Some Ways to Lessen Worries about Climate Change

Technology can bring cheap and effective solutions to adapting to climate change, offsetting and preventing emissions. The trick is easing in the changes when existing technologies turn over, at the point where obsolete processes are substituted anyway.

Jesse H. Ausubel

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Hope is a better companion than fear. Science has effectively alarmed many people about the chances that human activities will harm Earth's climate. But science and engineering can lessen worries about climate change, offering positive solutions by providing needed services or products rather than continuing the negative actions of issuing scary press releases and shutting down plants.

Let me first briefly offer my premises about the climatic outlook. All we firmly know is that human activities are changing the chemical composition of the atmosphere, above all with additions of carbon dioxide. Changing what is in the air will very likely change the climate. We do not know to what.

In fact, I believe the future climate is not only unknown but, more important, remains unknowable. The complexity of the climate system, the numerous factors that can vary, and their interactions, forbid reliable calculations beyond the broad generality about likely global warming. My colleagues gulping research grants hate me for saying it, but I do not believe more research will reduce uncertainty. Over the 23 years I have now worked on the climate problem, the $10 billion or more spent on research have not reduced uncertainty about the future climate or provided a convincing, detailed picture. The

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spray of views is undiminished, and a new mystery arises for every one apparently solved. Meanwhile, we have definitely added more than 100 billion tons of CO_2 to the atmosphere, and notable amounts of other stuffs that also absorb and reflect radiation.

Because the future climate is unknowable, the operative question is "How risk-averse are we?" "We" may be a country, a household, or a firm. In general, I consider myself risk-accepting. I bicycle hundreds of hours each year, an extremely dangerous use of time, and usually pedal without a helmet. I often eat sushi, a frequent cause of food poisoning. I choose to live in a neighborhood in New York City where during the 1980s, most mornings I found crack vials on my doorstep. But gambling with the climate does not strike me as a good bet.

Of course, Earth now presents a climate horrible for humans over much of the planet much of the year. Still, humanity has invested heavily in adjusting to the recent climate. We are attached to the system of reservoirs providing New York City's tasty water, vineyards in Bordeaux, and the National Park designated around the precipitous waterfalls of Yosemite. Moreover, there is some—unknowable—chance that our activities will trigger a catastrophic change, say to a severe Ice Age.

So, I say, let us prepare, just in case. Purchase some insurance. We routinely do. Insurance, in its literal form of policies in fine print, is now about 2 percent of U.S. gross domestic product. Inspired spending, even against hypothetical threats, can bring great and lasting achievements, such as Europe's gothic cathedrals. The sorts of insurance I shall propose, however, resemble building a fire escape, storing fuel outside rather than in the stairwell, and using diesel rather than 100-octane fuel.

Three forms of climate insurance exist. I will call them adaptation, offsets, and prevention. Public and private entities should research and invest in all three.

Because the future climate is unknowable, the operative question is "How risk-averse are we?"

I. Adaptation

Let me begin with adaptation, which tends to get short shrift. Many of our devices and strategies, from anti-freeze, air conditioning, and corn futures markets to windshield wipers, radar, and domed stadiums, already adapt for climate. Societies are always trying to climate-proof themselves. According to Genesis, Joseph helped the Pharaoh during the seven fat years to insure against the stress of the seven lean years to come.

To a considerable extent, societies have now climate-proofed themselves.[1] In the summer of 1998, China experienced one of the most extreme floods in its long recorded history, affecting some 20 million hectares, or 80,000 square miles. Yet, compared to 1997, rice production reportedly fell only about 1 percent and total cereal production increased slightly. Still, we can adapt more.

Water is paramount. Technologies for tunneling and pumping can ease the creation of new supply. Numerous technologies can also moderate demand, for example, by spying and stopping leaks and waste. Prosperous societies can also afford large-scale coastal protection, as the Thames Barrage and the Netherlands Rhine Delta schemes show. Because populations are imploding into cities, making cities habitable in unwelcoming climates helps a lot. We already do in Phoenix and Edmonton. Cheap, efficient, and environmentally benign refrigeration will win ever-larger markets. So will means to lift moisture-use efficiency in agriculture. Everyone concerned with changing climate can benefit from better weather forecasts, because eventually the climate becomes the weather of the next few days, and a forecast of rain can save water that would have been sprinkled on a lawn or pumped on a crop. Some adaptations, like carrying an umbrella, need finally be implemented only when the front nears.

As hinted, adaptation comes through both hardware and software, through both markets and regulation. Markets allow us to average over larger spaces and longer times, lessening the consequence, for example, of a poor crop in Kansas with a bumper crop in Australia. Regulation, such as wise zoning, can lessen the amount that societies build in hazard-prone settings. A strategy such as making fresh water from one basin available in another, benefits both from markets aimed at encouraging high valued uses and from regulation aimed at assuring protection of poor consumers.

