4.1 POWERING THE PLANET

Dr. Nathan Lewis

It is great to be giving you this talk by carbon-neutral methods (i.e., video teleconference) in lieu of actually traveling to your location. I will talk to you about energy because most people who look at this issue think, like Professor Richard E. Smalley testified in Congress, that it is the most important problem facing humanity today. Those are fighting words, so now we have to defend them. [1]

To do that, we will look at three aspects of the problem. First, we will talk about the scale of the challenge because you cannot solve a problem if you do not know the scale of the problem you are trying to solve. On the back end, we will talk about another aspect of the problem: namely, that we have run out of air to store the emissions from all the stuff we have burned. In between, we

Dr. Nathan Lewis has been on the faculty at the California Institute of Technology since 1988 as the George L. Argyros Professor of Chemistry, and he has served as Professor since 1991. In addition to his faculty appointment, he serves as the Principal Investigator of the Beckman Institute Molecular Materials Resource Center and is the Editor-in-Chief of Energy & Environmental Science*, a Royal Society of Chemistry journal. Dr. Lewis holds a Ph.D. in chemistry from the Massachusetts Institute of Technology. He has been an Alfred P. Sloan Fellow, a Camille and Henry Dreyfus Teacher-Scholar, and a Presidential Young Investigator. Dr. Lewis has received numerous awards for his work, including the Fresenius Award in 1990, the American Chemical Society Award in Pure Chemistry in 1991, the Orton Memorial Lecture Award in 2003, the Princeton Environmental Award in 2003, and the Michael Faraday Medal of the Royal Society of Chemistry Electrochemistry Group in 2008. He has published more than 300 papers and has supervised approximately 60 graduate students and postdoctoral associates. His research interests include artificial photosynthesis and electronic noses.*

will talk about what the laws of physics and chemistry, not the laws of politics, tell us we can do about this problem because, unlike the laws of politics, the laws of physics cannot be repealed. If you want to hear the longer version of this talk, you can go to my website: **http://nsl.caltech.edu/**.

So, let's begin with what I call the terawatt challenge. A laptop is an average load of about a few watts; a toaster is a kilowatt. A thousand toasters is a megawatt. A small jet engine is a thousand megawatts. The output of the typically rated nuclear power plant is a gigawatt. A thousand of those is a terawatt; that is the world's average electricity load. You cannot solve the energy problem without thinking about terawatts. But the situation is even more extreme than that because electricity is only a small fraction of total consumed energy. If you add up all the energy, the heat content of all the joules consumed in a year, divide by the number of seconds in a year, you get the average thermal burn rate of energy consumption in terawatts.

As it turns out, that number was about 13.5 TW in 2001 (Figure 1); it is pushing 15 TW right now. That is the scale of the problem with which we have to deal. Roughly 85% of that total is made up of approximately equal parts of the fossil energies—oil,

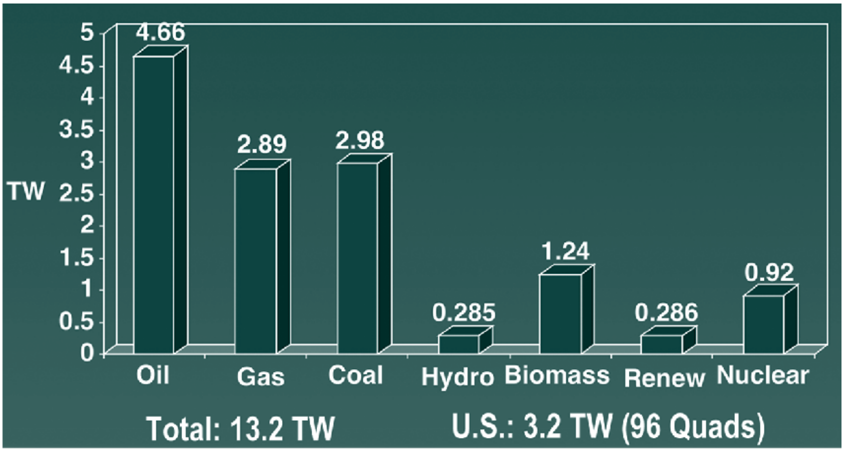
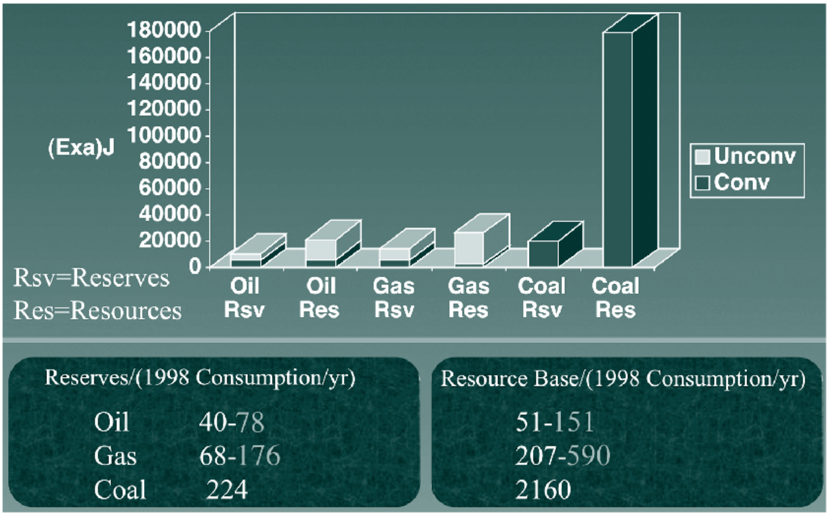


Figure 1. 2001 Global Energy Consumption Broken Down by Resource

gas, and coal. A little bit is hydro; nuclear power produces 0.9 TW, but the astute amongst you will know that we produce only 0.3 TW of electricity because 0.9 TW is the primary heat content of all the fission in nuclear reactors in the same way that 3 TW is the primary heat content of all the coal consumed. Conversion losses account for the difference between the heat content and the electrical energy actually produced.

