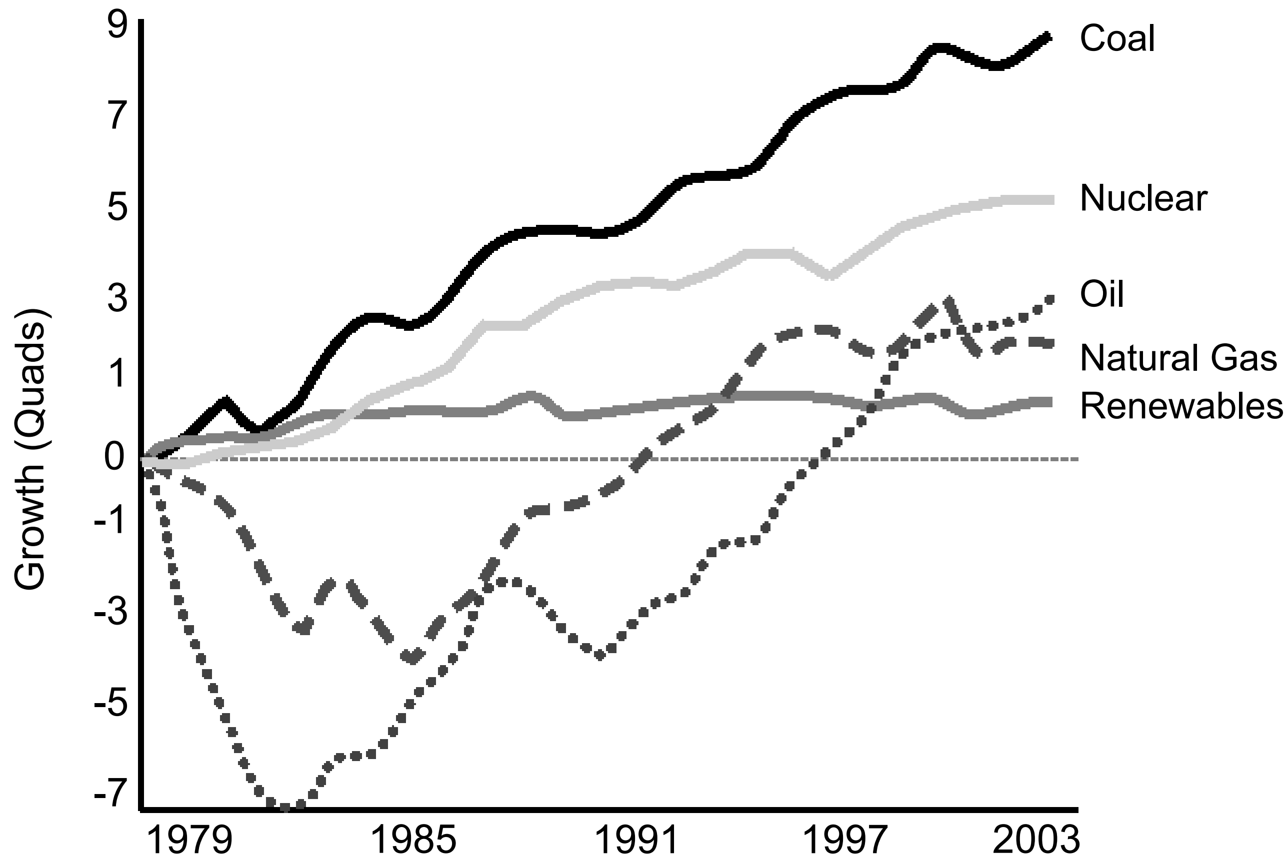
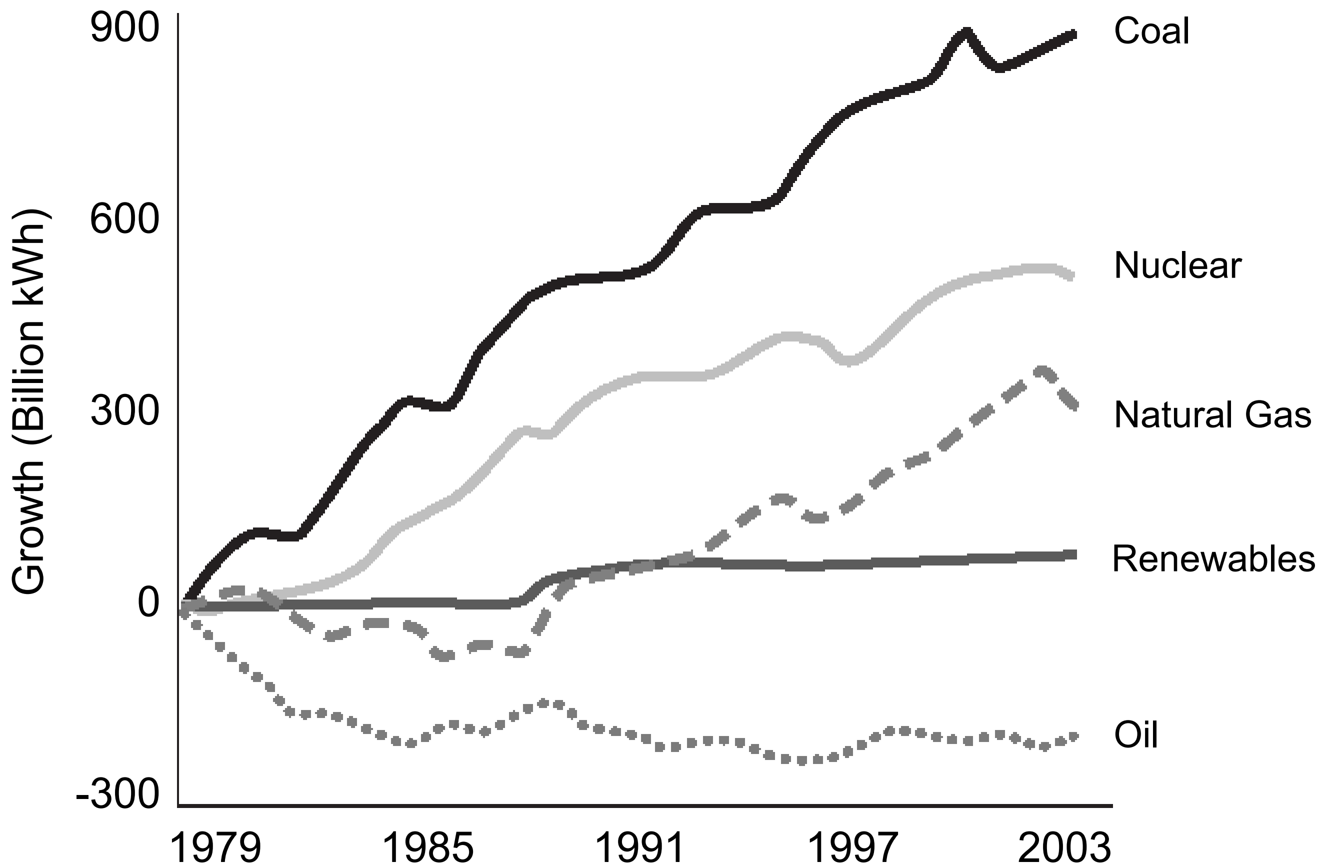
Figure P.1 Growth in Total U.S. Fuel Consumption – Post-TMI



Source: EIA *Annual Energy Review 2003*.

After the 1979 accident at the Three Mile Island nuclear power plant, many energy pundits concluded that efficiency would curb future demand, and renewable sources would accommodate any future growth. Efficiency did improve dramatically, but demand far outpaced new supplies of renewable fuels. The U.S. now burns an additional 400 million tons of coal every year.

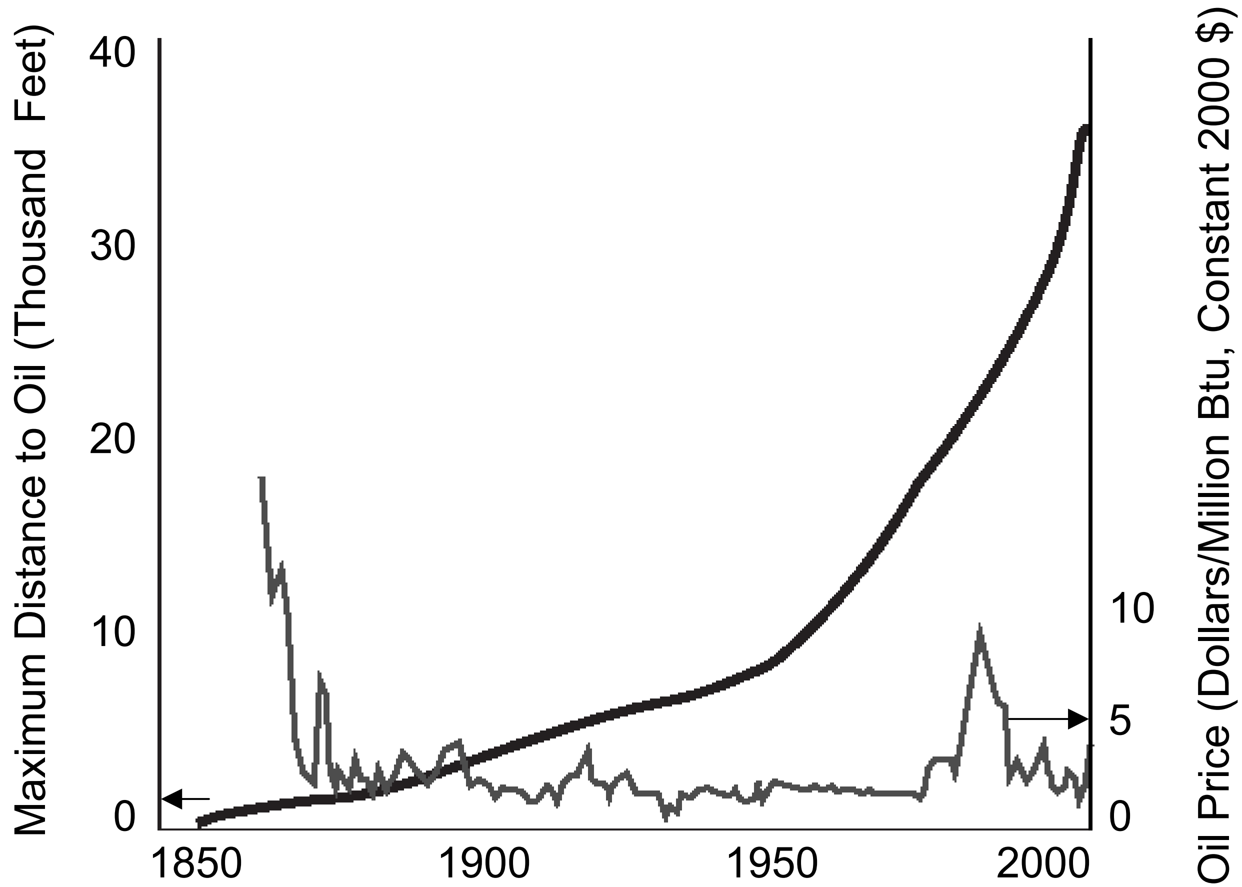
Figure P.2 Growth in Fuels Used to Generate Electricity – Post-TMI



Source: EIA *Annual Energy Review 2003*.

Coal-fired plants accommodated half of the growth in demand for electricity in the 25 years after Three Mile Island, and continue to satisfy half of the total demand. The accident notwithstanding, nuclear output rose steadily, too. By comparison, gas-fired power has lagged; by and large, gas has merely displaced oil.

Figure 1.1 Maximum Distance to Oil vs. Average Price

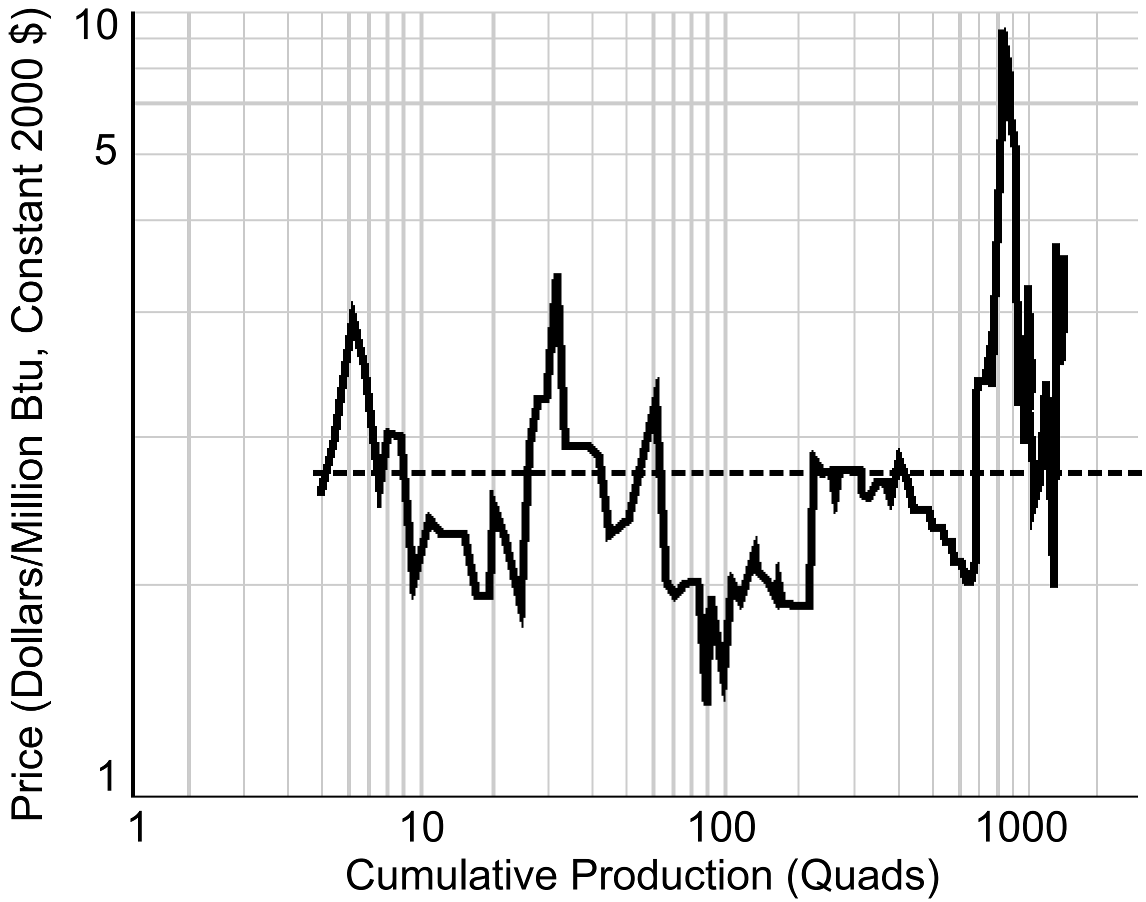


$5/million Btu equivalent to $29/barrel.

Source: WTRG Economics; EIA *Annual Energy Review 2003;* ExxonMobil; J. Ray McDermott Inc.

Over the long term, the price of oil has held remarkably steady, even as the distance from well-head to the oil has increased from hundreds of feet to miles. Today's production costs in the deep waters of the North Sea are not very different from costs in southeast Texas a century ago.

Figure 1.2 U.S. Oil Prices and Cumulative Production

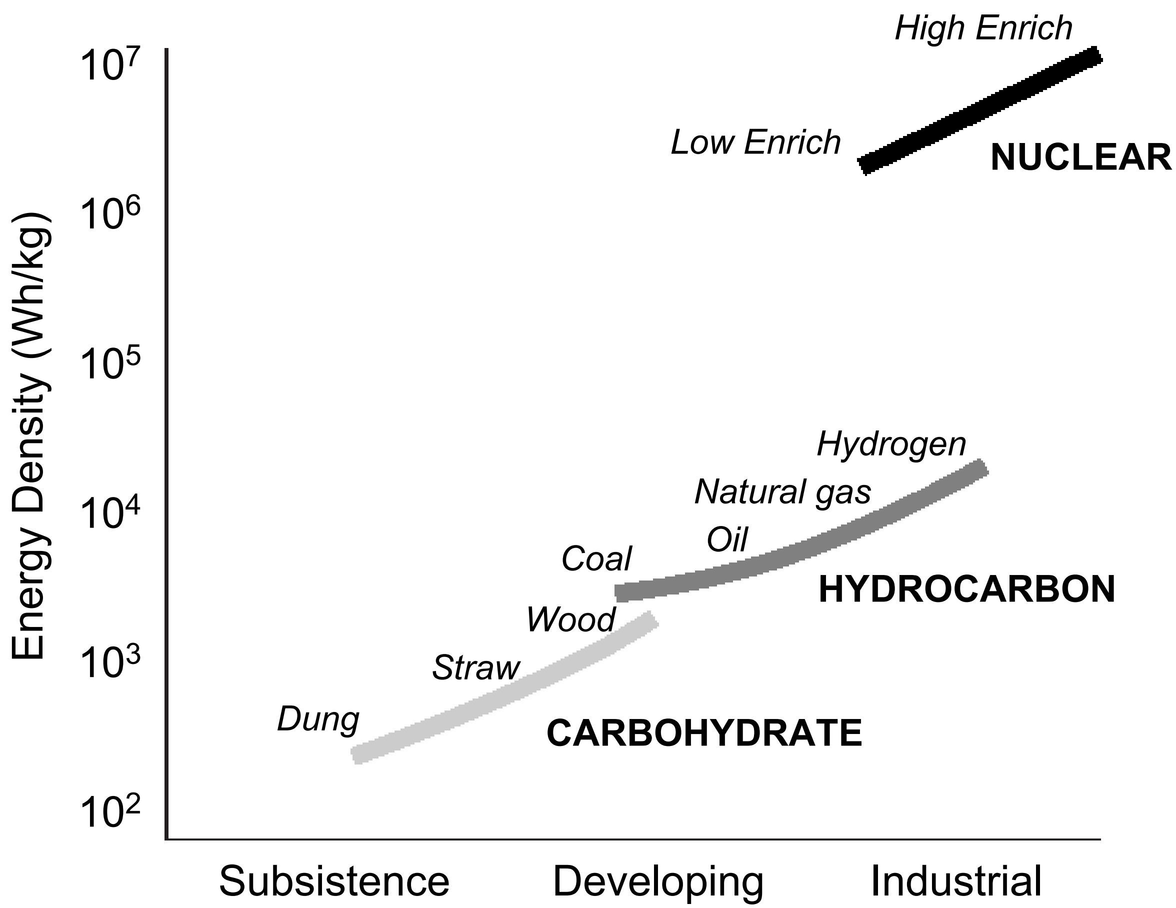


Cumulative U.S. oil production from 1896-2003; 1 Quad=172 million barrels of oil.

Source: EIA, *Annual Energy Review 2003*; American Petroleum Institute; John Fisher, *Energy Crises in Perspective* (Wiley, 1974).

Cumulative production from U.S. oil wells alone approaches two hundred billion barrels. Price spikes and sags have been driven by political and regulatory instabilities worldwide, not by changing discovery and extraction costs.

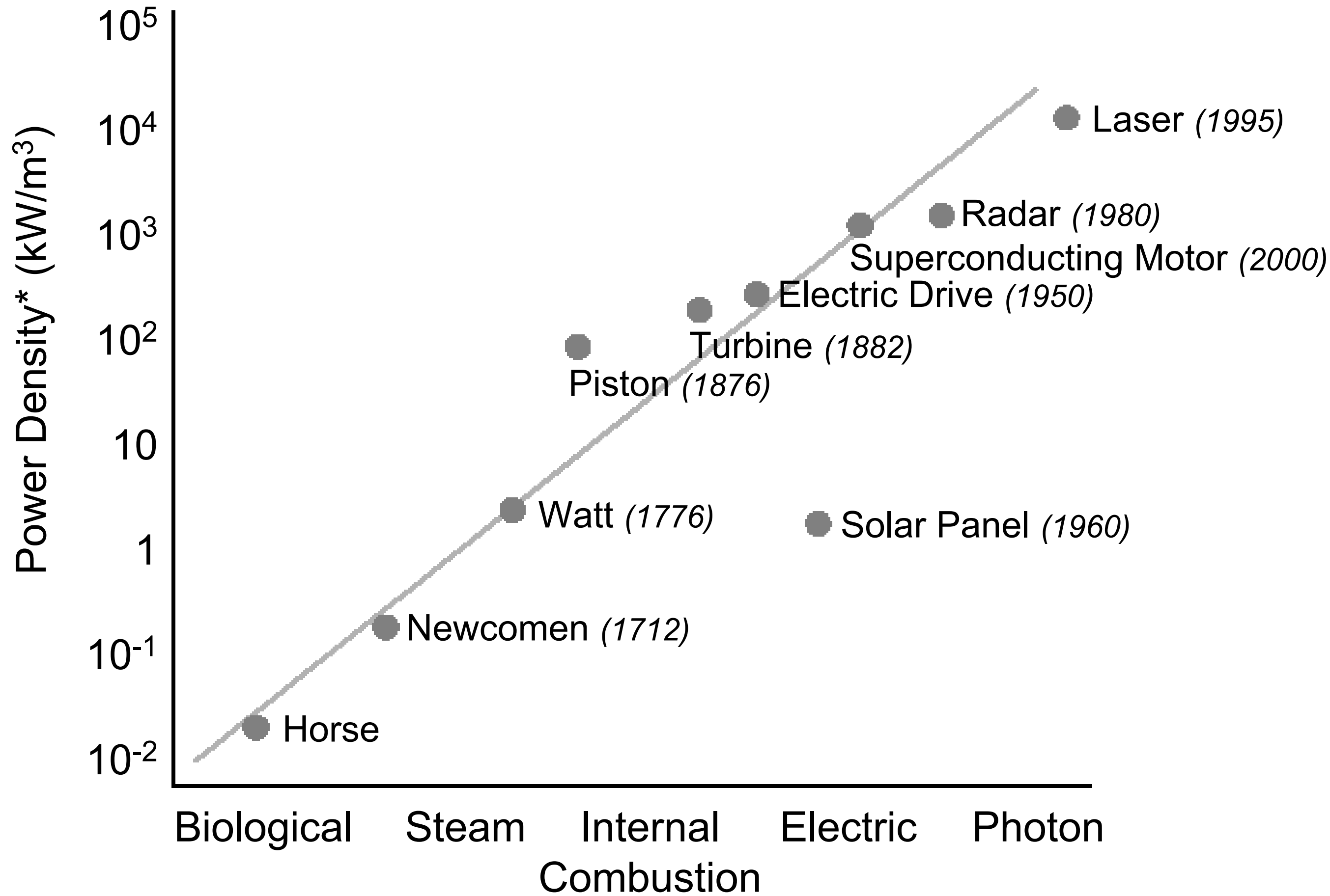
Figure 1.3 Energy Density of Primary Fuels



Source: Smil, *Energies* (MIT, 1999); B. Spletzer, "Power Systems Comparisons, Intelligent Systems and Robotics Center," Sandia National Laboratories, Sept. 1999.

A Quad's worth of wood is a huge forest. Pound for pound, coal supplies about twice as much heat. Oil is twice as good as coal. And a gram of uranium-235 is worth about four tons of coal. Historically, we have always pursued fuels that pack more energy in less space.

Figure 1.4 Power Density from Horses to Lasers

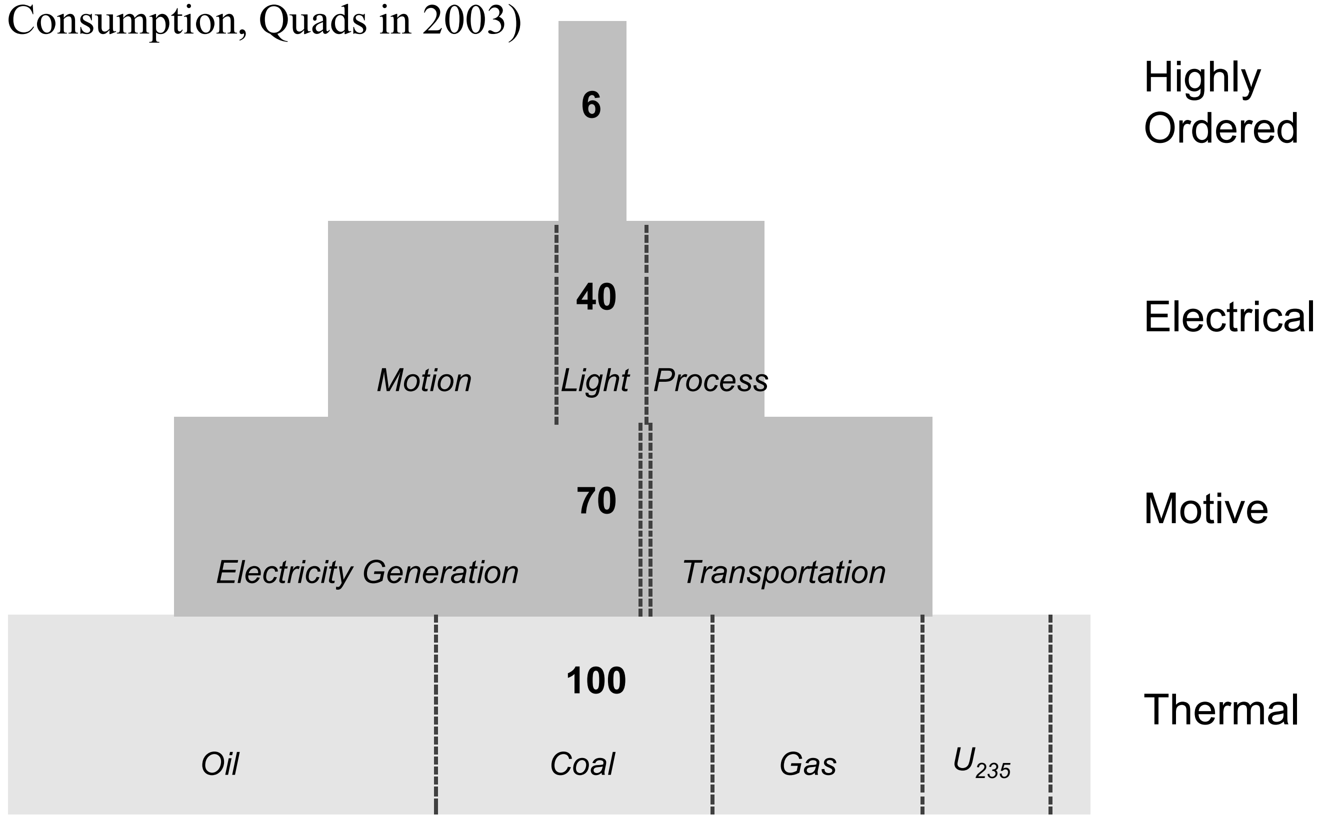


The horses, engines, motors, jets, antennas, and lasing cavities that transform primary fuels into motion and beams have evolved on a trajectory of more power in less space.

