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Reducing Vulnerability: The Energy Jugular

Massive attacks by nuclear-armed missiles are not this country's only strategic problem. National security is threatened not only by hostile ideology but also by misapplied technology; not only by threats imposed by enemies abroad but also by threats that America heedlessly—and needlessly—has imposed on itself. Despite its awesome military might, the United States has become extremely vulnerable, and is becoming more vulnerable, to the simple, low-technology disruption of such vital infrastructure as energy supply, water, food, data processing, and telecommunications.

Terrorism, technical mishap, or natural disaster that damaged the domestic energy system could be nearly as devastating as a sizeable war. Covert paramilitary or nonmilitary attacks on key infrastructure are so cheap, safe, and deniable that they may prove a fatally attractive instrument of surrogate warfare. The horizontal proliferation of nuclear weapons technology means that the delivery vehicle of choice for a miniature nuclear bomb may now be a Liberian freighter or a fishing boat, a delivery van or a U-Haul truck—modes that can be anonymous and therefore undeterrable. And *non*nuclear strategic attacks may likewise come in unfamiliar and unstoppable forms, appearing as sudden, complete, but perhaps seemingly accidental breakdowns of infrastructure vital to national life. American prosperity could end "not with a bang but a whimper," as the lights go out and the machines stop for a long time because our less visible dangers have been ignored.

The community of strategic planners needs to take fuller account of our self-imposed fragilities. Significant attacks upon energy systems are now occurring at a rate of about one a week around the world (not counting El Salvador, where they occur more or less daily). They are becoming more frequent, serious, and sophisticated. Yet federal energy policy is increasing U.S. vulnerability to such attacks, while ignoring alternatives that would make the American energy system both more resilient and cheaper.

Appropriate responses to threats against our overcentralized infrastructure are quite different from those required to defend against missile attack, though they would also improve nuclear and general military preparedness. Those responses, and the threat itself, were therefore ignored for decades. No analysis had comprehensively examined this strategic blindness until late 1981, when the Federal Emergency Management Agency released a study of U.S. energy vulnerability.[1] The findings of that study have important implications for any meaningful understanding of our national security.

What Is Energy Security?

Military planners have long appreciated that secure energy supplies are vital to maintaining military capabilities, civilian prosperity, and political stability. Threats to energy security, however, have recently been defined—especially since the 1973–74 Arab oil embargo—as the risk that oil imports may be cut off. Innumerable conferences, books, and articles have treated this risk. And it is certainly real and important. One aircraft, or even two people in dinghies, could probably shut down 85 percent of Saudi oil exports for up to three years (the period required to manufacture key components of the loading terminals).[2] Such an attack could be repeated once the damage was repaired. But insecure oil imports are only one of many forms of energy vulnerability. Foreign oil provides only a tenth of America's energy; yet most of the other nine-tenths is as easy to shut off, faster and in larger pieces.

This pervasive energy insecurity has evolved by haphazard ricochets from one vulnerability to another. America shifted from wood to coal in the 1800s in search of more secure and abundant supplies; thence to oil and gas—now three-fourths of our energy—after the 1919 coal strike; thence to oil and gas pipelines after World War II U-boat attacks on coastal oil shipments and labor problems with railway coal shipments. In 1973–74, policymakers rushed to embrace any domestic energy sources, however vulnerable, that could replace embargoed Arab on: massive electrification, an expanded nuclear power program, "coal by wire," and Arctic and offshore oil and gas. The 1979 Iranian revolution in turn sparked the abortive synthetic fuel program.

The oil crises of the 1970s, far from raising consciousness about the fragility of all centralized energy systems, focused attention exclusively on the vulnerability of oil imports. Most proposed substitutes have further *reduced* energy security. The domestic energy system is now so vulnerable that even *eliminating oil* imports—which could be done in the 1980s by making buildings and cars more efficient—would barely begin to reduce America's inventory of critical energy choke-points.

Generic Causes of Vulnerability

Complexity. Many modern energy systems are so complex that their modes of failure often *cannot be* foreseen. Rare, even bizarre, surprises do happen. Critical systems should therefore be designed not only to be reliable against calculable kinds of technical failure, but also resilient in the face of the incalculable: lunatics, guerrillas, social turmoil, freak weather, and those unexpected high-technology failures that are held to be impossible until, like the 1965 Northeast blackout, they happen. Yet this design philosophy of resilience for a surprise-full future is unfortunately very rare in modern energy engineering. If a relay failure blacks out New York, the engineers' usual response is to redesign the relay to fail less often—while doing nothing about the centralizing, monolithic architecture that caused the cascading grid failure in the first place.

Control and synchronism. Many structural features of modern energy systems make major failures more likely. For example, energy is generally hauled for hundreds or thousands of miles, and exploitation of more remote fuel deposits is increasing the distances. Along those energy lifelines are strung vital pumps, valves, switches, etc., which demand split-second computer timing and instantaneous communications. Electrical delivery demands a continuous, direct connection, and large, precise generating machines spread across a subcontinental area must rotate exactly in step with each other, threaded together by a frail network of aerial arteries. Gas grids, too, must maintain a certain mininum pressure; otherwise they can collapse, extinguishing pilot lights and causing an epidemic of fires and explosions. (Thus a city's urban redevelopment problem could be solved by interrupting its natural gas supply, then turning it back on again.)

