the global weather systems, i.e., will 'drive' an already chaotic system. In general terms, the results of that are likely to be greater extremes of weather: fiercer storms; longer periods of calm; torrential rains; severe droughts; areas of high temperature; areas of very low temperatures; rising sea levels; flooding; submerging of low-lying islands; etc., etc. But which of these is going to happen where and when is more difficult: global weather is a complex, nonlinear chaotic system of systems — see Generating Chaos on page 35.

# Choices

Meanwhile, armed with forecasts of this doomsday scenario, what can we do? There seem to be at least three approaches:

1. Try to prevent the continuing rise in atmospheric $CO_2$ levels with a view to curbing the greenhouse effect
2. Take measures to ameliorate the effects of climate change: e.g., build flood defenses, move populations to higher ground . . . .
3. Manage the climate and limit global warming — or cooling.

## Controlling rising greenhouse gas levels

Concerned politicians in some countries are trying to rally international support for a concerted, international effort at curbing emissions of carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, hydroflourocarbons, and perfluorocarbons. The Kyoto Accord was the first such effort, at which participating nations undertook to meet emission reduction targets. Many signatory nations are trying to meet agreed targets, reducing domestic energy consumption, reducing fossil fuel dependency, introducing alternative energy sources, etc.

Not every nation participated: notable exceptions were Australia and the US. Other countries, including India and China, ratified the Accord but were not required to cut their emissions because of their status as developing nations: it was agreed that developed nations had emitted most greenhouse gases, and that developing nations, with relatively low emissions per capita, should not be unfairly inhibited. With India and China being the most populated nations on Earth, they may soon overtake the USA, currently the world's biggest emitter. China is currently building a coal-fired power plant every week, and intends doing so for years to come. Some predict that China will overtake the US in 2–3 years as the principal emitter of greenhouse gases. China points out that their emissions *per capita* are still relatively low on account of their large population . . . .

Which brings to mind the Tragedy of the Commons (TOTC) (Hardin, 1968). Originally believed to have occurred in medieval times near Oxford in England, the Tragedy of the Commons came about through herdsmen sharing common land upon which they grazed their cattle. They could either graze on private land, for a price, or on common land, for nothing. Individual farmers found it beneficial to graze more of their stock on common land, free of charge: it was also beneficial to increase stock numbers since, with free grazing, there was more profit to be gained. Since all farmers, as individuals, came to the same conclusion, the common land became overgrazed and useless, leaving cattle to die. Hence, the tragedy: by acting separately, the herdsmen ruined each other and themselves.

TOTC applies to pollution, in a reverse sense. If several parties pollute their common environment, and if it would cost each of them to clean up waste rather than pollute, then it is not in their individual interest to clean up. Hence, none will clear up — unless, of course, some binding agreement can be reached in which all parties clean up. And, it has to be *all* parties, since any party left outside the agreement will see advantage — reduced cost — in not cleaning up their waste — and so will in effect have a polluter's license, granted by those who cleaned up their respective acts.

So, in greenhouse gas emissions, do we see an unfolding Tragedy of the Commons? It seems likely. In spite of Herculean efforts by the United Nations Framework Convention on Climate Change, and the setting of specific targets for signatories to the Kyoto Protocol, greenhouse gases are still rising alarmingly, the output from developing nations is rising dramatically, and developed nations with the best of intentions are experiencing difficulties in reaching their agreed targets.

Even supposing that further increases in atmospheric $CO_2$ levels were curbed over the next decade or two, it is possible that the damage has already been done. Kyoto and its possible successors may be too little, too late.

## Measures to ameliorate the effects of climate change

Not everyone accepts that global warming is caused by human agricultural and industrial activity. However, to some extent disagreements over the causes are irrelevant: the symptoms of climate change are presenting around the globe. Not sufficiently, perhaps, to cause wide-scale panic, but noticeably nonetheless. Ice caps are receding. Ocean currents are changing temperature and salinity: fish stocks are following the changing patterns. On average, winters are milder. Spring comes a little earlier; flowers may bloom out of season. Birds are laying eggs earlier. Severe storms may occur more frequently; so may severe droughts.

Accepting, for the moment at least, that climate change is inevitable: what can be done to protect the environment, the flora, fauna and, in particular, humanity? The answer seems to be: precious little.

- As climate shifts, the changes will affect food production: occasionally change may be beneficial; generally, it will mean that plants that grew well before the change will need to be replaced with different varieties or even different species altogether.
- As food production is disrupted, even if temporarily as old crops are replaced by new, major food shortages are predictable.
- Current practices in which developed countries import low-cost foods over vast distances may have to change, with a return to more homegrown foodstuffs.
- Climate change will be accompanied by local variations in rainfall, as well as temperature, so improved means will be needed for collecting and storing fresh water — already a commodity in short supply around the world.
- Plants for making fresh water from seawater by reverse osmosis may become more popular, increasing energy demand
- Domestic energy demand is likely to rise as people depend on cooling and heating systems to combat both rising and falling temperatures
- Mass migration may occur as people find their littoral environments threatened. Countries with Mediterranean coastlines would be greatly affected, for instance. Greece, with 160 permanently inhabited islands, and hundreds more uninhabited islands, would be particularly affected: Indonesia even more so.
- Major flood defenses would be raised around the world as people resisted rising waters. Major disasters would be inevitable as floodwaters found their way around, underneath, or over the top of such defenses

Climate change may also affect the viability of a number of so-called alternative energy sources, reliance on which is presently the cornerstone of some national strategies . . . .

# Rational and Irrational Alternative Energy Sources

Much reliance is being placed in some quarters on alternative energy sources, where ‘alternative’ implies alternative to fossil fuel burning — hence ‘green.’ Hydroelectric schemes have a history as alternative sources of energy, using as they do the Earth’s gravitation attraction as their driving force. Not all schemes have been entirely without their drawbacks.