*for complete power system

Figure 1.5 Pyramid of Energy: U.S. Economy

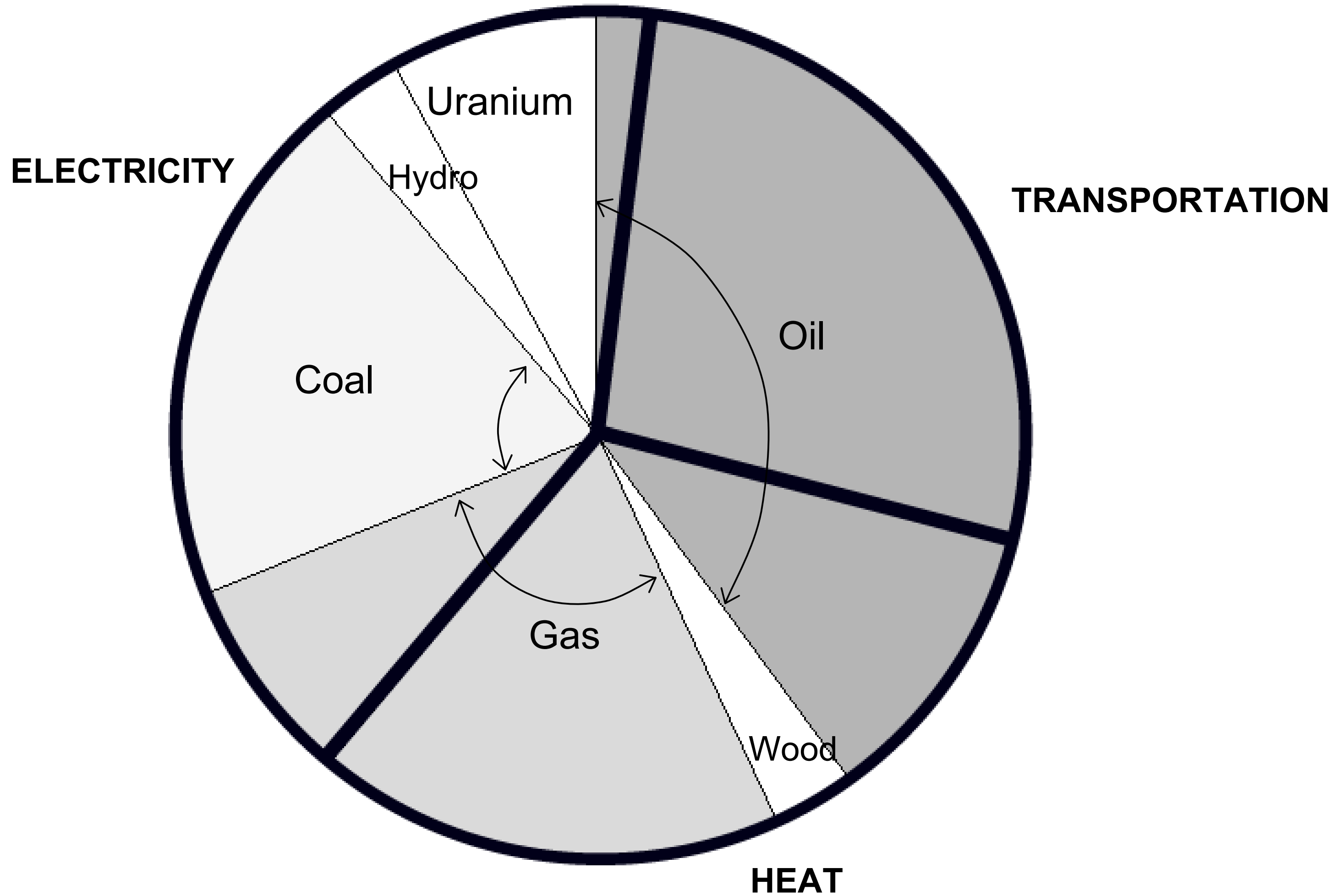
(Annual Consumption, Quads in 2003)



Source: EIA *Annual Energy Review 2003*.

Energy consumption is often totaled up in Quads--thermal units of raw heat. But this metric conceals more than it reveals. In the United States, about 6 Quads worth of raw thermal energy go through multiple stages of refinement every year, with 99 percent (or more) of the original thermal energy being discarded along the way, to yield the extremely highly ordered power required to drive such things as radios, microprocessors, lasers, and CAT scanners.

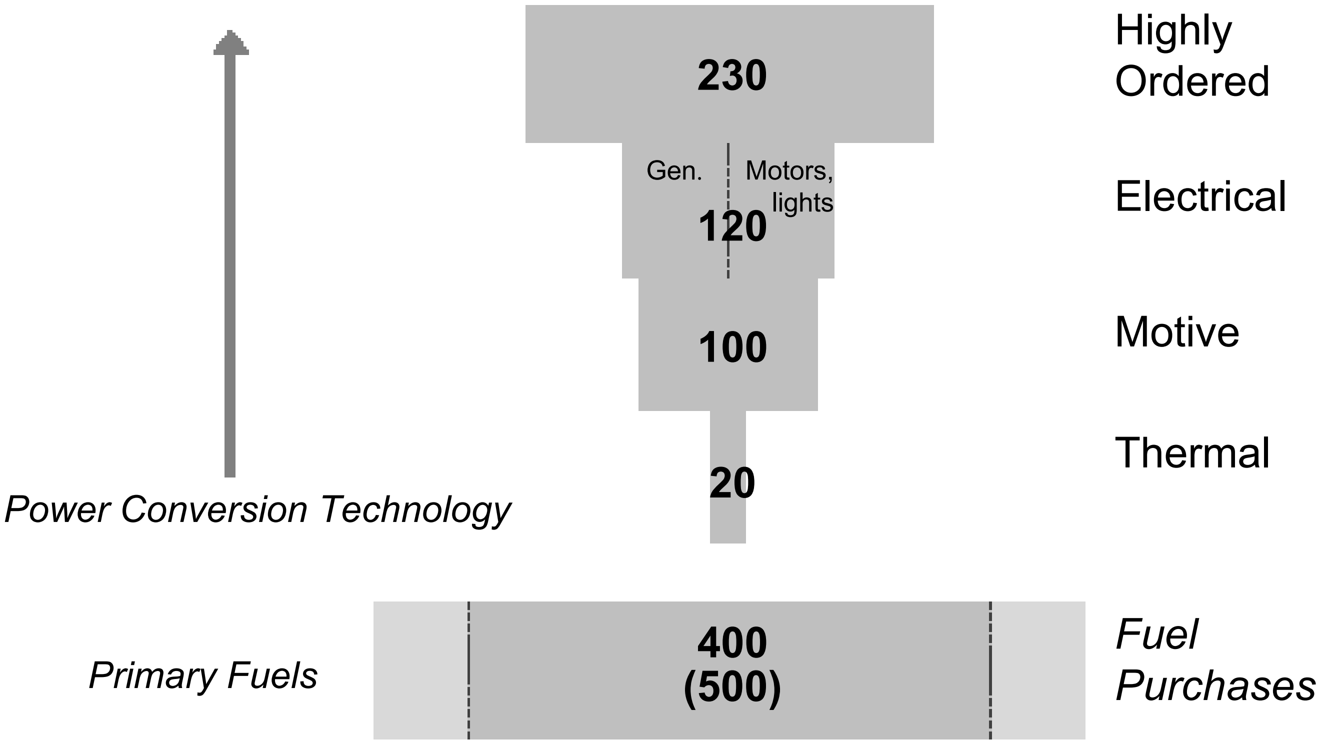
Figure 1.6 Primary U.S. Energy and Fuel Uses



We use primary fuels to make electricity, move vehicles, and produce heat. Coal generates electricity. Oil is the fuel of transportation. Natural gas is used principally for raw heat; it also now generates 18% of our electricity.

Figure 1.7 Pyramid of Spending

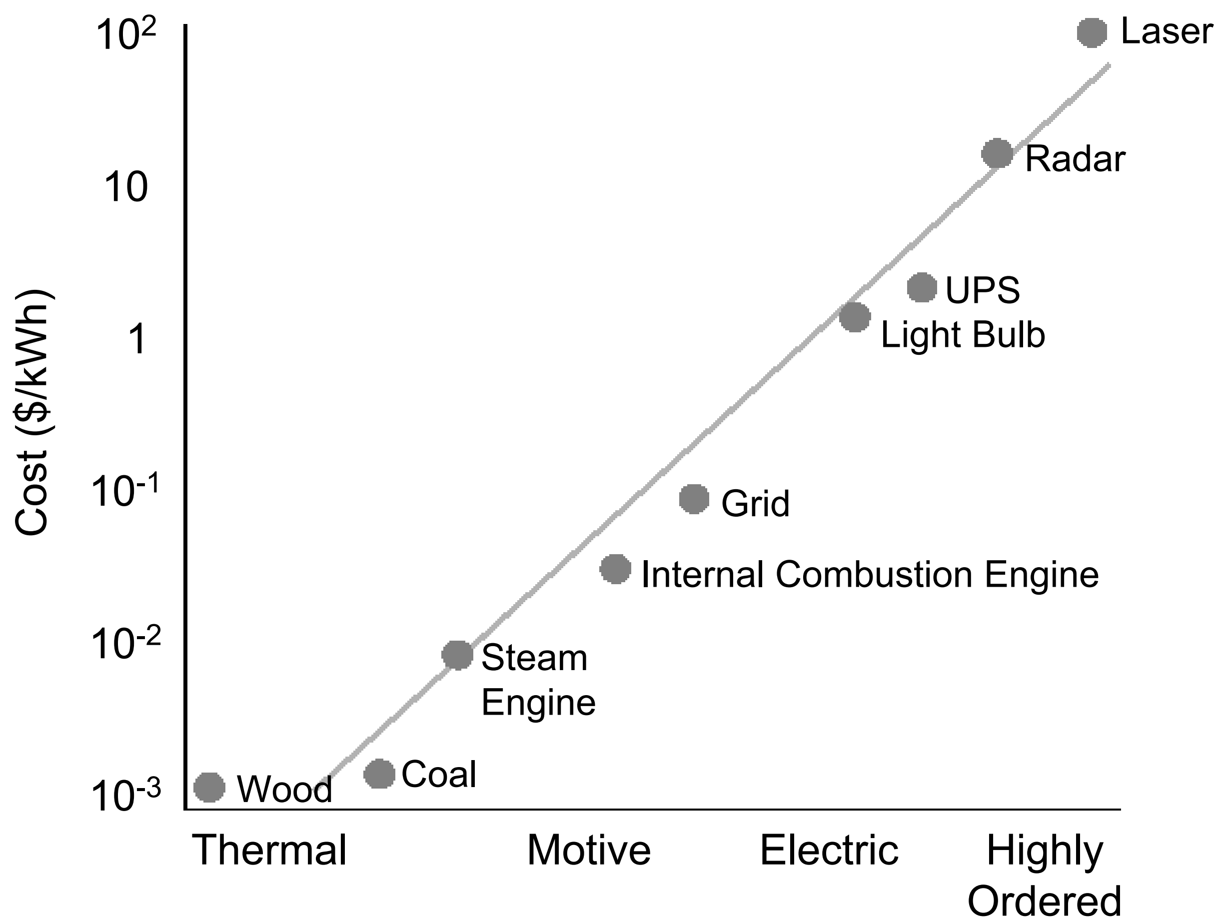
($ Billions, Constant 2000 $)



Source: U.S. Census Bureau; EIA, Annual Energy Review 2003.

America spends about $400 billion a year on raw fuel ($500 billion with oil priced in the $50/bbl range). But at least $500 billion a year is spent on equipment used in the higher tiers to concentrate and convert energy—generators (gen.), furnaces, car engines, motors, and light bulbs, for example. The largest and fastest-growing segment of the power-conversion economy now comprises such things as power semiconductors, lasers, ultrasound machines, magnetic resonance imagers, and telecommunications equipment that produce highly ordered power.

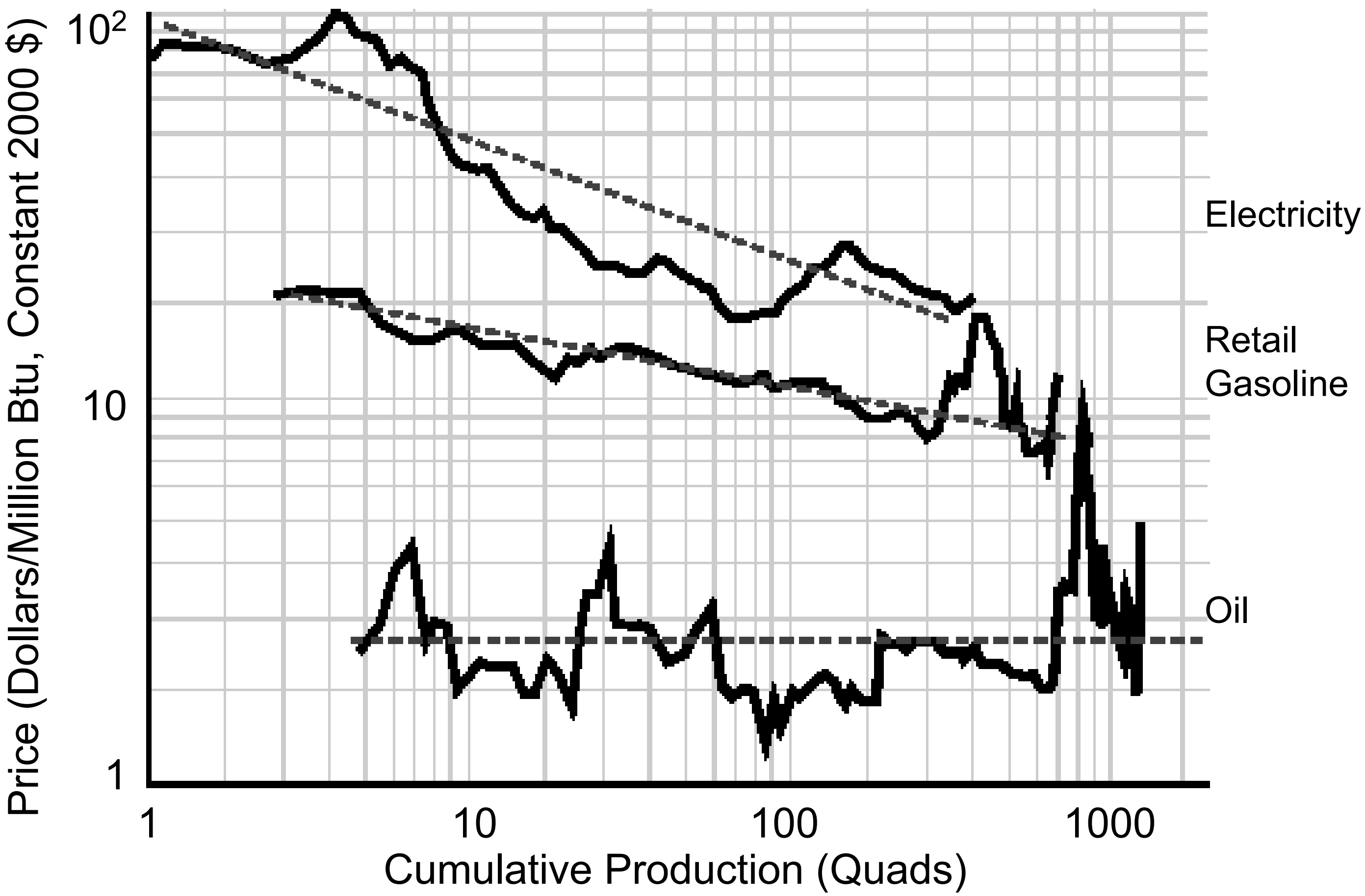
Figure 1.8 Cost of Energy



Source: Various; including EIA *Annual Energy Review 2003*.

The price of power rises sharply with rising power density. Relatively unreliable grid power retails for 10 cents per kWh. The same amount of thermal energy locked up in raw coal costs about 1/3 of a cent. Computer-grade power (UPS) costs $3 or more per kWh.

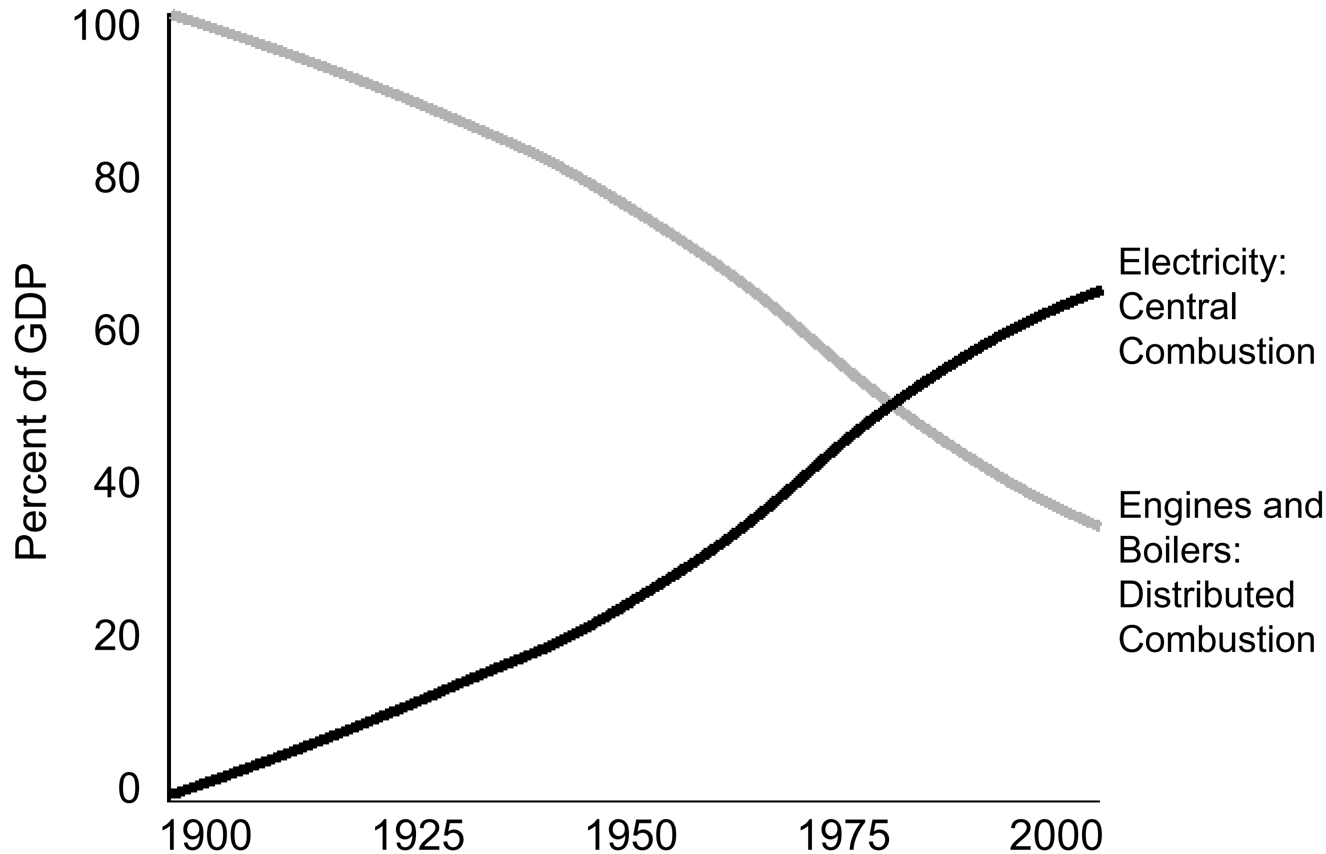
Figure 1.9 U.S. Energy Production and Cost



Source: EIA, *Annual Energy Review 2003*; American Petroleum Institute; John Fisher, *Energy Crises in Perspective* (Wiley, 1974).

Fuel prices have fluctuated, but new fuels and improvements in power-conversion hardware have steadily lowered the average retail price of electricity ever since Edison fired up his first generators in 1882. 1 million Btu of electricity is a 60 W light bulb running for 6 months; 1 million Btu of gasoline is about 8.1 gallons, and 1 million Btu of crude oil is about 7.1 gallons.

Figure 1.10 Fuels for the Economy*

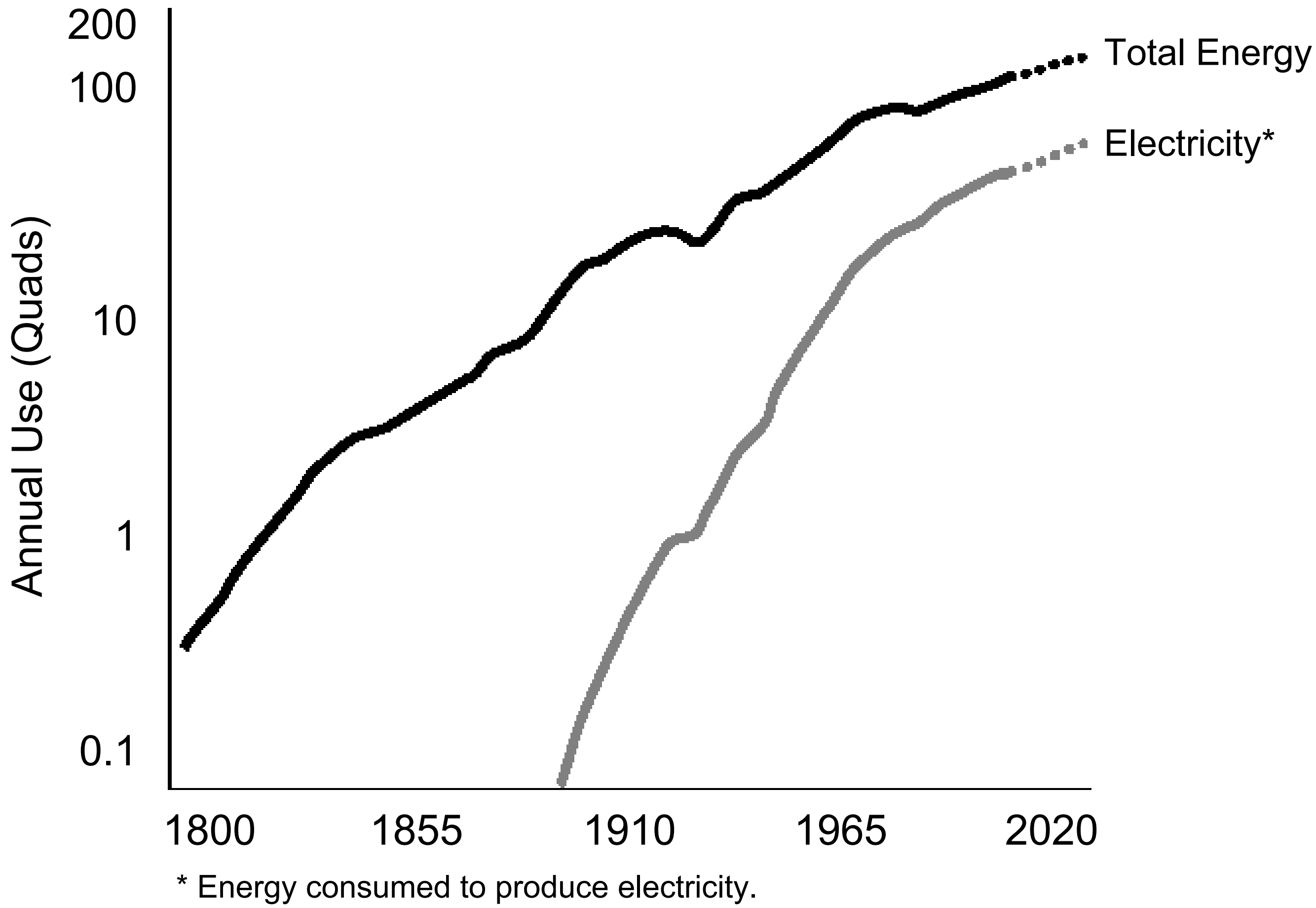


* Excludes residential energy: counts only fuels used by GDP-producing sectors; transportation, industry (incl. mining, agriculture), and services.

Source: EIA *Annual Energy Review 2003*, Bureau of Economic Analysis, and U.S. Census Bureau *Historical Statistics of the United States Colonial Times to 1970*.

Two-thirds of the U.S. GDP now comes from industries and services fueled by electricity. All the high-growth, information-centered sectors of the digital economy run entirely on electricity.

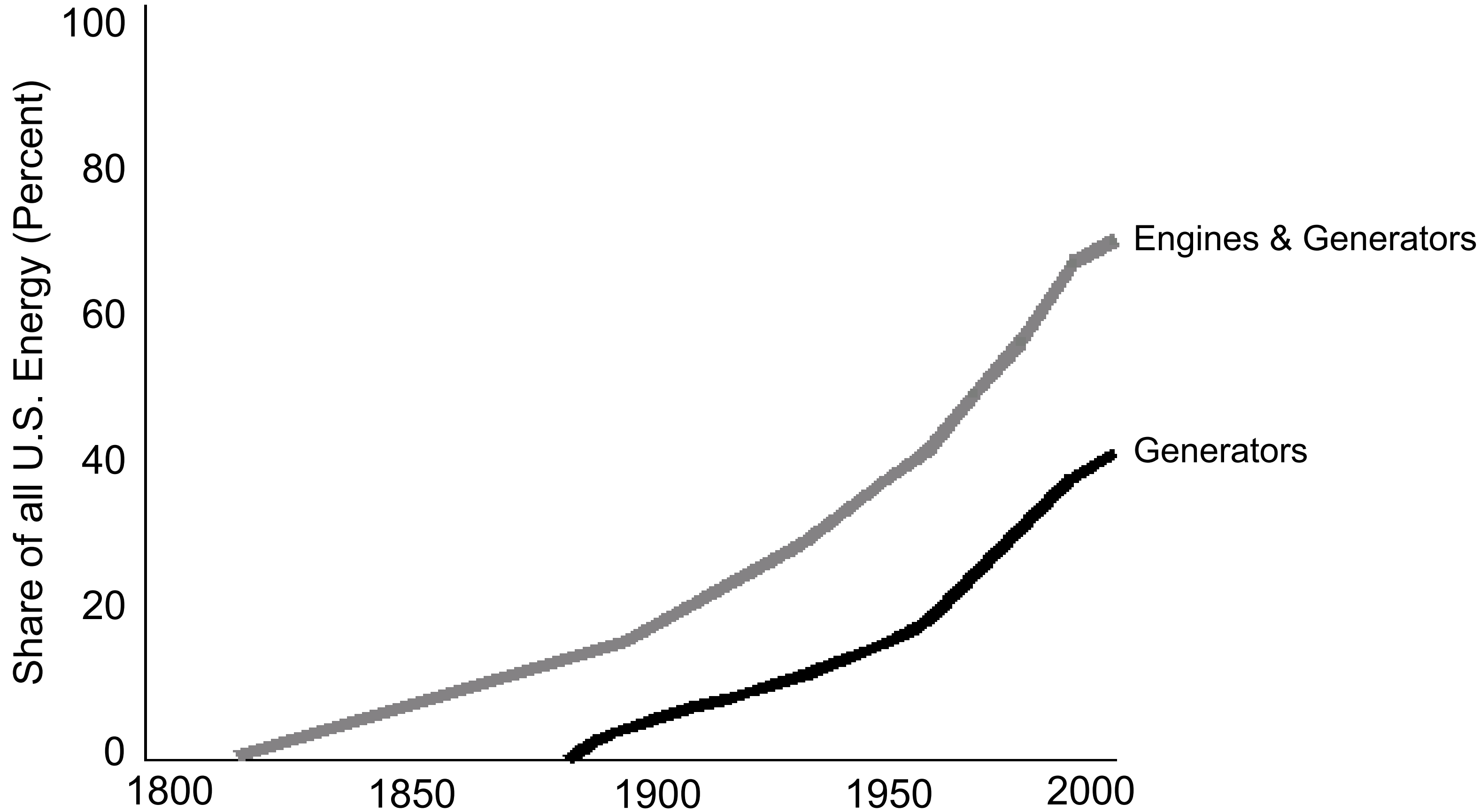
Figure 2.1 U.S. Energy and Electricity Consumption



Source: EIA *Annual Energy Review 2003* ; U.S. Census Bureau *Historical Statistics of the United States Colonial Times to 1970.*

U.S. consumption of Quads (raw energy) rose ten-fold in the twentieth century; electricity consumption rose thirty-fold.

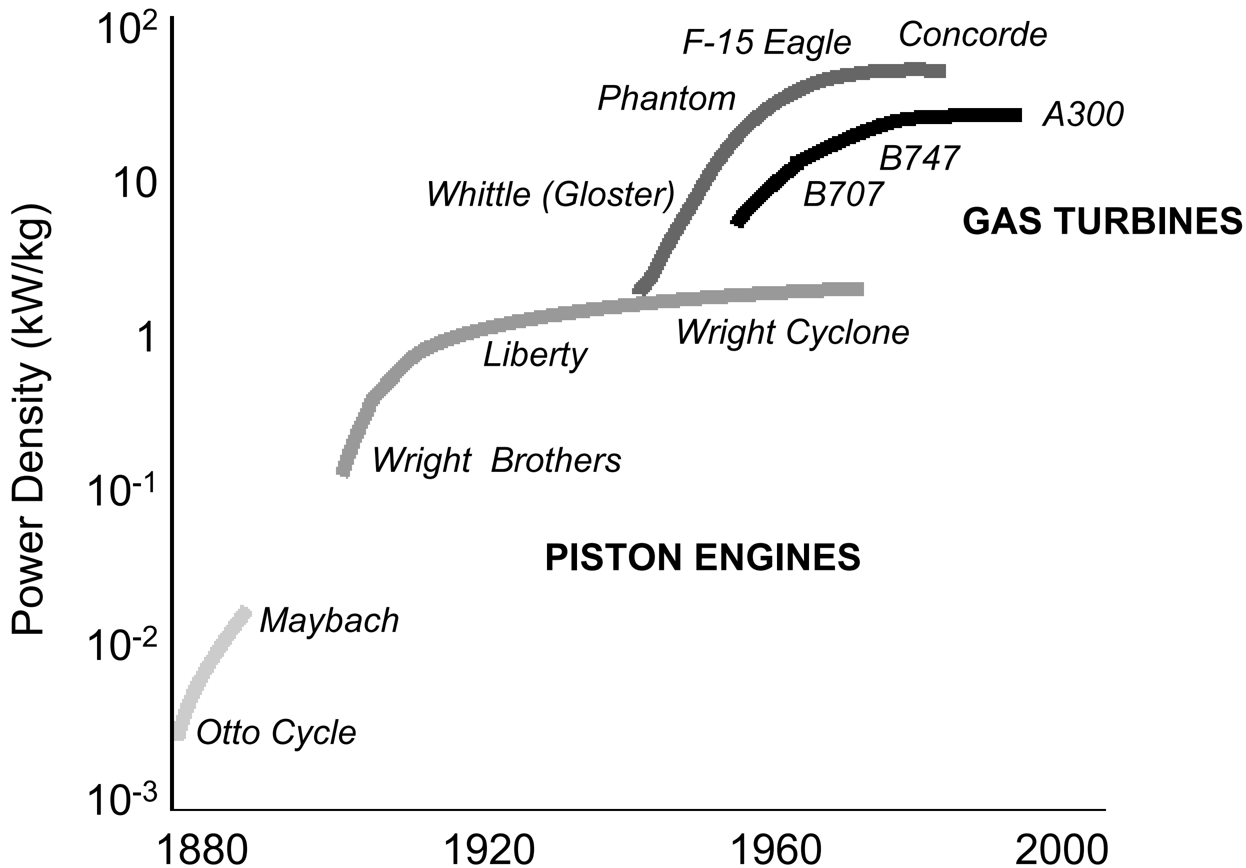
Figure 2.1a Energy to Power Shafts and Electrons



Source: EIA *Annual Energy Review 2003*; Sam H. Schurr et al., *Electricity in the American Economy: Agent of Technological Progress* (Greenwood, 1990).