Adaptation makes sense because, even if humans do not change the climate, nature will.

II. Offsets

My second strategy, offsets, recognizes that some greenhouse gases will surely be emitted and thereby seeks to capture or otherwise offset those emissions. The scope of effort needed to close the carbon cycle is huge. Globally, humans now average emission of a ton of carbon per year. An American emits about 5 tons per year or 14 kg per day. The volume of material involved in carbon waste management contrasts with that of another element useful for energy, uranium, where we deal in grams per capita per year.

Still, engineers, ecologists, and others have proposed many schemes for offsets. At this stage, most merit more study for their benefits and risks, and some are ready for demonstration and implementation.

One such scheme is to fertilize parts of the surface of the open ocean, basically with iron, setting in motion enhanced growth of marine plants and animals, which will eventually sink to the ocean floor with their captured carbon and thus encourage the surface ocean to absorb more carbon from the air. Rough calculations make ocean fertilization look cheap.

Foresters and farmers can also sequester carbon. My colleagues and I have shown that a widespread reversal of the deforestation that has prevailed for centuries is now underway, and that humanity can achieve a great restoration of the world's forests over the next 50 to 100 years.[2] We might, for example, set a goal of a 10 percent increase in the world's forest estate over the next 50 years. This could compensate for about five years of present emissions.

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The catch is that forests also darken the planet, and thus tend to make it warmer, lowering the so-called albedo or reflectivity of Earth's surface and thus increasing energy absorption. After all, the basic problem is not CO_2 but energy balances. Fearless engineers may prove that creating deserts, which like the ice have high albedo, will counter warming more than planting forests. So, let's breed and plant light-colored trees.

Farmers can also grow more food while storing more carbon. Unconsciously, Washington and Brussels may be storing carbon by paying farmers to idle land and thus increase the stash of soil organic matter. Washington and Brussels ought consciously to start paying farmers to plant trees instead of paying them not to grow more food.

Noting that some of the so-called aerosols or particles in the atmosphere tend to cool Earth's surface, like clouds do, some geoengineers have proposed offsetting increased greenhouse gases with distribution of shady particles. As mentioned, energy balance, not CO_2, is the basic problem. Indeed, the CO_2 itself, if not the other greenhouse gases, provides raw material for photosynthesis in the biosphere.

Many conferences, and now some grants from the U.S. Department of Energy, address how CO_2 might be stripped from power plant smokestacks and pumped back under the land or sea. The best way is to sequester the emissions in caverns underground, where the coal, oil, and gas came from. On a small scale, CO_2 already profitably helps tertiary recovery of oil. As I will explain, I support the idea of hydrogen (H_2) refineries, extracting H_2 from methane (CH_4) or other hydrocarbons and producing CO_2. Located near exploited oil fields, the refineries would find a market for their emitted CO_2 to recover oil.

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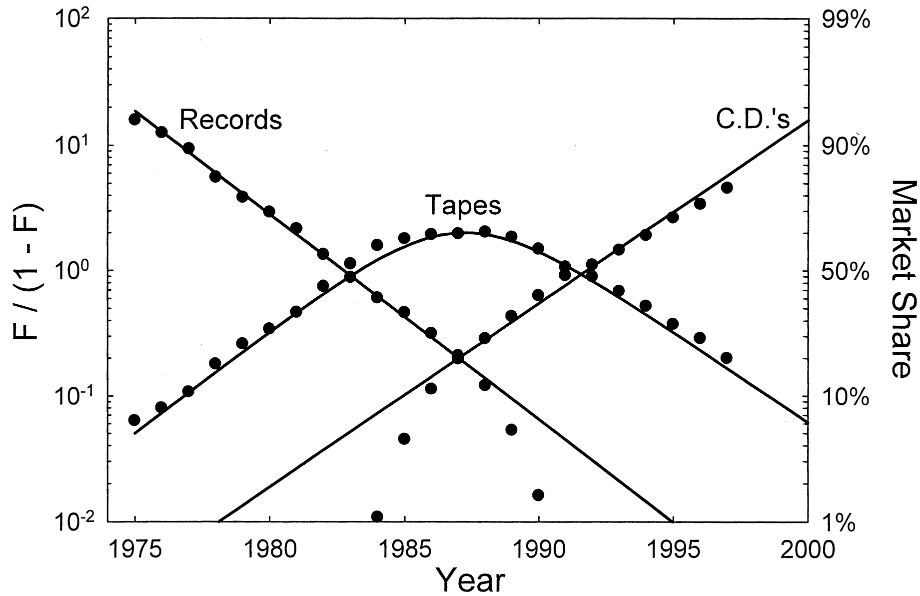
Oil and gas are preserved in natural geological traps that only occasionally contain them, so one can extend the storage to the traps that lack oil and gas that prospectors routinely find. Aquifers in silicate beds could be used to move the waste CO_2 to the silicates where "weathering" would make carbonates and silica, an offset good for millions of years.

