The Carbon Conundrum: Damned if We Do and Damned if We Don't?

A lecture presented by Joel Huberman to the RiverMead Retirement Community, Peterborough, NH, on December 2, 2013

Good morning, and welcome to this lecture on the carbon conundrum. By the end of this lecture, about 40 minutes from now, I hope you'll have at least learned what carbon is and why our human relationship to carbon poses a conundrum. Perhaps you'll also have a better appreciation of humanity's current dilemma, which I've summarized as "Damned if We Do, and Damned if We Don't?", with a question mark to indicate that we're not necessarily damned. If we act intelligently and rapidly to change our energy system, we'll be able to escape the Hell on Earth to which our current business-as-usual carbon-based energy system seems likely to condemn us.

Let's start with carbon. It's a remarkable substance, one of the most abundant elements in the universe. Here on Earth, under our terrestrial conditions, it exists in several forms, the best known of which are diamonds (which are clear, amazingly hard, and rare) and graphite (which is opaque, amazingly soft, and relatively abundant). Coal is composed mostly of carbon, but also contains small amounts of other elements such as oxygen, hydrogen, nitrogen and sulfur.

Carbon is an unusually promiscuous element. It forms stable compounds in combination with many other elements, including itself. The fact that carbon can bond to itself means that chains of carbon atoms can serve as backbones for more complicated molecules, including all the molecules of which living organisms are composed. You may have heard that human beings are mostly water. Water is composed of hydrogen and oxygen—recall the familiar formula H-two-O, where H stands for hydrogen and O stands for oxygen. You may be surprised to learn, therefore, that we human beings contain a greater mass of carbon than hydrogen. Carbon is second only to oxygen in terms of abundance by weight within our bodies.

Two chemical processes involving carbon provide the energy on which we—and all other living beings, bacteria, plants and animals—depend. The first process is *photosynthesis*. This is the process by which plants take up carbon dioxide, which is the fully oxidized form of carbon, from the air, mix it with water, and use the energy of sunlight to convert them to sugar and oxygen. The chemical formula for photosynthesis is shown on the slide, but for those of you not trained in chemical formulas, all you need to know is that plants use the energy of sunlight to convert carbon dioxide and water to sugar plus oxygen. Plants then go on to make many other substances from sugar. Animals—after they eat plants—make even more substances that are essential for animal life. But the important thing to remember is that the starting point for *all* the substances found in living organisms here on Earth is the sugars created by plants from two substances, water and carbon dioxide, and from one source of energy—the Sun.

The other chemical process on which all life depends is called *respiration*. Yes, I know "respiration" is commonly used to describe the breathing process, but biochemists also apply the term to the chemical process that is permitted when we breathe in oxygen and breathe out carbon dioxide. As you can see in the diagram, during chemical respiration, oxygen combines with sugars (or with other carbon-based chemicals contained in the food we eat) to generate carbon dioxide and water and to release energy. I hope you can see that respiration is essentially just the reverse of photosynthesis. The difference is that photosynthesis *requires* energy while respiration *releases* energy. The energy needed for photosynthesis comes from sunlight. The energy released during respiration goes to move our muscles, power our brains, and build our bodies. From a mechanistic point of view, therefore, we and all other life forms are simply solar-powered machines.

Human beings have been present on Earth for nearly 200,000 years. During 99.9% of that time, we have limited our sources of energy to the energy contained in the food we eat, the food we feed our work animals, and the burnable plants that we've harvested. In all those cases, the energy we used was recently stored by plants using photosynthesis. For that purpose, the plants used carbon dioxide recently removed from the air. When we burned that plant material to get energy for our use, the carbon dioxide went back into the air. There was no net change in the level of carbon dioxide in the air.

Then about 200 years ago we began to make more use of a different energy source, a source that at the time appeared independent of photosynthesis. That source was coal. More recently we started using oil in addition to coal, and more recently still we added natural gas. Since natural gas is invisible, the picture shows a chemical structural diagram for methane, the major component of natural gas. Methane molecules consist of a central atom of carbon surrounded by four hydrogen atoms.

