people are as wealthy as ours, they will begin to consider controlling their emissions, just as we are now doing. Although the carbon dioxide that they now produce exceeds that of the United States, their production per capita is less than one-fourth that of ours. If you were president of China instead of the United States, would you cut back? With a population that still suffers from poverty, malnutrition, poor health, lack of opportunity, widespread illiteracy and periodic famines, would you slow economic growth in order to keep the temperature from going up a few degrees? Add to this the facts that China has plenty of coal, certainly enough to meet the worst scenarios of the global-warming models, and that it is accelerating its exploitation of that resource.

Many people fear that cutting back on U.S. emission would not persuade the developing countries to follow suit. In fact, one vote has been taken by the U.S. Senate on the Kyoto accord, although not to ratify it. The vote was for the Byrd–Hagel Resolution, and it passed in a very bipartisan 95-to-0 vote. The resolution states that the United States should not ratify Kyoto until the treaty is rewritten to include binding targets and timetables for developing nations. The Senate simply did not trust that our CO_2 example would be sufficiently persuasive.

The Kyoto treaty expires in 2012, and negotiations have already begun for the follow-up treaty. The fact that China surpassed the U.S. in CO_2 emissions in 2006 has made it easier for opponents to argue that the U.S. is no longer the main problem. Most people believe that there is no easy solution, but that to manage the risk, many different options will have to be used, all at the same time.

Solutions

The discussion seems to suggest that even if the US were to abide by Kyoto, that the growth of the developing world will still result in enormous CO_2 increases. Is the situation hopeless? I don't think so, but unless our methods of reducing CO_2 can be afforded by developing countries, they are unlikely to do anything other than delay the predicted warming by only a few years. The emphasis must be on CO_2 reductions that can be used by all. By far the easiest is conservation.

Conservation

Ponder the following physics question: How much energy *should* it take to drive from San Francisco to New York City? The answer, from physics, is surprising. In principle, it could be done with *no* energy. After all, you can slide across ice effortlessly; the only energy it takes is to overcome friction. What if you eliminated friction? Is any other energy necessary? With an efficient hybrid engine, you can recover the energy used in accelerating a car and put it back into a battery when you slow down. That's called "regenerative braking"; it uses the motion of the car to turn a generator that charges the battery. Likewise it takes energy to go up a hill, but the same principle can be used to recover the energy when you coast down. The basic conclusion: with better auto design, we can *enormously* reduce the energy consumption of autos. My Prius already gets 50 miles per gallon; there is not reason why an auto could not achieve 100 mpg or more. Of course, an expensive hybrid like the Prius is not really an option to developing countries. But they could use the principle in their trucks and buses.

Similarly for heating our homes. The only reason we have to heat them is that energy is lost to the outside world primarily through convection (open or leaky windows, chimneys), and conduction (though glass windows and uninsulated walls and roofs). With good insulation (including double-paned windows), the amount of heat we need can be made tiny. In fact, recent analysis (by the respected firm of McKinsey) has shown that you save money by doing that; the cost of putting in better insulation is recovered in just a few years, and after that, it is pure profit. That makes it one of the best investments you can make; invest your money into insulation, and take as your "interest" in the form of money saved keeping your home warm. And you don't have to pay taxes on this kind of interest.

Use less energy for the same function; that's called conservation. Conservation is the easiest way to reduce greenhouse emissions, and because it is the least expensive way to do so, it will be particularly valuable in the developing countries such as China and India since it pays back whatever investment is needed in a short time.

A lot can be said about conservation. It has a bad reputation among consumers because they associate it with discomfort; in the 1970s, President Jimmy Carter encouraged people in winter to live in a cold house (65 °F) and to put on a sweater in order to save energy. But comfortable conservation should be more attractive. Put some insulation in your walls (rather than your bodies), and turn up the thermostat to whatever temperature you want. Save energy by not letting it leak out. And it is a great investment; your return on the money you put into conservation will pay higher interest than a savings account.

Similar principles work to save the energy used to air condition houses in summer. About half of the solar radiation hitting our roofs is in the form of infrared. If you use roofing material that reflects this, then the heating of the home is drastically reduced, and that lowers the energy needed to air condition. And to the human eye which does not see IR, the "cool roofs" can still be a pleasant brown color, or whatever the homeowner wants.

A whole chapter or even a book can be written on comfortable conservation. It is the cheapest way to avoid carbon dioxide in the atmosphere. But we need to discuss other possibilities.

Clean coal

Over half of the electric power in the United States is produced by burning coal and creating CO_2. If this CO_2 is produced at a central power plant, then in principle it is possible to capture it and store it. This is called Carbon Capture and Storage, or *CCS* – an acronym you *do* need to know, since it is already becoming an important national issue. Another related term is *sequestration*; that refers to the process of pumping the CO_2 underground where it is either stored in cavities or dissolved in deep brines (salt water).