The key to offsets is to determine how much carbon we need to sequester and when. For example, if humanity sets a goal of stabilizing CO_2 at 450 parts per million (ppm) by volume in the atmosphere, industries might need to sequester about 50 ppm, before the evolution of the energy system eliminates the emissions of CO_2 anyway. Among the several strategies available, offsetting for 50 ppm should certainly be achievable.

Offsets benefit from a system organized to collect CO_2 and move it to the disposal points. Because the energy industry is quite concentrated and the materials flow through a few large pipelines and refineries, I propose we concentrate the task of offsets.

III. Prevention

Before sharing my thoughts on my third mode of insurance, prevention of emissions, allow me to offer some necessary premises. The most fundamental is that evolution is a series of replacements. We experience these replacements daily. For example, compact disks replaced cassettes, which replaced long-playing records, which replaced 78-rpm records (**Figure 1**).



Source: Recording Industry Association of America, Washington, DC, annual report, 1999.

Figure 1: Successive Replacements of Recording Media in the U.S. Market. Presumably, digital video disks (DVDs) or some other new form of recording will in turn replace CDs. The data are analyzed as a logistic (S-shaped) growth process and plotted in the linear transform of the logistic curve. F is the market share expressed as a fraction.

A new generation of computer chips replaces the old every two to three years, as if programmed by robots in Silicon Valley. Importantly, the superior performance of the technology fits a larger market (**Figure 2**).

Replacements also mark the evolution of the energy system. Between about 1910 and 1930, cars replaced horses in the United States. Earlier, steam engines had replaced water wheels, and later, electric drives replaced steam engines. Each of these replacements required about 50 years in the marketplace. It required about the same amount of time for railways to replace canals as the lead mode of the U.S. transport infrastructure, and longer for roads to overtake railways and for air to overtake roads (**Figure 3**). Considering primary sources of energy, we find that coal replaced wood and hay, and oil in turn beat coal for the lead position in the power game. Now natural gas is overtaking oil. The so-called oil companies know it and invest accordingly. In turn, I believe, nuclear will beat the hydrocarbons.

The driving force in evolution of the energy system is the increasing spatial density of energy consumption at the level of the end user. At very high spatial density of consumption, finally only electricity and hydrogen will meet consumers' stringent requirements for versatility, cleanliness, and other attributes. Hydrogen of course produces only water vapor when burned, effectively zero emissions. So, hydrogen must replace carbon in the energy system, and in fact it is doing so. This replacement, called decarboniza-

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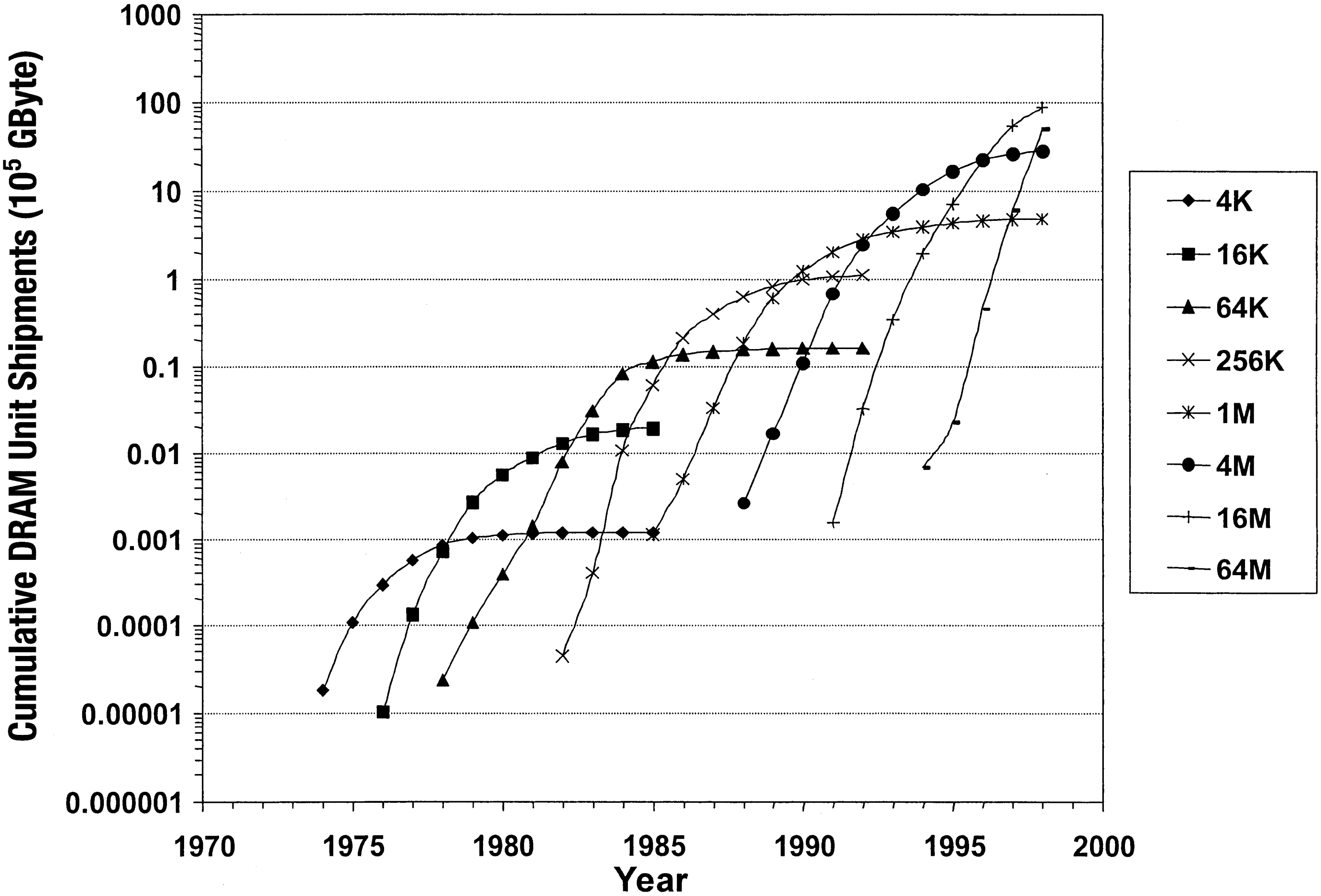