The progeny of James Watt's thermomechanical engine that burn fuel to move things—not just steam trains, but diesel trucks, jumbo jets, ski-doos, leaf blowers, Shuttles and SUVs—now collectively consume about 30 percent of all the energy we use. It was the advent of an engine that burns fuel to move electricity that would in due course dominate. Today's electric power plants consume 40 percent of all our raw fuel.

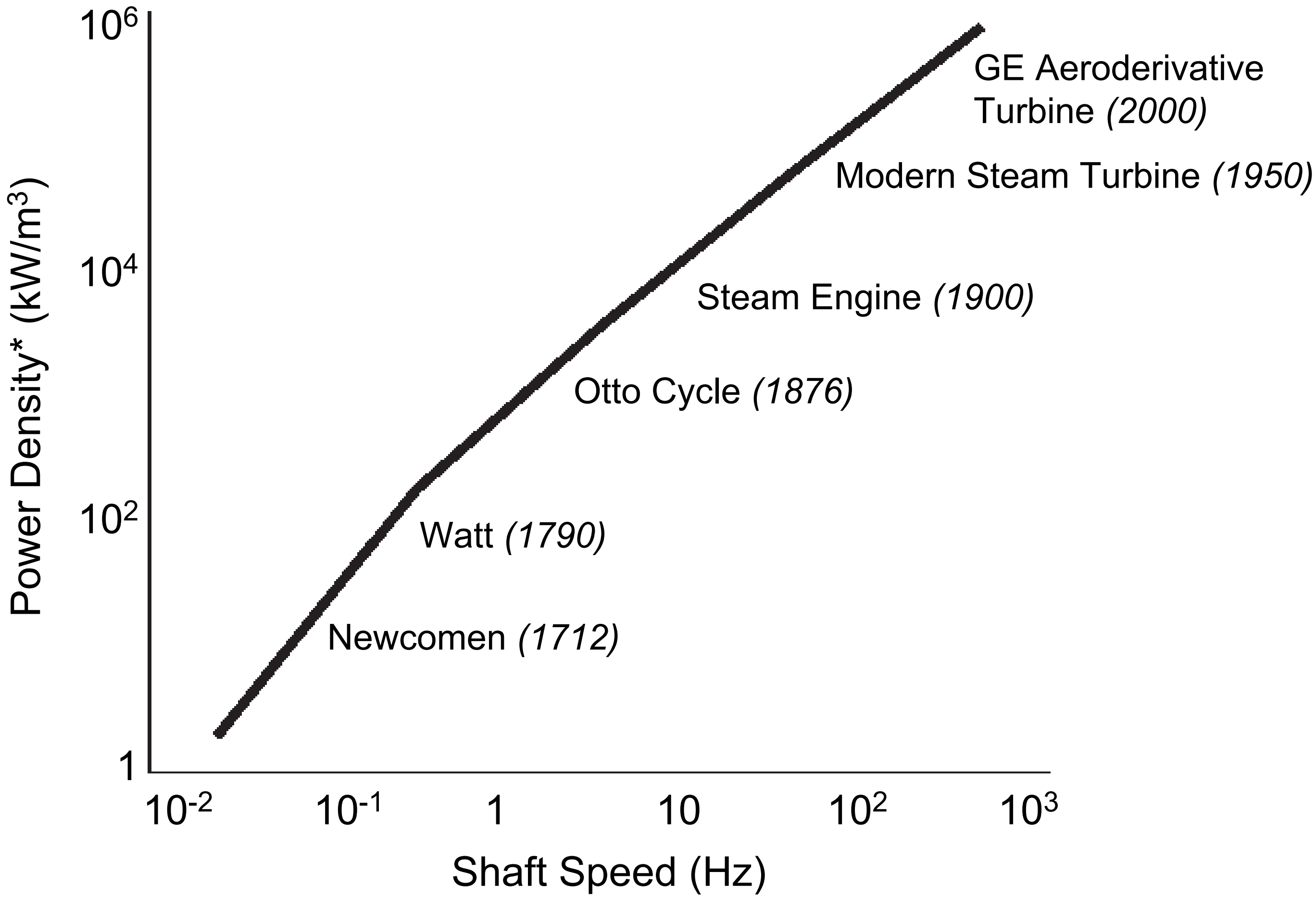
Figure 2.2 Aviation Engine Power Density



Source: Vaclav Smil, *General Energetics: Energy in the Biosphere and Civilization* (Wiley, 1991).

Piston engines supplied enough power per pound to get the Wright Brothers into the air. Supersonic jets required a hundred-fold increase in power density, which was supplied by gas turbines.

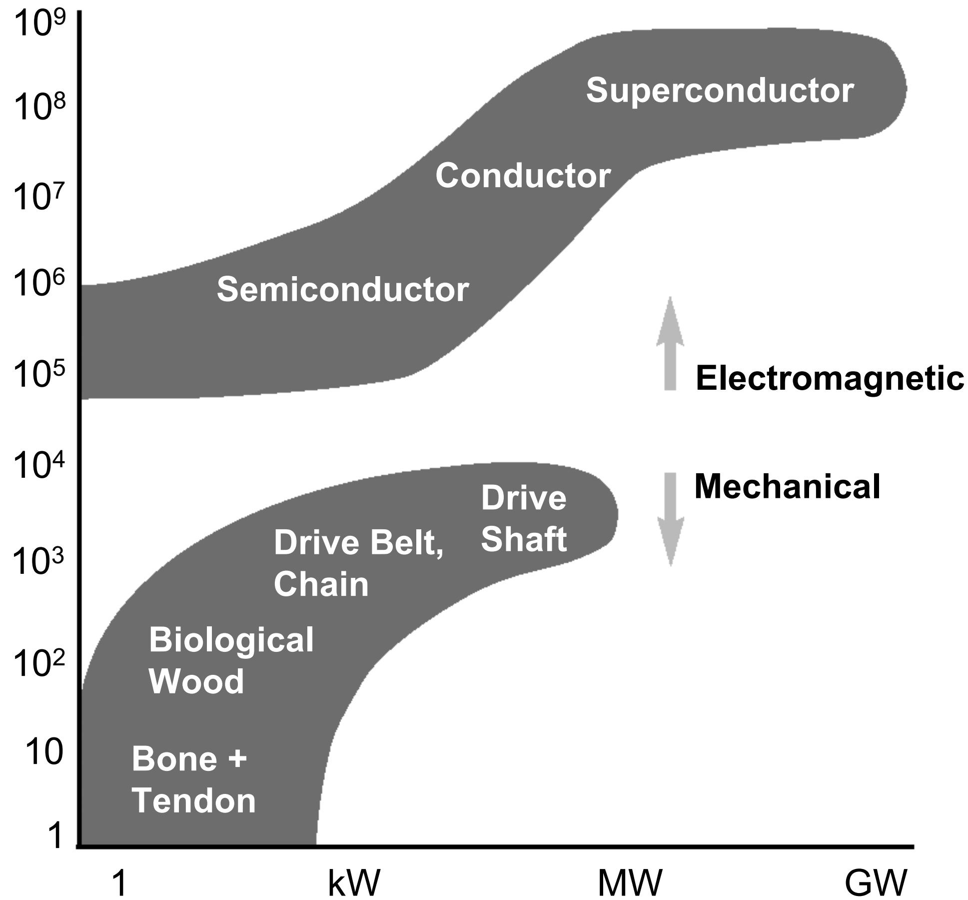
Figure 2.3 Engine Power Density and Shaft Speed



Engines have evolved along the same trajectory as the fuels they consume, burning more energy, faster, at higher temperature, to produce more power in less space.

*for engine only

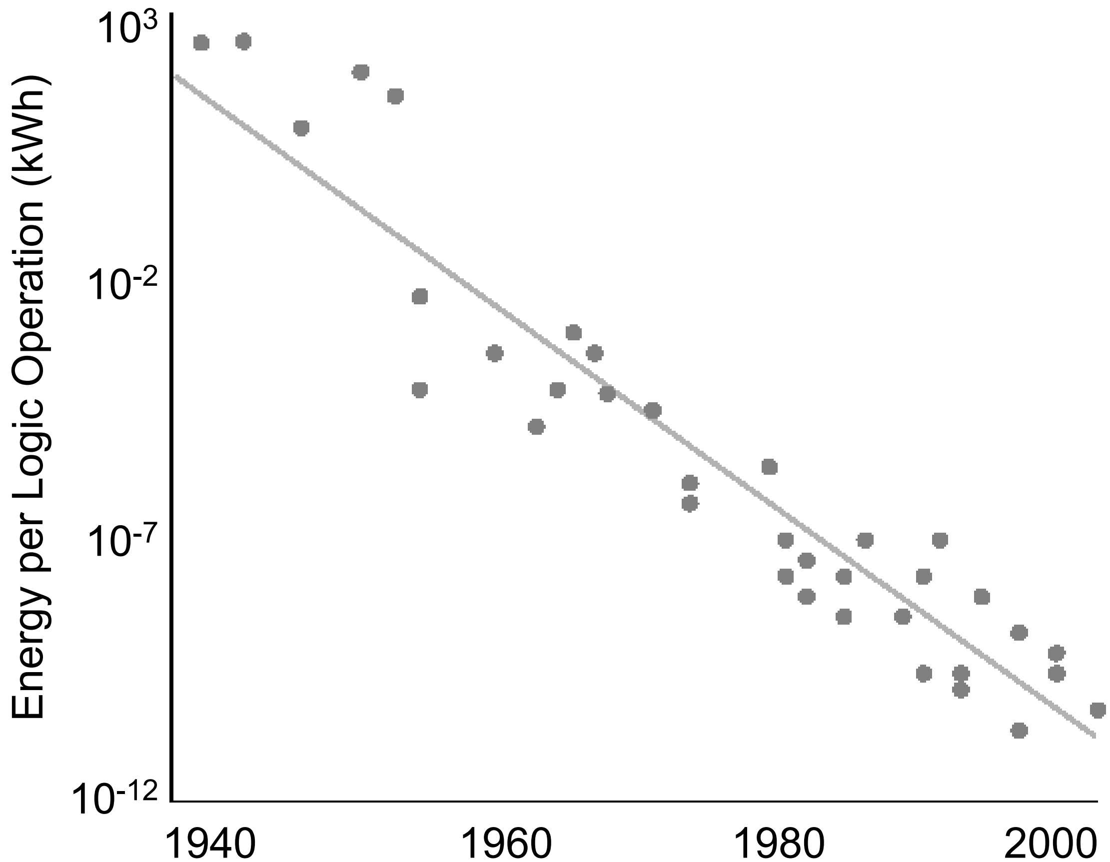
Figure 2.3a Bridging the Power Transmission Gap



Source: Peter Huber and Mark Mills, "Power Paradigm II: Broadband Power," *Digital Power Report*, December 2000.

The electrical power train is overwhelmingly superior to the mechanical—five orders of magnitude better on every key metric. Small wonder, then, that electric power has been steadily displacing all other forms, at the front end of our energy economy.

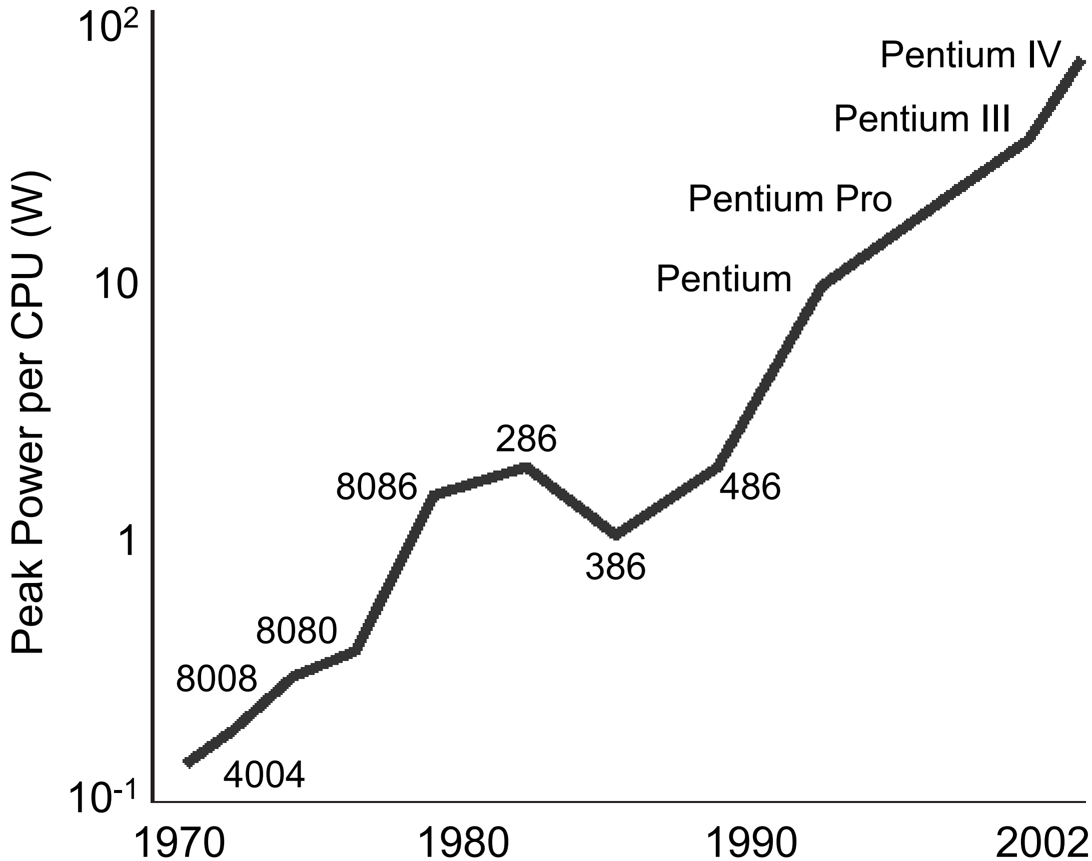
Figure 2.4 Energy and Logic



Source: Isaac, R. "Influence of Technology Directions on System Architecture," IBM Research Division, Sep. 10, 2001.

In 1946, the vacuum tubes in the ENIAC computer required 10 Watts or more to execute a single logic operation. Today's semiconductor gates are over ten million-fold more efficient.

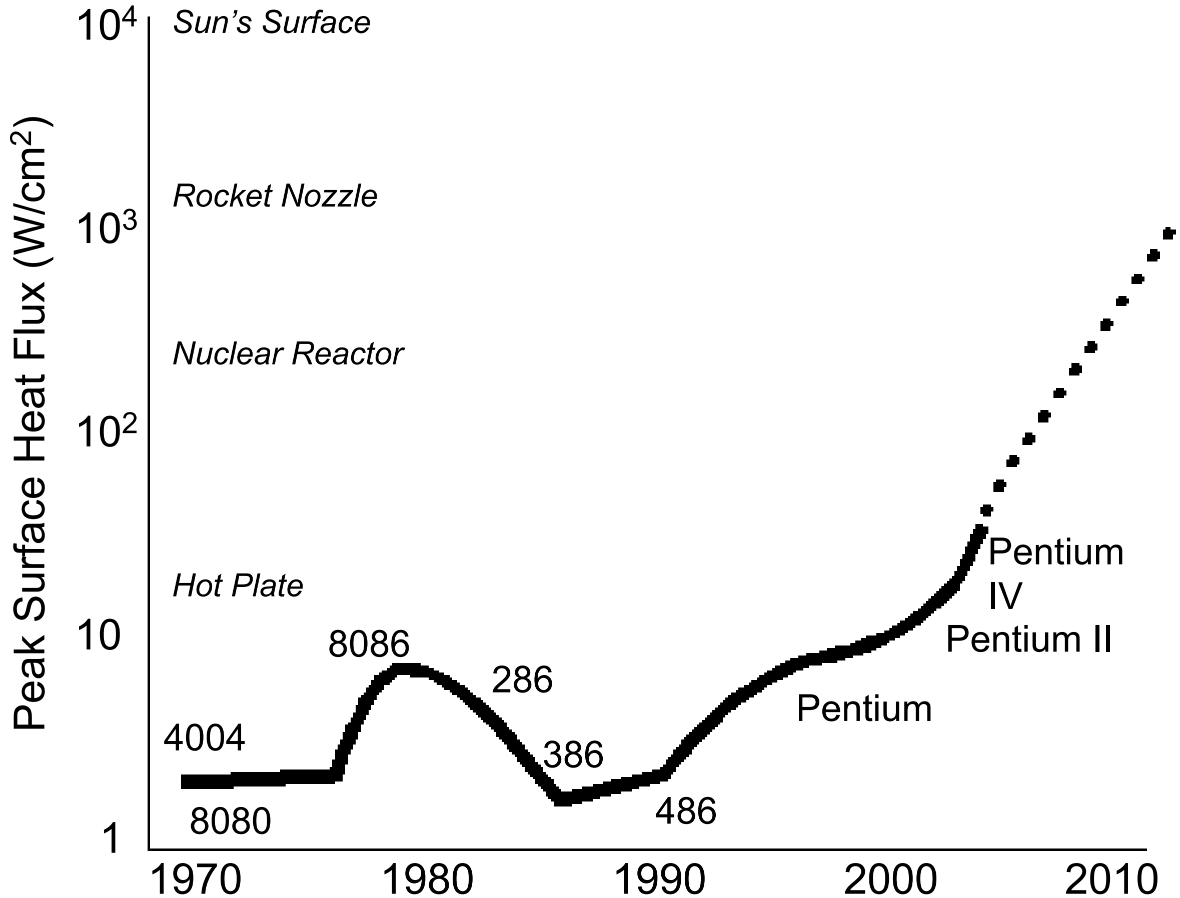
Figure 2.5 Microprocessor Peak Power



Source: Intel.

Total power per microprocessor rises because the number of gates per chip, and the speed at which they switch on and off, rise faster than the power-per-operation falls.

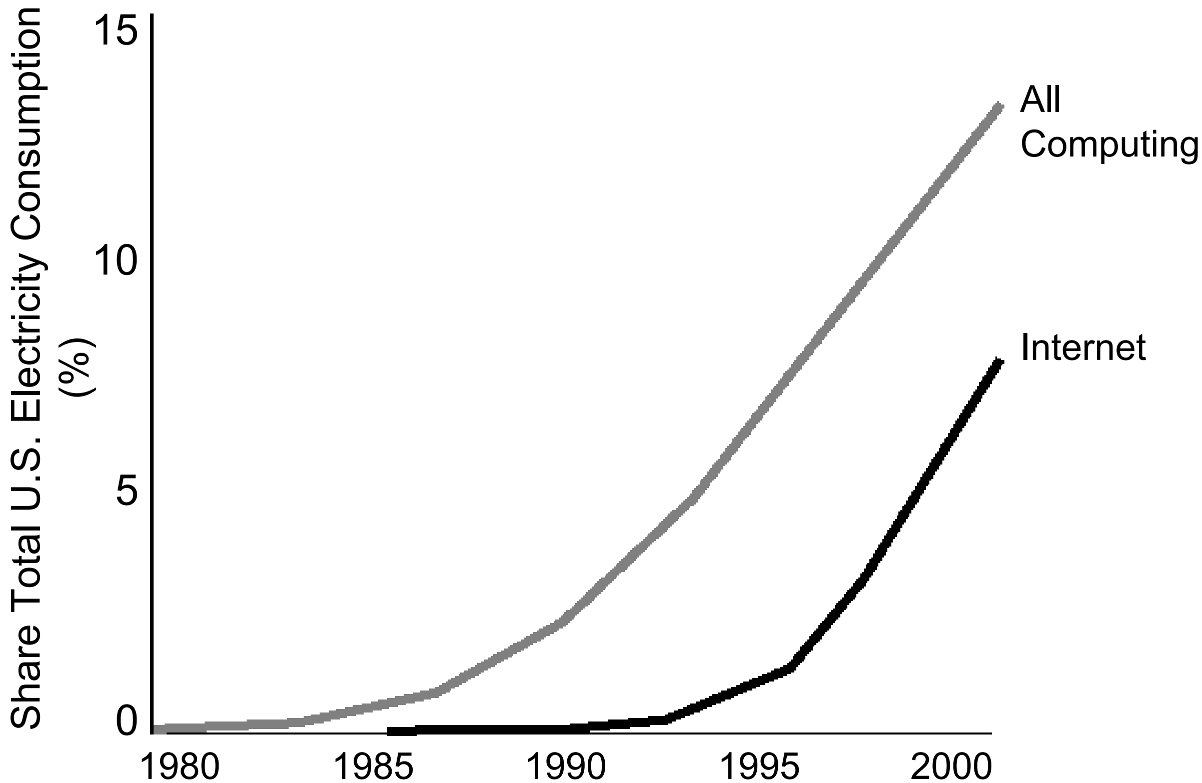
Figure 2.5a CPU Thermal Output



Source: Intel.

As the number of gates per chip and the speed of the chip both rise, the total power required by each chip rises even faster. Cooling microprocessors to keep them from melting down is already a major challenge.

Figure 2.6 Computing and the Internet: Aggregate U.S. Electricity Consumption*

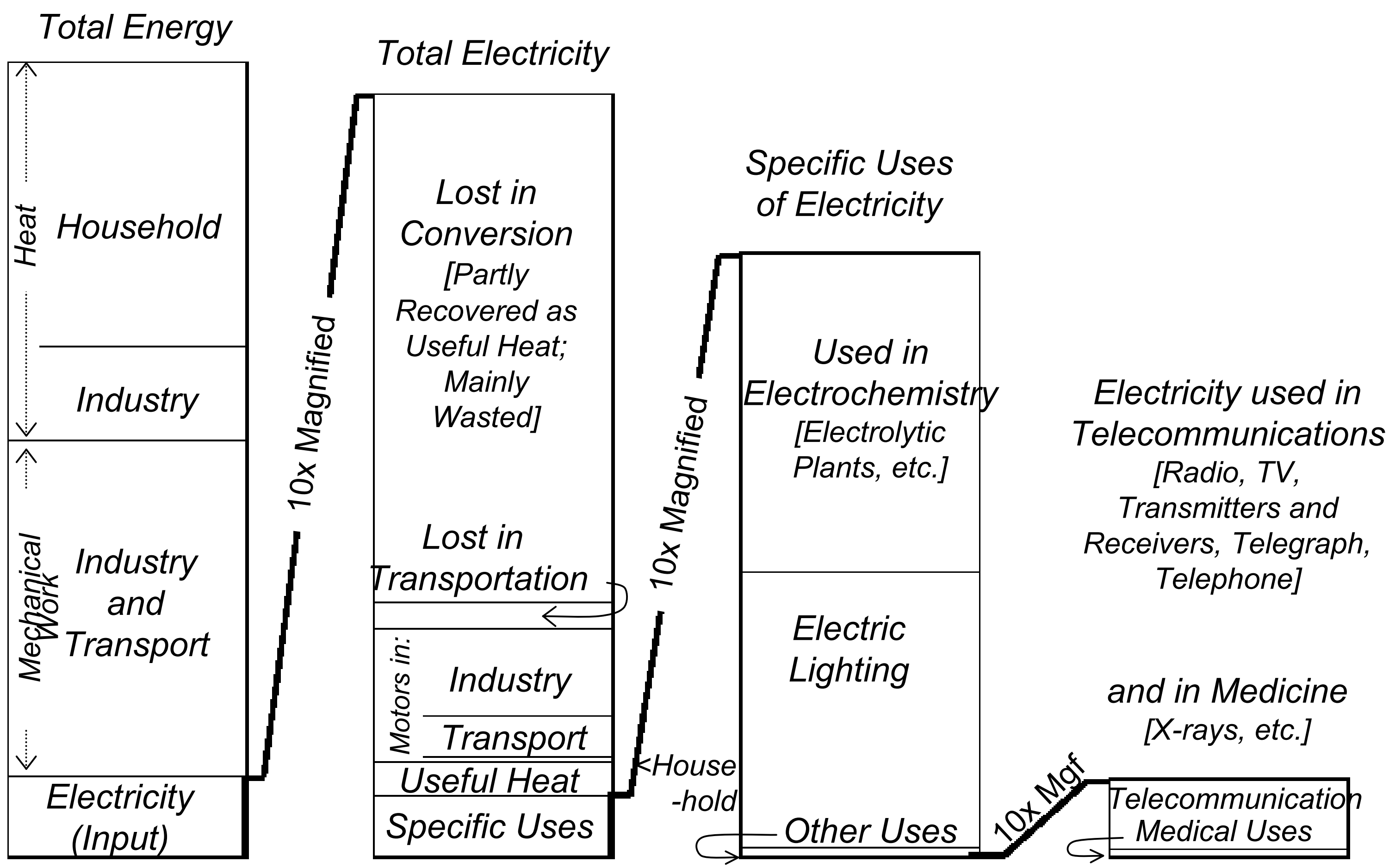


* Includes kWh in manufacturing, operation of end-use & network equipment, and infrastructure.

Source: Peter Huber and Mark Mills, "Silicon & Electrons," Dec. 2002, www.digitalpowergroup.com.

Billions of chips, hundreds of millions of phone lines, tens of millions of switches, routers, and servers, thousands of data warehouses, and power quality hardware add up to significant demand for electricity. The consumption totals shown include power consumed in manufacturing digital equipment, the operation of both terminals and networks, and cooling loads.