So that is the scale of the energy issue right now. You may think that this will naturally change because of market forces, and therefore we can just wait until the price goes up and let supply and demand drive us to a different mix, so no action needs to be taken before then.

Figure 2 shows the peer-reviewed numbers of all of the most conventional and unconventional globally proven reserves at the number the U.S. Securities and Exchange Commission (SEC) lets a company or a country book as having in the ground with 90% confidence. The resource base is more important because that is what the U.S. Geological Survey (USGS) estimates is available to be recovered by humans on our planet.



	Reserves/(1998 Consumption/yr)	Resource Base/(1998 Consumption/yr)
Oil	40-78	51-151
Gas	68-176	207-590
Coal	224	2160

Figure 2. Fossil Fuel Energy Reserves and Resources

The proven reserve is divided by the consumption rate in a recent year, so we have between 40 and 80 years' worth of oil, between 60 and 160 years' worth of natural gas, and almost 200+ years' worth of coal. Furthermore, the countries that have large demands also tend to have large coal reserves. Now some people look at this and say, "That means we're going to run out of oil in 40 years"; nothing could be further from the truth. The ratio of proven reserves to consumption of oil has been 40 years for the past 100 years, since the day after oil was discovered. This is because discovery never stops. We know exactly where two-thirds of the oil that has been discovered is—it is in the ground where we have left it because it was uneconomical to recover it at $8 a barrel when Saudi oil production now costs only $4 a barrel.

But we could go get all of that at $20 or $30 a barrel if we wanted to. What matters more is the resource base; the USGS and agencies such as the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA) say that we have, globally, between 50 and 150 years' worth of oil, between 200 and 600 years' worth of natural gas, and almost 2000 years' worth of coal. Furthermore, when oil eventually peaks, which it will because it is finite, we already know how to make coal into liquid hydrocarbons. Germany did that on a dime in World War II when denied oil by the Allies. South Africa also did that when denied oil from the apartheid boycotts. Moreover, these projections do not count the amount of methane clathrates present over the continental shelves, which is estimated to be more than all of the oil, coal, and gas on our planet combined.

So message number one here is that the Stone Age did not end because we ran out of stones, and the Fossil Energy Age is not going to end within our lifetimes because we are going to run out of cheap fossil energy. So do not wait for that to happen.

It seems that I have just told you there is no problem; however, when I began, I told you this was the biggest problem. So now we have to see why those two statements are still true. We need to summarize what the Intergovernmental Panel on Climate Change (IPCC) in 1992 projected, not about climate, but about energy in what is called the "business-as-usual" scenario, but it is hardly business by anybody's usual standard.

My favorite out-year to consider is 2050 because I teach college freshman, and they will turn my age in 2050. In addition, 2050 is important because the built-infrastructure turnover lifetime of the capital deployed in energy is about 40 years. You do not turn over a nuclear power plant like selling a used car, and you do not do the same thing with a solar farm or with a wind farm. When you build something, it must pay itself back over a 40-year lifetime, so we are building the 2050 infrastructure within the next 10 years. Now, you can figure out human energy demand by knowing first how many humans will be demanding energy. The IPCC said we are at 6 billion now, and we will grow to 9 or 10 billion, so let's stick to 9 billion, although it does not really matter.

Now we would not consume much energy if we did not do anything, so we have to understand gross domestic product (GDP) growth per capita because energy tracks GDP growth—it always has. After all, if we did not make any products and we did not go to work and I did not turn on a computer while giving this presentation, we would not consume much energy. As it turns out, globally averaged per-capita GDP has historically grown at 1.6% per year. So the IPCC said that, in the business-as-usual scenario, the next 50 years will bring what the last century brought. No one could have foreseen the unforeseeable at the time: sustained double-digit economic growth in China and India. But developed countries believe 3% or 4% growth is sustainable.

As we painfully see today, no country has a policy against economic growth, so it is unlikely that this number is going to go negative, and 1.6% is now viewed as a near-recession level. But we will assume that business as usual will continue and that GDP growth compounded with population growth would, if unmitigated, lead by 2050, through the magic of compounding, to a tripling of energy demand from 2000 levels, or to some 47 TW. On the other hand, energy consumption has been declining per unit of GDP because energy does cost money and we are using it more efficiently. It has been used more efficiently per unit of GDP at rates of 1% per year historically.

Now the United States is saving at twice the world's rate, that is because (1) we are so wasteful that it is easier for us to save and (2) when you have only one candle at night, like the 2 billion people who are not blessed with any modern electricity, how much can you actually save anyway? So, because the developing countries are not saving and the developed ones are saving about twice that rate, the world average is about half. But whether or not it is 1% or 2%, again, will not make any difference, so we will go with 1% here. Now this will not be easy, but, again, due to the magic of compound interest, we can determine that by the year 2050, the average energy demand per capita will be a total load of 2 kW thermal per person.

Let's compare that number to historical data for the average energy demand for people in different countries. That is five times less than the current per-capita U.S. energy consumption—not 50%; it is five times less. If you drove your car half an hour today, under this scenario, that is all the energy you would get—none to eat, none to heat, none to make electricity; that would be it. This is two and a half times better than the most advanced industrialized societies, the European Union (EU), Switzerland, and Japan. China is already above this level; India has a government policy to get above this level within 10 years as it brings another 700 million of its citizens out of extreme poverty (Figure 3).