Hazardous fuels. Energy is often delivered in concentrated, powerful forms that are themselves hazardous. In 1976, an exploding oil tanker in Los Angeles Harbor shattered windows 21 miles away. A standard tank truck of fuel oil contains energy equivalent to 0.3 kiloton; a standard marine tanker of liquefied natural gas, 0.7 megaton. Tanks, tankers, and pipelines rich in flammable or explosive fuels pervade our urban and industrial heartland.

Inflexibility and interdependence. Different fuels, or even different compositions of the same fuel, are seldom interchangeable, so shortages of one type cannot be made up by simply substituting others. Most energy transportation systems, too, have only limited flexibility, reversibility, capacity, speed, and convertibility.

Moreover, many supposedly independent energy systems actually depend on each other. Home oil and gas furnaces need electricity for pumping and ignition. So do gas station pumps, most water systems, most coal mines and oil refineries, and half of all domestic oil extraction. All heavy machinery needs lubricants from the oil industry. Nearly all coal transportation uses diesel fuel. Most power stations use standby diesel generators to run vital safety devices.

Specialized requirements. The extreme capital-intensity of most modem energy systems makes them high-value targets; reduces the financial slack that allows routine maintenance, builtin redundancy, and spare-parts inventories; and reduces adaptability to unforeseen changes in demand patterns. Such systems also often take a decade or so to build, increasing financial and technical risks, and depend on highly specialized skills for operation and maintenance. Without a few key people, many computerized pipeline systems or power plants become inoperable. Such dependence has helped to bring down governments in Britain (the 1974 coal strike), Iran (oil strikes and blackouts in 1978), and Chile (blackouts in 1973). Political disruptions of energy supplies have also threatened the stability of El Salvador (1972, 1980–), Portugal (1972), Puerto Rico (1973, 1977–78, 1981), Colombia (1977–), Israel (1981), and Peru (1981–). A strike of Salvadoran power workers in 1980, which cut off all power and half the water in the capital for only twenty-three hours, shut down 95 percent of the nation’s industry and created a national emergency. In 1983, when striking power workers blacked out sweltering Delhi, the government capitulated in five hours.

Energy systems can be not only severed but also misused: for example, by introducing noxious substances into the gas grid or oil storage depots; adding substances to oil that cause it to rot or make it unrefinable; or altering the frequency or voltage in electrical grids so as to destroy generators and end-use devices over a wide area. Many electrical grids are controlled by open communications links that, in the private estimation of some utility engineers, could probably be taken over and manipulated by amateurs.

Difficulty of repair. Reestablishing collapsed energy systems can be very difficult, as the July 1977 New York City blackout revealed. Many devices cannot be restored to service without some unaffected energy source from outside (e.g., to restart power stations and resynchronize electric grids).

Major spare parts are often special-order items with lead-times of months to years. Spare parts that are stockpiled alongside original components may be destroyed with them; spares stored elsewhere may be impossible to get to the site in an emergency. The national inventory of critical components—special motors and valves, extra-high-voltage transformers and switchgear, and a host of other key items—is very small, typically only enough to cope with failures in one or two plants. Essential repair skills, once available within energy companies, are now generally contracted out to small, specialized crews of very limited capacity. Making spare parts from scratch may require an intact industrial, transportation, and communication infrastructure that presupposes universally available energy.

All these constraints on repair, restoration, and recovery can enable a seemingly minor interruption to enmesh an industrial economy in waves of rapidly spreading chaos. Coordinated attacks designed to hamper recovery could cause abrupt backward lurches in our standard of living. The most powerful and sophisticated nations on earth might. suddenly find themselves grappling with the problems of daily survival that have long been confined chiefly to the poorest nations.

War and terrorism add new dimensions to this threat. Although analyses are inconclusive, some experts believe that the electromagnetic pulse from a single high-altitude thermonuclear burst over the central U.S. could instantaneously burn out virtually all unhardened electronic circuitry in the country, including power grids and their controls, computers (which control oil refineries and oil and gas pipelines), electronic car ignitions, telephones, radios, and televisions. Some analysts suspect that all operating nuclear plants could even melt down uncontrollably.[3]

Terrorist and criminal groups, too, are showing ever more sophisticated tactical and technical skills, and are acquiring such modern munitions as miniaturized silent firearms, precisionguided rockets, poison gases, specialized vehicles, electronic countermeasures, night-vision devices, and industrial lasers. Even the tiny fraction of key energy facilities. now hardened against small groups with light arms could not withstand a modern terrorist assault. At many sites, standoff attack with a rifle could cause damage of national significance.

Specific Vulnerabilities

Liquefied energy gases. liquefied natural and petroleum gases (LNG and LPG) are increasingly common items of commerce. A modem marine LNG tanker contains, at -260°F, enough gas to form a flammable gas-air mixture several hundred times the volume of the Great Pyramid of Cheops. Spilled LNG boils into gas so cold that it remains heavier than air. The plume can drift along the ground for miles before it ignites in a conflagration like a hundred *Hindenbergs*. Radiant heat from such a fire would cause third-degree bums and start fires a mile or two away. Despite safety precautions, there have been several significant LNG accidents and many near misses.[4] Most LNG facilities have minimal guards, no alarms, and key structures vulnerable to light arms.