## Hydroelectricity

The Aswan High Dam in Egypt, for instance, certainly generates a huge amount of electricity, but at the expense of submerging a nation (Nubia) and altering the climate and ecology of central and east Africa. Moreover, its life is limited. The dam traps silt being washed down the Nile which previously would have been carried into southern and northern Egypt and out into the Mediterranean. The dam basin is filling up, not with water, but with silt. It will not be many years before the dam is unusable . . . .

Some countries have capitalized on their mountainous terrain by developing hydroelectric schemes without such drawbacks: the Nordic countries are prime examples. However, with the advent of climate change, and the movement of weather systems, will such countries continue to have the abundance of snow and rain which fills the rivers and drives the turbines? It certainly cannot be guaranteed.

## Wind power

Wind power is popular with alternative energy buffs: it comes in several forms. Generally, they raise the issue of energy density: energy extracted from wind machines varies as the cube of the wind speed.

This means that windmill generators do best in windy locales — which is where people do not want to live. Electrical energy generated at a distance from its point of application will incur transmission costs and energy losses — as heat. Current estimates of the efficiency of propeller generators sited near centers of population are reputedly in the region of 23%. On the other hand, siting windmills in very windy locales not only distances them from centers of population, but can also result in them being overdriven by very strong winds, and damaged. And, with climate change, future strong winds could be much stronger than at present. Then again, places that are windy now may be becalmed as climate patterns shift . . .

Objections to siting windmill 'farms' inland on aesthetic grounds have resulted in many being sited offshore, in shallow waters. Their durability and reliability in the face of tornados, storm surges and rising tides has yet to be established: dipping blades in the water is, presumably, a showstopper.

## Tidal flow

Tidal flow schemes have been in use for some times, and they seem to be successful: suitable sites may prove difficult to locate, however, as a considerable flow of water is needed from which to extract energy — essentially Moon energy. And, of course, any site that is suitable now may not be suitable if and when the waters rise . . . .

A tidal barrier scheme is proposed for the Bristol Channel in England, which is famous as having a very high tidal reach, second in the world only to Newfoundland. A large barrier is proposed across the estuary, with a road running along the top between England and Wales. The barrier would serve as a flood defense, resisting rising tides and storm surges, and would protect a large, highly populated estuary coastal area. Additionally, it would also serve to generate large amounts of electricity through inset turbines. These would generate electricity both on the incoming and outgoing tides: enough, it has been estimated, to meet 6% of the UK's electricity demand. So, combined flood defense, road and power generation: win–win–win. Environmentalists, concerned that the barrier would affect shore flora and fauna, and upriver wetlands, have raised serious objections, however . . . .

## Wave power

Wave power seems attractive to some, with the short-term choppy motion of waves providing relatively rapid movements of generating elements, including Salter's Duck — a 300-tonne floating canister designed to drive a generator from the motion of bobbing up and down on waves like a duck. Named for Professor Salter of Edinburgh University, the Duck (project) was killed off in a dispute with proponents of wind power at the British Atomic Energy Authority!

## Moon power

Moon power can be extracted in a different way. A large floating platform tethered off shore would rise and fall with the tides: that motion could be used to turn electrical generators, effectively generating electricity from the Moon's gravitational attraction. Rising tides would not affect the capability, and may even enhance it.

If the large floating platform were to double as a floating airfield, for instance, then international flights could set down there and takeoff without polluting the land environment with noise and noxious emissions. Waves could be prevented from breaking over the edge of the platform/airfield by surrounding it with Salter's (dead) ducks, which would take energy out of the waves and prevent them from swamping the platform. The whole could contribute significant amounts of energy to the national grid . . .

## Biomass solar power

Biomass sources of alternative energy have a history.

> The fuel of the future is going to come from fruit like that sumac out by the road, or from apples, weeds, sawdust — almost anything. There is fuel in every bit of vegetable matter that can be fermented. There's enough alcohol in an acre of potatoes to drive the machinery necessary to cultivate the field for a hundred years. Henry Ford, 1906.

Prophetic, perhaps, in other ways, Henry Ford got this one wrong, although Cleveland Discol, for instance, a British subsidiary of Standard Oil, promoted alcohol blends from the 1930s to the 1960s for clean, cool and efficient combustion. It was particularly popular with riders of single-engine motorcycles as it made engines run 'smooth and cool.' However, the US oil industry has generally been opposed to synthetic oils, as they were called.

Recent interest in alternatives to imported petroleum products has focused on ethanol production, from corn (maize), sugar cane, etc. Although politicians in the US are pushing aggressively for ethanol from homegrown corn as a substitute for foreign oil, the conversion requires copious amounts of fossil fuels to achieve. Producing ethanol from corn creates almost the same amount of greenhouse gas as gasoline production does. Burning ethanol in vehicles offers little, if any, pollution reduction. (Wald, 2007)

Biomass, essentially solar energy, can be used in a quite different way. It may be practicable to run a power plant on wood grown for the purpose (Odum, 1971). A power plant might be sited at the center of a circular area divided into sectors, and planted with, e.g., fast-growing willow saplings. Each sector is coppiced (cut back) in turn to fuel the power plant. By the time that harvesting has gone right around the area and returned to the first sector, each coppice has grown a fresh stock of wood, such that power generation is continuous.

Such power generation is, of course, carbon neutral: burning the wood releases as much $CO_2$ as was absorbed into the growing trees from the atmosphere by photosynthesis. The amount of energy generated depends on the area under cultivation and the growth rate of the wood concerned. This is green, low technology solar power. Like other alternative sources, it is subject to the vagaries of sun, wind and weather. In the event that such a system grew large volumes of identical plants, there would also be a risk of systemic disease: crop rotation would be necessary. Large amounts of continuous power would require large estates to be put under cultivation.

## Alternative summary

In this brief overview of some of the principal alterative energy sources, none has been found to be ideal on its own: each has drawbacks when climate change is taken into account. Conventionally, however, things are looked at the other way around: if we convert to alternative energy sources, and if we ‘go green,’ then climate change will not occur.