Sources: Integrated Circuit Engineering Corporation, Status 1999; Douglas A. Irwin and Peter J. Klenow, *Learning-by-doing spillovers in the semiconductor industry*, 102 J. Pol. Econ., 1994, at 1200–27.

Figure 2: Cumulative Shipments of Dynamic Random Access Memory (DRAM) Chips in Gigabytes by Integrated Circuit Density of the Chip Type, Semi-Logarithmic Scale. Note that with each improved chip, the market effectively expanded by about 10 times.

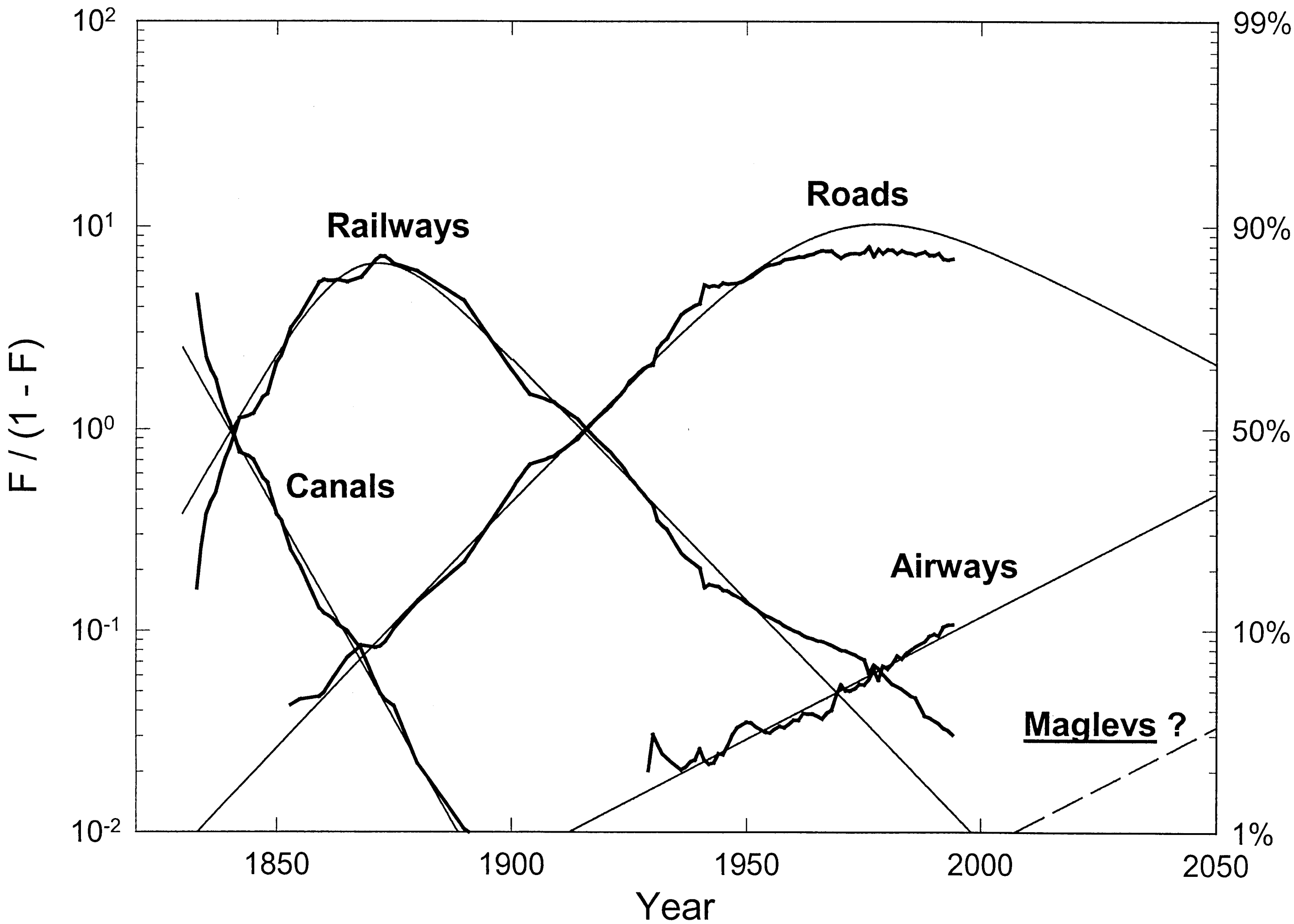
tion, is the most profound finding of 25 years of energy research.[3] It implies that ultimately, primary fuels that easily supply H_2 and electricity will win, too.