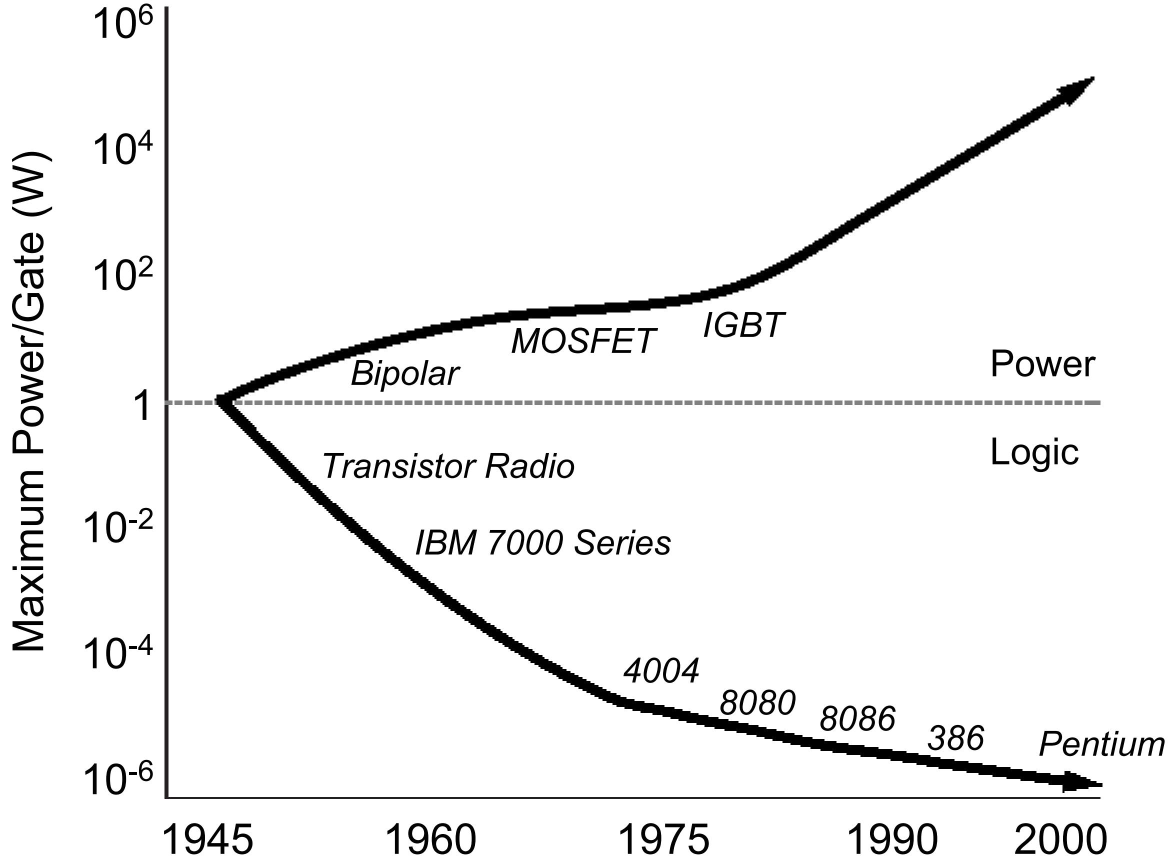
Figure 2.6a The First Analysis of Power Realities: 1958



Source: Hans Thirring, *Energy for Man: From Windmills to Nuclear Power* (Indiana University Press, 1958), p. 43.

In 1958, Hans Thirring quantified, almost certainly for the first time, how much energy might be required to power the hardware of telecommunications and medicine. One of his objectives was to debunk “widespread misconceptions about the influence of radio waves on the climate.”

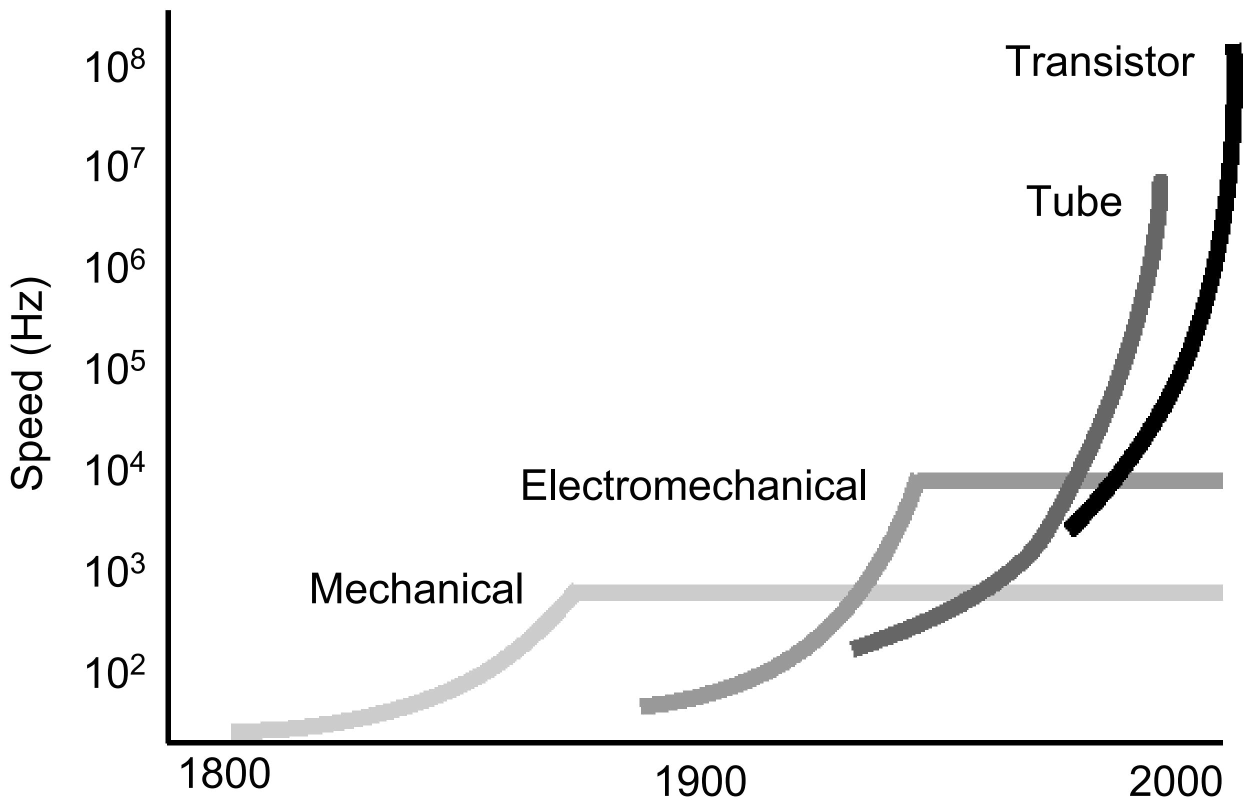
Figure 2.7 Transistors for Logic and Power



Source: Intel; IBM.

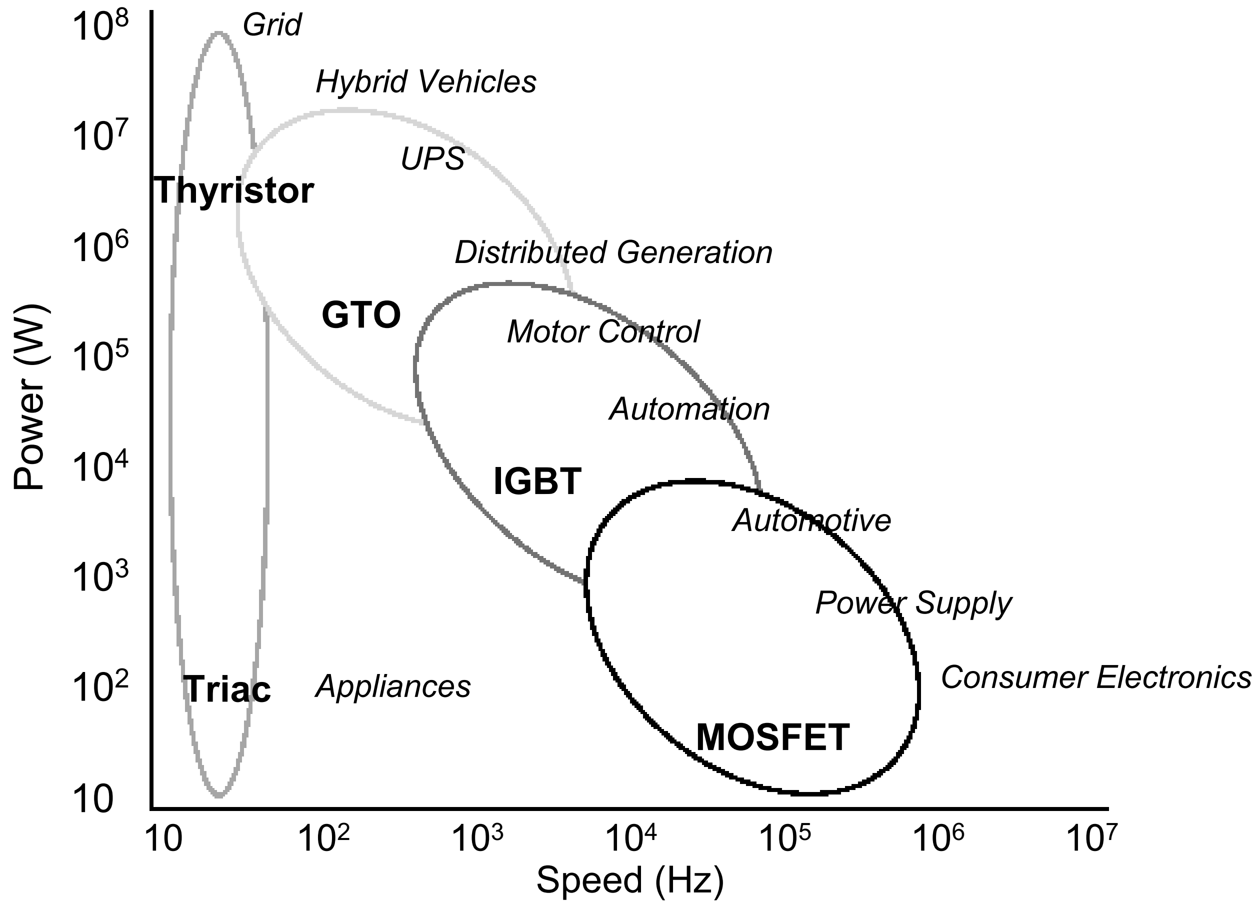
The power "regulator" of the digital age is the semiconductor gate that controls a flow of electrons or photons. William Shockley's team built the first transistor in 1949; the power switched by logic transistors has since been cut in half about every two years. Pushing semiconductors up the power curve took longer. It wasn't until 1980 (patent issued in 1982) that Frank Wheatley and Hans Becke of RCA invented the Insulated Gate Bipolar Transistor (IGBT), capable of switching kilowatts in industrial robots, hybrid cars, aircraft, trains, tanks, ships, and machine tools.

Figure 2.7a Switching Power



James Watt's mechanical regulator controlled the flow of steam; the revolutionary new regulator of our era is the semiconductor gate, which controls the flow of electrons and photons. Powerchips—chip-based arrays of ultra-high-power transistors—are now revolutionizing the control of power.

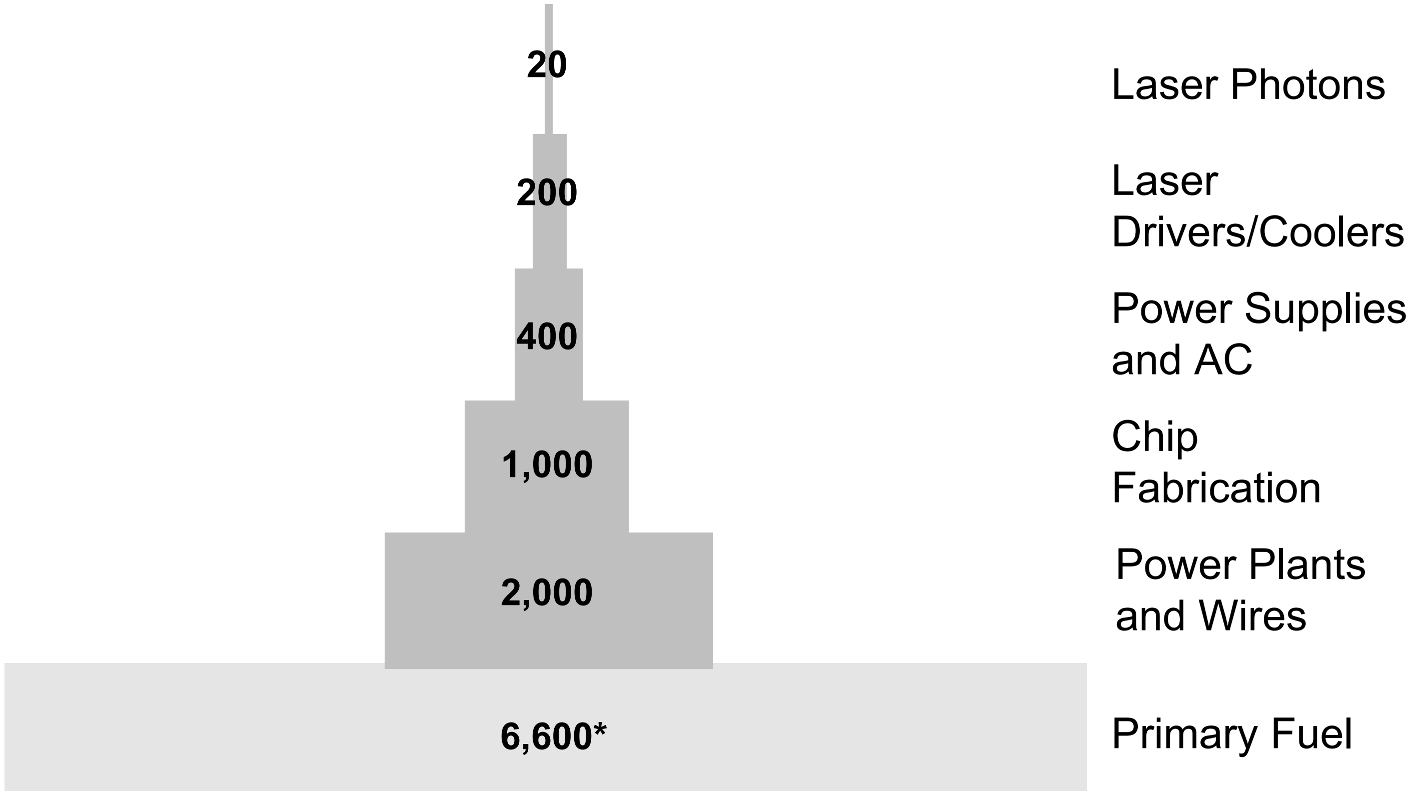
Figure 2.7b Silicon Power Devices and Applications



Source: Peter Huber and Mark Mills, "Analog Power," *Digital Power Report,* April 2001.

Power chips exploit the same quantum-physical phenomena that are harnessed by integrated circuits. But now the semiconductor junctions are handling hundreds of watts, or thousands or millions. Different powerchip architectures operate at different speeds, and can handle different amounts of power. Logic chips control the movement of bits; powerchips control the propulsion of high-speed trains, trucks, cars, and industrial machines.

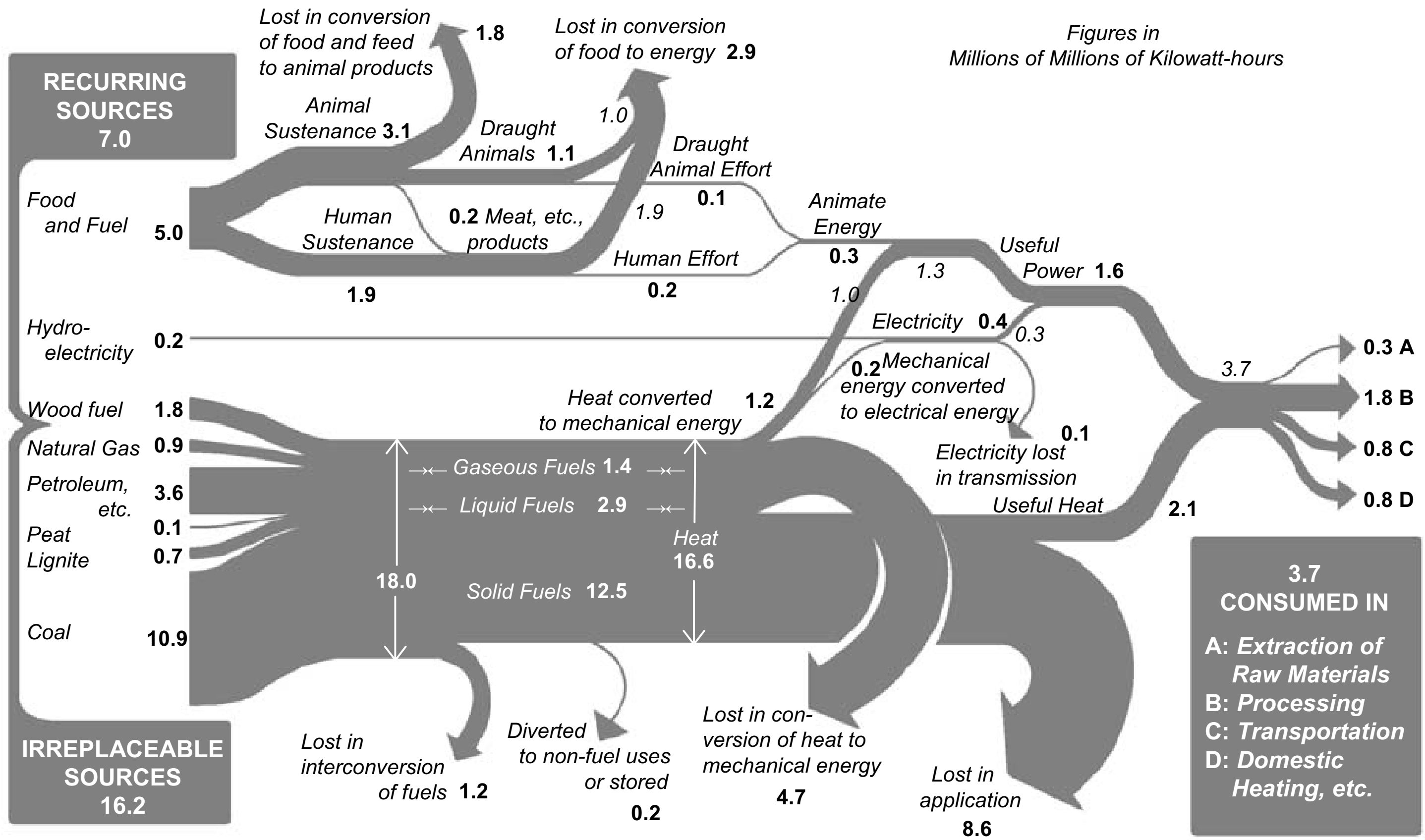
Figure 3.1 Pyramid of Energy: Bits and Photons



* 6,600 kWh thermal energy is roughly four barrels of oil.

A laser's intensely ordered flow of photons is far more useful than the sunlight that grows grass. But the laser beam depends on complex arrays of generators and power electronics behind it, which dissipate most of the energy in the raw fuel in the process of converting a tiny fraction of it into perfectly ordered photons.

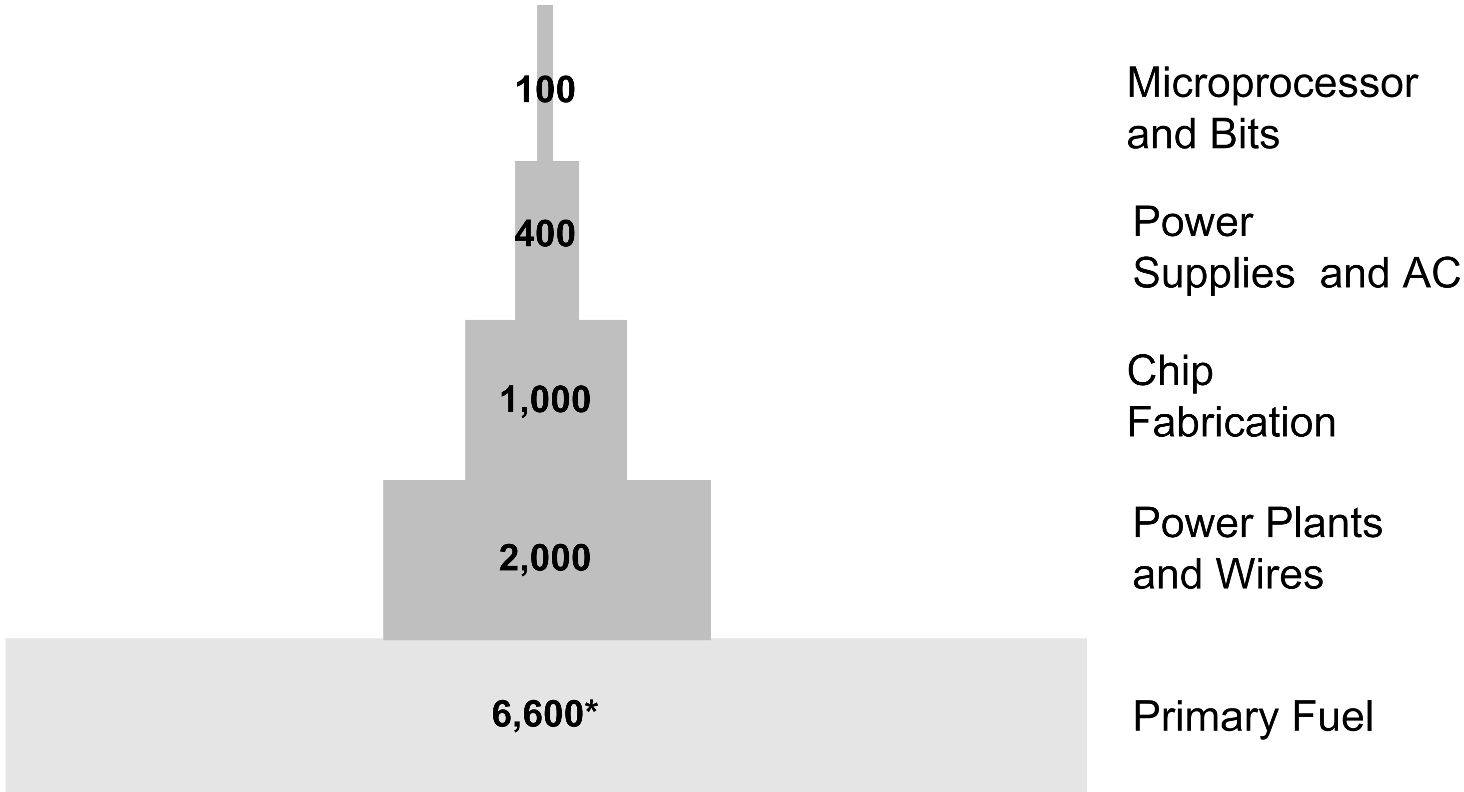
Figure 3.2 Origin and Utilization of the World's Energy in 1937



Source: N. B. Guyol, *Energy Resources of the World*, Department of State Publication 3428 (U.S. Government Printing Office, June 1949), reproduced in Hans Thirring, *Energy For Man: From Windmills to Nuclear Power*, (Indiana University Press, 1958), p. 43.

This graphical presentation of how energy is dissipated as it is purified was published in 1949. Updates are routinely used to show how most of the energy we use is simply "lost." All they really show is that it takes a great deal of energy to purify energy itself.

Figure 3.3 Pyramid of Energy: Bits and Electrons

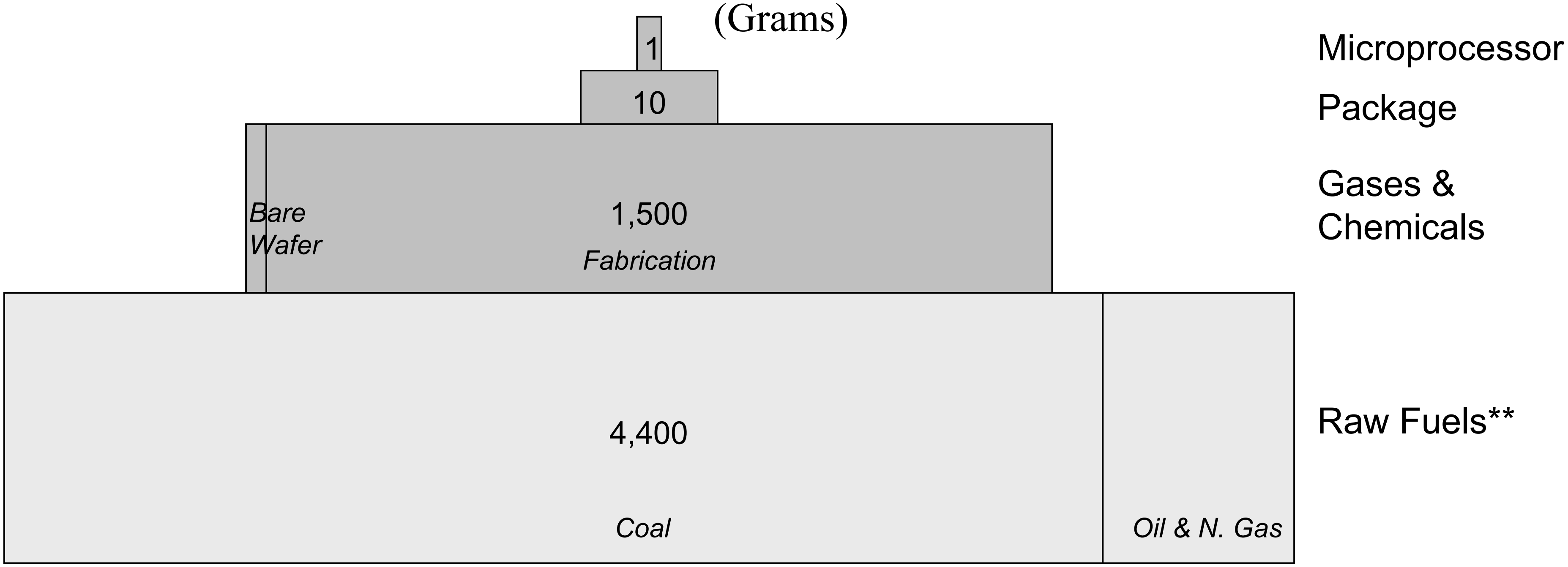


* 6,600 kWh thermal energy is roughly four barrels of oil.

A great deal of raw fuel is needed to get a trickle of ultra-reliable electricity into a microprocessor CPU. A rapidly growing share of our electricity is now used to transform ordinary grid electricity into computer-grade power.

Figure 3.3a Pyramid of Materials: Manufacturing Microprocessors*

(Grams)



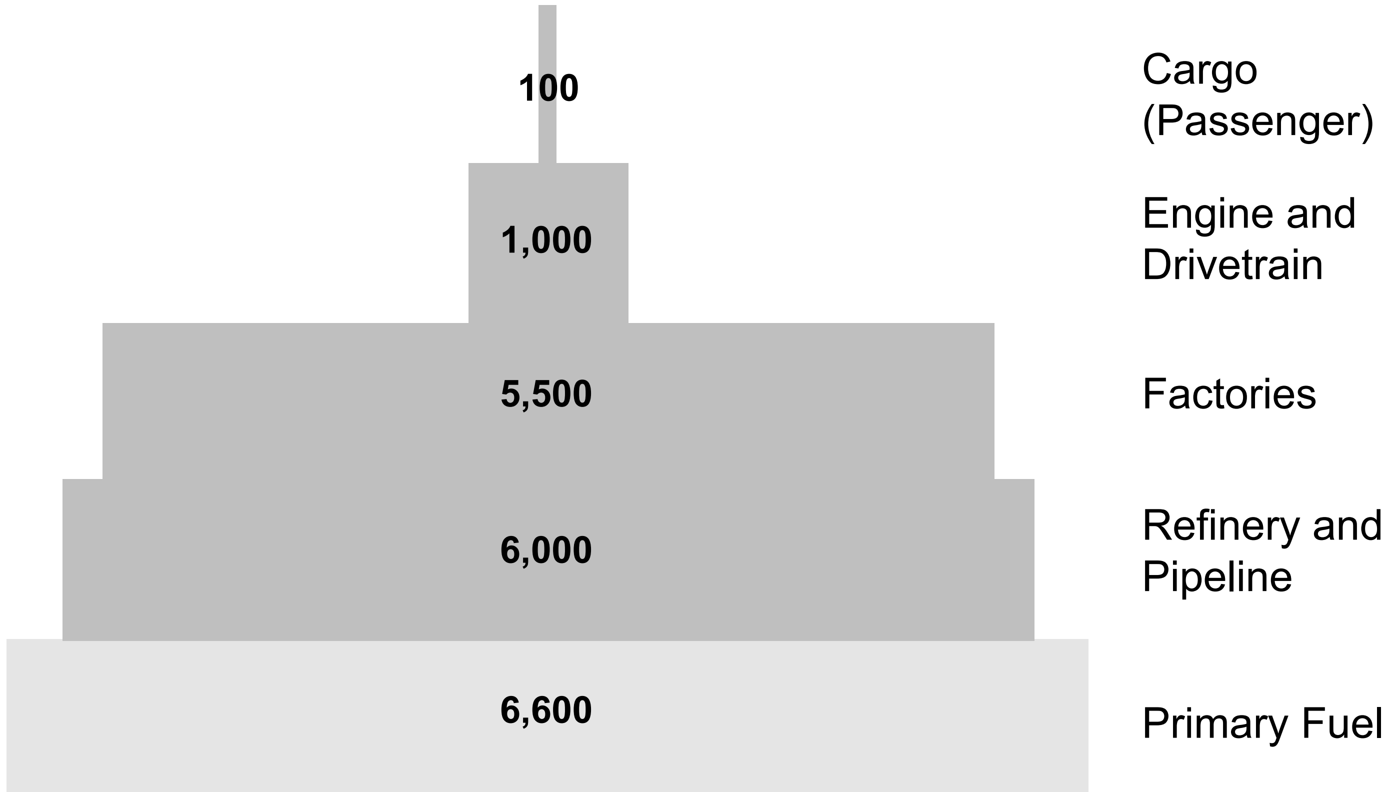
* An average microprocessor weighs about 0.2 grams in silicon.