If you can hold energy consumption at 2 kW per person, even if you did better than that by a factor of two, nothing I will tell you about will change. Now let me also tell you what 2 kW per person means. A 2000-food-calorie/day diet, divided by the number of seconds in a day, is 100 W. So humans are 100-W lightbulbs just to eat. That does not sound so bad because this is a 2-kW budget per person. But the energy embedded in food—the energy needed to grow the food, harvest the food, get it to the supermarket, and have you go get it, process it, and cook it—is between 10 and 25 times the energy in the food itself.

If you can hold it to 10, then a 100-W person burdens the system with 1 kW, and I am going to give you 2. So we will assume that we save energy down to twice the level it takes to eat, within our lifetimes, starting today. If we did twice as well as that, nothing

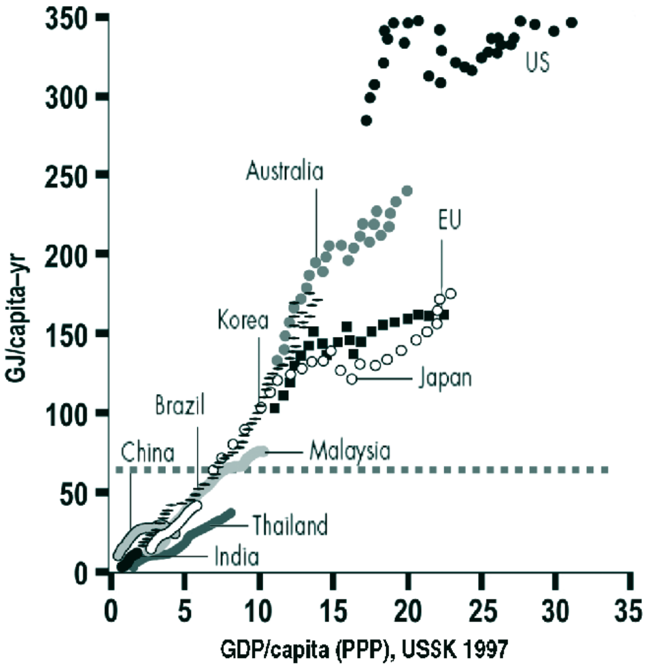


Figure 3. Energy Consumption vs. GDP per Capita [Measured in Thousands of 1997 U.S. Dollars and Adjusted for Purchasing Power Parity (PPP)]

I will tell you about will change. If we could do that, that would mitigate demand so that it only grows to double, 28 TW. Even if we saved so much energy that we kept energy demand flat, something the world has never done for a 4-year period in human history, nothing I will tell you about will change. This is because we have plenty of fossil energy.

We are using coal to meet this increased level of demand, both regionally and globally, like it is not going out of style because it is not. So what is the problem? We need one more fact. This is the carbon intensity, the average amount of carbon emitted to the atmosphere as CO_2 when averaged over the energy mix. Figure 4 shows historical data. We started out at that top horizontal line because we were bad engineers when we were cavemen. The worst way to make energy useful? You heat a lot of wood, most of

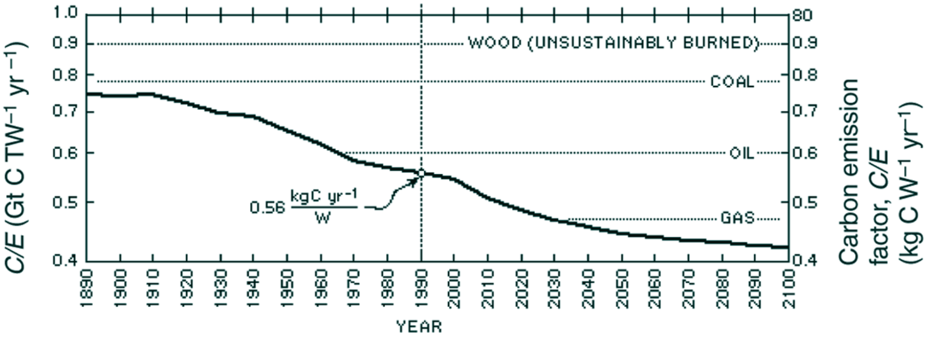


Figure 4. Carbon Intensity [Carbon-to-Energy Emissions (C/E)] of the Energy Mix of Fossil Fuels [2]

the heat makes CO_2 that goes into the air, and hardly any heat is delivered to the caveman. Then we got to be bad chemists because we burned coal to power our locomotives, and coal by mass is all carbon, so when you make it, you burn all of the carbon to make all CO_2. Natural gas is better because its chemical formula is CH_4; so for every molecule of CH_4 that you burn in air, you make one molecule of CO_2 but two molecules of water, H_2O. More of the heat goes off as water, less goes off as CO_2, so it is lighter in CO_2 emission per units of energy produced than is coal; oil is in-between because its chemical formula is in-between. Those three things you can do nothing about because they are properties of the fundamental heats of combustion and the molecular geometries of oil, coal, and gas.

We were about average between them (coal, oil, and gas) in 1990 (see the open circle in Figure 4), and the IPCC, in the business-as-usual scenario, projected that the next 50 years would continue the decline in carbon intensity of the last 100 years. If we continue on that path, you will realize that it brings you down to an average carbon intensity by 2050, lower than that of the least carbon-intensive fossil energy source. Now the only way you can get the average down below any of the individual values is to have a zero somewhere in the arithmetic. Furthermore, to the extent that we do not kick the habit starting tomorrow and we still burn roughly equal parts of oil, coal, and gas, you need even more zeroes to get this arithmetic to work out.