The stable dynamics of the energy system permit reliable forecasts. Globally, we are destined to use about 100 million tons more coal.[4] This is about half what humans have mined in all our earlier history, and 30 to 40 years' worth at present levels of production—so all the participants in the coal industry have a generation or two in which to remodel themselves. They can concentrate on extracting methane from coal seams and sinking CO_2 there, staying in business without coal extraction. Using CO_2 to displace CH_4 adsorbed in coal beds provides a two-for-one bargain.

Coal's market has progressively shrunk compared to electric power generation and steelmaking. We need still to invent better alternatives for the latter. Iron ores can be reduced with hydrogen and the metallurgical treatment done in arc furnaces.

Tunneling, by the way, matters immensely for future human well-being, so the coal industry has a valuable skill to sell. A good use of unemployed miners would be climate adaptation: digging tunnels under the cities to ease traffic and expand badly needed, and energetically superior, metro networks as well as water supply and sewer systems.

To conclude about coal, we should squeeze the maximum electricity from the black rocks with the minimum fallout of nasties; but coal is not our primary concern because its use will fade anyway.



Sources: A. Gruebler, The Rise and Fall of Infrastructure: Dynamics of Evolution and Technological Change in Transport (Heidelberg: Physica, 1990); U.S. Department of Transportation, National Transportation Statistics (Washington, DC, Bureau of Transportation Statistics, 1999), http://www.bts.gov/btsprod/nts/ (Jan. 10, 2001).

Figure 3: Shares of the Actual Total Length of the U.S. Transport Infrastructure (Squiggly Lines) Analyzed with the Logistic Substitution Model (Smooth Lines). Note the conjecture that magnetically levitated trains (maglevs) will enter the market; maglevs are a way for electricity to penetrate the market for power for transport.

Amazingly, neither is oil our prime concern. Globally, drivers and others will consume about 300 million tons more oil, before the fleet runs entirely on H_2 separated from methane or water. This amount is roughly double the petroleum that has so far been extracted, so oil companies can choose to play business as usual for a while. But the entry under the car's hood of fuel cells or other motors fueled by H_2 dooms oil, over the decades required for the turnover of the fleet, and creates a huge niche for the easy ways to make the needed hydrogen fuel.

Preaching the advent of the Methane Age 20 years ago, I felt myself a daring prophet, but now this prophecy is like invoking the sunrise. Between its uses to fuel turbines to make electric power and for fuel cells for transport, gas will dominate the primary energy picture for the next five or six decades. I expect methane to provide perhaps 70 percent of primary energy around the year 2030, and to reach a peak absolute use of 30×10^{12} m^3 of natural gas in 2060. Although simply substituting gas for coal or oil reduces CO_2 emissions by one-third to one-half, peak use would correspond to two to three times today's carbon emission to dispose of annually. Even in 2020, we could already need to dispose carbon from gas alone equal to half today's emission from all fuel, and later it would cause about 75 percent of total CO_2 emissions. So prevention—and offsets—must focus on methane.

Our plan must be to give the final consumer, whether the operator of a power plant or a car, a fuel that produces zero emissions—namely, hydrogen. Several paths reach hydrogen. In principle, we could start from heavy oil and end in hydrogen and CO_2. Refiners have done it since the 1960s. Refiners can more easily transform methane into hydrogen and CO_2. The methods now come from chemistry like that used to make ammonia, but the energy companies could whip the imaginations of the petrochemists to make more efficient processes suitable for plants two orders of magnitude larger than present fertilizer plants, but with less requirement for purity.