Coal, oil and natural gas seemed like ideal energy sources. We didn't have grow them, all we needed to do was take them out of the ground. In the cases of oil and natural gas, they frequently came out of the ground of their own accord, as shown in the picture for oil.

Since coal, oil and natural gas come from the Earth, they were of great interest to geologists, who study the Earth. Geologists noticed that coal frequently contained fossils of plant leaves. Later they discovered, by close microscopic inspection of coal and oil, and by study of the rock formations surrounding coal, oil and gas deposits, that all three fuels are in fact the carbon-containing remains of plants and animals that lived millions of years ago. Coal is mostly formed from the remains of plants that were buried under sediments, then compressed and heated over millions of years. Oil is mostly formed by similar mechanisms from the remains of algae and plankton. Natural gas is formed by two mechanisms, one similar to oil and the other a consequence of microorganisms that are able, in oxygen-free environments, to use hydrogen to convert carbon dioxide to methane and water.

What coal, oil and most natural gas have in common is that all were formed from the remains of organisms that lived millions of years ago. That's why we refer to them, collectively, as "fossil fuels."

The energy contained in fossil fuels is the energy from sunlight, used by plants millions of years ago in photosynthesis to create sugar from carbon dioxide and water. Consequently, when we use fossil fuels to generate energy, we're using a form of solar power. We're using the power of sunlight that fell on the Earth millions of years ago. So much for the myth that solar energy can't be stored!

When we burn fossil fuels, the carbon dioxide that's released is from carbon dioxide that was taken from the atmosphere millions of years ago. Now we're returning that carbon dioxide to the atmosphere. Consequently, burning fossil fuels increases the level of carbon dioxide in today's atmosphere.

At the beginning of the industrial age in 1850, before we started burning significant amounts of fossil fuels, the amount of carbon dioxide in the atmosphere was 280 parts per million. Now it's 400 parts per million, and it's heading higher. This is a reason for concern, because, as I will explain in the next few minutes, carbon dioxide in the atmosphere acts in some ways like the glass in a greenhouse. It's warming up the Earth.

The basic science of the atmospheric greenhouse effect was worked out by scientists in the 19th century, long before anyone dreamed that global warming due to burning fossil fuels would ever be a cause for worry. Scientists in the 19th century were concerned about the opposite possibility, that *lack* of sufficient carbon dioxide in the atmosphere may have been the cause of the ice ages that geologists were beginning to describe.

The first scientist to attempt to explain how the Earth's surface temperature is determined was Joseph Fourier, whose scientific prowess led Napoleon to ask him to serve as top scientist for his invasion of Egypt. In that capacity, Fourier was responsible for having the Rosetta Stone brought back to France and translated. But Egyptian antiquities were not Fourier's major interest. What really got him excited was attempting to understand how heat is conducted through solids and liquids of various shapes. He invented a whole new type of mathematics (now called Fourier analysis) in order to solve the equations of heat flow. Using theses equations, he showed that the Earth's surface temperature is not significantly affected by heat rising to the Earth's surface from the molten lava within. Instead, he concluded, the Earth's temperature is primarily determined by visible light radiation from the Sun. He speculated that the atmosphere may let visible sunlight pass through to the Earth, but may trap invisible heat radiation emanating from the Earth, similar to the way the glass in a greenhouse is transparent to visible light but partly opaque to invisible heat radiation. Subsequent work by many other scientists, living in the 19th, 20th and 21st centuries, has confirmed and re-confirmed the basic atmospheric greenhouse phenomenon postulated by Fourier.