But we will assume we do that too. So in addition to saving energy down to twice the level it takes to eat, we will assume that, starting today, we follow this business-as-usual scenario, hardly business by anybody's usual, and decarbonize the energy mix down to a level that is better than a pure natural-gas economy within our lifetimes. Well if we know the amount of energy demanded in each year and we know the amount of carbon emitted per unit of energy demanded in each year, it is just arithmetic to multiply those two numbers together to get, with no assumptions, the amount of CO_2 that will absolutely go into our air if we adopt that trajectory.

The significance of that brings us onto the top curve of Figure 5. Even the scenario that I showed you is not close to what would be needed to stabilize the concentrations of CO_2 in our atmosphere at levels given by these numbers, in parts per million (ppm). The pre-epigenetic of CO_2 was stable for 10,000 years at 280 ppm. If you wanted to hold it to 350 ppm, you would have to follow that bottom curve because you could never burn a molecule of oil, coal, or gas on our planet again within our lifetimes. If you wanted to hold it to 550 ppm, double what any human would have

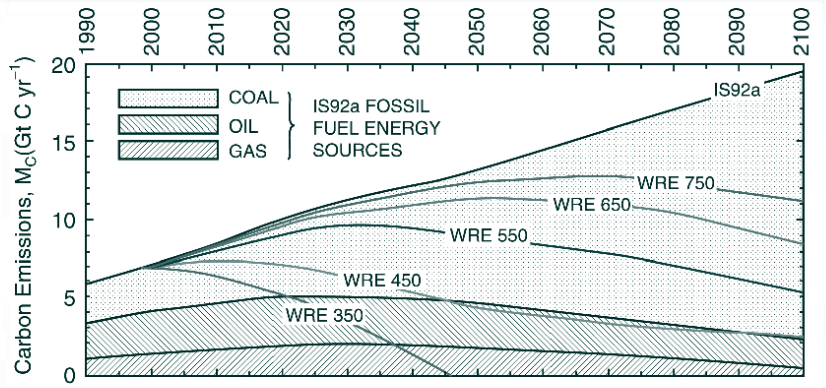


Figure 5. CO_2 Emission vs. CO_2 in the Atmosphere Projected Through 2100

otherwise experienced, you still have to do better than the scenario that I just showed you.

Now outside of a climate model, nobody knows which levels of CO_2 are or are not "safe." This is absolutely not about sound science; this is absolutely all about risk management. If we wait until we can predict the climate in 2050, I will tell you the scientifically accurate day this will occur: New Year's Day, January 1st, 2050, when we look outside. Now we know a little bit more than that. We know that CO_2 levels have never exceeded 300 ppm for the last 470,000 years. In fact, we can extend that with new data to 670,000 straight years.

We know that swings of CO_2 of 100 ppm have been seen seven times and repeatedly correlated with, but not necessarily proven to be the cause of, temperatures that have repeatedly sent us into and out of planetary ice ages. We do not know with absolute certainty what 550 ppm or higher would bring. We do know that no human has experienced this, nor would it have been in the record of our planet for more than modern human history. We know that we see ice melting. Our inability to predict cuts both ways. In Figure 6, you can see the predicted spread of the rates of ice melting and that the actual satellite data show that it is melting more rapidly than the most pessimistic predictions.

No matter what you think about the radiative effects of adding absorbing gas to the atmosphere, anybody who has ever opened a can of soda knows that when you add CO_2 to water you make it acidic. The pH of the oceans is now lower than it has been in 4 million years and probably in the last 20 million years. Twenty percent of the coral is already bleached. Most, but not all, climate models say that between half and all of it will be bleached within our lifetimes. Even these so-called linear effects are not potentially the big game changers. The permafrost is clearly melting; isotopic dating tells us it is melting in areas that have not melted in at least 40,000 years.

As it melts, the white ice that would have reflected light now turns into dark, absorbing matter that then absorbs more light and warms further and releases the trapped methane in permafrost.

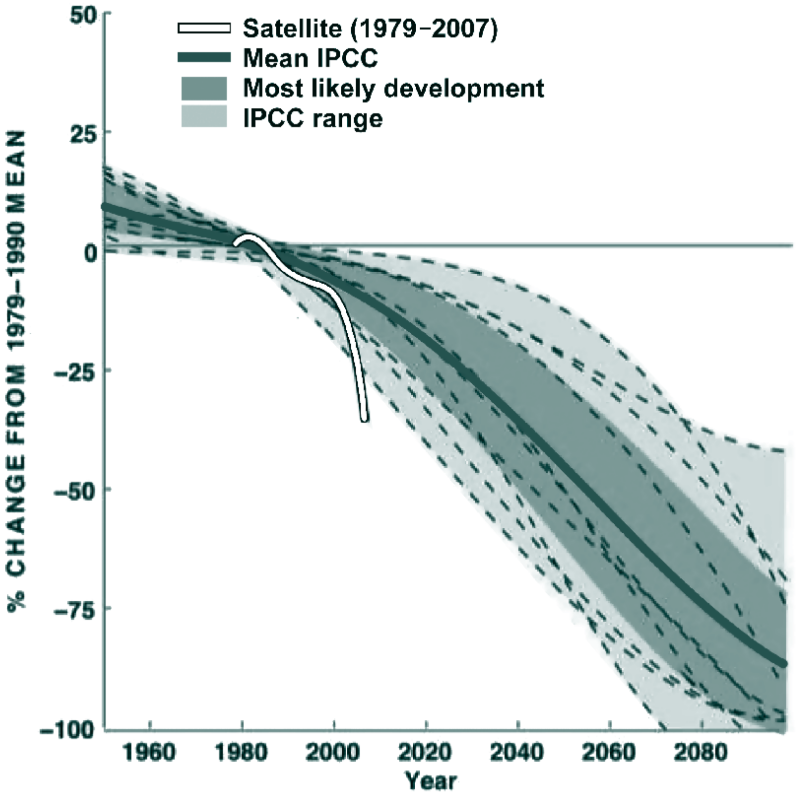


Figure 6. Predicted and Actual Percentage Change (Melting) in the Greenland Ice Sheet