The cat is out of that bag, however. Climate change has been occurring, and is occurring, even at current gas emission levels — and they are still rising. There is no evidence that an immediate switch to totally green power sources — even if such a switch were feasible — would make a difference.

In the circumstances, it might seem rather late in the day to switch to alternative energy sources, particularly since they seem to be threatened right now by the very climate change they seek to prevent in the future. It might, on the other hand, be socially and psychologically comforting to think that we are ‘doing something.’

# Nuclear Energy

Nuclear energy is not alternative energy, of course, but it is nonetheless green: very green. The mainstay for energy needs in the future is unlikely to be anything other than nuclear energy: this, despite the risks and costs that undoubtedly exist in creating, running and decommissioning nuclear power plants.

The general public is taught to fear nuclear energy by the media. Much is made of the problems of disposing of highly radioactive waste, yet the total amount of such waste in the UK, for instance, since nuclear energy generation started half a century ago, is less than the volume of the average small cottage!

In practice, there are remarkably few nuclear power plant incidents around the world. France has 59 nuclear plants producing 78% of the entire country’s electricity, and is the largest exporter of nuclear electricity in the European Union. France is second in the world (behind the United States) in terms of total nuclear power generation, contributing 15.9% of the world’s nuclear electricity. Their $CO_2$ emissions per capita are correspondingly low.

However, the goal for mass power generation seems to be nuclear fusion, which promises cheap, plentiful energy with no radioactive side effects. Nuclear fission energy is sometimes regarded as a stopgap, waiting for nuclear fusion to emerge from its protracted research and development program. It is taking a long time . . . .

Meantime, the rise in international terrorism has highlighted other risks from nuclear fission power plants, i.e., that they may be attacked, and that fissionable materials may be stolen to make nuclear bombs. It is a risk that we may have to guard against, but there seems to be little sensible alternative to nuclear fission energy in the short to mid term. Besides, there are other ways for terrorists to extract fissionable materials besides stealing them . . . In any event, it hardly seems sensible to address the risk from terrorism by degrading our energy generation capabilities and running down our economies in the process. If there is a threat, then either it must be faced, or civilization will rollover and submit to chaos.

## Future Imperfect...

Taking a step back, and looking in the longer term, the current global warming/fossil fuel debacle will, hopefully, appear as a ‘blip’ on the continuing development of human civilization on Planet Earth. Why? Well, the trading environment as it stands is one of competitive international economies, each trying to expand at a sustainable rate: competition makes for vibrant and energetic interchange between economies.

Sustainable growth has been founded, so far, on relatively stable climates and environmental conditions; and, sustained growth has meant, and will continue to mean, expanding energy demands. Alternative energy sources, unable to fully shoulder the increasing burden of energy supply in developed countries, will provide a reducing fraction of national energy supplies as demands continue to rise.

Faced with the prospects of switching entirely to alternative energy sources, with the concomitant inability to sustain economic growth, most nations are likely to opt for mixed energy supplies: fossil fuels will continue to be used by developing nations in the short to medium term, and with nuclear energy — fission first, then fusion - supplanting fossil fuels in the longer term, as dwindling supplies become unaffordable. (At this point, of not before, global energy conflict — World War III — must be a distinct possibility . . . .)

Despite valiant efforts to curb their growth, greenhouse gas levels will therefore continue to rise — perhaps not so quickly, but that remains to be seen. In any event, global warming will continue and — since humanity is ‘forcing’ an already-chaotic system — the climate is likely to change both drastically and unpredictably. At some point, politicians will realize that they will have to take radical action if their economies are not to be substantially shattered, and that will mean either:

- a means must be found of preventing more heat energy from entering the atmosphere, such that the earth’s mean temperature can stabilize and perhaps drop a notch, or . . .
- An alternative means must be found of removing energy from the atmosphere and similarly curbing temperature rises and restoring climatic status quo.
- At the same time, sustained economic growth will necessitate continuing growth in global energy supplies.

So, a conundrum presents itself: Earth will, as things go, contain too much energy in the atmosphere, earth and seas, yet at the same time it will be demanding more and more energy to sustain its burgeoning human population and their economies. Using that increasing energy to do work will generate heat, which — in the circumstances — will be like throwing gasoline on a burning fire!

## Dyson spheres

In the 1950s, mathematician Freeman Dyson observed that every human technological civilization had constantly increased its demand for energy. If human civilization were to survive for long enough, he reasoned, it would eventually reach a point where it required the total output from the Sun as its energy supply.

Dyson reasoned that an advanced civilization would create a system of orbiting structures that would surround their sun, so capturing all its emitted radiation. These orbiting structures would constitute a sphere, centered on their sun. The concept became known as the Dyson sphere. (Dyson, 1959). He went on to reason that the energy receptors in the sphere would re-radiate energy in such a way as to alter the stellar spectrum perceived by others at a distance: human-like entities would probably re-radiate energy predominantly in the infrared. Hence, one way to search for advanced alien civilizations was to look for atypical radiation spectra in space.

Dyson did not concern himself with the physical form that such a sphere might take, nor with issues such as global warming. However, the concept of the Dyson sphere captured the minds of scientists and of the general public at the time. The technological capability for constructing such a sphere was thought to be beyond humanity at the time, but perhaps in the future? And, interestingly, the energy captured by such a sphere would be clean, green, solar fusion energy.

## Nuclear winter

Research into the possible effects of global nuclear war in the second half of the 20th Century suggested that one outcome would be a so-called nuclear winter (Turco *et al*., 1983). This would arise from fallout dust clouds obscuring the Sun for many months, possibly many years, with a consequent cooling of the Earth. Later estimates by the same authors (Turco *et al*., 1990) suggested temperature drops of several degrees in land temperatures and 2–6 °C drop in ocean temperatures, together with an ozone depletion of 50% leading to 200% increase in solar UV radiation incident on the ground.