Helpfully, so-called "city gas," basically impure hydrogen, was the fuel gas of much of Europe until World War II. In a neat reversal, the easiest market for hydrogen now to conquer is the household in Europe and North America, where most residences already connect to the gas net. Sometimes the change back requires merely enlarging the nozzles of the burners.

Hydrogen-electric cars still have barriers to overcome, particularly a high accelerating capacity. I say begin with buses and trucks and leave final victory with cars for a little later.

Airplanes consume ever more fuel. Although hydrogen attracts because of its light weight and combustion properties precious for high performance, compact, safe storage of liquid H_2 still offers barriers to overcome for the engineers and scientists of the air and space carriers. The prizes will include the markets for the new super-jumbos and the commercial hypersonics—to speed the ever-more-numerous climate negotiators cleanly to their next meeting.

Nuclear fission probably, or possibly some other noncarbon alternative, will eventually close the hydrocarbon fuel era. Nuclear plants can economically make electricity by day and hydrogen by night, when electricity demand falls. After Three Mile Island, and especially Chernobyl, the pundits said such accidents would be common. The world has now experienced 5,000 reactor years of operation since Chernobyl without a significant nuclear power plant accident. That is, more than 400 plants have operated safely for 14 years each. Nuclear power technology works, and punditry about the China Syndrome did not. Now is the time to actively promote the development of high-temperature, gas-cooled reactors and other plant designs especially well-suited for the joint production of electricity and hydrogen.

The first step on the road to zero-emission power plants is focusing on natural gas.

In the interim before nuclear, however, can we find technology consistent with the evolution of the energy system to economically and conveniently dispose of the carbon from making kilowatts? The practical means to dispose of the carbon from generating electricity, consistent with the future context, is what I and my associates call "ZEPPs"—zero-emission power plants.[5]

IV. ZEPPs

The first step on the road to ZEPPs is focusing on natural gas, simply because within a couple of decades half of CO_2 emissions will come from natural gas. A criterion for ZEPPs is working on a big scale. One reason is the information economy. Even with increasing efficiency, the information economy demands huge amounts of electricity. Observe the recent rapid growth of demand in a college dormitory, or in the State of California and especially Silicon Valley. Chips could well go into 1,000 objects per capita, or 10 trillion objects, as China and India log into the game.

Big total energy use means big individual ZEPPs because the size of generating plants grows even faster than use, though in spurts. Plants grow because large is cheap if technology can cope. Although the last wave of power station construction reached

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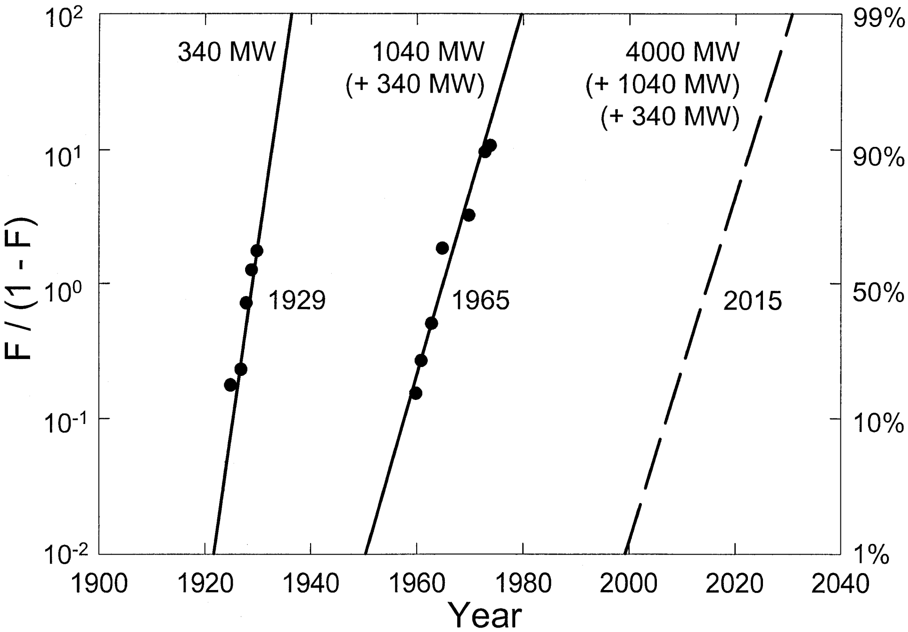

Source: World Electric Power Data CDROM UDI-2454, Utility Data Institute, Washington, DC, July 2000.