If this continues to melt, CO_2 levels will not go up by a factor of 2, but could go up by as much as a factor of 10. We know this happened at least once before, 230 million years ago, when there was an isotopically light, rapid release of CO_2 thought to be permafrost melting. We know temperatures spiked by 6°C on average, and we know from the fossil record that 90% of the species then on Earth could not adapt and went extinct.

We absolutely do not know that this would happen again. We absolutely do know that there is only one way to find out. Another important consideration is the lifetime of CO_2 in our atmosphere. There is no natural destruction mechanism for it because CO_2 is the most oxidized form of carbon in the oxidizing atmosphere in which we live. Our best scientific knowledge says that, if we get to 550 ppm—and we are on a path to do more than that pretty fast—and then we kick the habit in the delta function and stop the next day, three-quarters of the CO_2 that is already there would decay in 300 or 400 years, and the last quarter would take 10,000 years on the weathering cycle to decay, for an average recovery time of the planet to the one we know today of 3000 years.

So we are going to simply do an experiment that is going to persist for a timescale comparable to that of modern human history. If you want to avoid that experiment, you can talk all you want about global warming solution acts, but the Earth balances its books every single day. On the business-as-usual trajectory, just to keep that average mix down, assuming we save energy down to twice the level it takes to eat, the arithmetic showed that you had to bring on almost 10 trillion W of carbon-free power by 2050. If you wanted to hold CO_2 levels to double, you had to bring on more than that.

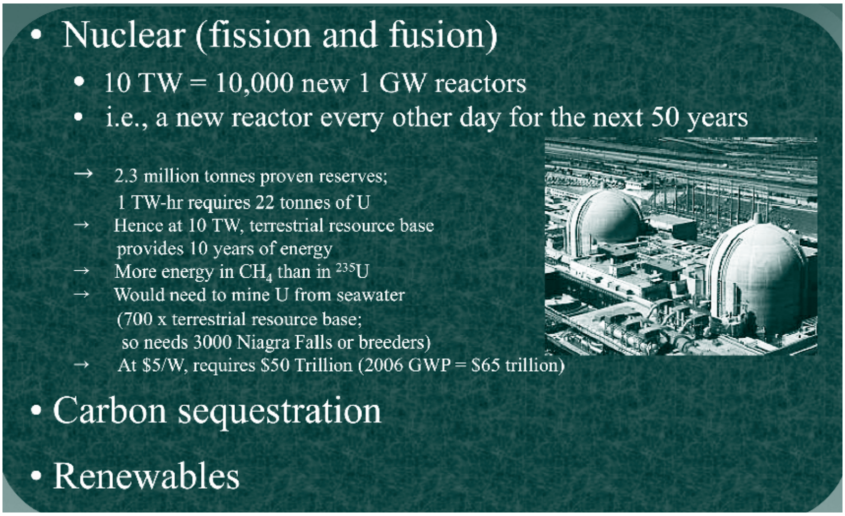
If you did not save as much energy, you would have to bring on even more than that; by any measure, you have to bring on as much carbon-neutral or carbon-free power by 2050 as all the oil, coal, gas, and nuclear power on our planet combined, starting today. If you wait 40 years to do this, you will have 40 more years of emissions under your belt that simply do not go away; that is why this is a problem. If you believe that this is a risk that you do not want to take, then we need to start addressing the problem today.

So the question then is where in the world are we going to get 15 or so trillion W of carbon-free power within our lifetimes? The cruel arithmetic of energy says that if you do what we heard in the presidential campaign, build 46 new nuclear power plants, that is not even a tiny drop in the bucket of what is needed to solve this problem. Well, let's look at what the laws of physics say the allowed solutions can actually come from.

The only proven technology that we have that can scale to these levels is nuclear power. Although I am not personally against nuclear power, others are. Nevertheless, it is hard to see how you can get from here to there without a significant contribution from nuclear power to the energy mix (Figure 7).

On the other hand, we need to understand what we are voting for because if we do nothing else, this will be the only card we have to play. I already told you that, in that scale of things, the output of a typical nuclear power plant—built to scale, to safely confine with known materials, the heat flux and neutron flux in the core—is a billion watts, a gigawatt. I told you at minimum we need 10 trillion W. So, you will see that we do not need 46 nuclear power plants; we need over 10,000 nuclear power plants.

You need to build a new nuclear reactor now, every single day, for the next 40 straight years if you want to hold CO_2 levels to double, assuming you save energy down to twice the level it takes to eat, starting today. There are a few other small facts, one being that there is not enough terrestrial uranium to do this at this level for more than 10 years. You could get it from seawater if you want to build the equivalent of 300 Niagara Falls, mining all the oceans of the world to get out the 3 parts per billion of the needed uranium. You could also build these at $5 a peak watt, a conservative



- Nuclear (fission and fusion)
  - 10 TW = 10,000 new 1 GW reactors
  - i.e., a new reactor every other day for the next 50 years
    - → 2.3 million tonnes proven reserves; 1 TW-hr requires 22 tonnes of U
    - → Hence at 10 TW, terrestrial resource base provides 10 years of energy
    - → More energy in CH_4 than in ^{235}U
    - → Would need to mine U from seawater (700 x terrestrial resource base; so needs 3000 Niagra Falls or breeders)
    - → At $5/W, requires $50 Trillion (2006 GWP = $65 trillion)
- Carbon sequestration
- Renewables

Figure 7. Sources of Carbon-Free Power

estimate if you only had $50 trillion to spend, which used to sound like a lot of money.