LNG is shipped by marine tanker into terminals, one of which is in Boston Harbor. Each terminal contains several LNG tanks, each equivalent in energy content to over half a megaton. The U.S. has about 50 additional LNG storage depots aboveground, each equivalent to more than 130 kilotons. LNG is also delivered by trucks, each with a quarter kiloton of energy content, routinely traveling over key bridges. and through urban centers. Under suitable circumstances, one LNG truck falling off of Boston’s Southeast Expressway could fill with flammable air-gas mixture the entire Boston subway system, or the city’s major tunnels, or enough of the sewer system to blow up virtually every street in the city. LPG is shipped by marine tanker, high-pressure pipeline, tail, and ubiquitous trucks. Each LPG railcar contains energy equivalent to about three-fourths of a kiloton, releasable in a violent fuel-air explosion that can hurl large shrapnel and cause second-degree bums by radiation up to a mile away.[5] LPG and LNG trucks could readily be hijacked and detonated next to a high-value target. LPG and LNG facilities are often next to or surrounded by such targets already: cities, ports, refineries, oil depots, the Calvert Cliffs

[Maryland] nuclear power plant. In 1981, an FB-111 aircraft crashed a quarter mile from New England's second-largest LNG/LPG facility—two miles from the center of a town of 27,000, two and a half miles from a nuclear submarine base, and threequarters of a mile (well within the range of radiant third-degree burns) from Pease Air Force Base with its huge. fuel depot. Because the plane did not score a direct hit, the General Accounting Office's devastating 1978 report on the risk of disastrous LNG explosions and firestorms continued to be ignored.

Oil and gas systems. Nearly three-fourths of America's energy comes from oil, gas, and natural gas liquids. (So do most rubber, plastics, fertilizers, paints, solvents, and medicines—all the products of petrochemical plants, 60 percent of which are tightly clustered along the Texas Gulf Coast.) In 1982, a fourth of the oil used was imported, and less than a fifth of that came from Arab OPEC nations.

Extraction and transport. Middle Eastern oil fields are valued at more than one gross world product-year. Oil extraction in the Persian Gulf is astonishingly concentrated. Saudi Arabia has until recently lifted oil at nearly the rate of the United States, but from about a thousandth as many wells—with a single supergiant Saudi field lifting oil faster than any other *country* except the U.S. and the USSR. Just the five hundred-odd miles of eastern Saudi pipelines carry a sixth of the non-Communist world's oil. All such facilities are militarily indefensible, and many have been under attack throughout the Middle East for more than a decade.

The lumbering supertankers that bring Middle Eastern oil through strategic straits to Europe, Japan, and North America managed to. destroy themselves without assistance at a rate averaging three per month in early 1980.[6] During eight months in 1981, twenty-one of them were boarded and robbed near Singapore by pirates in small native boats; one was even hijacked in the Strait of Malacca.

Oil platforms off the U.S. coast, often proposed as a substitute for imported oil, are sitting ducks laden with highly flammable fuel under pressure. A single platform may cost upwards of $50 million, carry over forty wells, and feed mainland pipelines through a single frail link. The Coast Guard in New Orleans has contingency plans that, in good weather, can bring a protective vessel to any of 3,000 platforms in eight hours. A competent terrorist could destroy such a platform in eight minutes. Gulf of Mexico fireboats might handle up to three modest platform fires at once—if not bottled up by sinking a barge in a single canal. In the North and Beaufort seas, fire fighting, protection, and repairs are often rendered impossible by hundred-foot waves.

Storage. The average barrel of oil takes about three months to get from the wellhead to the final American user. Usable storage capacity in between represents at most a few months' normal demand. The oil system is so tightly coupled that if normal flows are interrupted, refineries typically run out of crude oil in three to five, days, and pipeline customers run out, of products in five to ten days.[7] 0il stockpiles therefore represent high-value targets. On December 19 and 22, 1982, respectively, major-oil depots in Venezuela and Kenya went up in smoke in apparent accidents. Rhodesia's main stocks were blown up in 1978, increasing the national budget deficit by 18 percent overnight. Attacks on oil depots have succeeded in Mozambique, Britain, and Italy; partly succeeded in Namibia, The Netherlands, West Germany, France, and the U.S.; and been narrowly foiled in Chile and Israel. The U.S. Strategic Petroleum Reserve—the only major oil or gas facility in the country where some serious thought has been given to security—is mostly underground; but one person could render it useless in three nights by knocking out the three pipelines meant to deliver SPR oil to refineries.

Processing plants. Oil refineries are typically the most vulnerable, capital-intensive, and indispensable element of the oil system downstream of the wellhead. Just as three-fourths of domestic oil is lifted in four states, over half the refinery capacity is concentrated in three (Texas, Louisiana, and California), and more than 69 percent is in six states. This concentration is increasing. The Office of Technology Assessment noted that in 1978, destruction of the seventy-seven largest U.S. refineries would have eliminated two-thirds of U.S. capacity and "shattered" the economy.[8] This would not, however, require dozens of nuclear warheads—only a wrench, rifle bullet, grenade, or turned valve at each of seventyseven plants. Many design trends are making refineries ever more vulnerable to the simple, unstoppable sorts of sabotage that have already occurred in several U.S. plants. Thus simple damage to a coking unit of a TOSCO refinery on the first day of a California strike did many millions of dollars' worth of damage and shut down the whole refinery for more than three months. "Physical disaster," reported the company's president, "was narrowly averted" by luck and by the prompt action of supervisory staff.[9] In 1980, when an extortionist threatened to set off a remote-control bomb at a $250 million refinery in Edmonton, Alberta, the Imperial Oil Company paid up—reportedly $1 million.