** Does not include water use at fab (200,000 grams flow per 1 gram silicon), nor additional primary materials required to produce semiconductor-grade chemicals. Coal, natural gas, and oil are for electricity consumption, at national average fuel mix. (Uranium is a significant source of the electricity, but near zero physical consumption of material.)

Source: Martin Abrahamsson et al, "Life Cycle Assessment on Silicon and Gallium Arsenide Transistors," Chalmers University of Technology, Gothenburg, Oct. 1998; Pacific Northwest Pollution Prevention Resource Center, "Energy and Water Efficiency for Semiconductor Manufacturing," Feb. 2000; International Technology Roadmap for Semiconductors, "Environment, Safety, and Health," 2001 ed; Eric D. Williams et al., "The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices," *Environment, Science, and Technology*, American Chemical Society.

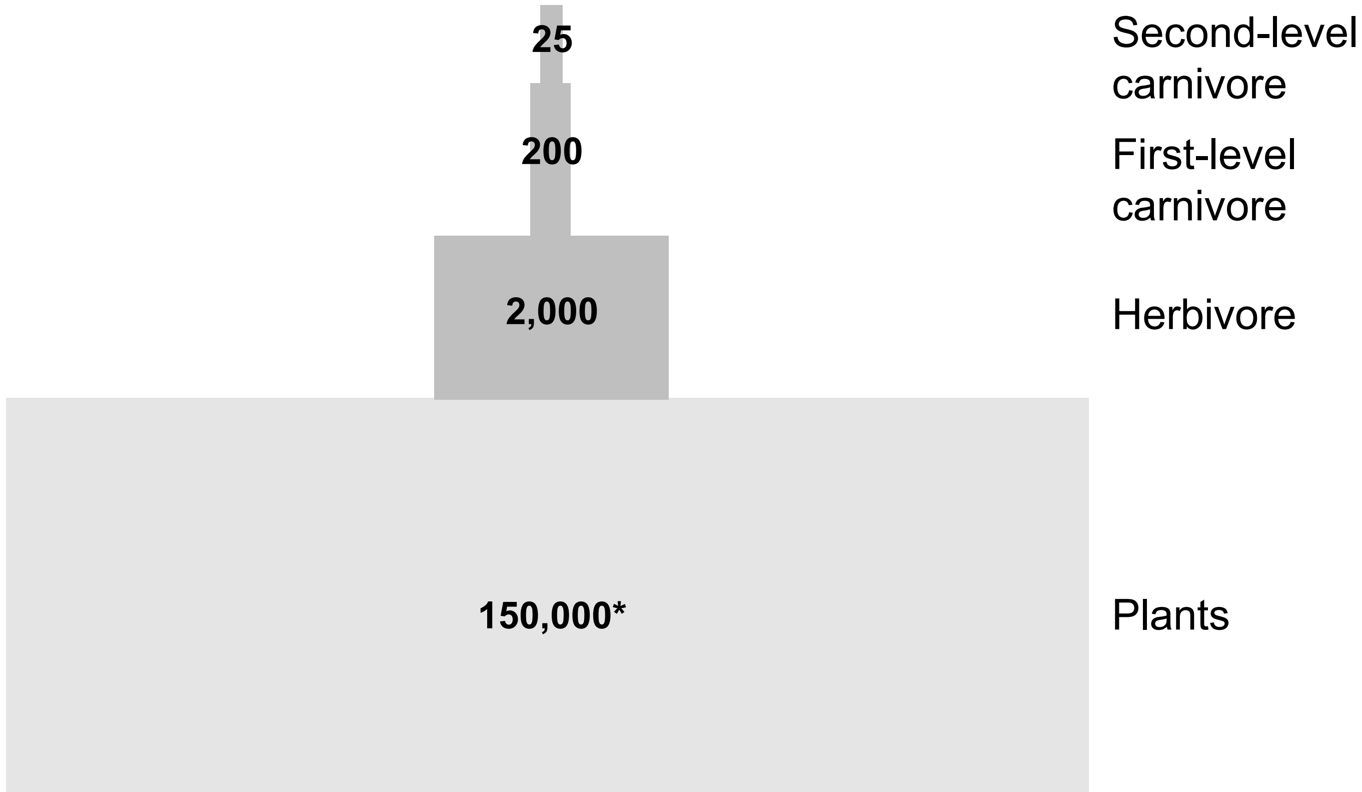
Huge amounts of raw materials go into erecting the atomic-scale edifices that comprise a microprocessor. Hundreds of tons of earth and rock are mined to extract the pounds of rare earths, lanthanides, erbium, cerium, gold, gallium, tantalum, bismuth, indium, and perovskite that serve as raw materials required to manufacture the multiple copies of a single integrated circuit. Chip fabs pump air, water, chemicals, and fuels by the ton.

Figure 3.4 Pyramid of Energy: SUV



Energy consumes itself at every stage of its own production and conversion. Only about 2 percent of the energy that starts out in an oil pool two miles under the Gulf of Mexico ends up propelling two hundred pounds of mom-and-the-kids two miles to the soccer field.

Figure 3.5 Pyramid of Energy: Life and Food

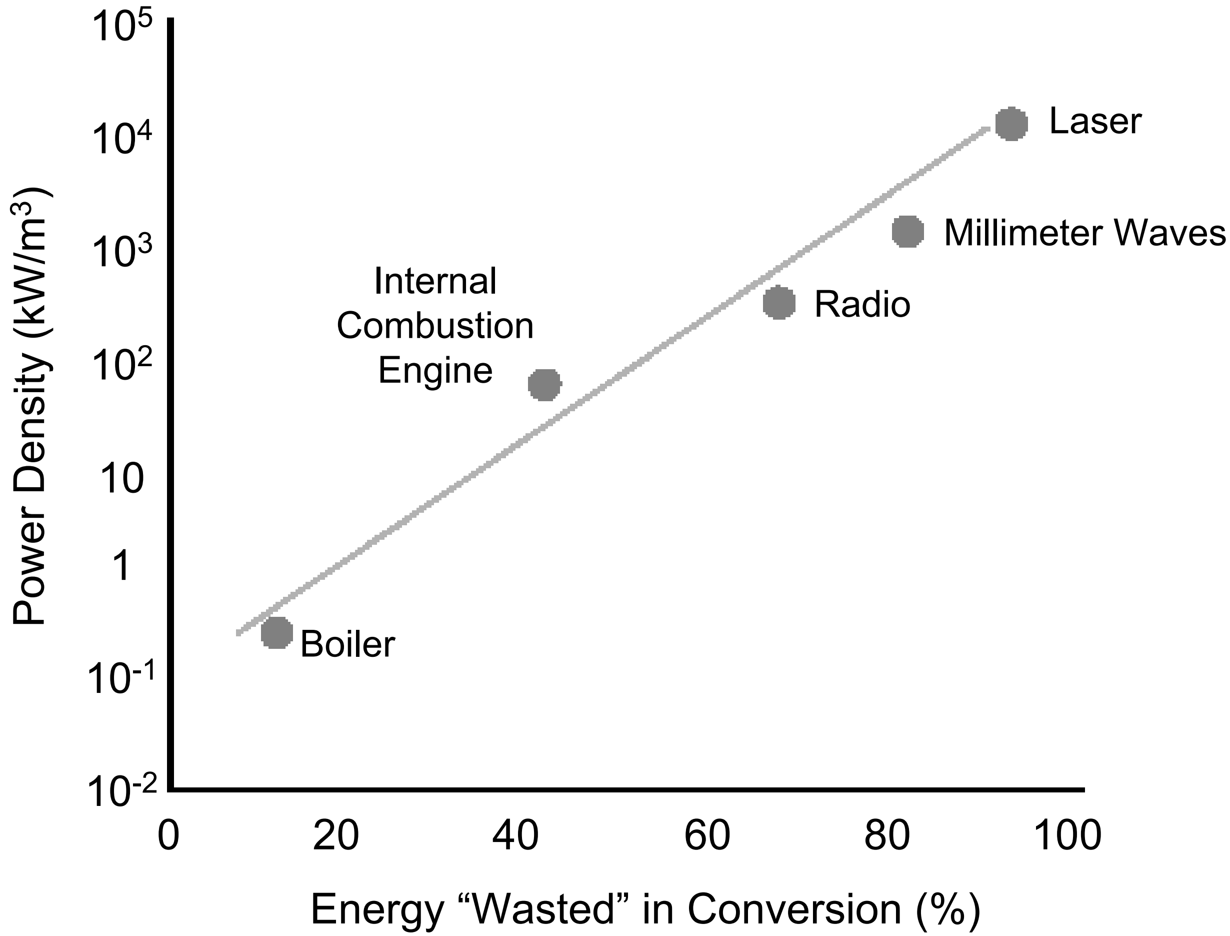


* Btu/m^2/Year (150,000 Btu roughly the energy in one gallon gasoline)

Source: George B. Johnson and Peter H. Raven, *Biology*, McGraw-Hill (6th ed.), Figure 28.13c.

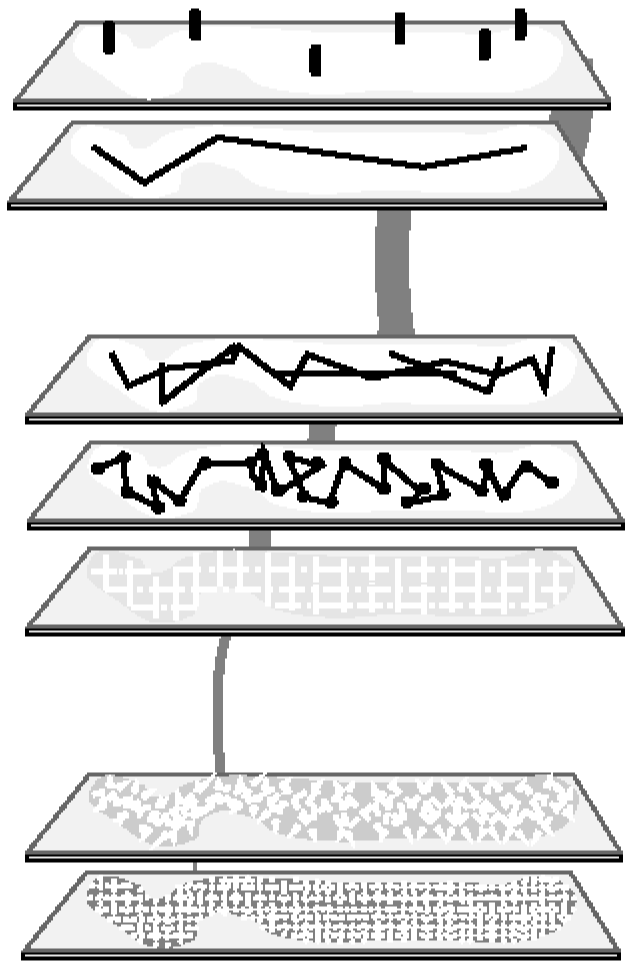
Energy is both purified and dissipated as it moves up the food chain in the biosphere. High-level carnivores depend for their survival on a huge expanse of plant life three steps below.

Figure 3.6 Power Density and Energy Waste



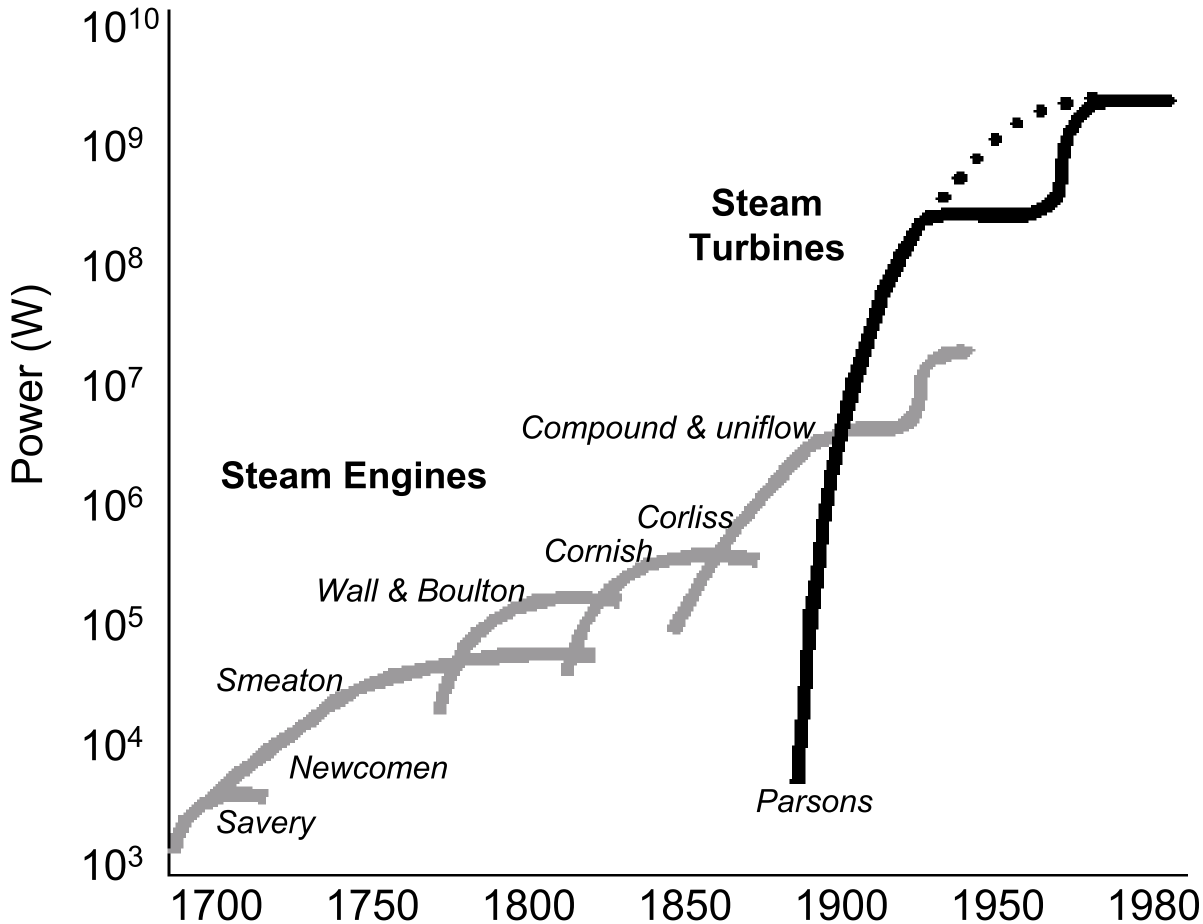
A system sheds "entropy"—chaos—only by shedding energy itself, in the form of waste heat. To produce more well-ordered energy, faster, in less space--to increase "power density," roughly speaking—one must throw away more energy, faster.

Figure 4.1 The Multitiered Grid



Measured by route miles and physical footprint, the multitiered North American grid is the second largest network on the planet, after the roads and highways. Generating stations dispatch electrical power through some 680,000 miles of high-voltage, long-haul transmission lines, which feed power into 100,000 substations. The substations dispatch power, in turn, through 2.5 million miles of local distribution wires to our toasters, computers, and industrial robots.

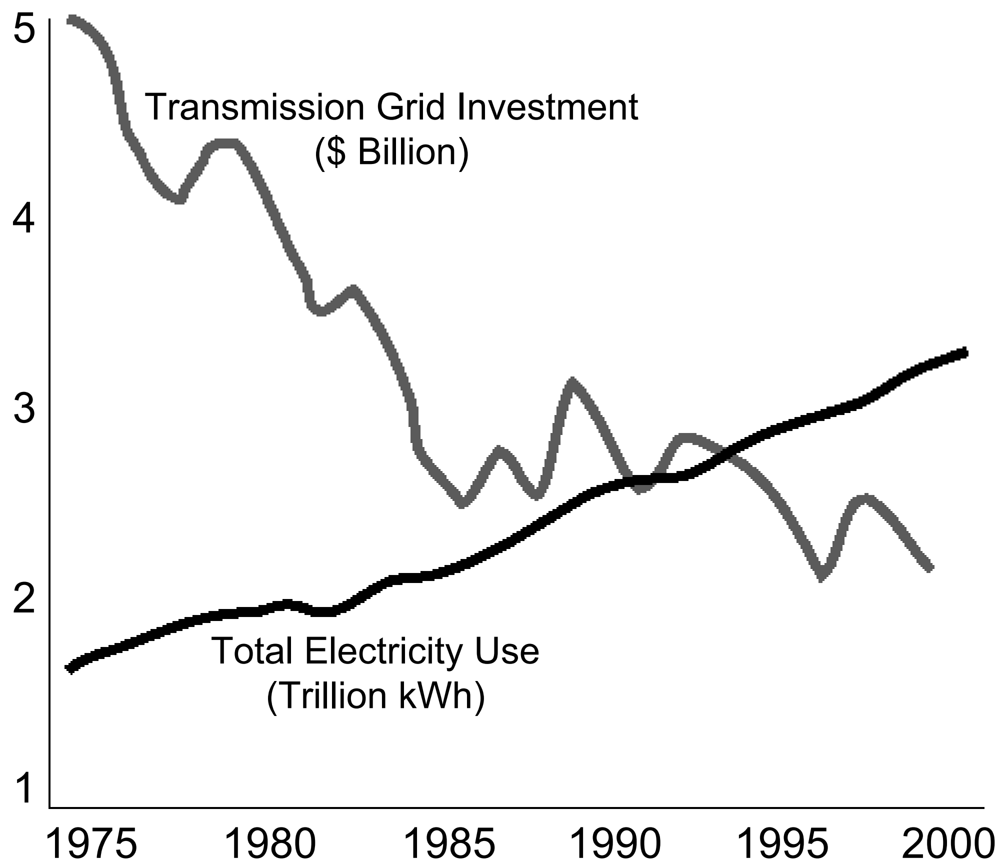
Figure 4.1a The Power of Scale



Source: Vaclav Smil, *General Energetics: Energy in the Biosphere and Civilization* (Wiley, 1991).

To burn fuel more efficiently in a stationary power plant, you build a bigger furnace. There are enormous economies of scale in building and maintaining bigger engines and generators, as well. Thus, decade by decade, power plants have grown bigger, and in so doing have grown more efficient.

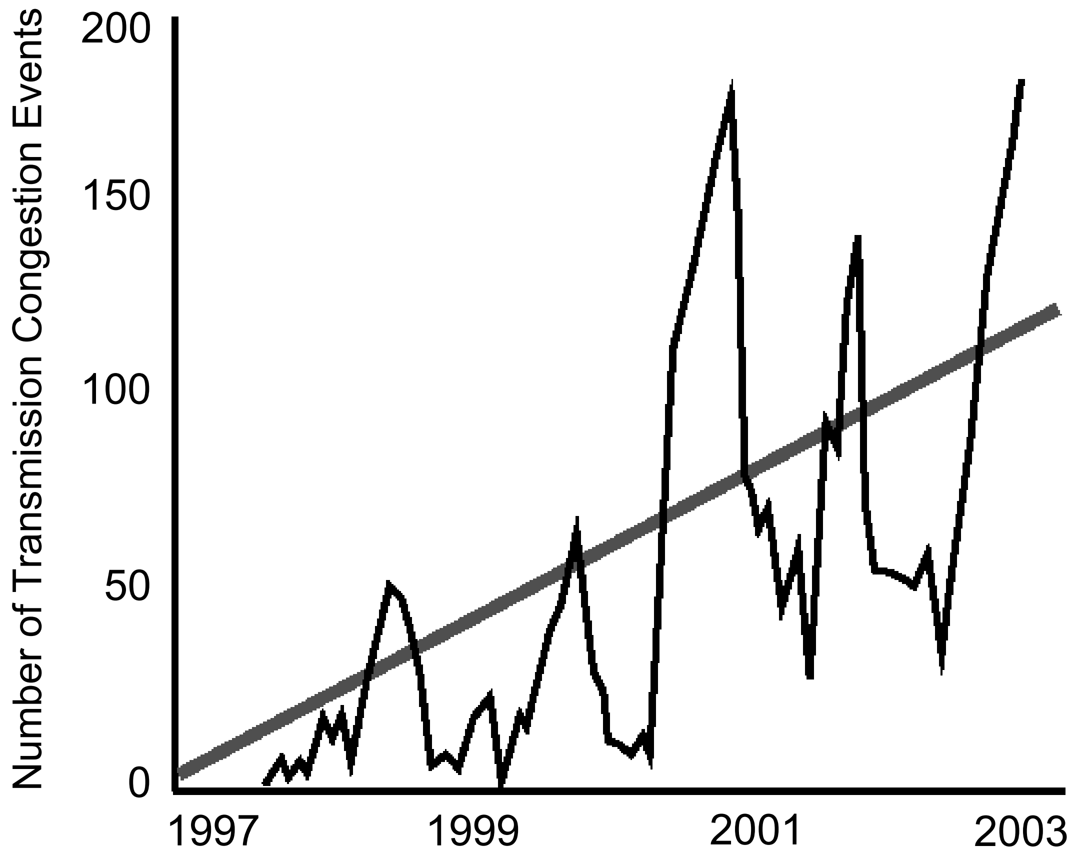
Figure 4.2 U.S. Electricity Transmission



Source: Eric Hirst and Brendan Kirby, "Transmission Planning for a Restructuring U.S. Electricity Industry," Edison Electric Institute, June 2001; EIA, *Annual Energy Review 2003*.

The deregulation of interstate electric power sales promoted investment in new, unregulated power plants, but reduced incentives to invest in the grid.

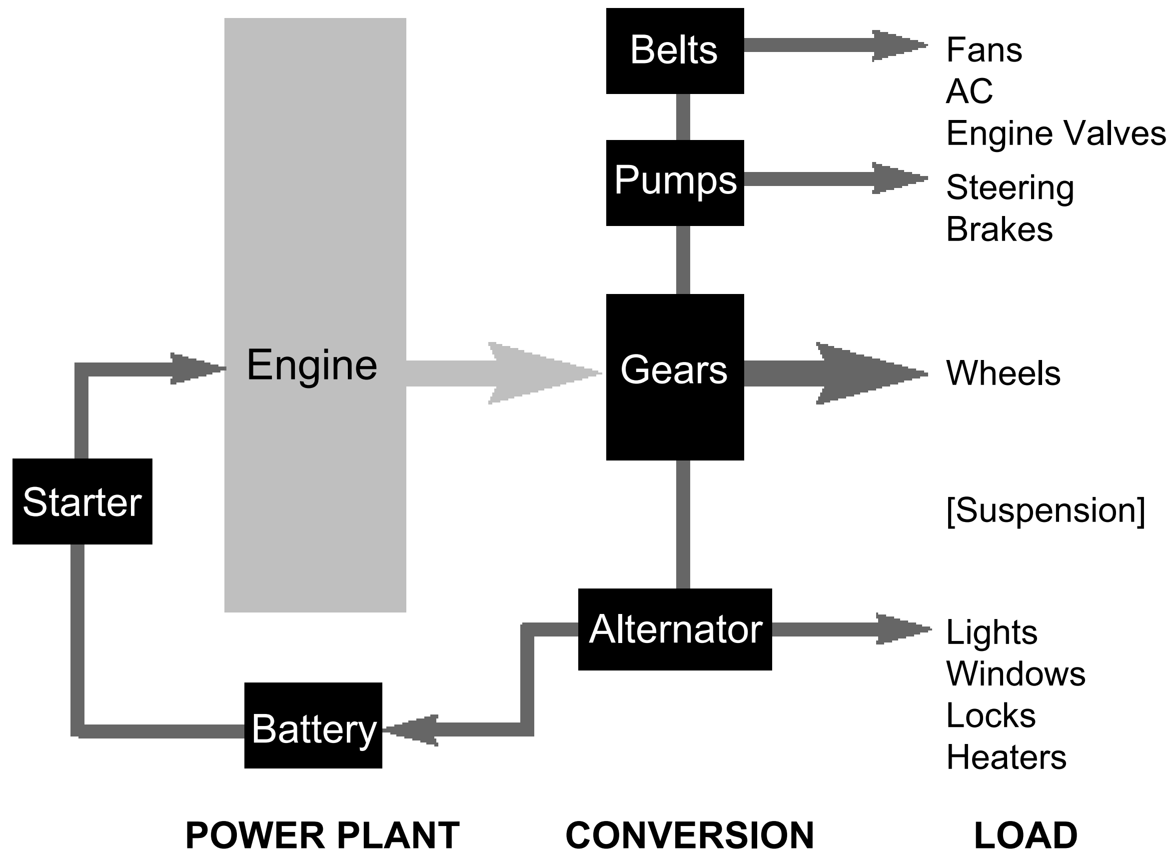
Figure 4.2a Rising Electric Grid Congestion



Source: North American Reliability Council (NERC) Transmission Loading Relief Logs; Peter Huber and Mark Mills, "Transmission and Distribution," *Digital Power Report*, October 2002.

The deregulation of interstate power sales had a number of consequences, including spurring investment in the new, unregulated power plants. And, to stay well clear of regulation, these merchant generators steered clear of wires. As for the grid companies, they remain snarled in regulation, their rates have been kept low, and investment in the wires has plummeted. The combined effect: rising grid congestion.

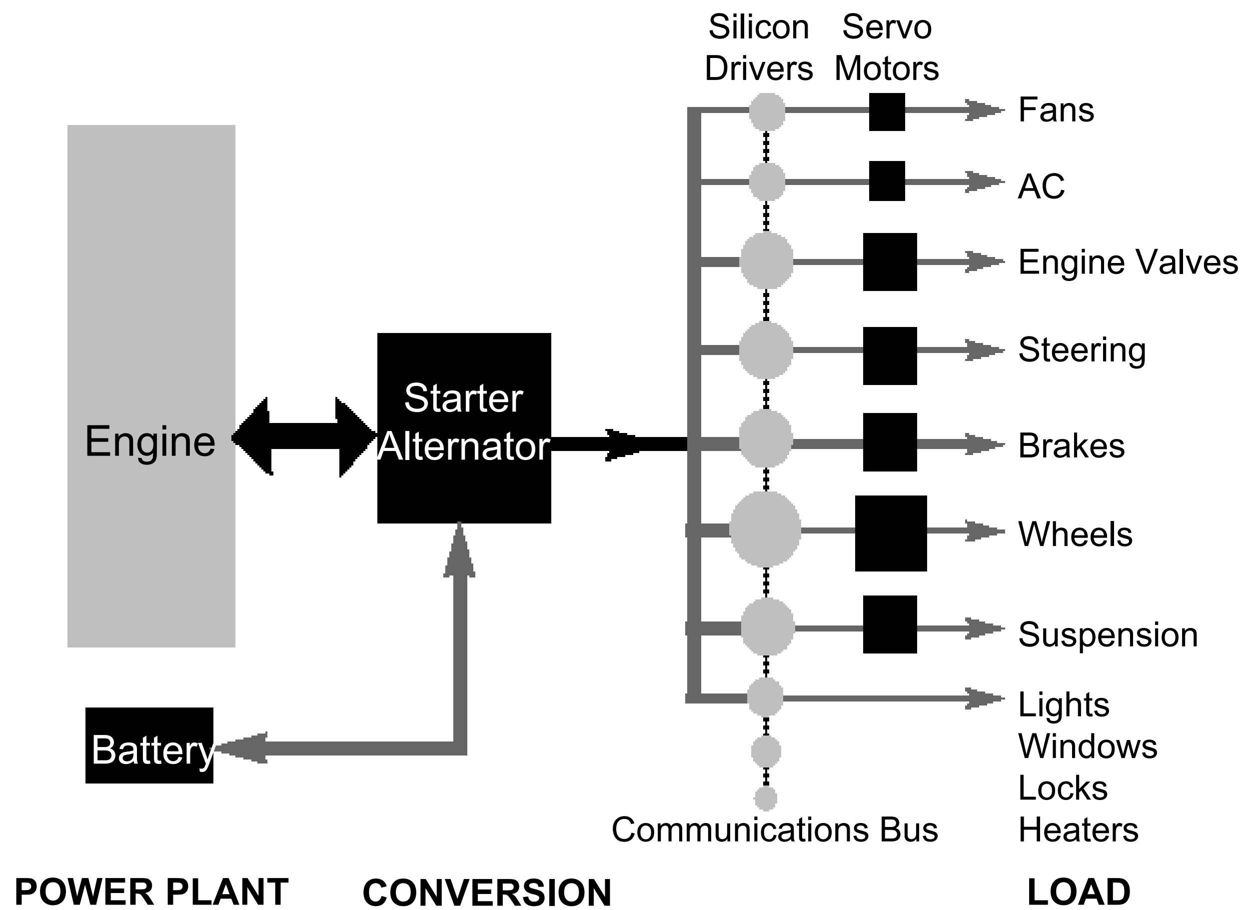
Figure 5.1 Mechanical Drive Train



Source: Peter Huber and Mark Mills, "The Powerchip Paradigm II: Broadband Power," *Digital Power Report*, Dec. 2000, www.digitalpowergroup.com.