According to the IPCC, this process seems to be feasible. Sequestration is already being tried at several locations around the world, although with a different purpose: pumping CO_2 into oil wells can help bring up additional oil. There is debate over how safe CCS will be. Will the CO_2 really stay there for thousands of years, or will it eventually leak out? The IPCC has written an extensive report on this subject. Most experts believe that if it stays down for a few years, it is very likely to stay down for thousands, and so we will quickly learn how reliable sequestration can be.

In the olden days, when people referred to "clean coal" they meant coal that did not pollute the nearby regions with soot, nitrous oxides (which produce smog), sulfur dioxide (which produces acid rain) and mercury. But today, when the term is used, many people include CO_2, and when they refer to "clean coal", CCS is included. But when you read about clean coal, make sure you know which definition is being used.

The biggest issue may not be whether CCS can be done, but whether it can be done economically; remember, China has huge coal supplies, and is actively building new plants. In 2007 it built over one new gigawatt plant every week, on average! CCS will make the power cost more, perhaps 50% to 100% more. China may argue that it should not have to pay the premium until its citizens live at Western standards of living. If they do, then perhaps the wealthier countries will have to pay the difference. That could be accomplished through carbon "cap and trade", a topic we'll discuss shortly.

The U.S. had a major clean coal demonstration power plant under construction. It was called "FutureGen" and its goal was to show that an efficient and inexpensive clean coal production of electricity with CCS was feasible. The program was cancelled in 2008. Some people think it was a terrible mistake to cancel a demonstration of this essential technology. Others think it was a good idea; the demonstration plant was rushing ahead so fast that it was proving to be expensive, and proponents of CCS worried that it would give a misimpression that clean coal was far more expensive than it need be.

Biofuels

Biofuels are fuels that are made by plants; they include wood, pulp, and liquid fuels such as ethanol that are made from plant products. Early railroads used the wood that grew along the track; that was an example of a biofuel. When biofuels burn they emit CO_2, but no more than they took out of the atmosphere when they grew. Therefore they are described as "carbon neutral." That's not always true, however, since many plants grown on farms require fertilizer and machinery to grow them, and oil to run the tractors; these are often made using fossil fuel. Transporting the fuel also creates CO_2. Ethanol made from corn is particularly bad; you use almost as much fossil fuel to make the ethanol as you get in biofuel. In contrast, ethanol made from sugar cane is a good biofuel, provided that you don't have to cut down a forest in order to clear a growing region. But a new generation of biofuels is under development, using materials such as tall grasses (switch grass and miscanthus) that require little water, grow fast, and truly are carbon neutral. To use these grasses as liquid fuels, we need to develop methods to convert the cellulose in the plant stalks to ethanol. Ways of doing that are under active development around the world; that is the goal of a large new Berkeley Energy Biosciences Institute funded by BP (British Petroleum).

Some states have already passed legislation requiring that autos use a mixture of gasoline and bio-ethanol, a combination often called "gasohol." Much of this legislation was passed prior to the analysis that showed ethanol-based alcohol is not really energy neutral. (Or it was done to subsidize farmers in the critical presidential primary state of Iowa.) But with the new crops and new technology, biofuels could make a significant contribution to both CO_2 reduction and energy independence.

Nuclear power

There are 104 nuclear power plants in the United States, producing on average about 1 gigawatt of electric power each, and providing about 20% of the US electric power. Construction of new nuclear power plants came to a virtual halt in the United States after the 1986 Three Mile Island accident, although plants that had been under construction were eventually commissioned (such as the Watts Bar nuclear power plant, in 1996).

The reasons for the halt were fear of accidents, concerns about waste storage, and the high cost of operation. The fears are now being reevaluated, thanks to the recognition that fossil fuels also have risks, and because there are nuclear reactor designs that have little or no accident probability. (Look up "pebble bed reactors" on the web.) Many people think the waste storage issue was exaggerated; I discussed this in Chapter 5. Moreover, the cost of operation of nuclear plants has come down, largely through better management. The "capacity factor" (the fraction of time that a nuclear reactor is actually working and delivering power) was barely above 50% in 1980 and now it is nearly 90%. This has made nuclear power much cheaper than it had been.

Some environmentalists now argue that coal is so bad in its CO_2 production, that a larger part of our electric power should come from nuclear. China has been building about 2 new nuclear power plants each year; France gets about 80% of its power from nuclear reactors; and in the U.S. several companies are applying for licenses to begin construction of new plants.

Wind

The use of wind to generate electric power has recently grown enormously in the United States. In the last four years, the installed capabilities in the US have doubled, from a half percent to one percent of US electric production. It is still small, but that is a huge change, and it is expected to grow even more. The technology is old but innovative; new wind turbines[7] are quiet and efficient. The biggest fields are being installed in Texas, which has the advantage that the wind is close to the population centers. Right now the growth of this technology appears to be limited by the US limited capability to manufacture the wind turbines.