Natural gas processing plants are similarly vulnerable and even more concentrated. A single plant in Louisiana handles 3.5 percent of America's natural gas, equivalent to the output of more than twenty giant power plants. About 84 percent of all interstate gas in the country flows from or through Louisiana. So concentrated are the pipelines and their controls that a few people could shut off, for upwards of a year, three-fourths of the gas and oil supplies to the eastern U.S. in one evening's work without even leaving Louisiana. The head of a major oil production company recently told us, "With a hundred pounds of dynamite, distributed among about eight places, I could cripple the country."

Pipelines. Oil and gas pipelines depend on prime movers (usually electric motors or gas turbines), pumps or compressors, and complex computer controls and telecommunications equipment. Few if any pipeline companies have, or know where to get, enough skilled people to run the pipeline grids manually by turning valves and controls. Pipelines are easily located and cut using low technology; gas pipelines can be made to explode and rip themselves up—automatically for miles. Many key pipelines are co-located, and have vital but easily cut junction points. River and swamp crossings are very hard to repair. Many times longer than, the Equator, crossing remote and rugged terrain, major pipeline systems are indefensible. They have already been successfully attacked in most parts of the United States.[10]

Pipelines move about three-fourths of the crude oil used by U.S. refineries, a third of the refined products sent from refineries to consumers, and nearly all natural gas. The pipeline grid, especially interstate, is not flexible enough for rerouting to bypass major damage. Cutting just three domestic oil pipelines (TransAlaska, Colonial, and Capline) would stop a flow totaling nearly five million barrels per day—substantially more than all 1982 net oil imports.

East Coast refineries get crude oil only from tankers, not from pipelines. Their output is supplemented by a few product pipelines too big to replace with tankers. Six hits could sever pipeline service between the main oil fields and the East and Midwest; ten could cut off 63 percent of U.S. capacity for piping refined products. A single pipeline system (Colonial) carries about half the barrel-miles of refined products pipelines in the country, yet it has only recently acquired a duplicate (but soft-target) control center. Security arrangements for major pipelines and their control systems are so lax that a 1979 General Accounting Office audit.found easy public access to major terminals, computers, and power sources: some pumping stations were the sites of juvenile beer parties.[11]

Arctic pipelines are especially vulnerable. The Trans-Alaska Pipeline System (TAPS) is four feet in diameter, cost eight billion dollars, moves one-seventh of all crude used by U.S. refineries, displaces oil imports worth nearly $600 a second, and has no substitute. Over half of its nearly 800-mile length is held aloft on stanchions. It crosses readily accessible rivers. State highways lead to five of its eight pumping. stations. The line crosses three mountain ranges and five seismic areas. Interrupted pumping for three winter weeks would congeal nine million barrels of hot oil, turning TAPS into the world's largest Chapstick. (Laboratory tests give hope that the pumps may be powerful enough to get the oil moving again, but nobody is eager to try a full-scale expeiriment.) Trouble in the plumbing or tanks at either end of the line, or in the gale-prone Valdez Narrows at the southern end, could do the same. The uninsurably vulnerable labyrinth of pipes feeding oil into TAPS would take at least eight months to rebuild plus two to ship from Japan.

TAPS has been lightly bombed twice, shot at, and sabotaged by other means; the U.S. Army found it indefensible. But its operators still perceive no security threat.[12] In 1977, the southernmost pumping station—the least vital and the easiest to fix—was blown up by operator error. The line was shut down for ten days, then ran at half-capacity during nine months of intensive repairs.

Three-fourths of America's energy reaches its destination only because nobody tries very hard to stop it. The highly complex, centralized oil and gas system is designed for a "technological paradise" in which everything works according to the blueprints. The future may not be like that at all.

Power stations and electric grids. Central-electric systems deliver 13 percent of U.S. energy and consume a third of all primary fuels, including four-fifths of the coal burned. Electricity is essential to most people's lives—even, in many cities, to seeing and breathing. The lack of electrical storage makes any disruption instantaneous, and widespread (as when a 1982 Oregon relay failure caused blackouts in Arizona). Yet electrical supplies are even more vulnerable than oil and gas supplies. A 1981 General Accounting Office audit found that sabotage of eight easily accessible substations could black out a typical U.S. region, while sabotage of only four could leave a city without power for days and with rotating blackouts for a year. A worker in a major Eastern utility recently remarked, "I could shut down my grid with a coat hanger."

The three U.S. regional power grids are probably just as brittle, for three reasons. Having no significant storage capacity, the grid requires immediate bypassing of failed transmission links (the main cause of failures); failed generating plants (a minor cause) must also be very rapidly replaced by spare capacity; and these corrective actions absolutely require that key transmission segments be available and that switchgear and computerized controls and communication links work properly.