Now if you build only one nuclear power plant a week, starting today, every week, somewhere in the world for the next 40 straight years—and because they last only 40 or 50 years, that means building one basically forever—you still leave 90% of the problem on the table. So where else can you turn? Well we can take all the fossil energy and bury the CO_2 somewhere (Figure 8); you could put it in the oceans, but we are already adding too much acidity to the oceans. You could put it in the oil and gas fields, but there is not capacity to do it there for more than 30 years globally. So the favorite technical idea is to put in the underground aquifers in the brine, where the good news is that the CO_2 will dissolve in the water and make Perrier, which costs more than a gallon of gasoline, and we could export it to fix our balance of trade with the French.

The news is that CO_2 is buoyant, and when you are burying billions of tons of this stuff, it will migrate and move, and nobody knows where it will go and, more importantly, whether or not it might leak. If 1% of it leaks after 100 years, then the net flux is the same as what you tried to mitigate in the first place. So technically,

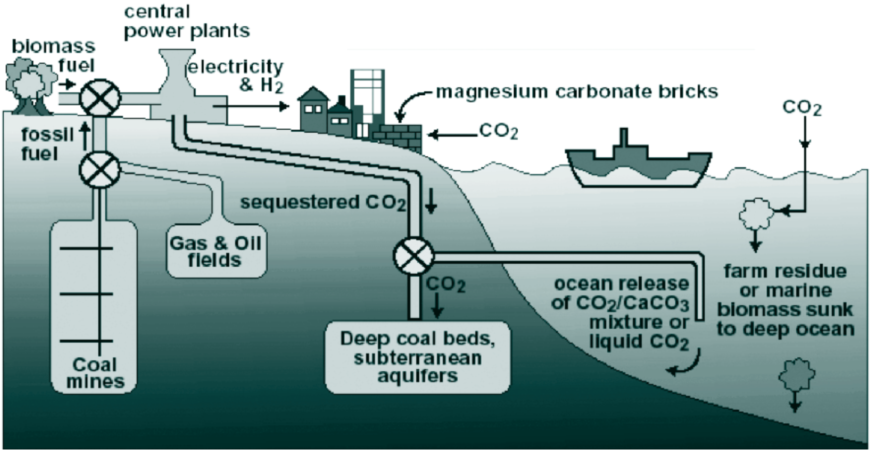


Figure 8. Carbon Sequestration

clean coal does not exist yet; it does exist in advertising slogans on TV. It exists only if we can technically prove that we can bury billions of tons in underground aquifers and know that it will not move on a multi-scale and multi-time and multi-live modeling effort at 0.1% per year for something like 1000 years with less than 10 years' worth of data.

Moreover, every site is different, so even if you prove it at one site, that is no guarantee at all about the other thousands of sites at which you would have to practice this. Now again, I think we should be doing everything we can to see if this works technically because if you tie the second hand behind your back, you do not have many cards left to play. But do not think that this will get you from here to there by itself, even in your most optimistic, wildest dreams.

Well, if you cannot get it all from fossil energy and you do not build more than one nuclear power plant a week, where are you going to get 10 TW? I can tell you where you are not going to get it. You are not going to get it from all the hydroelectric flows on our planet using every river, lake, and stream; there are not nearly enough. You are not going to get it from sustainable geothermal energy—when you know the temperature of the core of Earth and the surface of the Earth, when you know the heat flux. If you have 100% of this in heat engines over all land on Earth, you can get only 12 TW. You are not going to get it from the tides; you are not going to get it from the wind. You might get a few terawatts from biomass—that is important.

So, let's see where we are. You can get about a terawatt in all the hydroelectric flows, and you can get about 12 TW in all the geothermal and all the land on Earth with 100% efficient heat engines, of which there is no such thing. You get about 2 TW in all the tides of all the ocean currents on our planet combined. You have about 2 to 3 extractable TW in all the high-wind-speed areas on land. You can get a few out of biomass, which brings us to 5–7 TW gross, but that is for all land not used to grow food currently. But you cannot do that because when somebody converts land that is now growing crops into crops for fuel, you till the soil.

When you till the soil, you release soil carbons, and the amount of carbon trapped in the soil is almost twice as much as all the carbon in the air in the entire vertical atmospheric column above the same square meter. And you have just released all that into the air, which is what we are trying to prevent. You can pay back that carbon debt, but it takes between 40 and 400 years to pay it back, depending on the crop. So, you were better off leaving it alone and burning gasoline than making biofuels on that land for the next 40 to 400 years. You can really do this only on land that is now out of commission, that is not used for anything, and optimists estimate you might get a terawatt.

Now that is an important terawatt because it provides liquid transportation fuels, and 40% of current global transportation is in heavy-duty trucks, ships, and airplanes. We are going to need those liquid biofuels—not for light-duty vehicles when there are other modes of moving us around and it is silly to use them there. We are going to need them for ships, aircraft, and heavy-duty trucks, for which there is no credible substitute because nobody has yet, to my knowledge, invented a plug-in hybrid airplane. But even if you have a terawatt of biofuels, you are still about 8 or 10 TW short.