Figure 4: The Maximum Size of U.S. Power Plants. Each line represents an S-shaped (logistic) curve normalized to 100 percent, with estimates for the midpoint of the process and saturation level indicated. So, the pulse centered in 1929 quickly expanded power plants from a few tens of MW to about 340 MW. After a period in which plant size stagnated, the pulse centered in 1965 quadrupled maximum plant size to almost 1,400 MW. The patterns for the world and a dozen other countries we have analyzed closely resemble the United States. Note the projection for another spurt in plant size centered around the year 2015, quadrupling the maximum again, to more than 5 GW. F is fraction of the process completed.

about 1.5 GW, growth of electricity use for the next 50 years can reasonably raise plant size to about 5 GW (**Figure 4**). For reference, the New York metropolitan area now draws above 12 GW on a peak summer day.

Bigness has a hidden plus for controlling emission. Although one big plant emits no more than many small plants, emission from one is easier to collect. Society cannot close the carbon cycle if we need to collect emissions from millions of microturbines.

Big ZEPPs means transmitting immense mechanical power from larger and larger generators through a large steel axle as fast as 3,000 revolutions per minute (rpm). The way around the limits of mechanical power transmission may be shrinking the machinery. Begin with a very-high-pressure CO_2 gas turbine where fuel burns with oxygen. Needed pressure ranges from 40 to 1,000 Atm, where CO_2 would be recirculated as a liquid. The liquid combustion products would be bled out.

Fortunately for transmitting mechanical power, the high pressures shrink the machinery in a revolutionary way and so permit the turbine to rotate very fast. The generator could then also turn very fast, operating at high frequency, with appropriate power electronics to slow the generated electricity to 60 cycles.

Our envisioned hot temperature of 1,500 degrees C will probably require using new ceramics now being engineered for aviation. Problems of stress corrosion and cracking will arise at the high temperatures and pressures, and need to be solved. Power electronics to slow the cycles of the alternating current also raises big questions. What we envision is beyond the state of the art, but power electronics is still young (meaning expensive and unreliable), and we are thinking of the year 2020 and beyond.

The requisite oxygen for a 5 GW ZEPP also exceeds present capacity, but could be made by cryoseparation. Moreover, the cryogenic plant may introduce a further benefit. Superconductors fit well with a cryogenic plant nearby. Superconducting generators are one of the sweetest cherries of prevention.

One criterion of great interest for ZEPPs is their overall projected plant efficiency. Colleagues at Tokyo Electric Power calculate the efficiency could be 70 percent, well above the 50 to 55 percent peak performance of today.

With a ZEPP fueled by natural gas transmitting immense power at 60 cycles, the next step is sequestering the waste carbon. At the high pressure, the waste carbon is, of course, already liquid carbon dioxide and thus easily handled. Opportunity for storing CO_2 will join access to customers and fuel in determining plant locations. Because most natural gas travels far through a few large pipelines, these pipelines are the logical sites for ZEPPs.

In short, the vision is a super-compact (1 to 2-m diameter), superpowerful (potentially 10 GW or double the expected maximum demand), superfast (30,000 rpm) turbine putting out electricity at 60 cycles plus CO_2 that can be sequestered. ZEPPs the size of a locomotive or even an automobile, attached to gas pipelines, might replace the fleet of carbon-emitting monsters now cluttering our landscape.

We propose starting introduction of ZEPPs in 2020, leading to a fleet of 500 5 GW ZEPPs by 2050. This does not seem an impossible feat for a world that built today's worldwide fleet of some 430 nuclear power plants in about 30 years. Combined with other offset strategies, ZEPPs, together with another generation of nuclear power plants in various configurations, can stop CO_2 increase in the atmosphere near 2050 AD in the range of 450–500 ppm without sacrificing energy consumption.

ZEPPs merit tens of billions in research and development, because the plants will form a profitable industry worth much more to those who can capture the expertise to design, build, and operate them. Research on ZEPPs could occupy legions of academic researchers, and restore an authentic mission to the National Laboratories of the U.S. Department of Energy (DOE), working on development in conjunction with private companies. ZEPPs need champions, and I hope they will be found among the readers of *The Electricity Journal*.

To summarize, I have searched for technologies that handle the separation and sequestration of amounts of carbon matching future fuel use. Like the jumbo jets that carry the majority of passenger kilometers, compact, ultrapowerful ZEPPs could be the workhorses of the energy system in the middle of the next century.

No one has figured out how to achieve economics of scale with solar and renewable sources.

V. Remarks and Conclusions

Before concluding, I would like to offer a few remarks about popular aspects of the climate debate.

Conventionally, it would be pleasant to make the usual warm and very fuzzy remarks about so-called solar and renewable sources. The reality is that each is dirty in its own way: hydro kills rivers, biomass gobbles habitat that could be wilderness, windmills kill birds (and could easily become still relics if the winds change), fields of photovoltaics are Earth painted black, and so on. After 20 years and more than $12 billion in R&D from the DOE, and friendly words from consumers, solar and new renewables do not provide the United States with a single new quad of the more than 90 quadrillion BTUs the U.S. consumed in the year 2000.