About 82 percent of U.S. electricity comes from 900-odd large thermal power plants; most of hydroelectricity's .12 percent comes from a few large dams. These complex, billion-dollar facilities are tempting targets and very slow to mend. Their key components are so huge, yet so delicate, that in 1978 someone with a bludgeon was able to damage dozens of coils, many beyond repair, on three of the world's largest electric generators in the bowels of Grand Coulee Dam. Lost production was estimated to cost $35 per minute.

Centralized generation places heavy burdens on the transmission system, switchgear, and controls—the most frequent target of attacks in numerous countries (including the U.S.). Such assaults are now a characteristic target of Soviet-trained guerrillas.[13] Transmission and substation attacks have been frequent and coordinated: during 1978, on average, an American utility was bombed (in most cases more symbolically than seriously) every twelve days.[14]

The officially encouraged trend toward more and bigger power stations, more remote siting (e.g., in Western coalfields), and longer, higher-voltage transmission lines is increasing the instability and potential uncontrollability of large grids for which no adequate control theory yet exists.

Nuclear facilities. Nuclear power plants, reprocessing plants, and spent-fuel storage depots contain prodigious amounts of long lived radioactivity. They are valuable and highly visible economic and political targets. They also facilitate the manufacture of nuclear bombs by providing fissionable materials, information, skills, equipment, and organizational structures suited to that purpose.[15] Such bombs can in turn be used to attack nuclear facilities.

More than a hundred significant attacks on, incidents of sabotage at, and security breaches in nuclear facilities have already occurred worldwide. More' than seventy nuclear power plants are operable in the United States, fewer than sixty under construction. Each large plant, when operating, contains over fifteen billion curies of radioactivity (equivalent to the fallout from some 2,000 Hiroshima bombs) plus heat, mechanical energy, and chemical energy that could facilitate its release. Despite extensive precautions, the plants remain vulnerable. For example, none of the safety devices can work if electricity from outside the plant and from its own emergency generators is cut off.[16] Straightforward attacks could cause unstoppable releases comparable in radiological effect to a sizeable nuclear bomb, with lethal ranges of tens or even hundreds of miles.[17] The saboteur could deliberately choose the worst weather conditions, the ripest fuel, and the reactor upwind of the biggest city.

A bomb yielding one kiloton or less, detonated thousands of feet from a nuclear power plant, is probably enough to cause an uncontrollable meltdown. Shortening the range to a few hundred feet (within public access to many sites) would release virtually all of the reactor core. The long-term radiological consequences of bombing a reactor with a crude nuclear explosive in the tenthkiloton range would probably be similar to those of a one-megaton ground burst at ranges up to a few hundred miles. Longer-range effects would exceed those of the ground burst. Tens of thousands of square miles could be seriously contaminated for centuries.[18]

Is the Threat Real?

Readers unfamiliar with the hundreds of actual attacks, in over forty countries, cited in *Brittle Power* may feel that such energy related threats to national security are implausible. One might also have been excused for thinking that regionwide power blackouts were unlikely until 1965, or the hijacking of three jumbo jets in a single day until 1970, or the take-over of more than fifty embassies until the 1970s. But given the potential consequences, nobody would want to be in the position of the British intelligence officer who, on retiring in 1950 after forty-seven years' service, reminisced: "Year after year the worriers and fretters would come to me with awful predictions of the outbreak of war. I denied it each time. I was only wrong twice."[19]

Some military planners already know better. Goering and Speer stated after World War II that the Allies could have saved two years by bombing the highly centralized German electric-power system. In contrast, 78 percent of Japanese electricity in World War II—like most Vietnamese electricity later—came from small, dispersed hydroelectric plants that, in contrast to the centralized thermal plants, sustained only 0.3 percent of the bombing damage.

The accidental blackout of virtually all of France in 1978, of Israel in 1979, and of most of southern Britain in 1981 has renewed interest in less vulnerable designs for the energy system. Even the Red Army is said to seek energy decentralization as a preparedness measure—though the Politburo forbids this because it would reduce the Party's political control. Several countries are analyzing, and at least Sweden, China, and Israel are systematically seeking, the strategic benefits of energy decentralization.

Yet the Reagan administration, despite its concern for national security, is emphasizing—and subsidizing with more than $10 billion per year—precisely the most vulnerable energy technologies. Federal plans call for a trillion dollars' worth of new power stations and grids in the next twenty years (including trebled or quadrupled nuclear power capacity), vastly more Arctic and offshore oil and gas, an Arctic gas pipeline, a new inland version of the Strait of Hormuz to be created in the Powder River Basin of Wyoming, and a synthetic fuels industry—an option so vulnerable that both times it has been tried before (Nazi Germany and contemporary South Africa) it was promptly and successfully attacked.

These brittle devices are supposed to form the backbone of America's energy supplies well into the twenty-first century—a period likely to bring increasing uncertainty, surprise, unrest, and violence. The United States cannot afford vulnerabilities that so alter the power balance between large and small groups in society as to erode not only military security but also the freedom and trust that underpin constitutional government.