A car engine's logic still consists mainly of primitive linkages, rocker arms, contacts, valves, and gears. Much of the weight of the conventional car engine, most of its cost, and all of the logical complexity, are located in these peripherals that surround the pistons and cylinders at the core.

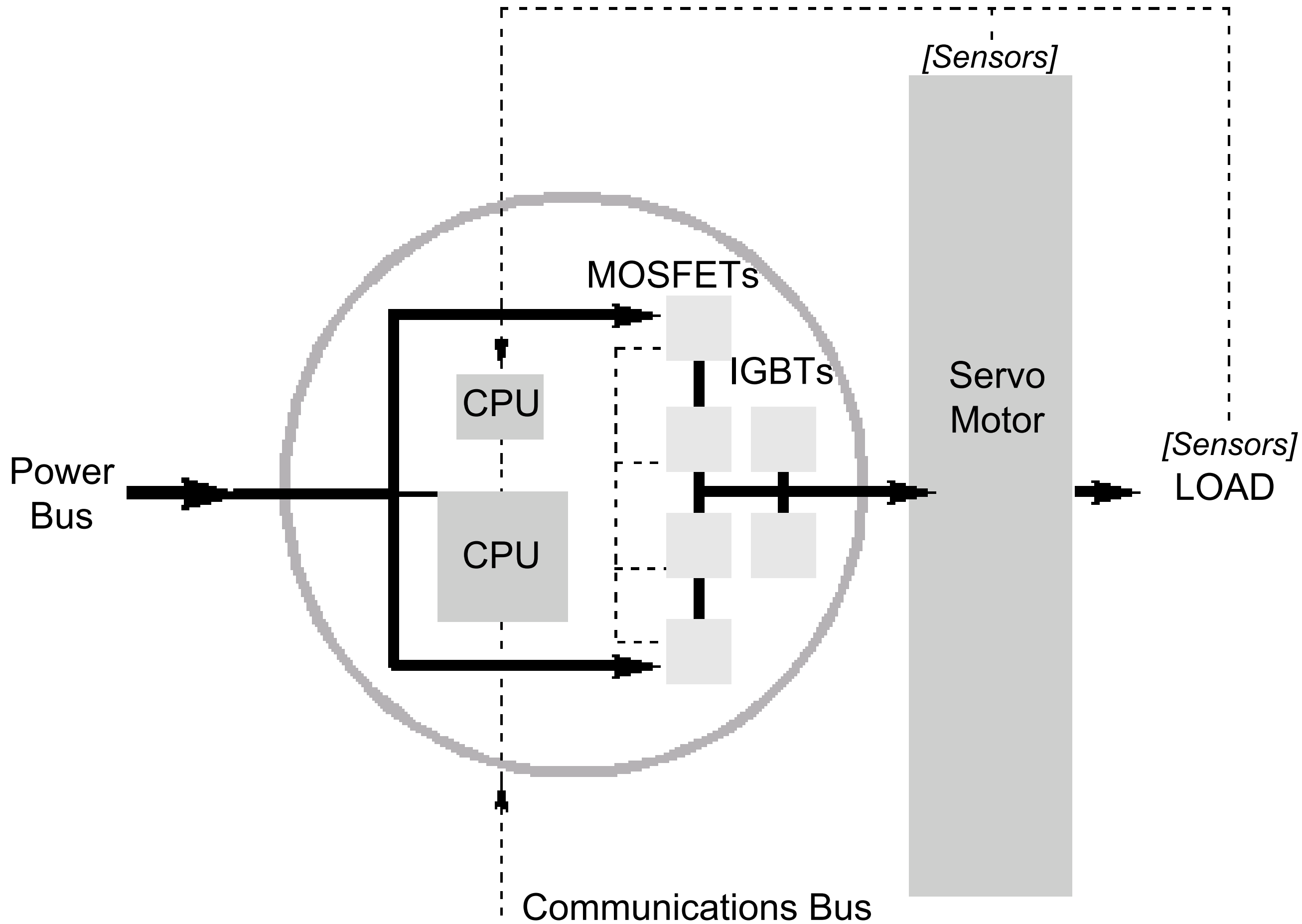
Figure 5.2 Electric Drive Train



Source: Peter Huber and Mark Mills, "The Powerchip Paradigm II: Broadband Power," *Digital Power Report*, Dec. 2000, www.digitalpowergroup.com.

The car's power train is being transformed from mechanical-hydraulic to digital-electric because low-cost semiconductors can now control kilowatts of power faster, more precisely, more reliably, and in less space, than mechanical alternatives. Car makers already spend more on etched silicon than on steel.

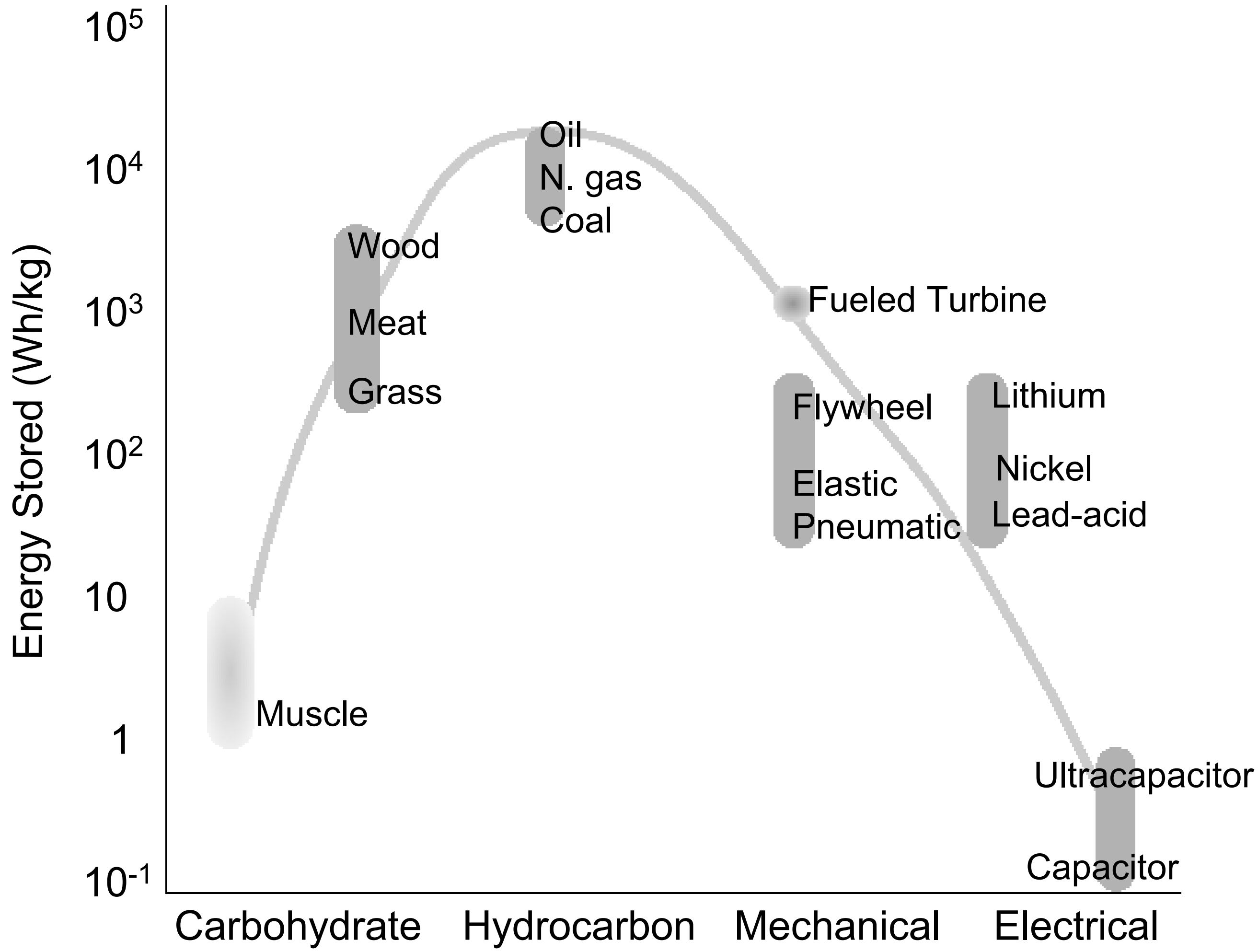
Figure 5.2a Silicon Regulator



Source: Peter Huber and Mark Mills, "Power Paradigm II: Broadband Power," *Digital Power Report*, December 2000.

Silicon-controlled electric actuators are now set to displace the steel camshafts, belts, rods and pulleys in every part of the conventional engine and drive-train. Everything shrinks, everything gets lighter, and every aspect of performance improves—dramatically.

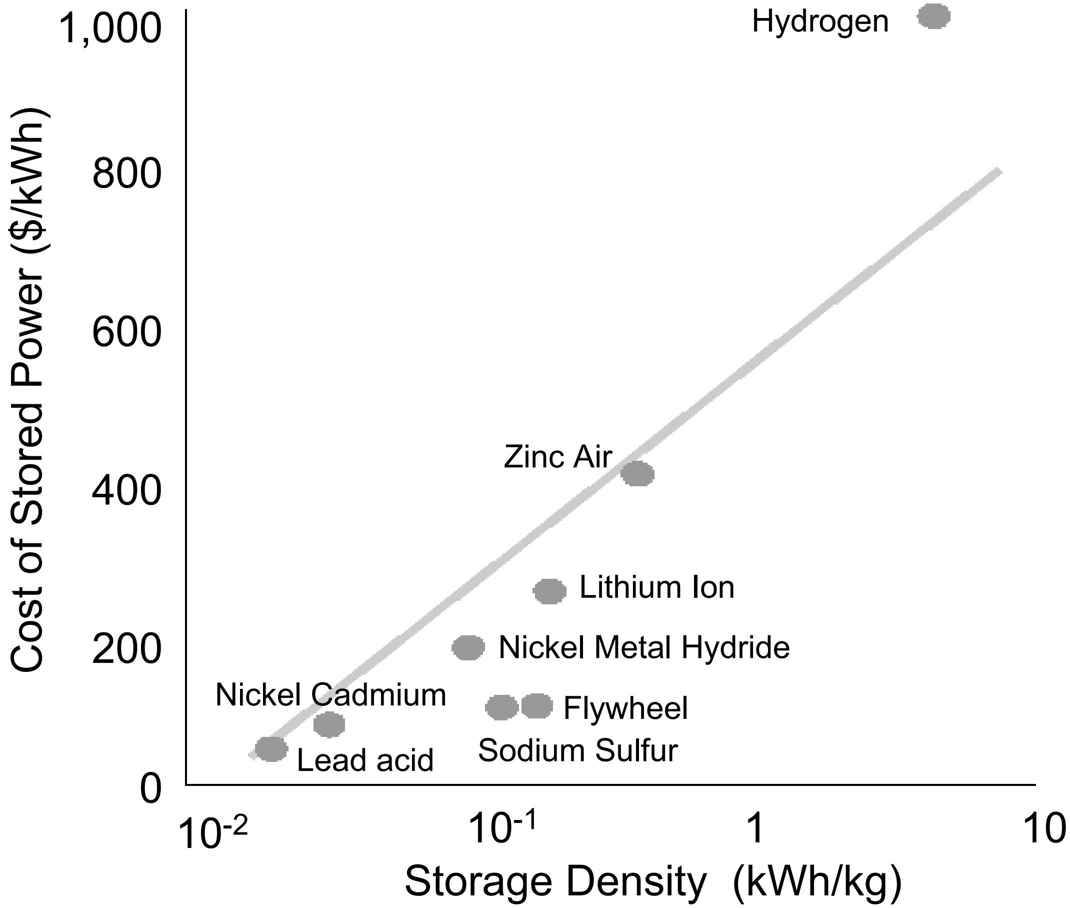
Figure 5.2b Storing Energy for Mobile Power



Source: Vaclav Smil, *General Energetics: Energy in the Biosphere and Civilization* (Wiley, 1991); Jean-Paul Rodrigue, "Transport Geography," Hofstra University (1999).

Electric batteries fail dismally on the energy-per-pound metric.

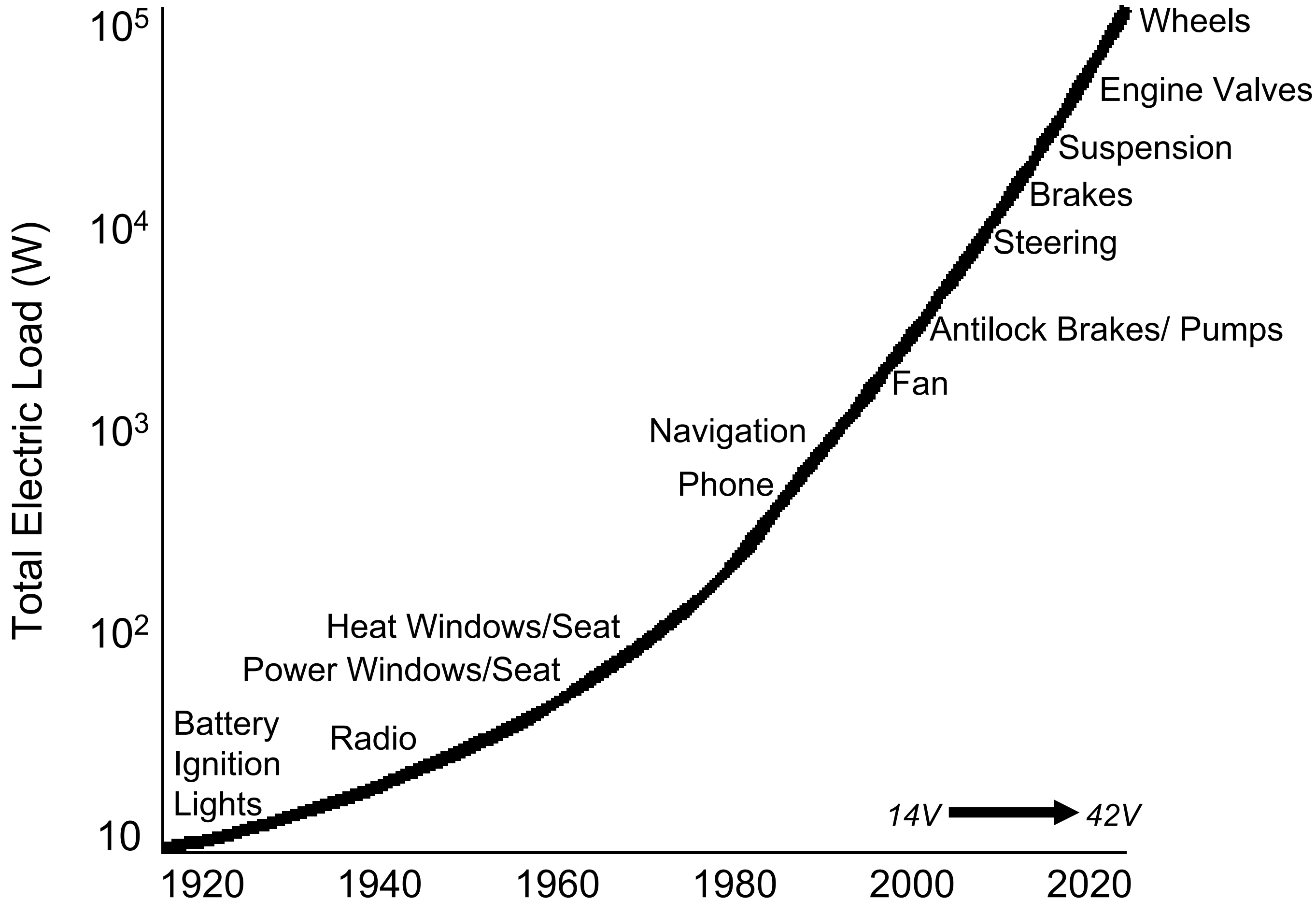
Figure 5.2c Cost to Store Electric Power



Source: M.J. Riezenman, "Metal Fuel Cells," IEEE *Spectrum*, June 2001; Isidor Buchmann, "Portable Power," Cadex Electronics, 2000; "Exoskeletons for Human Performance Augmentation," DARPA Workshop 1999, Defense Sciences Office; Electricity Storage Association.

When electricity is used to extract hydrogen from water, the hydrogen-water combination serves, in effect, as a rechargeable battery. But not a very efficient one—it takes about 4 kilowatt-hours of electricity pumped into the water to get 1 kilowatt-hour of electricity back out of the hydrogen. Other battery chemistries are much more efficient and cost-effective, but store far less energy per unit of weight.

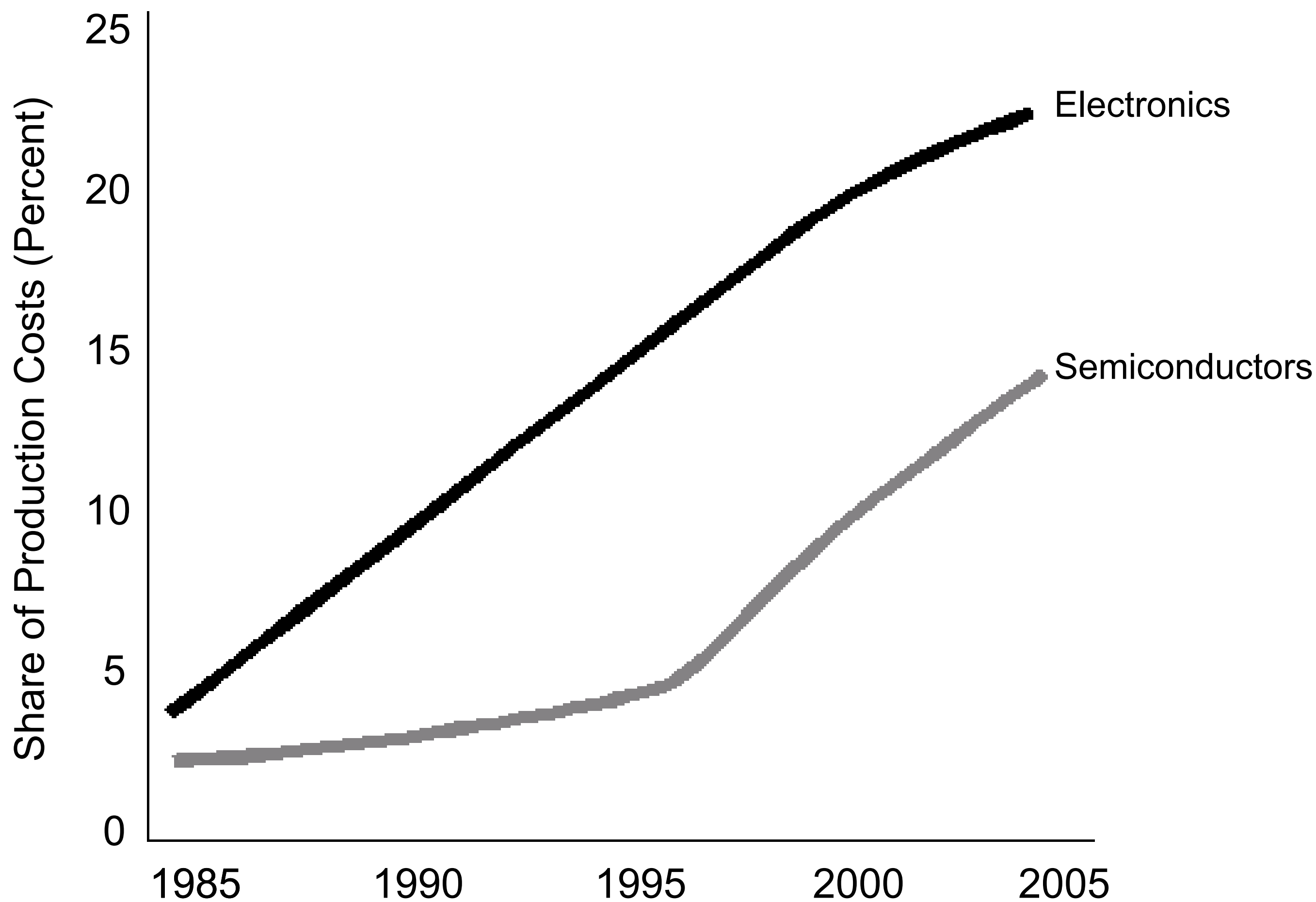
Figure 5.2d Electrification of the Automobile



Source: John G. Kassakian et al, "Automotive Electronics Power Up," IEEE *Spectrum* (May 2000); Peter Huber and Mark Mills, "Pontiacs and Powerchips," *Digital Power Report*, Nov. 2002.

The last step in the electric evolution of the automobile will be the largest: silicon and electric power will knock out the entire gear box, drive shaft, differential, and related hardware—all of which disappear when direct electric drives end up turning the wheels. When the wheels are driven electrically, the entire output of the engine—from 20 kW to 100 kW—will have to be converted immediately into electricity before it is distributed, used, or stored throughout the car.

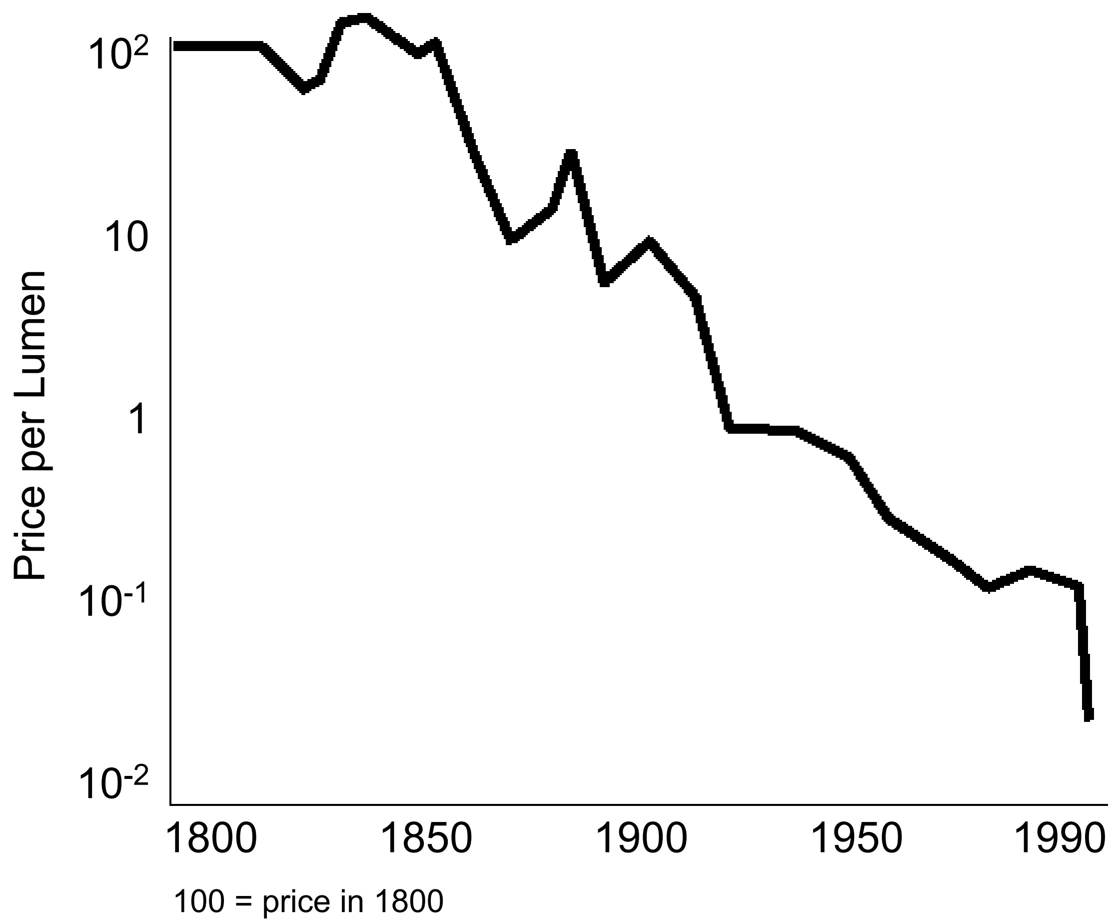
Figure 5.2e Silicon and Electronics in the Automobile



Source: Bosch, courtesy DaimlerChrysler.

The internal combustion engine won't be eliminated in our time. But the engine itself will be changed beyond recognition, as electronics and semiconductors continue to infiltrate the drivetrain and account for a steadily growing fraction of the cost of manufacturing the vehicle.

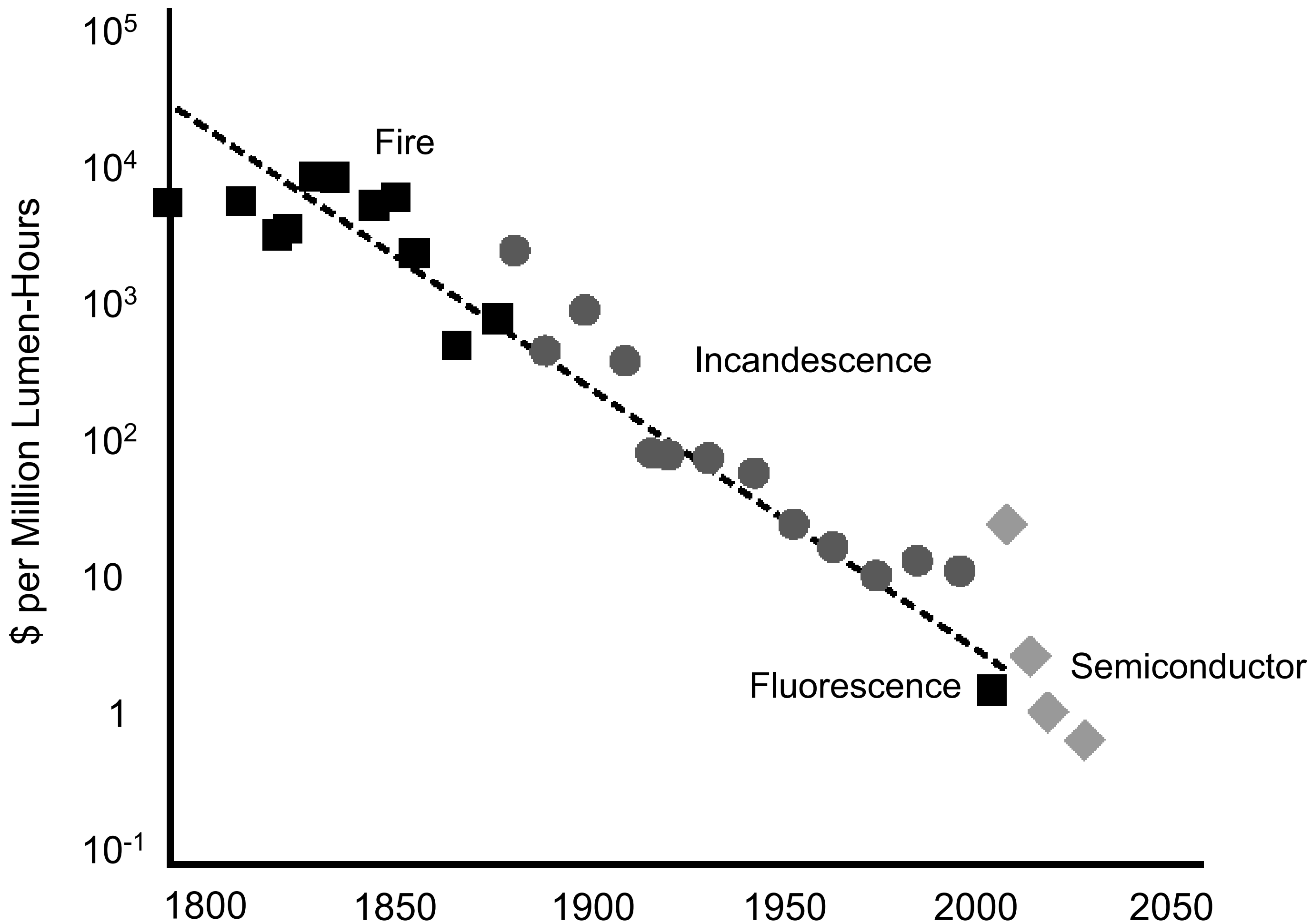
Figure 6.1 The Cost of Illumination



Source: Fortune, Nov. 22, 1999.