Most important, no one has figured out how to achieve economies of scale with these energy sources. When increasing spatial density of energy consumption drives the system, we must match it with economies of scale in production. We need B-747s as the backbone of the energy system, not two-seater Piper Cubs. Of course, the little planes play crucial roles in the capillary ends of the system and in providing back-up and flexibility. But they will not prevent greenhouse gas build-up.

And what about efficiency? The opportunity appears huge, because the efficiency of most aspects of the energy system—extraction of resources, generation and transmission of power, and especially the devices used finally by consumers—is a small fraction of what it could be. Alas, historically, inefficiency tends to lessen at an implicit, steady, gradual rate. The rate appears the outcome of a complex of factors, including how consumers spend their money and time, and the ability to maintain and service products. Rates of efficiency gain do not seem persistently altered by so-called policy.

Better efficiency, by the way, is not particularly driven by prices.

For example, the prize for more efficient aircraft engines has been range. Fuel economy enabled the Airbus 340 to fly nonstop from Frankfurt to Honolulu and thus gain a new market. Reducing the fuel bill was not the game. The prizes for more efficient electronics are often time and portability. Spartan electronics extend the operational time of a cell phone and reduce the weight of its batteries. Consumers cheerfully pay for these benefits, unlike for energy efficiency *per se.*

More generally, I doubt fiddling with prices has much long-run effect on the energy system. Carbon taxes are just more taxes, with a smell of morality. Carbon taxes will have negligible impact on transport fuel consumption in particular. The usual car owner with a constant travel money budget saves money by continuing to drive the old car and offsetting higher fuel prices by lowering capital or amortization costs. As we saw during the so-called Oil Crisis, the behavior spreads havoc through the auto industry without benefiting the environment.

Although emission trading might in principle lower the cost of decarbonizing, I doubt whether societies can solve the hardest problem of a trading system: the allocation of permits worth about a trillion dollars.

If solar and renewables, efficiency, taxes, and emission trading all count for little, what adaptation, offsets, and prevention shall we choose?

Since the nineteenth century, Earth has had a 30 percent increase in CO_2, from about 280 to about 360 ppm with no discernible harm. We probably cannot avoid about as much again, say a 25 percent increase to 450 ppm. So, we should invest in adaptation to live with likely change.

We should choose long-term solutions for emissions compatible with the evolution of the energy system. This means shift to methane, focus offsets on the carbon in methane, prepare the hydrogen economy, and anticipate the nuclear millennium that will follow our Methane Age.

Technology can make adapting to climate change, offsetting emissions, and preventing emissions cheap and effective. The companies that provide the appropriate goods and services will profit. However, entering the marketing too early can cost as much as entering too late. Society does not want to risk being too late. Thus, cooperative efforts boosted publicly make sense now, especially for momentous developments such as interbasin water transfer or 5 GW ZEPPs that may cost dearly and need widespread social acceptance.

The trick is easing in the changes when the technologies turn over, operating at the point where old things are substituted anyway. Even a refinery is metabolized in a decade or two; that is, machinery is substantially replaced due to wear and tear and obsolescence.

In contrast, beliefs, such as kosher dietary laws, can last thousands of years. As a nineteenth century rabbi said, the loudest sound in the world is a habit breaking. Infiltrating technology, we can avoid screams while lessening worries about climate change.

Mechanisms such as the Electric Power Research Institute and the Gas Research Institute, both now unintentionally endangered by the re-regulation of their industries, have already played great roles in the United States in helping the timely evolution of climate-friendly technologies such as fuel cells and superconducting materials. Adapting and expanding these organizations, and making comparably valuable institutional innovations, also make a worthy goal.

Great sins can elicit great cathedrals. In fact, the people of medieval Europe were not more evil than those of other times and places, but they channeled their guilt to glorious, enduring expression. Let us similarly channel the diffuse anxiety that is environmentalism into immense achievement. ■

Endnotes:

1. J.H. Ausubel, *Does Climate Still Matter?* Nature, April 25, 1991, at 649–52.

2. D.G. Victor and J. H. Ausubel, *Restoring the Forests*, Foreign Affairs, Nov.–Dec. 2000, at 127–44.

3. See J.H. Ausubel, *Productivity, Electricity, Science: Powering a Green Future*, Elec. J., April 1996, at 54–60, especially Figures 2 and 3.

4. J.H. Ausubel, A. Gruebler, and N. Nakicenovic, *Carbon Dioxide Emissions in a Methane Economy,* Climatic Change, June 1988, at 245–63.

5. For more information on ZEPPs, see J.H. Ausubel, *Five Worthy Ways to Spend Large Amounts of Money for Research on Environment and Resources*, The Bridge, Fall 1999, at 4–16.

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