Such escalating energy insecurity, however, is not necessary. It is not even economic. Alternatives exist—and are cheaper anyhow. Design lessons from biology and from many kinds of engineering suggest twenty or so principles of a design science of resilience. Embodying those principles in practical, available, and cost-effective technologies can make energy supply so resilient that debilitating failures become impossible. Best of all, this enhancement of national and individual security, far from costing an "insurance premium,[19] would actually put money back in our pockets. A resilient energy strategy would enhance American preparedness, make it less necessary, and at the same time save several trillion dollars and about a million jobs over just the next twenty years.

Designing for Resilience

An inherently resilient system should include many relatively small, fine-grained elements, dispersed in space, each having a low cost of failure. These substitutible components should be richly interconnected by short, redundant links—rather as a tree has many leaves, and each leaf has many veins, so that random nibbling by insects cannot disrupt vital nutrient flows. Failed components or links should be promptly detected, isolated, and repaired. Components need to be so organized that each element can interconnect with the rest at will but stand alone at need, and that each successive level of function is little affected by failures or substitutions at a subordinate level. Systems should be so designed that any failures are slow and graceful. Components, finally, should be understandable, maintainable, reproducible at a variety of scales, capable of rapid evolution, and societally compatible.

Redundancy and diversity. These principles are already being applied in data p rocessing, where tens or hundreds of microcomputers can be organized into a network that can do the same job as a large mainframe computer but with far greater reliability, resilience, and data security. The failure of some components or interconnections does not interfere with normal operation: each task being done by a failed part is safely completed by others. Multiple failures may make the system a bit sluggish, but it will perk up again as soon as the parts are repaired (which is done without shutting the system down). Commercial "distributed processing" systems organized in this way can make the mean time between failures arbitrarily long—thousands of years, for example—at a trivial extra cost, more than paid for by avoided downtime.

Energy systems offer equally striking examples. When the engineer running the power system in Holyoke, Massachusetts, saw the 1965 Northeast blackout rolling toward him, he quickly isolated the city from the grid and powered it with a local gas turbine. The money saved by not having to black out Holyoke paid off the cost of building that power plant in four hours.[20]

The advantages of diverse energy supplies became clear in West Chicago in 1980 when Department of Energy officials had just finished cutting the ribbon on a photovoltaic-powered gas station. Just then a thunderstorm blacked out the area—leaving only that one station pumping gas.[21] Likewise, in the bitter winter of early 1977, while the Midwest reeled under an acute shortage of natural gas, consumers in equally chilly rural New England were virtually unaffectedbecause the gas used there (LPG) came in bottles. Therefore not everyone ran out at once, and systemwide collapses of distribution pressure were not possible. As in Israel, the independent, highly dispersed gas storage was all but invulnerable.

Efficient energy use. The most striking contribution to energy resilience, however—the most "bounce per buck"—comes from more efficient energy use, for many reasons. Efficiency is the fastest and cheapest way to eliminate the most vulnerable marginal supplies (such as Persian Gulf oil), making their failure inconsequential. Those failures that efficiency cannot altogether prevent it makes slower, more graceful, less severe, and more fix-able. It also buys time to improvise substitutes, and stretches the job they can do.

For example, if you live in a superinsulated house *in Minnesota, and your heating system (assuming you even need one) fails in January, you won't know it for weeks. You'll find out only because the indoor temperature will slowly drift down from 72°F to the high 50s—but no lower, because of the "free heat" from bodies, windows, lights, and appliances. Thus neither you nor your pipes will freeze. If a few neighbors come in to take refuge from their sieve, their body heat alone will restore your house to 72°. If they bring a few kids, the house will overheat and you'll have to open the windows. Alternatively, any improvised point source of heat could keep the whole house warm—such as burning junk mail in a #10 can.

On a national scale, a light-vehicle fleet getting, say, 65 miles per gallon (15 worse than the city performance of an advanced Volkswagen Rabbit prototype tested in 1981) would make oil stocks last four times as long as they, could today. The tanks of the vehicles would constitute a highly dispersed Strategic Petroleum Reserve, already delivered in usable form. An average car with a half-full tank could run for about three weeks without filling up at all. The "pipeline inventory" between the wellhead and the gas pump would last, not for days or weeks as at present, but for nearly a year—buying precious time to mend major damage to the national oil system or to improvise alternative supplies.

Likewise, cost-effectively efficient use of electricity would enable small and improvised supplies—industrial cogeneration, wind, small hydro, even the car and truck alternators and generators that now total a sixth as much capacity as all U.S. power stations to maintain fairly normal production and amenities and provide abundant nuclei for restoring damaged grids.

Any more efficient use of U.S. vulnerable energy sources would increase the ability of inherently resilient energy sources—the diverse, dispersed, uninterruptible, renewable sources—to meet a larger fraction of total energy needs. Those sources, chosen carefully and built sensibly, are already more reliable and less costly than the centralized, nonrenewable sources they would gradually replace.[22] Within a few decades, appropriate renewable sources could replace, largely or *wholly,* the vulnerable supplies on *which* the U.S. now depends. Using energy in an economically efficient way[23] can thus buy the American—energy system time to complete comfortably the transition from living on energy capital to living on energy income.