Horrifying though the prospect of a global nuclear war might be, nonetheless the studies did show that it was possible to reverse some of the effects of global warming by reducing the amount of solar energy penetrating the atmosphere and reaching the ground.

## Volcanic effects on climate

The climatic effects of volcanic eruptions had been apparent long before the possibilities of nuclear fallout on climate had been considered. However research focused on the Mount Pinatubo, Philippines, eruption in June, 1991, indicated that: 'the direct radiative effect of volcanic aerosols causes general stratospheric heating and tropospheric cooling, with a tropospheric warming pattern in the winter.' (Kirchner *et al*., 1999). Evidently, volcanic eruptions can affect climate in unpredictable ways . . . .

## Industrial pollution

There are controversial suggestions that a drought from 1970 to 1985 in the Sahel region of Africa, stretching from Senegal to Ethiopia, may have been 'assisted' by European industrial pollution.

Sulfur dioxide aerosols from coal burning seem to contribute to drought by altering cloud formations. Researchers said the particles remain suspended in the clouds instead of falling as rain, and the heavier clouds reflected more of the sun's energy back to space. The aerosols add to conventional causes of drought, such as the overuse of land and natural atmospheric changes.

Taking these unconfirmed suggestions at face value suggests that it is possible to effectively alter the Earth's albedo at high altitude: clearly, in this instance, that would be a risky thing to do; on the other hand, if it were possible to alter the albedo uniformly, and to a very small degree, the net effect might be simply to reduce the solar energy reaching Earth, and hence reduce global warming.

The suspicion that drought in the Sahel was assisted by industrial pollution as far away as Europe points to the degree of coupling between complex weather systems in the environment.

# The Case for Active Climate Control

Foregoing paragraphs have indicated that global warming is probably inevitable: that current attempts to limit the emission of greenhouse gases, presuming them to be the causative warming agents, are unlikely to be successful; that, even if they were successful, it may already be too late; and that the prospects from global warming are potentially damaging to life on the planet.

Current political considerations focus on a short time horizon of less than 100 years. If human civilization is to continue, much longer time horizons must be considered, many thousands of years into the future. From that perspective it is possible to see that energy demands will continue to rise, far beyond the meager capabilities of today's alternative energy sources, even beyond nuclear energy sources. If they do not continue to rise, it will because economies and societies will have failed, and technological civilizations along with them.

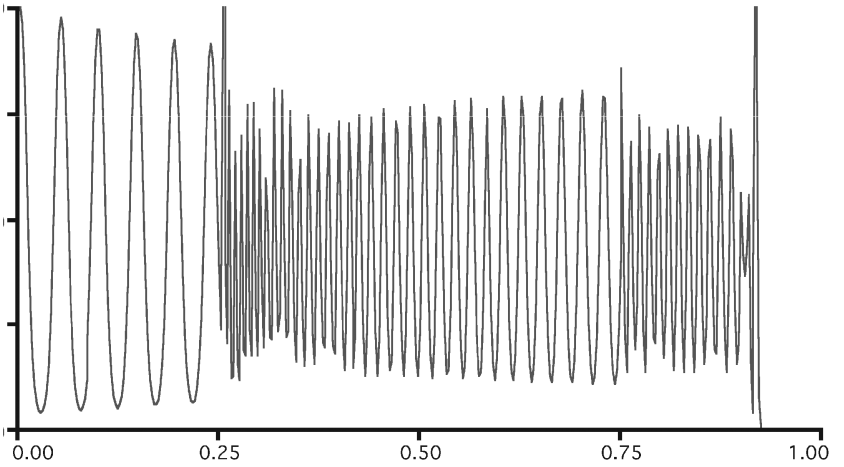
So, on the one hand we have too much low-grade energy in the environment while on the other hand, we will demand ever more high-grade energy to sustain our technological, economy-based civilizations. Meanwhile, the basis for economic stability, a stable environment, is threatened by climate change.

If, as seems not unlikely, Man is responsible for global warming and climate change, then Man is surely responsible for doing something to either prevent or ameliorate the damaging prospect. Unpleasant though the conclusion may be, it is nonetheless unavoidable: at some point, sooner rather than later, Homo sapiens will attempt to control the climate, to combat global warming in such a way as to restore the stable environment of the last 5000 years of developing human civilization. Unless, that is, Homo sapiens leaves it too late . . . .

## Risk from 'doing too little, too late'

The dangers of attempting to control Earth's climate are evident. But the dangers from not controlling the situation may be even greater.

Graph H.1 shows the varying output from a simple system model that can be set to be near the edge of, but not in, a chaotic state: see page 35. The initial ordered state is evident in the regular behavior between zero and $x = 0.25$ on the graph. The simple model is then stimulated by an impulse at time $x = 0.25$, after which it recovers to its former, ordered state. A second impulse at time $x = 0.75$ drives the system into chaotic behavior again, from which it starts to recover, only to be stimulated once more at time $x = 0.9$ before the system has had sufficient time to 'recover' from the previous impulse. This last impulse drives the system into catastrophic instability, from which there is no recovery.




**Graph H.1** Chaotic stability. A nonlinear, orderly system is stimulated to behave chaotically at time $x = 0.25$, and $x = 0.75$. The first stimulation promotes the system into a chaotic state, from which it recovers towards its former ordered state. The second stimulation, at time $x = 0.75$, promotes the system into a chaotic state again, from which it starts to recover. However, it is stimulated a third time at time $x = 0.9$, before it has had time to recover. The consequence of this last stimulation, occurring before recovery has taken place, is catastrophic system instability from which there is no recovery . . .