The Irish physicist John Tyndall provided the next advance. He showed that the major gasses of which air is composed, nitrogen and oxygen, are transparent to both visible light *and* to heat radiation, so oxygen and nitrogen are *not* greenhouse gases. In contrast, Tyndall found that certain other gases, all of which are present in the atmosphere in much smaller amounts than oxygen and nitrogen, are partly opaque to heat radiation and therefore are responsible for the atmospheric greenhouse effect. These gases include carbon dioxide, water vapor and methane.

Two other physicists, Josef Stefan and his pupil Ludwig Boltzmann, studied the kind of electromagnetic radiation that is responsible for transferring both light and heat between the Earth and the Sun. This radiation is called "black body radiation". It is NOT the same as the radioactivity that comes from nuclear reactors. Instead, it is a kind of electromagnetic radiation, and it may include visible light. Whether blackbody radiation generates visible light depends on the temperature of the emitting body. A body like the Sun, whose temperature is thousands of degrees, produces blackbody radiation that is mostly visible light. But the Earth, whose average surface temperature is about 59°F, produces blackbody radiation that is mostly invisible heat.

Human beings, who are slightly warmer (at 98.6°F) than the average Earth temperature generate blackbody radiation that is slightly stronger than that of the Earth. The picture shows human beings inside a room with walls and a window. All objects in the room (indeed, all physical objects everywhere) generate blackbody radiation, but the quality of the radiation depends on the temperature of the emitting body. The camera that took this picture was sensitive to blackbody invisible heat radiation, and the camera was able to discriminate such radiation depending on the temperature of the emitting body. Note that the average temperature of human beings, 98.6°F, is the same as 37°C—which, according to the scale at the right, corresponds to an orange-yellow color. But the window in the room, which looked out on a pleasant day outside, had a temperature of about 22°C —that's about 72°F—as indicated by its dark blue color.

The important lesson from this picture is that every object in the universe has a temperature and gives off blackbody radiation appropriate for its temperature. The contribution of Stefan and Boltzmann was to identify a quantitative relationship between the temperature of a body and the intensity of the blackbody radiation it would emit.

The next piece of the puzzle was the law of conservation of energy, which was first stated in its modern form by Hermann von Helmholtz. According to the conservation law, energy can be neither created nor destroyed. However, energy can be transformed from one type (for example, the energy contained in visible sunlight) to another (for example, the invisible heat energy emitted as blackbody radiation by the planet Earth).

Conservation of energy is important for understanding the temperature of the Earth's surface, because from this law we can deduce that, for the Earth's temperature to be stable (to remain constant), the energy coming in to the Earth from the Sun's visible blackbody radiation must be balanced by energy leaving the Earth as a consequence of the Earth's own invisible blackbody radiation. If the incoming solar energy is greater than the outgoing Earth energy as in this diagram with the Earth at temperature T_0, then the Earth's surface temperature must increase to a higher value, T_1, at which —according to the law described by Stefan and Boltzmann—the energy of the Earth's outgoing invisible heat radiation would equal the energy of the incoming visible solar radiation. Note the thicker blue lines in the second diagram, which indicate increased invisible blackbody heat radiation leaving the Earth.

As I said before, scientists in the 19th century were not concerned with global warming, but they did manage to convince themselves that reductions in the level of carbon dioxide in the atmosphere could, in theory, have been responsible for the ice ages. During the 20th century, scientists of a new type—paleoclimatologists—demonstrated that this hypothesis was largely correct. They found that ice ages, and the intervening warm periods, were *triggered* by small variations in the amount of sunlight reaching the Earth, due to irregularities in the shape of the Earth's orbit and in the Earth's tilt within that orbit. However, paleoclimatologists discovered that the *major* contributor to ice-age cooling and warming was a consequence of variations in the level of carbon dioxide in the atmosphere. These variations were due to the fact that, when the ocean gets warmer, it can hold less carbon dioxide.

You're all familiar with the decreased ability of warm water to dissolve carbon dioxide, because you're all familiar with the way your ginger ale loses its fizz if it's allowed to warm up. The fizz in ginger ale is due to dissolved carbon dioxide. As your ginger ale warms in its glass, carbon dioxide comes out of solution (generating fizzy bubbles) and then evaporates into the air.