One problem with wind is that it is irregular, and it may not blow when you most need power. To address this issue people are studying energy storage methods, such as batteries. One of the most practical may turn out to be one of the most surprising: use excess power to compress air, stored underground; when the power is needed, use the compressed air to run another turbine.

Solar

There is a gigawatt of solar power in a square kilometer, and that's as much power as you get from a large nuclear or fossil fuel power plant. So solar power sounds reasonable. There are several difficulties. It is often cloudy; solar isn't as reliable as methods that burn fuel. Not all of the power can be converted to electricity; the efficiency to do this is between 10 and 40%. And most importantly, it is still more expensive than other methods. Proponents say that isn't true; it is not more expensive when you include the environmental costs of other methods, and if we figure out how to charge coal plants for their CO_2 emissions, then solar becomes competitive.

To install solar cells now costs about $3 for each watt of capability. Many economists say that the cost must be brought down to about $1 per watt (equivalent to $1 billion for a gigawatt plant). That may happen in the near future,

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[7] The term *wind mill* is usually reserved for wind-operated mills, that is, structures that grind flour. For electricity generation, we use the term *wind turbine*.

thanks to advances in technology, and the possibility of paying for the installation using "carbon credits", a topic we will discuss in the next section.

Solar power has many traditional uses, from drying clothes to warming rooms (through windows) to heating water for baths. These uses are important for conservation, for example, for reducing our dependence on fossil fuels. In this section, however, I will limit the discussion to *big* solar – the kind that could be used to replace large fossil fuel-burning electric power plants.

Here is a quick rundown of the possibility for solar:

Solar thermal

Mirrors are used to concentrate the solar power onto a small area to heat a fluid such as water. (Heat can also liquefy salt, and that is sometimes used.) Steam from heated water can power a turbine that runs an electric generator.

Several of these solar thermal plants are already in operation. One famous one is a "power tower" near Seville, Spain, which consists of a boiler on a high tower with mirrors aimed at it from the surrounding countryside. The mirrors must be redirected as the sun moves. This plant currently delivers electric power at the relatively high price of 28¢ per kilowatt-hour; that is expensive compared to the price in the US from fossil fuels, which averages 10¢ per kWh). The Spanish government subsidizes the price of electricity from this plant in order to encourage solar construction, study the costs, and because it is trying to meet its goals under the Kyoto treaty.

There is also a solar energy generating system (called SEGS) in California that works with smaller reflectors placed in long parabolic troughs. Other solar thermal plants are operating in California and Nevada, in desert regions where the sunlight is abundant, but not too far from the factories and cities where the power is used. Transmission line loses in the United States average about 20%, and it would be worse if the lines were longer than a few hundred miles. A disadvantage of the solar concentrator technology is that it works only on sunny days; if the light is diffused by clouds, then the mirrors can't concentrate the light enough to heat the water. But there is optimism that the solar thermal plants could deliver power at a cost cheaper than that of natural gas by about 2020.

The efficiency of these plants is low if you consider that only a fraction of the area is covered by mirrors – so much of the sunlight falls on land. But in many places in the world, the key issue is cost, not land area covered, so that measure of efficiency is not relevant. Of the light that hits the mirrors, typically 20% to 40% is converted to electric power.

Solar cells (PVs)

Solar cells are also called "photovoltaic cells" or simple PVs; they get this name from the fact that photons (light) interact in the cell to caused electrons to flow to metal plates, so they produce a voltage. We'll discuss how they do this in the next chapter, on quantum physics. Traditional solar cells were based on crystals of silicon, and they typically converted about 10% of the sunlight to electricity. For a 1 Gigawatt plant, when the sun is directly overhead, that would require 10 square kilometers of these cells. Traditional solar cells cost about $3 per installed watt, and so are not really considered competitive with fossil fuels. These are the kinds being installed by homeowners, sometimes because they think they are saving money, but more often because they want to reduce the CO_2 that they are personally responsible for. But the field is advancing rapidly.

One of the truly hopeful developments in recent years has been the development of highly efficient solar cells. These are complex devices because extracting as much energy as possible out of sunlight requires having separate layers to convert different colors. These sophisticated solar cells are now being built, and one major producer, Boeing (yes, the airplane company; it started producing solar cells when they were needed for space) is selling solar cells that convert 41% of the incident sun power to electric power. They say that the efficiency should rise to 45% in the near future. Wow!