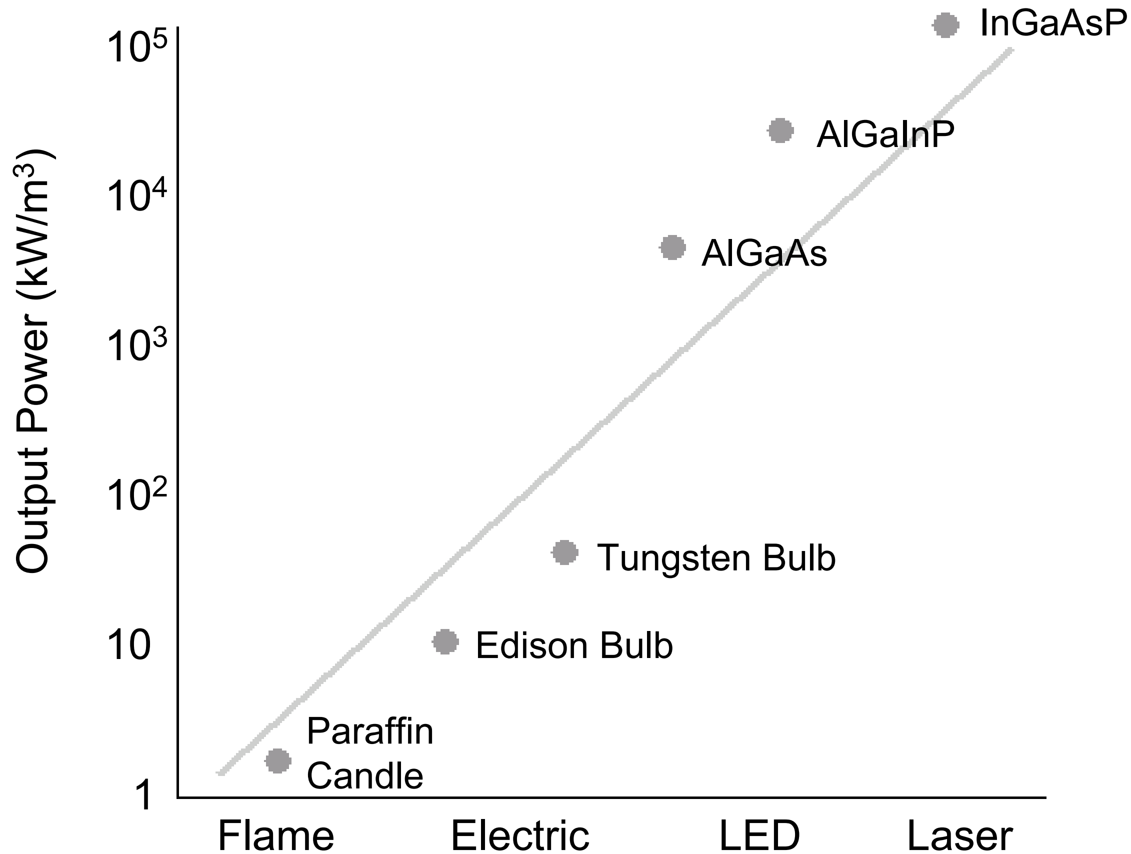
The cost of light has dropped ten-thousand-fold over the last two hundred years.

Figure 6.1A Cost of Illumination



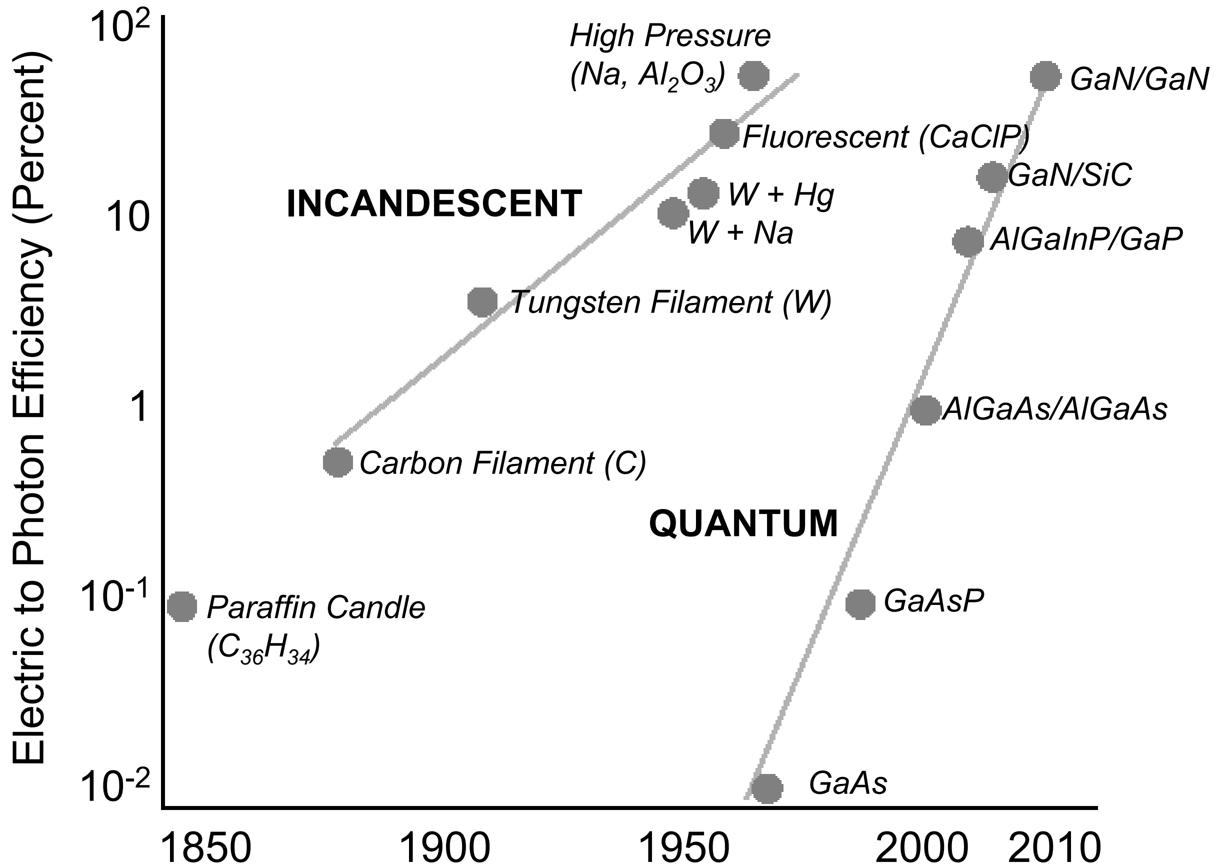
Source: Jeff Y. Tsao, ed., Light Emitting Diodes (LEDs) for General Illumination: An OIDA Technology Roadmap Update 2002, Optoelectronics Industry Development Association, November 2002.

Figure 6.1b Photon Power Density



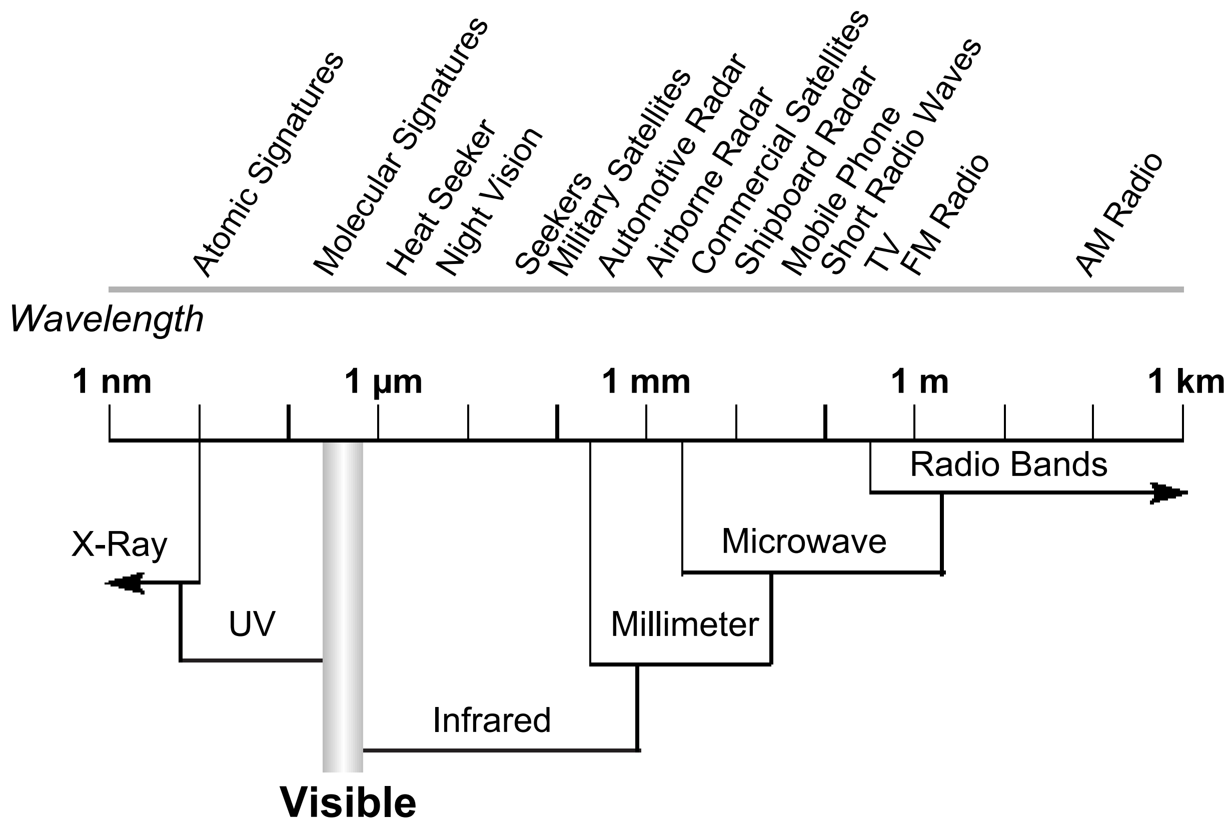
The demise of the evacuated bulb "gas lamp" began with the invention of the transistor, in 1948. In 1962, Nick Holonyak, a General Electric researcher, managed to transform one of the three streams of current that flow through a transistor into a stream of light—the light emitting diode (LED). In certain semiconductors, such as gallium (Ga) mixed with aluminum (Al) and arsenic (As), the quantum changes in electron states at a semiconductor junction are very efficient at emitting photons. The shift from Edison's filament to quantum technology radically improves performance—the new devices are much more compact, efficient, and cool. In 1963, Herbert Kroemer and Zhores Alferov proposed a theory for a heterostructure semiconductor device which would produce coherent laser beams; semiconductor lasers are now ubiquitous as well.

Figure 6.2 The Materials of Illumination



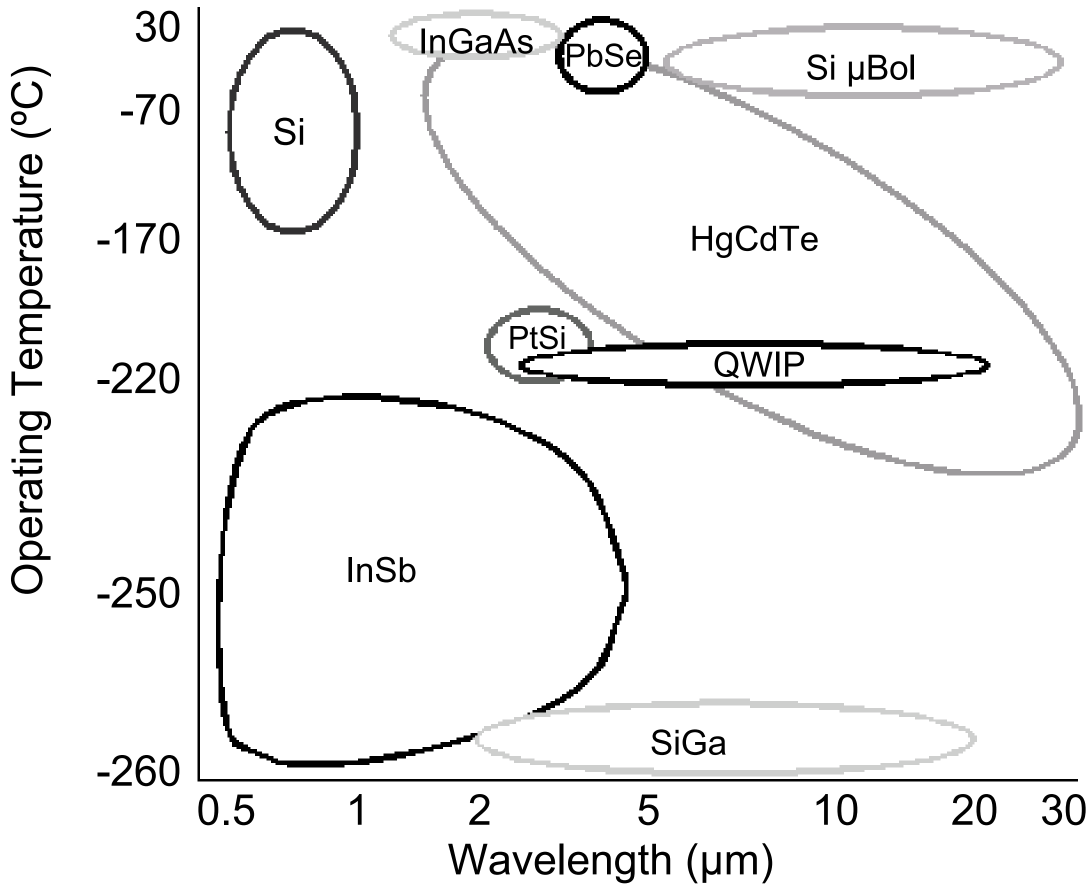
Semiconductor junctions exploit the bizarre phenomena of quantum physics to convert electricity into light far more efficiently than is possible with conventional incandescent technologies. Aluminum gallium arsenide (AlGaAs) shines red, gallium phosphide (GaP) green, gallium phosphide with arsenic (GaAsP) yellow, gallium nitride (GaN) blue.

Figure 6.3 The Spectrum of Photon Power



Most wavelengths of "light" are invisible to the human eye. Different wavelengths illuminate, penetrate, and reflect in quite different ways. The new semiconductor "light bulbs" can be configured to emit photons all across the electromagnetic rainbow. The new transmitters and receivers of photon power can thus illuminate and see far more than the unassisted eye.

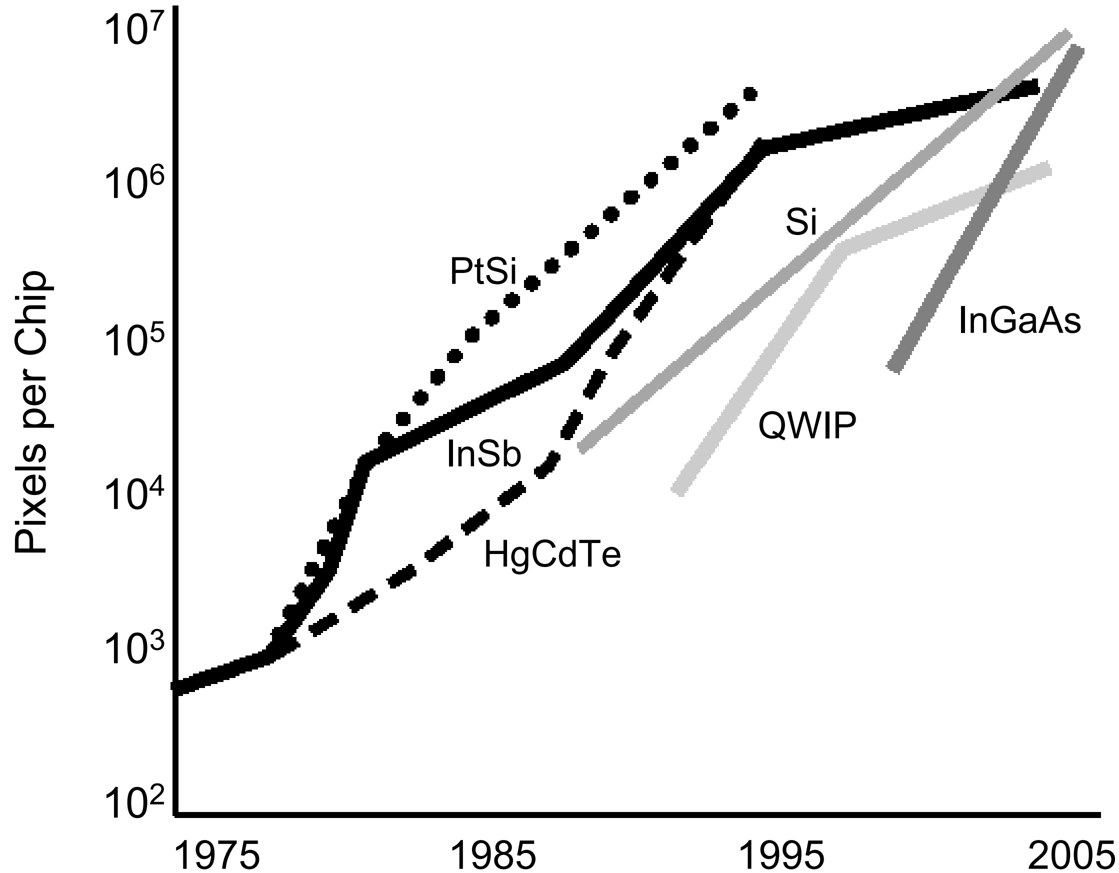
Figure 6.3a Infrared Sensing Materials



Source: L. Chen, "Advanced FPAs for Multiple Applications," Raytheon, SPIE Proceedings on Infrared Detectors and Focal Plane Arrays VII, April 2002; Maxtech International.

Different combinations of semiconductors are extremely sensitive to infrared light over a broad range of wavelengths. Infrared imagers are proliferating on the factory floor, the highway, and the battlefield.

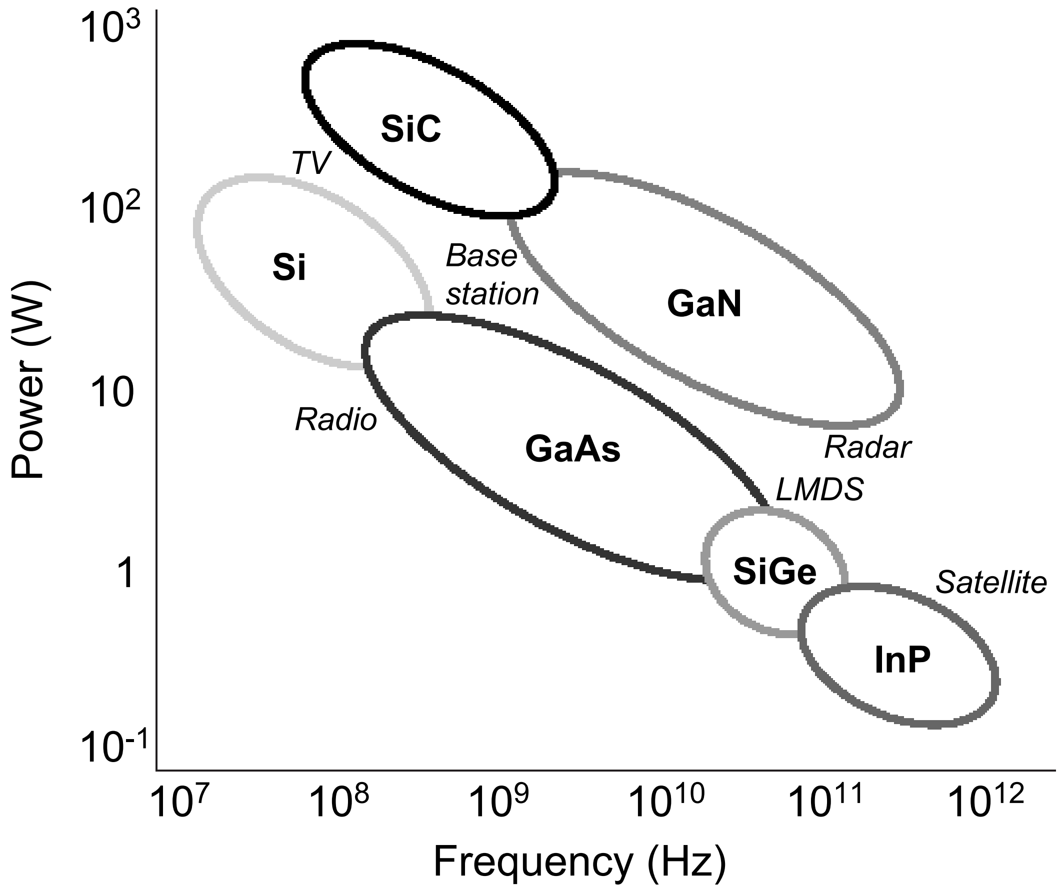
Figure 6.3b Infrared Cameras



Source: "Commercial and Dual-Use Military Infrared Imaging," Maxtech International; P. R. Norton, "Status of Infrared Detectors," Raytheon, SPIE Conference on Infrared Detectors and Focal Plane Arrays, August 2004.

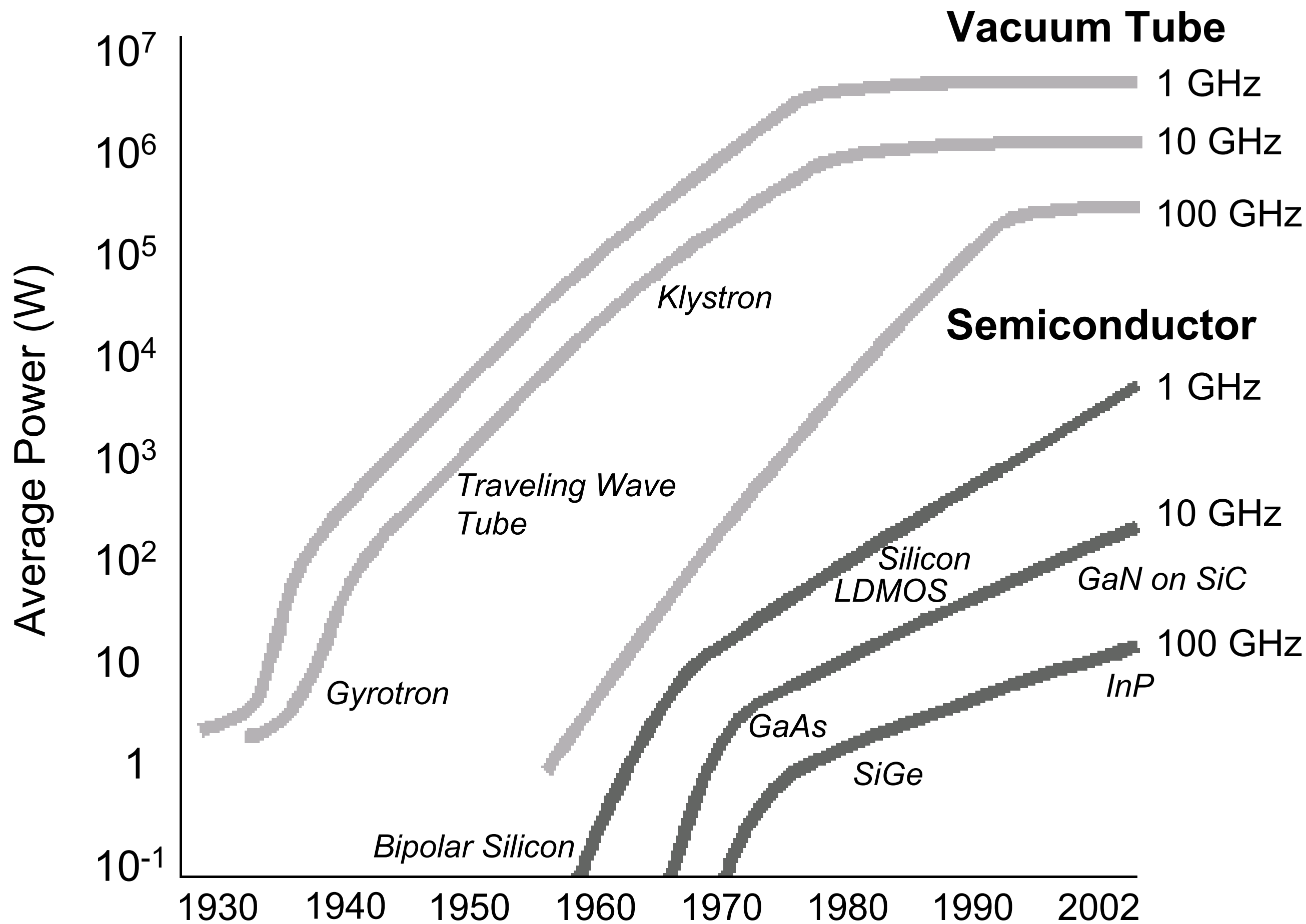
The infrared imaging chips now being incorporated in solid-state digital cameras are catching up with the resolution (pixels per chip) of conventional digital cameras that sense visible light.

Figure 6.3c RF Power from Semiconductors



New families of semiconductor-materials are dramatically expanding the frequency range and power-handling capabilities of radio-frequency amplifiers. Engineers can now use radio waves not just for communication but also to cut through clutter to see hidden targets, to measure liquid levels in tanks, to process chemicals and pharmaceuticals, to detect deterioration in concrete, pavements, bridges, and railroad beds, to map oil spills, and to locate buried wastes, underground, pipes, tunnels, and buried mines.

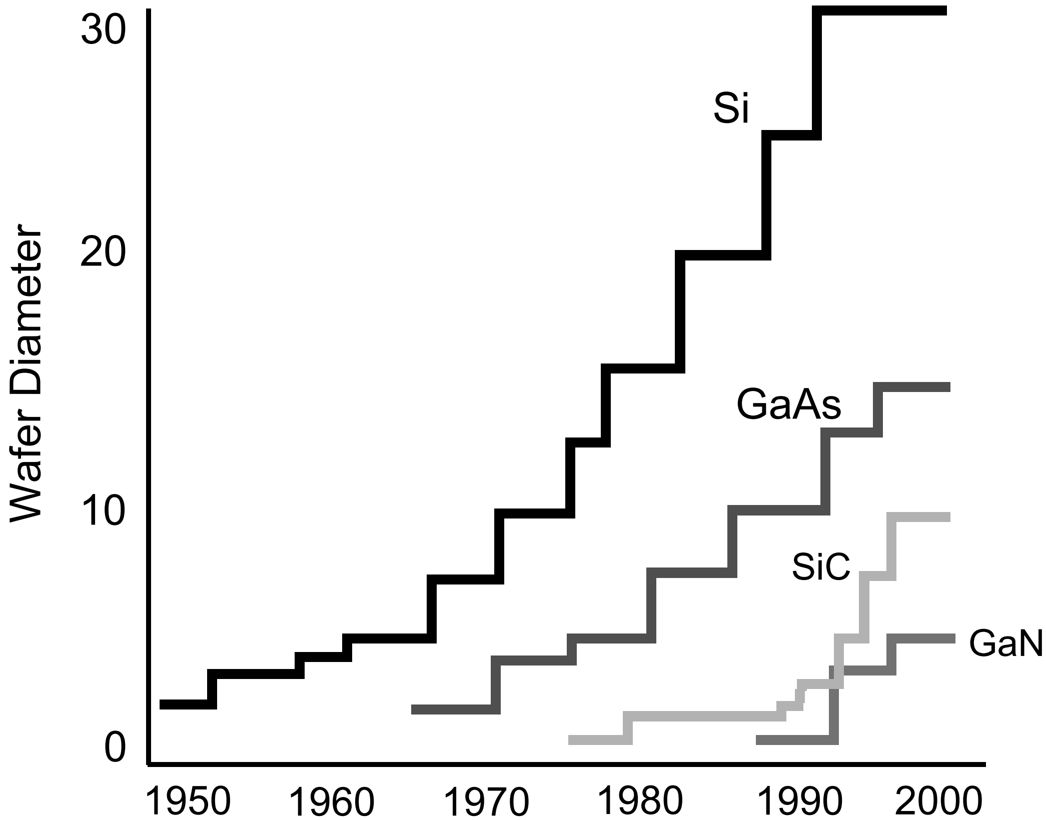
Figure 6.3d High-Power RF Transmitters



Source: R. S. Symons, "Tubes: Still Vital After All These Years," IEEE *Spectrum*, April 1998.