The only other big number left is the champion of all energy sources. The Sun provides us with 10^5 TW and we need 10. If you had 10% solar, on something that would be meadowland you would have to cover, you would use 0.18% of the land on Earth to provide 20 TW. Now this is not a small area because solar energy is more diffuse than fossil energy. But it is either that or build 20,000 plutonium-containing nuclear power cycles somewhere in the world (because we do not have enough natural uranium to do it), and that means that we have to close the fuel cycle in every country that wants clean energy.

So the bottom line is, despite playing the nuclear card, as much as you feel comfortable, even if you build 1000 of them, one a week, you are 9000 short. You play the fossil card with a little bit of wind and a little bit of biofuels, and you are still short. The biggest energy source we have is the Sun; more energy from the Sun hits the Earth in 1 hour than all of the energy consumed on our planet in an entire year. Nothing else comes close, so it is pretty obvious that the third big card that we have, should we chose to play it, is to tap that resource.

Figure 9 gives you a feeling for the United States, of a 10% efficiency at a representative mid-latitude of how much area you would have to cover; you would never do it all this way, but it gives you a feeling for the amount of land needed. It is not small; it is the equivalent of the nation's numbered highway systems. It is also the equivalent of adding a million solar roofs every single day for the next 40 straight years. It is either this or build 3000 nuclear power plants or some combination thereof; this is what the arithmetic of energy turns out to be.

I argue that we cannot do that with any known technology today because it would take more than the army of installers who currently install glass panels. We have to get this into a form that can be painted on a roof by a person or rolled out like a carpet; there are nanotechnology approaches to making thin, flexible films that can be reasonably efficient and are good enough to mitigate this issue of installing them everywhere. And I think that, if we

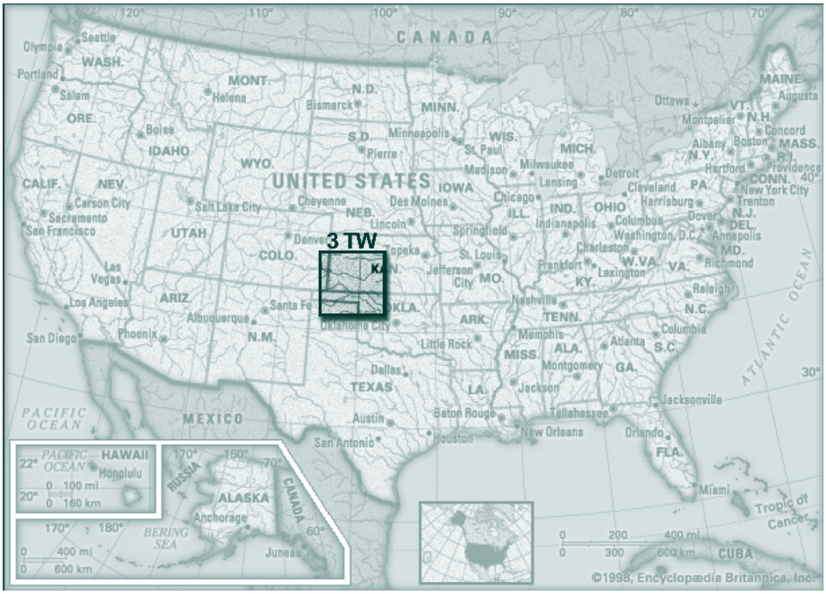


Figure 9. Solar Land Area Requirements

use the technology that we have today—you hear we have all the technology we need—we just need the political will, but that is only half true.

We need the political will and we absolutely need to get going, but we do not have all the technology we need to get from here to there at the rate that is needed to declare victory. There is one little problem, though. The Sun has this nasty little habit of going out locally every single night, and humans do not. "Thee that cannot store, shall not have power after four." So, we need to find a way to make stored energy, which photosynthesis does, which solar cells do not do; they make the wrong product.

There is no proven way to store massive quantities of electricity. If you have one, you will be able to buy electricity every night at a nickel a kilowatt hour and sell it to your friends and neighbors for 25 cents the next day and laugh all the way to the bank. You can do this by pumping water uphill; if you want to pump a lot of water, there is not enough water to buffer the day/night cycle of the United States every day and every night. To store the energy in 1 gallon of gasoline, you have to pump 55,000 gallons of water up the height of Hoover Dam.

The most energy-dense ways we have are either in the nucleus or in chemical bonds. Nothing else comes close. So you cannot exploit this intermittent resource unless, at scale, you store its energy in chemical bonds. You could do that today with solar thermal troughs, provided you wanted to build one of these troughs that would focus on this dual-access parabolic dish, the sunlight onto that external sterling engine, it would put it into this electrolysis unit on the lower right, probably at the half the world's supply of platinum just there. Every day that dish plus that unit would fill up that little tank with hydrogen.

You would have to build one of these every second for the next 50 straight years to meet our energy demand. This is just not a scalable technology. We need to get rid of the platinum; we need to re-engineer these systems. When the amount of platinum in a fuel cell to power a school bus costs $0.5 million, like it does today, we are going to have a vigorous hydrogen economy consisting of stolen school buses. However, we know that nature knows how to do this. It turns out that green algae (*Chlamydomonas moewusii*) that produce hydrogen can be used as a clean biological energy source. Best of all, they do so without using platinum. Instead, the algae use iron, and they are not poisoned by carbon monoxide or sulfur but actually make use of those materials in the process of making hydrogen.

We know that nature does not use an expensive and rare metal such as rubidium to make oxygen like fuel cells do; it uses manganese, a cheap metal. So we have to fish out these compounds and make our own systems like nature does, to convert electrons into chemical bonds and back again, so we can actually store sunlight and chemical bond energy where we can deliver it as a fuel whenever people need it, wherever they want and need it. Otherwise, we will not have much out of that intermittent resource.