Thus a small amount of warming caused by a slight increase in solar energy reaching the planet would force some carbon dioxide to evaporate from the ocean and go into the atmosphere. In the atmosphere, the carbon dioxide would strengthen the greenhouse effect, leading to even more warming. This is one of several amplifying feedback pathways known to operate in the climate system.

By studying the amounts of carbon dioxide in tiny air bubbles trapped in deep Antarctic ice cores, paleoclimatologists found that atmospheric carbon dioxide levels were consistently about 180 parts per million during the depths of the multiple ice ages that took place over the past 800,000 years. They also found that carbon dioxide levels were never greater than 300 parts per million during the warm periods between ice ages. Thus the magnitude of carbon dioxide increase from the depths of an ice age to the height of a warm period, 120 parts per million, is the same as the magnitude of carbon dioxide increase due to our burning of fossil fuels from 1850 to 2013. The 19th-century scientists who worked out the physics of the greenhouse effect never anticipated that human beings could put so much carbon dioxide into the atmosphere in so short a time.

The extra carbon dioxide we've put into our atmosphere is affecting Earth's temperature, via the greenhouse effect, in two ways. First, the carbon dioxide is causing a direct warming of Earth's surface temperature as a simple consequence of the fact that some of Earth's invisible blackbody heat radiation is being trapped in the atmosphere by carbon dioxide and then radiated back to Earth. My understanding is that this quick, direct warming is the primary cause of the temperature increases we've measured so far.

Second, the fact that some of Earth's outgoing invisible black body radiation is being trapped in our atmosphere and re-radiated back to Earth means that Earth's energy balance with the Sun has been disrupted. The Earth is no longer in energy balance with the Sun. More solar energy is reaching the Earth than the Earth is presently capable of radiating out into space. That means the Earth's surface temperature will have to rise even more, until energy equilibrium is re-established with the Sun. That process will be slow compared to human life spans, because 93.4% of the extra heat energy is going into the oceans, and the oceans can take a thousand or more years to reach a uniform temperature. Although the surface layers of the ocean can warm up quickly, the deeper layers mix with the surface layers only very slowly.

How fast is the Earth system warming? The answer can be determined in two ways. Using modern instruments, scientists can measure how much energy is coming in to the Earth from the sun, how much is being reflected back into space by clouds and ice sheets, how much is striking the Earth's surface and warming it up, how much is being re-radiated from the Earth up into the atmosphere, how much of that radiation is trapped by greenhouse gases in the atmosphere and how much makes the journey through the atmosphere and onward into outer space. The answer, obtained by subtracting the outgoing invisible heat radiation from the incoming visible solar radiation, is six tenths of a watt per square meter of the Earth's surface. That doesn't seem like much—it's only the energy used by two LED night-lights.

The same answer can be arrived at by a second method. In 2000–2007, as a result of international scientific cooperation, over 3000 submersible measuring stations, called Argo floats, were deployed throughout the world's oceans. These floats accurately measure temperature, pressure, and salinity at depths down to 2 kilometers. Every 10 days they rise to the ocean surface and send their data to satellites overhead. As a result of Argo floats, scientists can now accurately calculate the average rate at which the oceans are warming up.

That rate also corresponds to about 6 tenths of a Watt per square meter—two night lights per square meter.

Considering that 93.4% of total global warming is going into heating the oceans, it's not surprising that the rate at which the oceans are heating—as measured by Argo satellites—is essentially identical to the total rate of global warming as measured by comparing incoming visible solar radiation with outgoing invisible heat radiation.