Of course, Graph H.1 does not represent the complex behavior of Earth's climate: but it may be an allegory. The model indicates that chaotically stable systems can be driven too far, beyond a point of no return. Earth's climate is already in a chaotic state: adding energy to the system will undoubtedly make the chaotic behavior more pronounced: but, will it drive the already chaotic system unstable? That is probably impossible to predict; but there is a distinct risk that all life on Earth might be extinguished — Planet Earth could end up like our sister planet, Venus, where:

- the greenhouse effect has resulted in surface temperatures of up to 400 °C;
- water and water vapor are rare due to the high temperature;
- the atmosphere is mostly $CO_2$ with a small percentage of nitrogen;
- the atmospheric pressure at the surface is 90 times that on Earth; and
- the clouds are composed of high concentrations of sulfuric acid.

Exaggeration? Could not happen here on Earth? Who knows? Predicting the behavior of complex chaotic systems such as Earth's climate system is extremely difficult. And, as Graph H.1 suggests, different stresses on the system may be cumulative . . . .

# Remedial Solution Concept

## Appreciating the problem

Treating earth as a whole, the problem is seen as one of failing homeostasis — see The Concept of the Open System on page 11, and Equation (1.1) in particular. As an open system, earth receives radiated energy from the sun, on the side of earth facing the sun by day, and earth reradiates (largely infrared) energy into space predominantly on the side facing away from the sun at night. For homeostasis, the energy received should equal the energy re-radiated. Essentially, the earth is less able to reradiate infrared energy because of greenhouse gases. So, there are two potential remedies:

- Reduce the greenhouse gases, allowing reradiated energy levels to rise back to their former, steady-state levels, or . . .
- . . . reduce radiated energy received from the Sun.

The first bullet seems to represent an insurmountable obstacle, at least in the short term. Earth is presently having great difficulties in trying to stop the rise in greenhouse gases, let alone reduce the levels significantly.

But what about the second bullet? Is that feasible? If it were, if the energy inflow to earth's systems could be reduced, even by a small amount, and if that reduction were uniform, then the net effect would be to simply 'take the heat out of the system:' literally. In principle, that would not so much change climate, as limit its more extreme manifestations — weather systems would revert slowly to what they had always been over recent millennia. And, if at the same time greenhouse gas emissions and atmospheric levels could be brought under control, and even perhaps reversed; then the status quo would have been restored with minimal risk.

## Regulating the solar constant

The solar constant is the solar energy incident on unit area normal to the Sun's rays at the Earth's mean distance per unit time. It is currently some 1366 J $m^{-2}$ $s^{-1}$, although it varies over the course of a day and is affected by sunspots. The energy received at ground level is affected by latitude. It is largely this energy, with its latitude variation, together with the Earth's rotation, that generates Earth's chaotic weather systems.

One approach to counteracting global warming would be to cut down the energy reaching earth, i.e., effectively to reduce the solar constant. Even modest reductions, say of 1–2%, might be expected to have a significant effect over time. It would be important to make any such reduction entirely uniform — as would be the case if the sun's output were to reduce slightly. Uniformity would be vital to prevent disproportionate effects upon different areas of the Earth, which would not so much 'take the heat of out of the situation' as perturb the interacting chaotic weather systems, inevitably making things worse — at least locally.

Two complementary concepts come to mind: one that could be implemented in the near term, hopefully before things get out of hand; and a second for the medium to long term. Both involve reducing the solar energy received on earth by a small amount. To appreciate how this might be sensibly achieved, consider the schematic at Figure H.1. The figure shows five Lagrange points, $L_1$–$L_5$ that will exist in theory between any two orbiting bodies. In the diagram, assuming that the massive central body is the sun and the small orbiting body is earth, the Lagrange point of immediate interest is $L_1$. Lagrange point $L_1$ is located directly between the Earth and the Sun, and at 1500 000 km ($1.5 \times 10^9$m) from Earth, is outside the Moon's orbit (mean distance from earth $= 3.844 \times 10^8$m).

A small object placed at $L_1$ would tend to remain in position relative to the other rotating bodies: Although $L_1$ is closer to the Sun than Earth, and would be expected to orbit more quickly due to increased pull from the Sun, Earth's gravity acts to reduce the effect of the Sun's gravity, thereby reducing the object's orbital velocity to coincide with that of Earth. Hence, $L_1$, and the other Lagrange points, which similarly balance out opposing centripetal and gravitational forces,

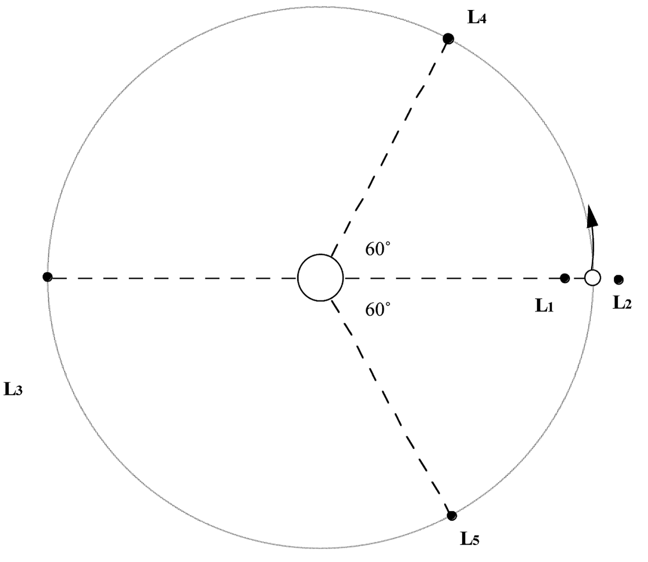



**Figure H.1** Lagrange points. Where two orbiting bodies exist, one much more massive than the other, five Lagrange, or libration, points exist. At these points, a small object placed there will feel no net force, and so will remain in position relative to the other bodies. The Earth and Moon generate five Lagrange points: so do the Sun and Earth.

are stationary with respect to each other; i.e., they rotate together with the orbiting body. $L_4$ and $L_5$ are sometimes described as 'gravity wells,' for this reason. $L_2$ is on the other side of Earth from $L_1$, away from the Sun, at about the same distance from the Earth as $L_1$. $L_3$ is opposite Earth, on the other side of the Sun, and is never visible from Earth: for many years, science fiction writers conceived of a ghost planet Earth at $L_3$. . . .