So in conclusion, it is eminently clear that the world needs a lot of energy and probably more and more every day. It is not that we are going to run out of fossil fuels, it is going to be that we have already run out of air in which we can put those fossil fuel products. The case for daunting amounts of carbon-free power is either plausible or imperative, depending how well you feel about rolling the dice once with our planet. How have we done? We talked all about Kyoto, and CO_2 emissions grew at 1.1% per year. Then we tightened our belt and showed the world what we could do and you know what we did, we tripled it. Now we are emitting even faster than even the worst scenario thought possible.

We are emitting at 3.1 growth rate per year, and even that business-as-usual scenario I showed you is in our rear-view mirrors. So, it will be harder than that to make that arithmetic come true. That being said, I have told you only about hard scientific facts—not opinions or policy. And I will not go there except to say that no sound energy policy would start with energy deficiency. It is cheaper to save energy than it is to make energy, and every joule you save, saves having to make more joules up front. It is also good for energy security as well as our environmental security.

If you do not save energy like our lives depend on it, you turn an improbable solution into an impossible one. That being said, do not be fooled because no amount of saving energy ever turned on a lightbulb, no amount of saving energy ever put food on somebody's table, and no amount of saving energy ever got an aircraft carrier in or out of port or moved an airplane from point A to point B. You still have to make tremendous amounts of clean energy within our lifetimes. The only three big cards that we have are coal, if we can sequester all of that CO_2; nuclear power, if we go to fuller burns and/or complete fuel cycles and/or in some combination; or, the biggest energy source that we have, the Sun.

But we better make it really cheap, and we better find a way to store it or we will not have much. I am not going to give you a policy recommendation. I am just going to pose the two extremes that are the dominant extremes into which this is cast in the public debate. One says this is something that we cannot afford to do because it will cost money. Of course it will cost money. You cannot switch from 100-year-old energy technology without spending some money. So by that metric, it is true that we cannot afford to do it.

The flip side is that this is something that cannot fail because we get to do, or not do, this experiment exactly once. The choice of which path our planet takes rests with no generation other than ours; we are uniquely in a position to decide on which path we are going to put our planet. If we wait 40 years to decide, then nature will have decided for us what it wants to do. You cannot do a cost–benefit analysis of this because we do not know the costs and we do not know the benefits. I never said I knew whether this would be good or bad or in-between. I just told you what science allows us to say about where we are going if we stay on the path we are on.

So the question is, do we actually have the energy needed, the human energy, to do the research and development as well as the deployment starting today—to do the things that we know how to do as well as the things that we do not yet know how to do, but do know where the answers lie to get them done in time to get from here to there? I think we could do it, but we would have to be really serious about doing it, treating it as if our lives depended on it. Because you know what? They just might. With that, thanks very much for listening, and I would be happy to answer questions.

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Q&A WITH DR. NATHAN LEWIS

Q: *Sir, I am wondering if anyone has looked at how would nature solve this problem for us?*

DR. NATHAN LEWIS: There are two different interpretations of that. One is what would be the natural restoration time of CO_2 levels, and that, I told you, would be about 3000 years. The second is how would nature solve the problems, in other words, what would be the reaction of the ecosystems and human systems on the planet if we let the trajectory continue? The answer to that is, we do not really know. Most of the predictions, for whatever they are worth, are on the bad side of things, but not all of them. So some places could be better or worse. There will be winners and losers; it will be different.

In some cases, it is predicted to be very different. Many people believe that there is no steady-state ice in the Northern Hemisphere at 375 ppm of CO_2. The consensus predictions now state there is no ice in the Northern Hemisphere at all. That does not mean everybody believes that; it means that there is some sound, scientific basis to expect that might be possible. We do not really know for sure. So we just know that the historical data show the Earth was a very, very different place when CO_2 excursions of these magnitudes were there, and they were imposed on a much slower time scale than the ones with which humans are now perturbing the system.

Q: *Could you address any of the potential geoengineering approaches to reducing the temperatures?*

Dr. Nathan Lewis: That question comes up more and more now as the time clocks tick closer and closer to the point of apparent no return. There is one geoengineering approach that involves launching aerosols into the stratosphere. First, we need to realize that we have a nonlinear system that we admit we do not understand, and we will be trying to exert single-point, open-loop control over that, which sounds pretty dicey to me. Moreover, if a hurricane hits shortly after you have done that, they are going to want to blame you.

What are you going to do? Other than those issues, the bigger issue is that even those things do not affect the ocean acidity issues because they would affect the rate of transporting air but not the thermal warming of the oceans or its acidity as it affects the ecosystem. So it is a method of potentially two wrongs possibly getting lucky to make a right, but you would have to be pretty good and pretty lucky to get it to work out.

Q: *I find that in terms of public opinion, we almost seem to be going backward. When one of your undergraduates tells you that he/she is very skeptical and does not believe in some of the things you laid out, what is your reaction to that? Why do we seem to be going backward on this?*

Dr. Nathan Lewis: Well you know, just because you advertise clean coal on TV does not mean it exists. Now I never said the public is "skeptical" about the affects of CO_2 or global warming. I never mentioned the words. I never even told you I thought it necessarily would be bad from a scientific perspective. So when you say the public is skeptical, there is nothing in what I told you that one could possibly be skeptical about because my presentation was based on proven, undisputed scientific facts. Maybe it will not be bad. On the other hand, maybe it will be pretty bad. The real issue is, you get to roll the dice here just once. How lucky do we feel?