There is a catch, of course. Even when purchased in large quantities, these special cells cost about $10 per square centimeter; that's equal to $70 per square inch, or about $10,000 per square foot. A foot-sized cell would yield 41 watts—not much for the $10,000 investment. Why do I call this hopeful? The reason is that sunlight (if there are no clouds) can be focused using a lens or mirror. You can make a plastic lens that is 1 foot square for less than $1 and use it to focus the sunlight onto a cell 0.4 inch on a side. A cell of that size costs $10. Your total cost for the 41 watts is now reduced to $10, plus $1 for the lens, plus whatever you spend to build the module. The cell is only 25¢ per installed watt! That sounds *very* attractive. The tricky part is that you have to keep the cell pointed at the sun, and that requires a mechanical system. If our goal is to spend no more than $1 per installed watt, then the total cost for the square-foot device must be less than $41. Can that be done? It is not obviously impossible, and several companies in California are already building such systems to see if they can be cost-effective. Even if it costs three times that, this system still becomes the cheapest form of solar power.

This approach is called *solar concentrator technology*. Its greatest drawback is that it works only on sunny days, when the sun is visible and its rays can be focused. Imagine now an array of foot-sized concentrator solar cells covering a square mile of sunny Nevada. Since there are 5280 feet in a mile, there would be 5280 × 5280 = 27,878,400 modules. Each module would be only a foot high, making the system quite robust against wind. Driven by tiny electric motors, the modules would all point in the same direction: toward the sun. With 41 watts from each, the total electric power output at midday would be over a gigawatt. Of course, there may be other expenses, such as keeping the reflectors clean. In a recent trip to Nevada I found that much of the region I visited had over a foot of "bug dust" that whirled around every time the wind blew.

Another hopeful developing are cheap solar cells made without growing crystals; these are called "amorphous" (non-crystalline) cells. There is much excitement over a particular kind called CIGS. (The letters stand for the elements that go into the material: Copper Indium Gallium and Selenium.) CIGS are manufactured using a technique similar to that of an ink-jet printer: they are basically sprayed on a piece of plastic. CIGS have already achieved an efficiency of 19%, and enough people are convinced of their future that factories costing hundreds of million of dollars are under construction to build CIGS cells. For business reasons, many of the details have not yet been released; as of May 2008 (when I am writing this) these companies have not released a public number for the price at which they will guarantee to sell their cells. The price may be determined by competition, since sales of the cells will have to pay back the huge investment being put into these plants. And people worry that with huge numbers of solar cells being built, that the world will not be able to supply enough gallium for the cells! But optimism in the solar energy business is rampant. Many investors are jumping in. They believe the future of solar is sunny.

Carbon credits: "cap and trade"

Clean technologies would be more competitive with traditional ones if the environmental costs of CO_2 pollution were taken into account. One way to do this is by a global treaty, in which power plants that pollute the atmosphere are required to buy "carbon credits" for the harm they do. Non-polluting plants, such as solar or wind, would get credits; they could then make additional profit by selling these credits to organizations that emit CO_2. The whole thing would be managed in such a way that there would be a net reduction of CO_2, and the hope is that it could be done in such a way that market forces would make the process economically efficient.

The Kyoto protocol set up such a system, and the countries that endorsed that treaty are now using these credits. The approach is called *cap and trade*. A country is given a limit for the amount of CO_2 that it emits; that's the cap. If they go under that limit, they get credits that they can trade; if they go over the limit, they are required to buy credits to cover the pollution.

Other names for this procedure are "carbon dioxide trading" and "carbon trading." Despite these names, the credits are also used for other gases that contribute to greenhouse warming, such as methane.

Opponents of this system say it allows too much cheating. A collapsing economy in Russia, for example, enabled that country to sell a large number of credits for carbon dioxide that it never would have produced. Trading of credits, in this case, led to an increase in the carbon dioxide dumped into the atmosphere over that which would have otherwise been emitted.

Developing countries who signed the treaty do not have caps assigned to them; such caps could stunt their growth, and doing that was considered unfair. Opponents of the treaty argue that the major pollution in the coming century will come from those countries, so unless they too have caps, the problem will not be solved. Some people argue that giving generous carbon credits to the developing world may be a politically viable way to subsidize the construction of clean energy in these countries. Suppose a developing country builds a plant that emits half as much CO_2 as current plants? Should they be given credits for doing this, even though they are adding to the CO_2 problem?

The Kyoto treaty did not allow credits for new nuclear plants, even though they emit essentially no carbon dioxide. The reason was the fear that nuclear plants created a different kind of pollution, radioactivity. However the radioactivity issue needs to be reevaluated. Many people now think that the dangers of CO_2 far exceed those of buried radioactive waste.

Keep in mind all of these complexities. The solution to CO_2 pollution, if one exists, probably involves a very wide range of approaches, including conservation, carbon credits, solar, wind, biofuels, nuclear, and CO_2 sequestration. (In the jargon of the global warming community, these many approaches are called "wedges", and many wedges are needed. No one by itself is enough.