The Lagrange points are well known to space scientists: The Sun— Earth $L_1$ is ideal for observing the Sun: neither Earth nor Moon ever occults satellites there. The Solar and Heliospheric Observatory (SOHO) and the Advanced Composition Explorer (ACE) are both in orbits at the $L_1$ point.

## The $L_1$ cloud concept

It is known that the solar system occasionally passes through galactic spiral arms of interstellar dust, and that these have the effect of reducing the energy received on earth from the Sun. The $L_1$ cloud concept consists of emulating the effects of the interstellar dust, by injecting a cloud of particles at, or near the $L_1$ Lagrange point, to scatter a small proportion of solar radiation. The concept is illustrated in Figure H.2.

The figure shows a particle cloud, which has been injected into the path of the Sun's rays just to the Sunward side of the $L_1$ point. A small proportion of the Sun's radiation is scattered by the particles in the cloud and does not reach Earth: the bulk of the radiation does reach Earth, otherwise unaffected.

As explained above, the $L_1$ is the balance point between the gravitational attractions of the Sun and Earth and the centripetal force that arises because the earth is orbiting the Sun. The forces at $L_1$

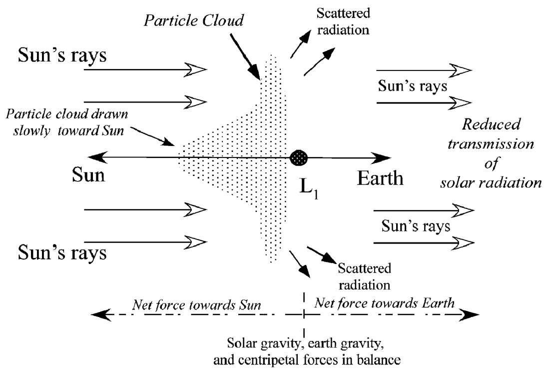



**Figure H.2** Particle cloud screen. To reduce solar energy arriving at Earth, a cloud of particles is injected just to the Sunward side of the $L_1$ Lagrange point, where it is held near and about the Sun–Earth axis. The cloud scatters a small proportion of the Sun's energy, principally infrared emissions, with the bulk passing through unaffected. The cloud disperses gradually under the Sun's gravitational attraction and the solar wind.

are such that a small object to either side of the Sun–Earth line would be moved back towards that line. However, a small object placed nearer to the sun than the $L_1$ would be attracted differentially toward the Sun. So, the $L_1$ is stable only in a plane at right angles to the Sun–Earth axis. By placing the cloud just to the sunward side of that axis, the particles will be slowly drawn toward the sun over time, and the cloud will disperse.

## $L_1$ cloud CONOPS

So, the concept of operations would be to position a satellite in halo orbit at the $L_1$ point: to inject a plume of particles outwards around the halo orbit; to create a disc of particles about the diameter of the Earth just to the Sunward side of the $L_1$; to observe the effect of the cloud on earth; to observe the dispersion of the cloud toward the Sun; and to re-inject the cloud as needed, using the results of test and observations on earth as a guide to frequency of injection, particle cloud composition, etc.

Further, by carefully choosing the particle size in the cloud, it may be possible to scatter a small proportion of incoming infrared radiation only, leaving light and ultraviolet radiation unaffected: this would involve particles to scatter radiation of wavelength 700 nm – 1mm. Leaving visible light and ultraviolet unchanged would minimize even minor effects on photosynthesis, for instance. And, scattering only incoming infrared radiation would directly balance the adverse effects of greenhouse gases, which inhibit largely outgoing infrared radiation . . .

The $L_1$ cloud concept is one that could be implemented with today's technology: it could be controlled remotely; injections could be very limited initially, to anticipate any counterintuitive effects; in the scheme of things, it would be inexpensive; and it could be done now.

## The $L_1$ sunshield concept

$L_1$ would also be an ideal spot to locate a sunshield. $L_1$ is readily accessible from Earth and Moon, facilitating the construction and subsequent control/adjustment of the device, which would be large in area terms, but made of light, expendable materials. A large sunshield raised over the Earth, between the Earth and the Sun, could reduce the effective solar constant by a small amount across the full cross-sectional area of the Earth — some 127, 400, 000 $km^2$.

Consider, too, that any proposed solution will be uncertain in its effect. To mitigate risks, a viable solution will be one where any shielding effect can be controlled — reduced, increased, even removed altogether — in the event that the outcome is not as predicted.

## Sunshield construction

How would the sunshield be constructed, and from what would it be made?

It is not the intention here to solve all the engineering problems that deploying a shield at the Sun–Earth $L_1$ would incur. The $L_1$ is stable only in the plane perpendicular to the line joining Sun and Earth. Moving an object either nearer to the Sun or to the Earth would result in a corresponding increase in the respective gravitational attraction. Nonetheless, stable orbits can be formed around $L_1$.

Positioning a stationary structure, then, is not going to be simple. Another factor to consider is the solar wind — exposed to the solar wind, a sunshield would be pushed from $L_1$ towards Earth. On the other hand, it might be possible to take advantage of the solar wind. Major projects have been proposed in which the solar wind is used to sail a satellite in space much as a sailing yacht uses the Earth's winds. The Advanced Composition Explorer provides continual real-time measurements of varying solar wind velocity, temperature, density and pressure at the $L_1$ point. Pressure, for example is typically about 1nPa (1 nanoPascal), but variable.