From vulnerability to resilience. That transformation is well under way. Since 1979, the United States has gotten more than a hundred times as much new energy from savings as from all expansions of energy supply combined. Of those expansions, more new energy has come from renewable sources (now nearly 8 percent of total U.S. supplies) than from any or all of the non renewables.[24] That is, sun, wind, water, and wood (which now delivers about twice as much energy as nuclear power)[25] are collectively outcompeting and outpacing oil, gas, coal, and uranium, or any one of them—and higher energy productivity is far outpacing them all. Even in the electric utility sector, more new generat ing capacity has been ordered since 1979 from small hydro plants and windpower than from coal and nuclear plants.

Americans spent some $15 billion on efficiency and renewables just in 1980. The problem of secure and affordable energy supplies is starting to be solved—but from the bottom up, not from the top down; Washington will be the last to know. Community programs[26] are vital to this transition from high-cost to lower-cost and from high-risk to low-risk investments. But even the strongest community sentiment would not be enough without economic rationality. The marketplace is confirming that efficiency and appropriate renewable sources, the keys to energy security, are also the best buys in the narrowest economic terms—the options that would win in a truly free market, even if all their security benefits were valued at zero. Removal of the severe price distortions caused by federal subsidies, and a few limited federal policy initiatives to ensure that potential resiliency benefits are not lost through poor or incompatible designs, could make theAmerican energy system resilient even faster. But this win require greater willingness than the Reagan administration's to expose all technologies to free competition.

A New Security Paradigm?

These principles of energy security suggest broader conclusions for strategic planners: Exclusive attention to overt military threats risks building some very expensive Maginot Lines while' the back door swings wide open. Better security does not always cost more money; at least in the case of energy—and probably of food and water, too—it costs less. And most importantly, better security may not require, and may not even be able to tolerate, central management.

The past decade's experience proves that effective programs to make energy secure and affordable tend to work on the same political scale as the Founding Fathers' concept of a local militia. Might not other kinds of security also be best obtained on a scale more local than national? Real security, after all, must include not only reliable supplies of energy, but also of food and water; a sustainable, flexible system of production and exchange; a healthful environment; free expression and debate; a legitimate system of self-government. But all these things can be more responsively provided at the scale of a county commission, a town meeting, a city council, or a block association than of a federal Congress or president.

Does the central government indeed hold any monopoly on providing security? Our government spends about $10 thousand a second on a stronger military establishment; but success seems elusive. In 1947 the U.S. was militarily invulnerable, while today, thirty thousand nuclear warheads later, it lies entirely exposed to devastation. Clearly, military might is an insufficient basis for security. But with the freedom to act as individuals and communities, we can largely provide real security for ourselves by building it into the infrastructure, the economy, and the polity of every locality in the land—by building a society so resilient that it defends itself. Perhaps security, in its broadest sense, can come only from the bottom up—from individuals and communitiesand not from bureaucracies.

But security, whatever its source, and whether on the scale of the village or the globe, cannot be taken from or denied to others; it must be shared. Achieving security is never a zero-sum game. If we ourselves enjoyed the elements of a secure life while others did not, we would live in fear that they might seek to take from us what they lack. Real security, then, comes not from a siege mentality, but from making both ourselves and our neighbors more secure.

1. Republished as A. B. and L. H. Lovins, *Brittle Power—Energy Strategy for National Security* (Andover, Maas.: Brick House, 1982); translations forthcoming, including Japanese (Tokyo: Jiji Tsushin, 1983). This brief summary of the book's major findings cannot do justice to its rich technical background, documented by three technical appendices and more than 1,200 references. Classification review and extensive peer review of the substantially identical FEMA report ensured that the analysis would not provide a cookbook for the malicious.

2. The main terminals at Ras Tanura and Ju'aymah are highly vulnerable: -Even a near miss at Ras Tanura could ignite successive oil tank explosions and damage the basic pumping infrastructure" (Senate Committee on Foreign Relations, "The Proposed AWACS/F-15 Enhancement Sale to Saudi Arabia" Washington, D.C.: U.S. Government Printing Office, September 19811). Supplementary pipeline capacity meant to diversify Saudi oil-shipping capabilities will be equally fragile. Certain components without which the terminals cannot load oil into tankers are among the largest metal fabrications in the world. and only a handful of plants can build them. Ayatollah Khomeini of Iran has recently threatened to attack the terminals (Y. M. Ibrahim, "Iran Threatens Persian Gulf's oil Shipments." *The Wall Street Journal*, September 20,1983, p. 31). Iran has already bombed Iraq's main refinery, and Iraq has bombed Iran's main oil terminal.

3. See, e.g., W. J. Broad, "Nuclear Pulse," *Science* 212 (1980): 1009–12; E. J. Lerner, "Electromagnetic Pulses: Potential Crippler," *IEEE Spectrum* (May 1981): 41–46, and "EMPs and Nuclear Power," *IEEE Spectrum* (June 1981): 4849.

4. For example, the Canvey Island LNG terminal on the Thames below London has on four occasions narrowly avoided involvement in nearby oil spills and fires, one arising from an IRA bombing of a nearby kerosene tank. A $4 billion LNG plant in Arzew, Algeria, narrowly escaped destruction one night a few years ago when a gas cloud from a leaking tank drifted through it and dispersed without igniting.

5. See, e.g., U.S. General Accounting Office, *Liquefied Energy* Gases *Safety,* 3 vols., EMD-78-28, July 28,1978; B. IL Williamson and L. IL B. Mann, "Thermal Hazards from Propane (LPG) Fireballs," *Combustion Science and Technology* 25 (1981): 141–45.