Two night-lights per square meter may seem small, but when multiplied by the huge number of square meters over the surface of the Earth, it becomes very, very large. It's the amount of heat that would be generated if each of Earth's 7.1 *billion* human beings were operating two dozen—24—hair dryers of 1500 Watts each, 24 hours a day, 365 days a year. Imagine how hot this auditorium would quickly become if each of us had brought our 24 hair dryers in with us. I'm certainly grateful that the oceans are currently soaking up 93.4% of the global warming caused by our releasing carbon dioxide when we burn fossil fuels.

Although the oceans are soaking up most of the global warming, the remaining 6.6% of the warming is already having noticeable effects. The Earth's average land and ocean surface temperatures have been rising, especially since the 1970s, when the effect of human carbon dioxide emissions began to overwhelm natural variation. Although this graph shows temperature in degrees Celsius, it implies that average global surface temperatures have risen by 1.4°F since 1850.

That amount, 1.4°F, may not seem like much, but it has led to an increased frequency of very strong storms, an increased frequency of very large forest fires, accelerated melting of most glaciers throughout the world, an increasing rate of melting of the Greenland ice sheet, which is contributing to sea level rise, and a similar increasing rate of melting of the Antarctic ice sheet, which also contributes to sea level rise.

I think that now you are beginning to see what I mean by our "carbon conundrum". Fossil fuels are wonderful, convenient sources of energy. Their use has made our individual lives much more comfortable than in 1850. It has permitted world agricultural output to expand tremendously since that time, thus allowing human population to expand from just over 1 billion people in 1850 to about 7.1 billion people now, and rising. But the carbon dioxide that we've added to the atmosphere as we've burned those fossil fuels is already having deleterious effects on our climate, and climate scientists predict much worse if we continue burning fossil fuels at our current rate for more than a decade or two. If we persist in burning fossil fuels until they're nearly exhausted, we might even return to conditions like those during the age of the dinosaurs, when no warm-blooded mammal could be larger than a small rodent without lethally overheating. Thus we're certainly damned if we do continue burning fossil fuels much longer.

In fact, if we burn fossil fuels until they're nearly exhausted, we'll be damned in two ways. We'll suffer from climate change so extreme that it will almost certainly make impossible the continuation of human civilization, and it may also put an end to the not-so-wise human species. But we'll be damned in a second way as well. We've gotten used to the easy energy provided by fossil fuels and nuclear power. But, as I'll show in a few minutes, fossil fuels and nuclear power (which comes from uranium) are finite resources. Supplies of both may last until the 22nd century, but eventually we'll run out. Unless we have a renewable energy infrastructure in place at that time, we'll suffer the consequences of inadequate energy on top of our sufferings from global warming.

So we're certainly damned if we do continue burning fossil fuels for more than a few decades. But will we be damned if we reverse our course and stop burning fossil fuels?

The answer is, we'll have to go through a tough adjustment period, but on the other side of that adjustment period, our energy problems could be solved for the foreseeable future. The alternative to fossil fuels is renewable energy. This diagram shows the amount of energy *per year* available from renewable sources, and it also shows the amount of energy still available from fossil fuels (natural gas, petroleum, and coal) and from uranium via nuclear power. The amounts are represented by the volumes of the spheres, and also by the numbers printed on the spheres. Please notice the orange sphere, floating in front of the solar sphere at the far left. That small orange sphere represents the total amount of energy currently used by humankind *in a single year*. If we were to continue using this amount of energy, and if we were to burn only coal—which has the largest reserves—the coal would be gone just 56 years from now! In other words, fossil and nuclear fuels are finite. They can sustain our energy needs for a while longer, but they'll be exhausted some time in the next century. In contrast, renewable energy sources are *renewable*. The sun is, and will continue to be, a *huge* energy source, capable of providing for all our needs without assistance from any other source. Although not as large an energy source as sunlight, wind energy by itself is also capable of providing for all our needs.

The only problem with renewable energy is that the infrastructure needed to exploit it—solar panels, wind turbines, improved transmission lines, mechanisms for storing energy from these intermittent sources, has not yet been built. Building that infrastructure will require energy, and the only sources of energy currently available for building that infrastructure are fossil and nuclear fuels. So we'll need to continue burning fossil fuels while we build a renewable energy infrastructure.