Figure H.3 shows an outline schematic of the sunshield in elevation and plan. It is formed of a number of large louver slats, arranged concentrically around a central point $L_1$. The louver angles may be rotated in such a way that the solar wind (velocity 433 km $s^{-1}$, density 2.6 particles $cm^{-3}$ at the time of writing, but varying) impinges on each louvre and creates a thrust towards the center of the sunshield, which is rotated slowly to maintain the structure's integrity. By adjusting the louvers, the amplitudes and direction of the net thrust can be used to maintain the sunshield at the $L_1$ position and with its plane normal to the Sun's rays. As with sailing yachts, this might best be achieved using automatic steering to accommodate wind variability (Pressure has dropped 20% to 0.8 nPa in the time taken to write this paragraph.)

The solar wind would push the sunshield towards the Earth. This force towards the Earth may be countered by locating the sunshield on the sunwards side of the $L_1$, where the Sun's gravitational attraction is greater than that of the Earth, It may be possible for auto-navigation, using the louvres, to maintain the sunshield in this dynamically stable position, effectively 'resting' on the solar wind.

Louvre material will be an important consideration. The panels have to be

- thin enough to filter only a small proportion of the incident radiation;
- light enough to be easily transported and manipulated;
- firm enough to be rotated and to withstand the solar wind pressure;
- ideally, self-repairing to accommodate cosmic particles which will tear holes in them; and
- ideally able to conserve the filtered proportion of solar energy.

N.B. Although louvers are shown in the conceptual diagrams, the panels could be formed in many different ways, including geodetic panels for example. They could be hollow, and contain a working fluid or gas.

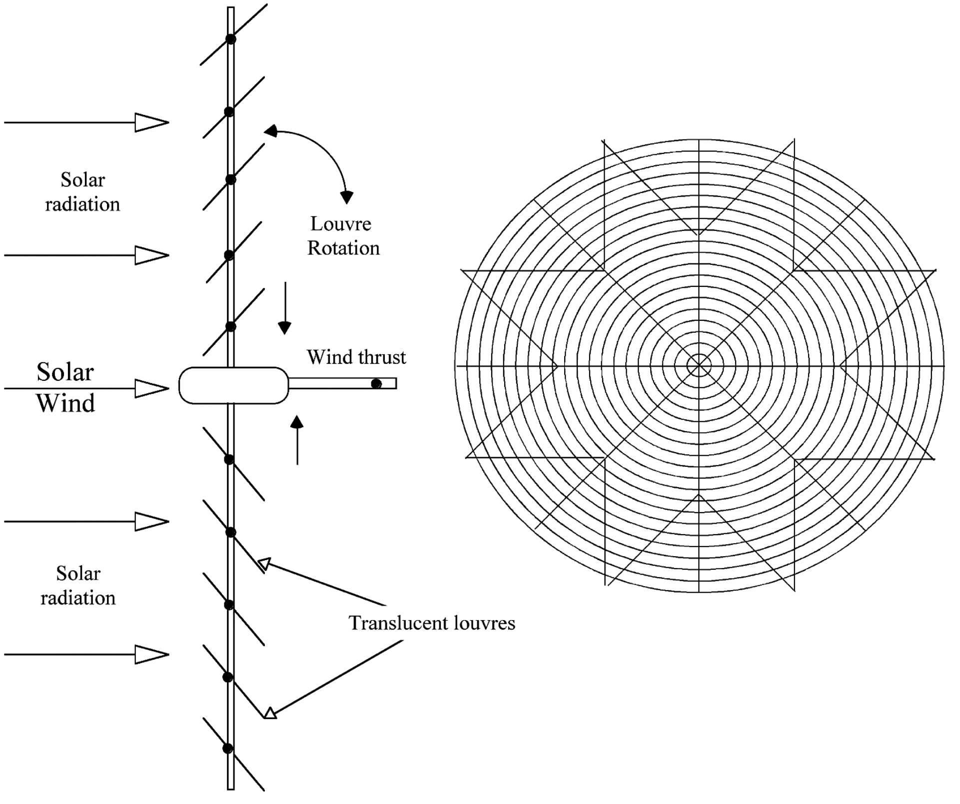



**Figure H.3** Sunshield concept. At right is a face-on view of the shield, showing a web-like structure supporting concentric 'louvre' panels of transparent material. The sunshield would be rotated around the central axis. At left, the structure can be seen side on. Louvres overlap, so that all radiation can be filtered in the fully closed position, or pass through unfiltered in the open position. Louvres are angled so that thrust from solar wind is directed towards the center of the web: louvre angles may be altered automatically to maintain the structure near the $L_1$ point, as with automatic steering on a sailing yacht, and may also be angled to rotate the whole sunshield structure. Locating the sunshield slightly nearer to the sun than the $L_1$ point will counter the axial thrust from the solar wind, and balance out solar tidal drag.

The last bullet is, of course, a tribute to the Dyson sphere: although different in form, and on a much smaller scale than Dyson envisaged, the sunshield could, in principle, gather a considerable amount of energy. And similar, even larger structures could be sited at $L_4$ and $L_5$ specifically for capturing solar energy and converting it for use on Earth, or on the Moon. They would thus have no direct impact on climate, but would affect it indirectly by reducing the generation of energy on the ground, with its concomitant heat wastage.

Solar energy arriving at the earth amounts to some $1.74 \times 10^{17}$ J $s^{-1}$ (i.e., solar constant multiplied by the cross-sectional area of the earth.) If only 1% of that energy were filtered off by the sunshield, that would amount to $1.74 \times 10^{16}$ W. It would be spread over a vast web of louver panels, so that power transmission might incur losses, suggesting a case for superconducting elements in the sunshield structure.

If it were possible to focus the captured energy, it might be transmitted separately to Earth or Moon, providing a much-needed alternative to dwindling fossil fuels, alternative energy sources and even, perhaps, nuclear fusion plants.

## $L_1$ sunshield concept of operations

The construction of the sunshield lends itself to flexible operational introduction and control. The complete structure could be constructed and assembled in space, and put into position at the $L_1$ point. Automatic navigation using the louvers as sails may render orbiting unnecessary. In any event, the structure would be set up with the louvers 'feathered,' i.e., edge into wind so that there would be no solar filtering, no energy generation, and no effect on the earth's solar constant.