6. The *Economist,* April 12, 1980, p. 52.

7. M. M. Stephens, *Vulnerability* of Total *Petroleum Systems,* DAHC20-70-C-0316, report to Defense Civil Preparedness Agency (Work Unit 4362A), May 1973, p. 38; idem, "The Oil and Natural Gas Industries: A Potential

Target of Terrorists,- in Terrorism: *Threat, Reality, Response,* ed. R. Kupperman and D. Trent (Stanford, Calif.: Hoover Institution Press, 1979), p. 208.

8. Office of Technology Assessment, *Vie Effects* of Nuclear War, OTA- NS- 89, May 1979, p. 64 The Soviet concentration is even heavier (A. M. Katz, *Life after Nuclear* War [Cambridge, Mass.: Ballinger, 19811, pp. 317ff).

9. "Tosco Says Refinery Was Hit by Sabotage- Dampening Earnings,- *Vie Wall Street Journal,* April 4, 1980, p. 6.

10. For example, a Shell gasoline pipeline in Oakland, California, was damaged in 1969; a Puerto Rican gasoline pipeline was sheared by ground shock from a bomb in 1975; and the Trans-Alaska pipeline was lightly damaged by bombs in 1977 and 1978 In -1974, twenty Kentucky gas pipelines and two of their cooling towers were dynamited.

11. U.S. General Accounting Office, Key *Chide Oil and Products Pipelines Are Vulnerable to Disruptions,* EMD- 9-63, August 27, 1979.

12. Ibid., p. 30.

13. Most noticeably in Central America and in southern Africa, where Soviet limpet mines are a trademark of the African National Congress's periodic attacks on South African power lines, power plants, and substations; see, e.g., Los *Angeles Times, July* 21, 1981, p. 1:1, and July 22, 1981, p. 1:2.

14. Federal Bureau of Investigation, *Bomb Summary* 1978. Uniform *Crime Reports* (Washington, D.C.: U.S. Government Printing Office, 1979).

15. A. B. and L. H. Lovins, *Energy/War: Breaking the Nuclear* Link (New York: Harper, 1981); A. B. Lovins, "Nuclear Weapons and Power-Reactor Plutonium," Nature 283 (1980): 817–23.

16. This can be inferred from fault and event trees in U.S. Nuclear Regulatory Commission, *Reactor Safety Study,* NUREG- 75- 014, October 1975.

17. S. Fetter and K. Tsipis, "Catastrophic Releases of Radioactivity," *Scientific American* 244, no. 4 (April 1981): 41-47; J. P. Holdren, letter in response (Energy and Resources Group, University of California at Berkeley), March 27, 1981; B. Ramberg, *The Destruction of Nuclear Energy Facilities* in *War* (Lexington, Mass.: Heath, 1980).

18. Ibid. This implies, incidentally, that a *non*nuclear NATO/Warsaw Pact conflict on the North German plain would probably release fallout equivalent to that from thousands of tactical warheads, just from collateral damage to the four large reactors already sited there.

19. Quoted in R. Drobnick and S. Enzer, "Future Environments of International Trade: A Summary and Report of the Fourth Twenty Year Forecast Project," F-42 (Los Angeles: Center for Futures Research, University of Southern California, March 1981).

20. "The Case for Emergency Power," *Electrical Construction and Maintenance* (New York: McGraw-Hill, December 1965).

21. U.S. Department of Energy, *Energy Insider 3,* no. 19 (September 15, 1980).

22. Lovins and Lovins, *Brittle Power,* app. 3; R. Stobaugh and D. Yergin, eds., *Energy Future* (New York: Ballantine, 1979); Solar Energy Research Institute, A *New Prosperity* (Andover, Mass.: Brick House, 1981).

23. Solar Energy Research Institute, op. cit.; A. B. and L. H. Lovins, F. Krause, and W. Bach, *Least-Cost Energy. Solving the CO2 Problem* (Andover, Mass.: Brick House, 1982); D. Olivier et al., *Energy-Efficient Futures: Opening the Solar Option* (London: Earth Resources Research, Ltd., 1983); A. B. and L. H. Lovins, "Electric Utilities: Key to Capitalizing the Energy Transition, *Technological Forecasting and Social Change 22* (1982): 153–66.

24. Energy Information Administration data show 1979–82 savings of 7.82 q/y (quadrillion BTU per year), over half of it from improved technical efficiency. Fossil fuel supply fell 1.00 q/y, nonrenewable supply 0.63 q/y (coal rose 0.80 but oil and gas fell 1.79). Renewable supply increased 0.34 q/y, so total U.S. supply fell 0.29 q/y—both excluding wood, which rose about 0.5 q/y. With the fluctuating hydroelectric output smoothed, the net total increase was somewhat under 0.1 q/y.

25. In 1980, nuclear power delivered 230 TW-h of electricity with a heat content of 0.785 q. Assuming average efficiency of 45 percent in houses and 75 percent in industry, the 2.0–2.4 q of wood burned delivered about 1.35–1.56 q, or 400–460 TW-h of heat. In 1982, nuclear power delivered 0.90 q and wood probably 1.5–1.8 q.

26. Lovins and Lovins, *Brittle* Power, ch. 17.