This diagram shows the magnitude of the problem. Our energy mix in 2008 was similar to our current mix. Nearly two thirds of our energy comes from fossil fuels. To avoid the worst consequences of global warming, we need to get from the 2008 energy mix to the kind of energy mix shown in this hypothetical diagram for 2020, and we need to get there as rapidly as possible.

Avoiding the worst consequences of global warming means keeping the temperature rise below 2°C (3.6°F). As shown in this diagram, to stay below that limit means burning only a small portion, about one fifth, of our declared fossil fuel reserves. That amount should be sufficient to permit us to build up a satisfactory renewable energy infrastructure, but only if we start doing so nearly immediately.

There are three policy options that can help stimulate rapid buildup of our renewable energy infrastructure. Two of the options are relatively benign and are partly market-based. The third option would be government-supervised, but could also be relatively benign.

A carbon tax policy is favored by many economists, scientists, and even politicians. It would be a gradually increasing tax on fossil fuels at their sites of production. The revenues could be returned to taxpayers as reductions in other tax rates, so a carbon tax could be revenue-neutral. The effect of a carbon tax would be to gradually raise the price of fossil-fuel energy, helping to make renewable energy sources competitive in the marketplace. In other words, a carbon tax would act something like a "stick" in the old parable of the carrot and the stick.

A policy that could serve the role of "carrot" is known throughout most of the world as "feed-in tariffs". In our country, the policy is better known as "power purchase agreements", in which producers of electrical energy from renewable sources are paid a set fee, or tariff, for every kilowatt-hour of electricity they feed into the grid. The fees are structured so that producers from all renewable sources—whether wind or solar or biomass—would be able to make a small profit on their investment, usually about 5% per year. The fees are also structured so that small projects, from individuals or small cooperatives or small communities, would be able to make the same profit as large corporations. Feed-in tariffs have already proved remarkably successful at building up renewable energy infrastructure in many jurisdictions throughout the world. Two notable examples are Germany and our near neighbor, Ontario Province in Canada.

In case these two policies, in combination, prove insufficient, there's a third alternative—a rapid mobilization of resources, directed cooperatively by the governments of the world—to build up the needed renewable energy infrastructure, very much as many governments, including ours, accomplished during World War II. Because world population growth, increasing scarcity of water, and increasing need for adequate food supplies are also parts of humankind's current crisis, we would all benefit if measures to mitigate those problems were also part of the world-wide mobilization. Several creative thinkers who specialize in analyzing the world's problems and suggesting solutions, for example Lester Brown and Jeffrey Sachs, have already calculated that the amount of money needed for such a mobilization need not be impossibly large. Indeed, they calculate that the amounts needed to solve all the indicated problems would be less than what the world currently spends on maintaining its military. We could think of such a world-wide mobilization as a well-justified part of our defense budget.

In other words, there's reason for hope. In my view, the title of this lecture should be changed from "Damned if we do and damned if we don't?" with a question mark to "Damned if we do and not necessarily damned if we don't," without the question mark. Indeed, if we can, in addition to building a renewable energy infrastructure, also manage to solve the problems of poverty, population growth, and food and water shortages—as Lester Brown and Jeffrey Sachs think we can—then the title should be further modified to "Damned if we do, and possibly blessed if we don't."

My friends, the planet Earth is still a beautiful place for us and for many other forms of life. But it's not infinite. We cannot continue to exploit the Earth's resources in uncontrolled fashion. But if we live up to the word "*sapiens*", which means "wise", in our species' name (*homo sapiens*), then by choosing *intentionally* to limit the rates at which we harvest the Earth's resources, we and especially our children and grandchildren, and *their* grandchildren, will be able to continue leading comfortable lives while enjoying our planet's wonders and beauty.

That's all for today. Now I'd be glad to attempt to answer your questions.