Testing would then commence to establish control of the structure to establish the reliability of the auto-navigation system, and to test the physical stability of the structure in the face of varying solar winds, solar sunspot perturbations, etc.

Operational tests would then commence with the louvers ('sails') being closed for short periods, sufficient to observe the impact on Earth, in terms of incident energy, ground, sea and air temperatures, and counterintuitive climatic reactions. Assuming tests to be satisfactory, the sails could be 'unfurled' for longer periods, with further tests, until finally — if all went according to plan — the sails could be left open, navigation could be set to automatic, and the whole would be subject to continual maintenance.

If at any time there was a suspicion of undesirable longer-term effects, then the sails could be partially or fully closed, so regulating effective solar constant, earth temperature and inhibiting climate change — but, essentially, without trying to control climate directly. As with the $L_1$ cloud concept, the sunshield could be designed to filter a proportion of infrared radiation only, if greenhouse gasses were still an issue on earth.

For the future, it might be advantageous to have a second shield positioned, but at $L_2$. Looking ahead to future times when greenhouse gases are reduced, and the possibility of a returning ice age arise, a shield at $L_2$ could be used to moderate the loss of infrared energy from the Earth at night, so providing a counterbalance to the sunshield at $L_1$.

## Comparative timescales

Unlike the $L_1$ cloud, the $L_1$ sunshield is presently beyond our technological capability — not by much perhaps, but we are unlikely to be able to mount such a project in less than a few decades — which may be too late. The two concepts are seen as complementary: the $L_1$ cloud, which we could tackle now, with today's technology and know-how, would buy earth enough time to get its act together, permit undeveloped nations to develop, exhaust our fossil fuel reserves, and get our atmosphere back on track with minimal greenhouse gases.

The $L_1$ cloud is not a long-term solution, however: the $L_1$ sunshield would be more appropriate for the mid-to-long term and it would take some considerable time to build, test and put into operation: even supposing we had the technology. However, were we to undertake a full feasibility and systems design study, it would point to the necessary goals for future research. All of which would seem to be in the best interests of the planet, the environment, the flora, fauna — oh; and yes, humanity, too!

## Risks

Of course, there are risks: risks are unavoidable; both concepts address risk. The $L_1$ cloud can be injected progressively, starting with a very 'thin' cloud to measure the effect. This can then be allowed to disperse, both to observe any after effects on earth and to observe the pattern of dispersion, which could be complex in view of the solar wind, which will flow against the solar gravitational 'tide.' If things go according to plan, a slightly denser cloud can be injected, and so on. If, on the other hand, things do not go according to plan, then there will be time to revise the plan and start again.

In any event, the $L_1$ cloud concept involves making only a slight change in the effective solar constant, and then only in the infrared region of the solar spectrum: although sensitive instruments may detect the effect on earth immediately, it would be decades before enough heat had been 'taken out of the system' to counteract the effects of global warming. Only when extreme weather events became rarer would the impact be realized.

The $L_1$ sunshield similarly addresses risk, particularly in terms of impact on earth environment and climate. The effects would be progressive, with the rate of energy flow reduction being very small. The $L_1$ sunshield is technologically challenging, however, particularly if we wish to 'harvest' the filtered solar energy for use on the moon or earth.

# Critique

The case for doing something to combat global warming, whether it be manmade or not, is mounting. Just what can be done to combat climate change is not really clear — the climate is, after all, a vast system of many, close-coupled, opens systems interacting chaotically. Any direct attempt to control climate in any particular region is unlikely to work. On the contrary, it is likely to make matters worse: if not in the region of interest, then counterintuitively in other regions.

Reducing the effective solar constant, as proposed above, is something to be concerned about. The solar constant appears to have varied naturally in the past, but then, we have had several ice ages in the past. Could we jump out of the frying pan into the refrigerator? It has to a possibility. However, if the concept worked, it would effectively take the heat, gently, smoothly and uniformly out of the chaotic climate, with a view to restoring the chaotic climate to its more moderate self — still chaotic, but without some of the recent, more frequent and forecast extremes.

Is the risk of reducing the effective solar constant worth taking? That is difficult. But it has to be weighed against a host of other risks, and possibilities. Could the planet be on the cusp of a new ice age, as some climatologists argue: if so, could global warming actually be deferring a serious problem?

What is the probability that the politicians will really get together and reduce global greenhouse gas emissions? Is the Tragedy of the Commons scenario on the cards? To believe that the politicians will succeed, and that none of the big players will opt out, in their own, selfish national interests, is to ignore both history and the current evidence.

Supposing that greenhouse gas emissions are eventually brought under control: will their control solve the problem? We are dealing with systems with enormously long time constants, sometimes in the millions of years. There has to be a significant prospect that immediate control of greenhouse gases would be accompanied by an overrun, such that the effect of the high gas levels took some time to wear off, just as they took some 5000 years to build.

Many of these factors are imponderables. Global warming is upon us, climate change is happening, and we seem, as an uncoordinated, antagonistic planet, helpless to do much about it.

Reducing the effective solar constant is doing something. The concept would, of course, create widespread opposition, even supposing the physics to be sound, the systems science to be solid, the engineering to be feasible, and the climatological impact to be as expected. Is it the right thing to do? It is a moral dilemma.

Consider as a comparison: is it right, having detecting a meteor on course to strike the Earth, to try to divert it, break it up, etc? Most people would say yes, although the outcome from attempts to divert such a large body, with so much momentum, is somewhat unpredictable. We might create a rain of intermediate-size meteors, which would hit the Earth, for instance. Should we still try? Most people would still say yes. So, perhaps we should try to save our planet. Else, we may behave like the boiled frog, which sits in water as it is gently warmed on the stove, unable to sense the slow rate of heating, until finally the frog expires — boiled alive without moving a muscle.