Lighting up a 100 kW broadcast antenna perched 1,000 feet above the ground, still requires hundreds of kilowatts of power pouring through banks of monster 30 kilowatt (or larger) vacuum tubes down at the base of the tower. Semiconductor RF powerchips are now emerging to displace these tubes.

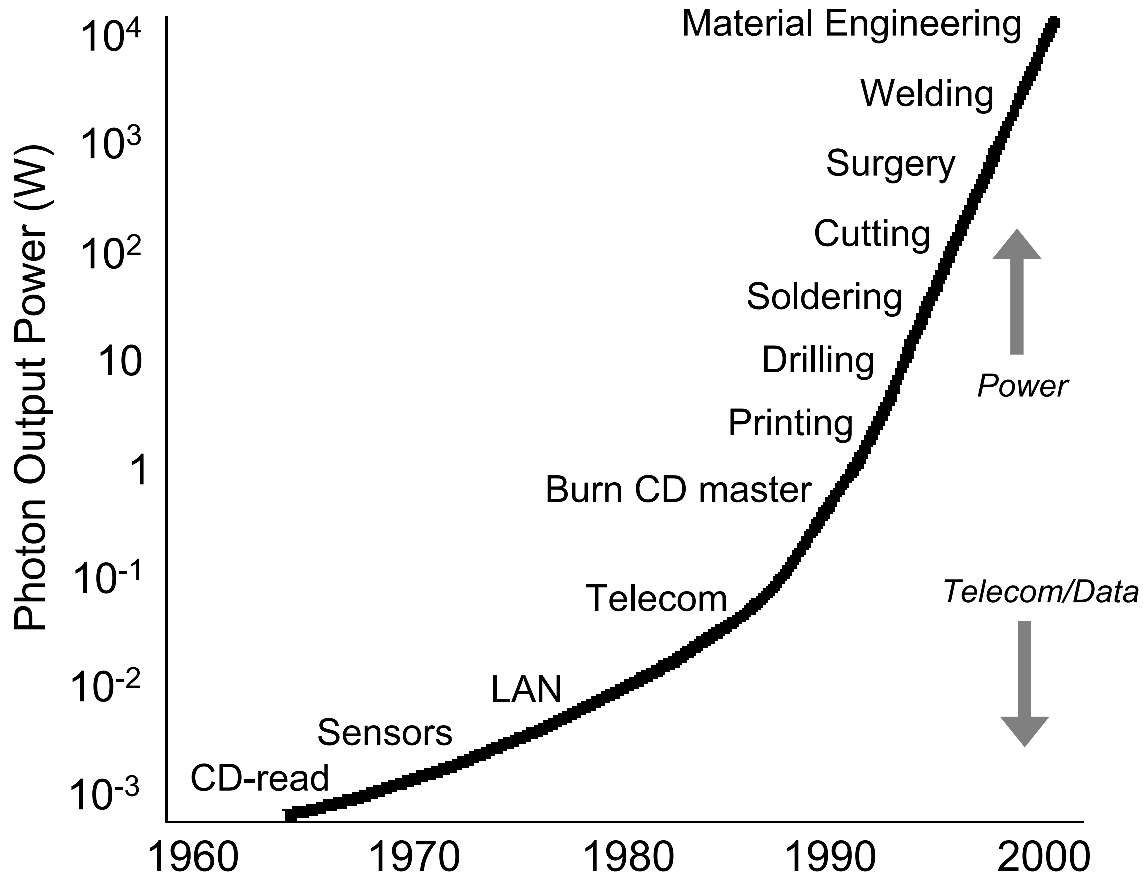
Figure 6.3e Economies of Scale in Semiconductors



Source: "Wide Bandgap Semiconductors," Proceedings of the IEEE (June 2002); Warren Weeks and Ricardo Borges, "Silicon Substrates Provide a Disruptive Technology for GaN," *Compound Semiconductor*, November 2001.

Semiconductor devices get cheaper as engineers master the art of growing larger crystal wafers, on which the chip fabs build the devices. The cost of cell phones dropped sharply with the availability of ever larger gallium arsenide (GaAs) wafers on which chip fabs manufacture the critical radio-frequency amplifiers. Silicon carbide (SiC) and gallium nitride (GaN) wafers, and the entirely new classes of devices that can be built on them, are now on a similar trajectory.

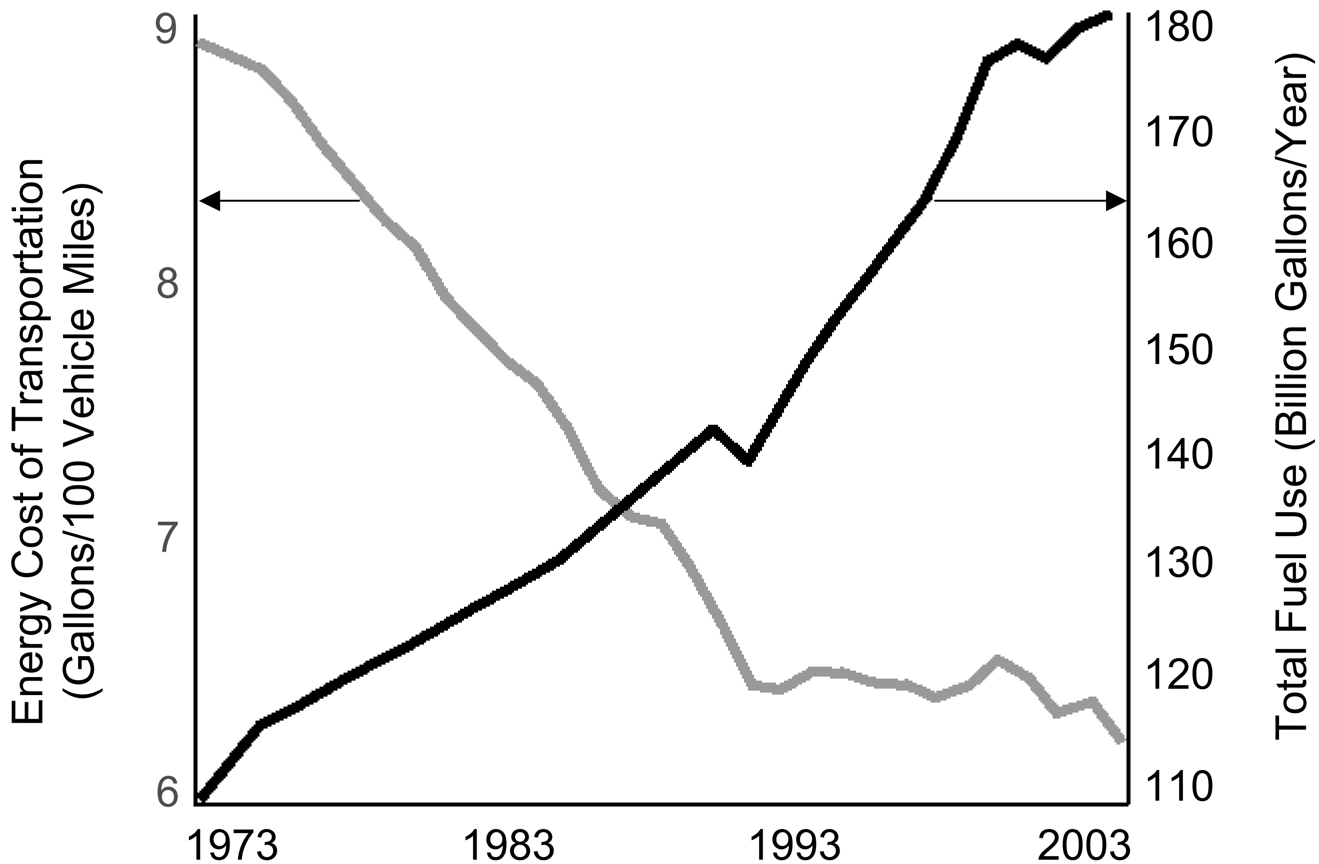
Figure 6.3f Semiconductor Lasers; From Bits to Atoms



Source: Laser Institute of America, Proceedings International Congress on Applications of Lasers & Electro-Optics: Laser Materials Processing, October 2000; Peter Huber and Mark Mills, "Photo Power," *Digital Power Report*, June 2001.

At high power levels, lasers don't move bits, they move atoms. They fuse powdered metals into finished parts, heat, cure, mill, solder, drill, cut, all with fantastic improvements in speed, precision, and efficiency. They create thermal pulses that can create entire new classes of material coatings, or move ink in mammoth commercial printing machines.

Figure 7.1 Energy Cost of Transportation versus Total U.S. Consumption*

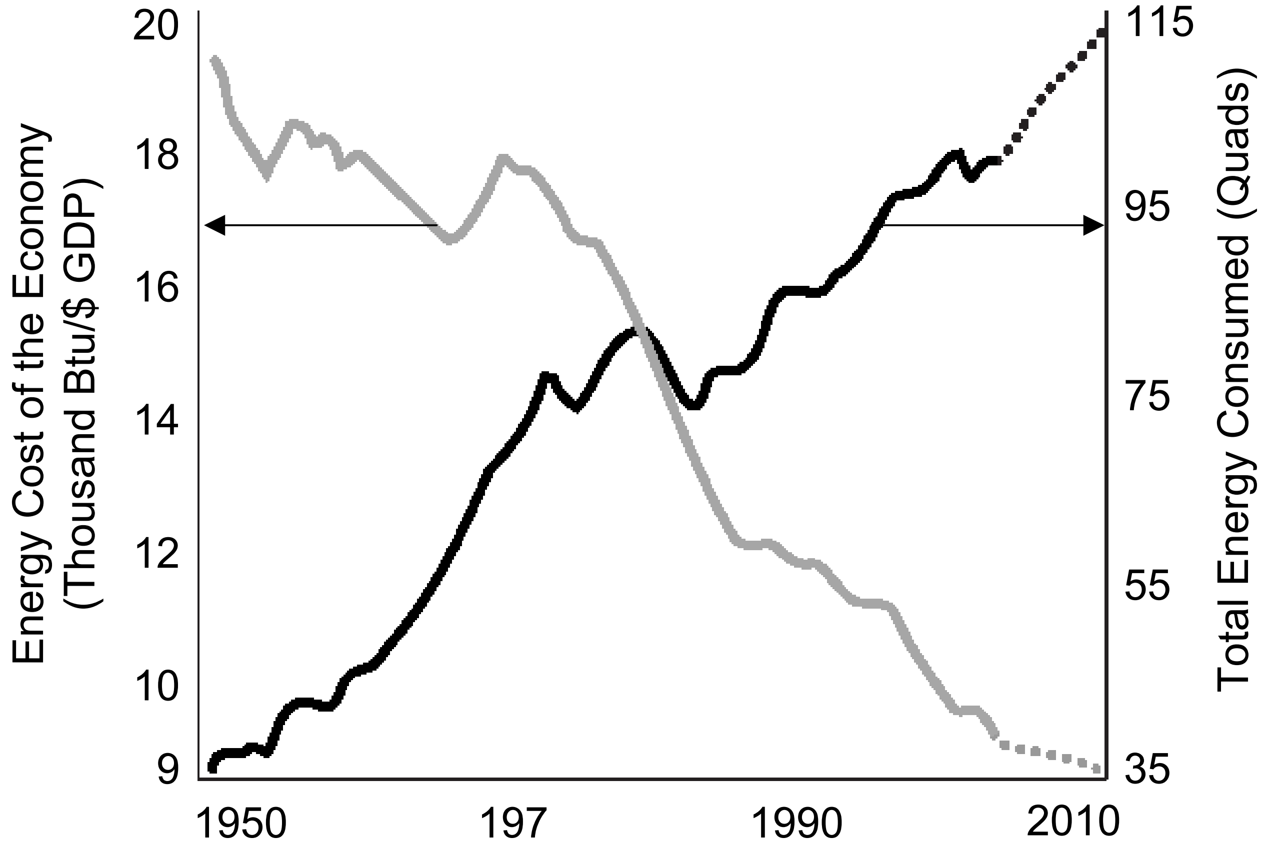


*All modes

Source: Department of Transportation, *National Transportation Statistics 2003*; EIA, *Annual Energy Review 2003.*

Efficiency improvements have not lowered the amount of fuel consumed in transportation. The amount of fuel needed to move a vehicle 100 miles has fallen steadily, but total fuel consumption in the transportation sector has gone up.

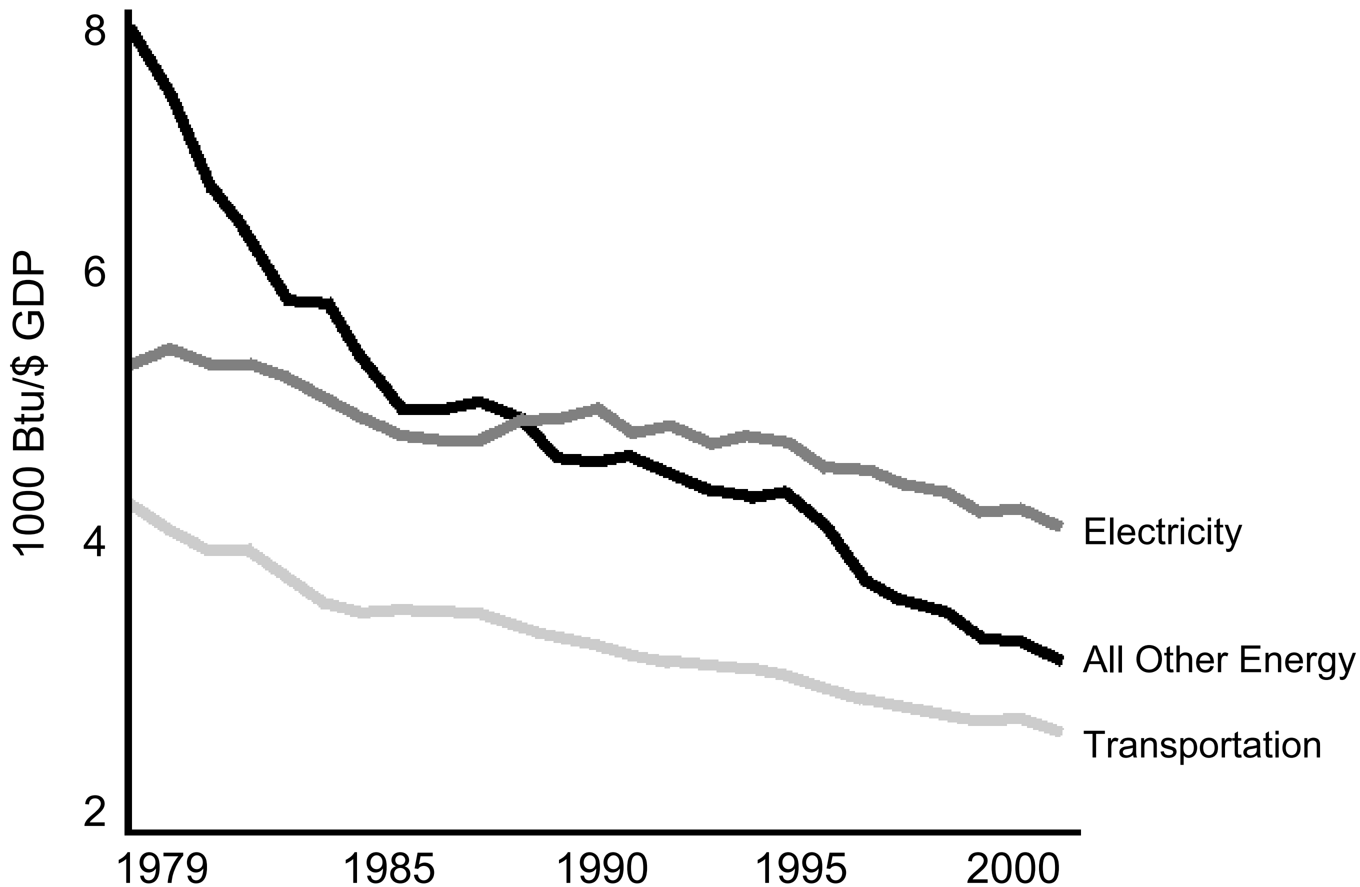
Figure 7.2 Energy Cost of the U.S. Economy versus Total Consumption



Source: EIA, *Annual Energy Review 2003* and *Annual Energy Outlook 2004*; Bureau of Economic Analysis.

The U.S. economy as a whole is twice as energy-efficient today as it was in 1950—the amount of fuel needed to produce $1 of GDP has been cut in half. But total energy consumption has almost tripled. As they grew more efficient, we built more steam power plants, jet turbines, and car engines, light bulbs, electric motors, air conditioners, and computers, and used them more heavily—and total energy consumption went up.

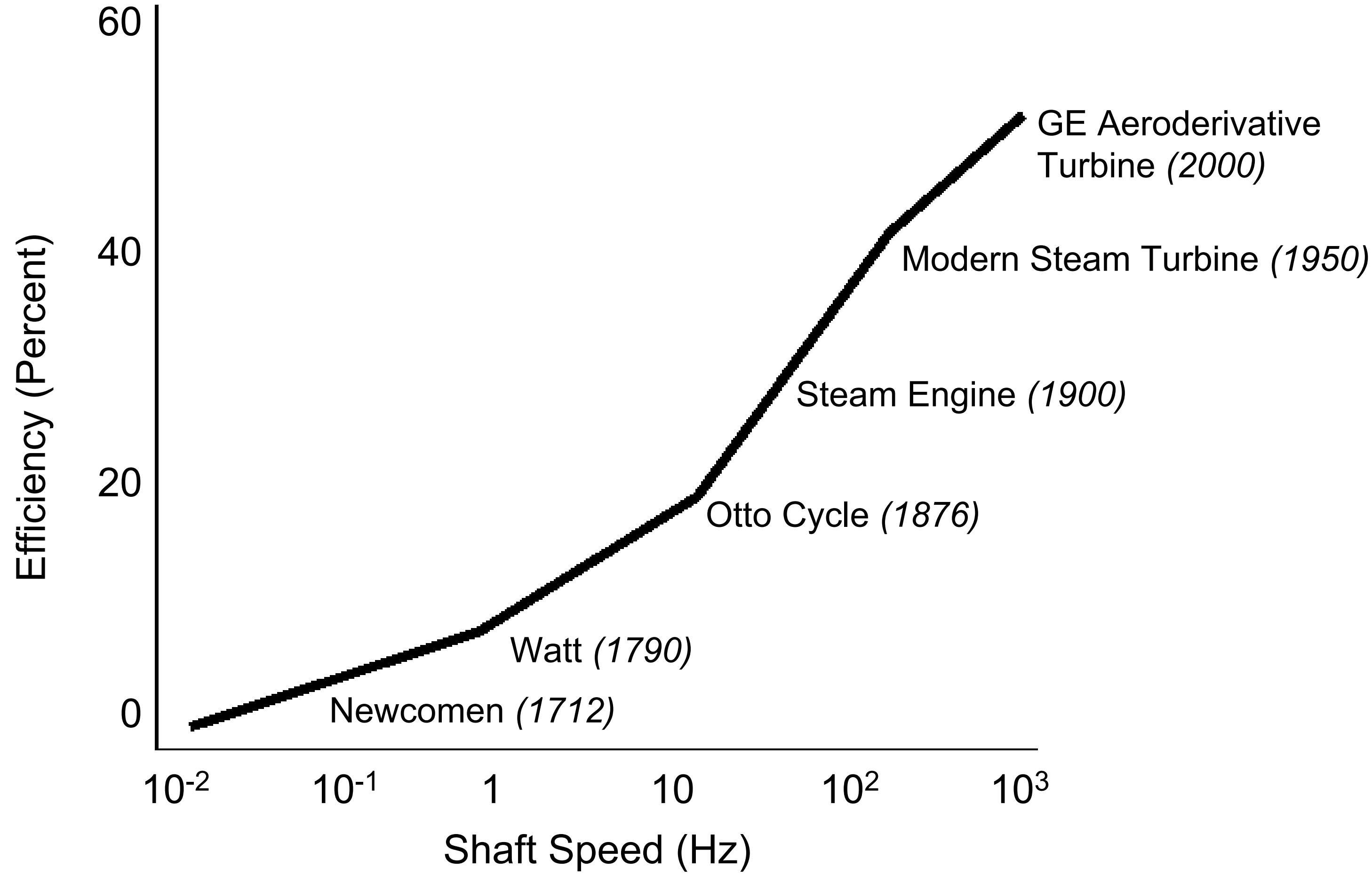
Figure 7.2a Electric and Non-Electric Energy Intensity



Source: EIA *Annual Energy Review* 2003.

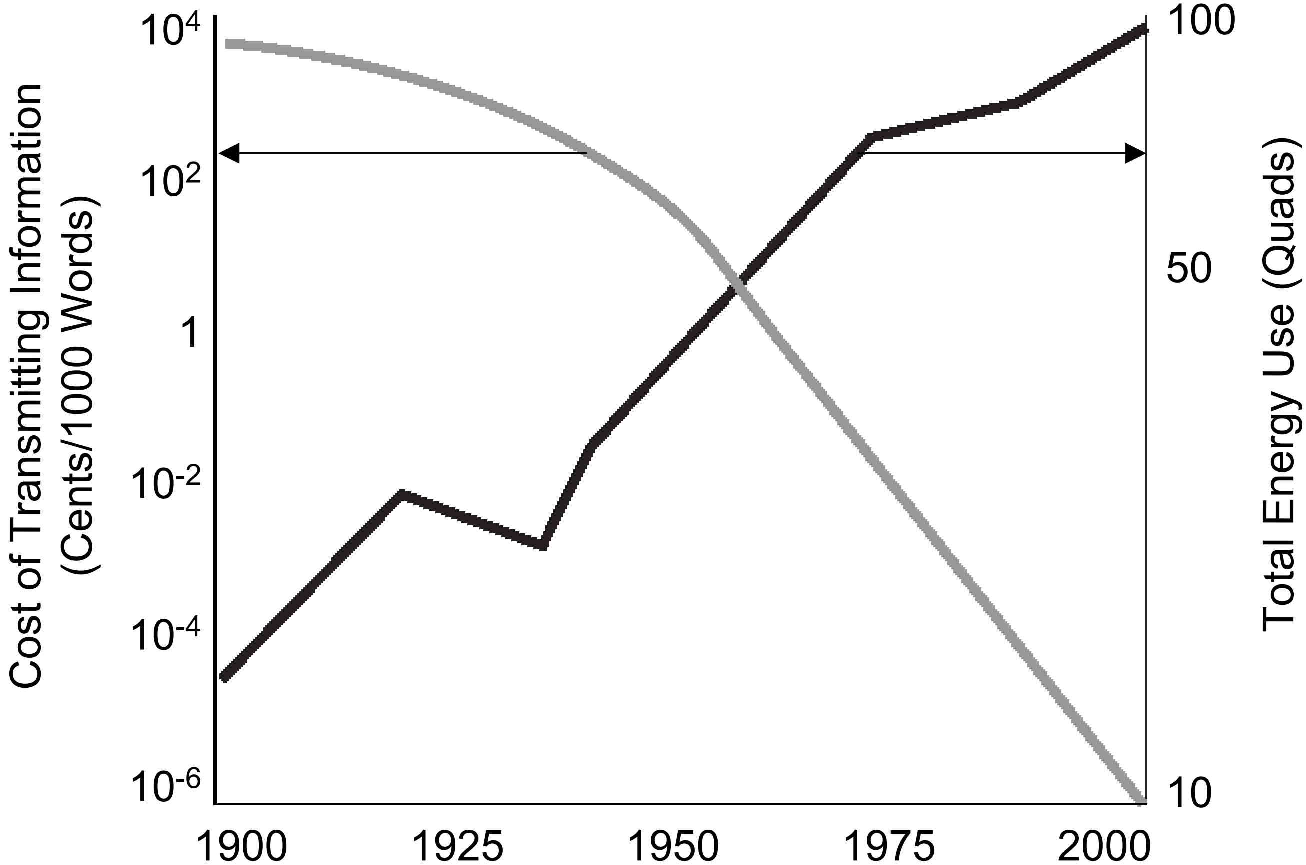
"Energy intensity"—the energy consumed per dollar of economic output—is declining. But it has been for the last 20,000 years. The GDP of our hunter-gatherer ancestors was nothing but energy, in the form of food calories. Wealthier economies add less energy-intensive goods to the mix, so energy consumption per unit of GDP falls. But adding a lot of energy-lite consumption is like adding artificial sweetener to a diet—it doesn't, in itself, lower total calories.

Figure 7.3 Combustion Engine Efficiency and Speed



More efficient devices are usually run faster--gas turbines are exceptionally efficient, but only when their blade tips move at near sonic speeds. But faster devices get used more, to deliver more miles, generate more electricity, weave more fabric, or reap more wheat.

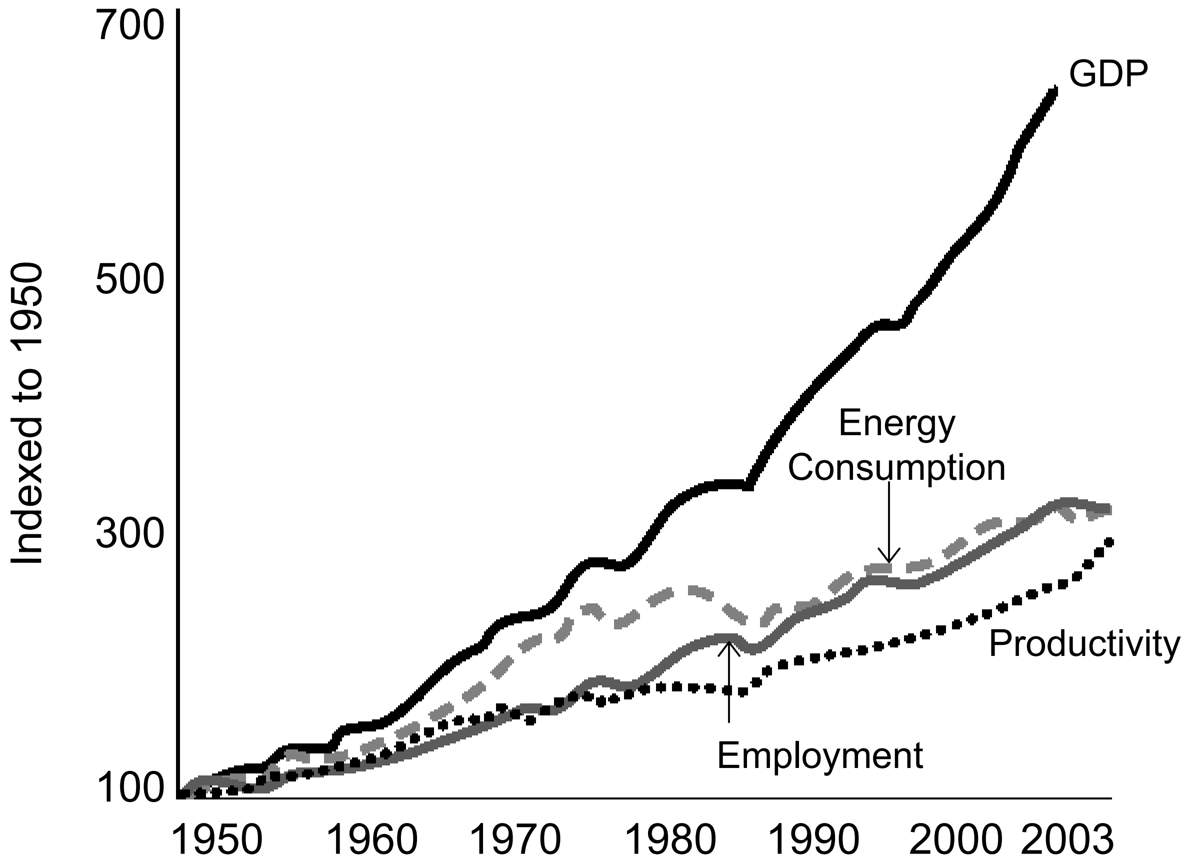
Figure 7.4 Cost of Transmitting Information versus Total U.S. Energy Demand



Source: EIA, *Annual Energy Review 2003*; U.S. Census Bureau, *Historical Statistics of the United States Colonial Times to 1970*; Ithiel de Sola Pool, *Technologies of Freedom* (Bellknap Press, 1983).

Historical trends do not support the suggestion that improvements in information technology will reduce demand for energy. The cost of conveying information has been dropping rapidly since the days of Bell and Marconi. But energy consumption has risen relentlessly.

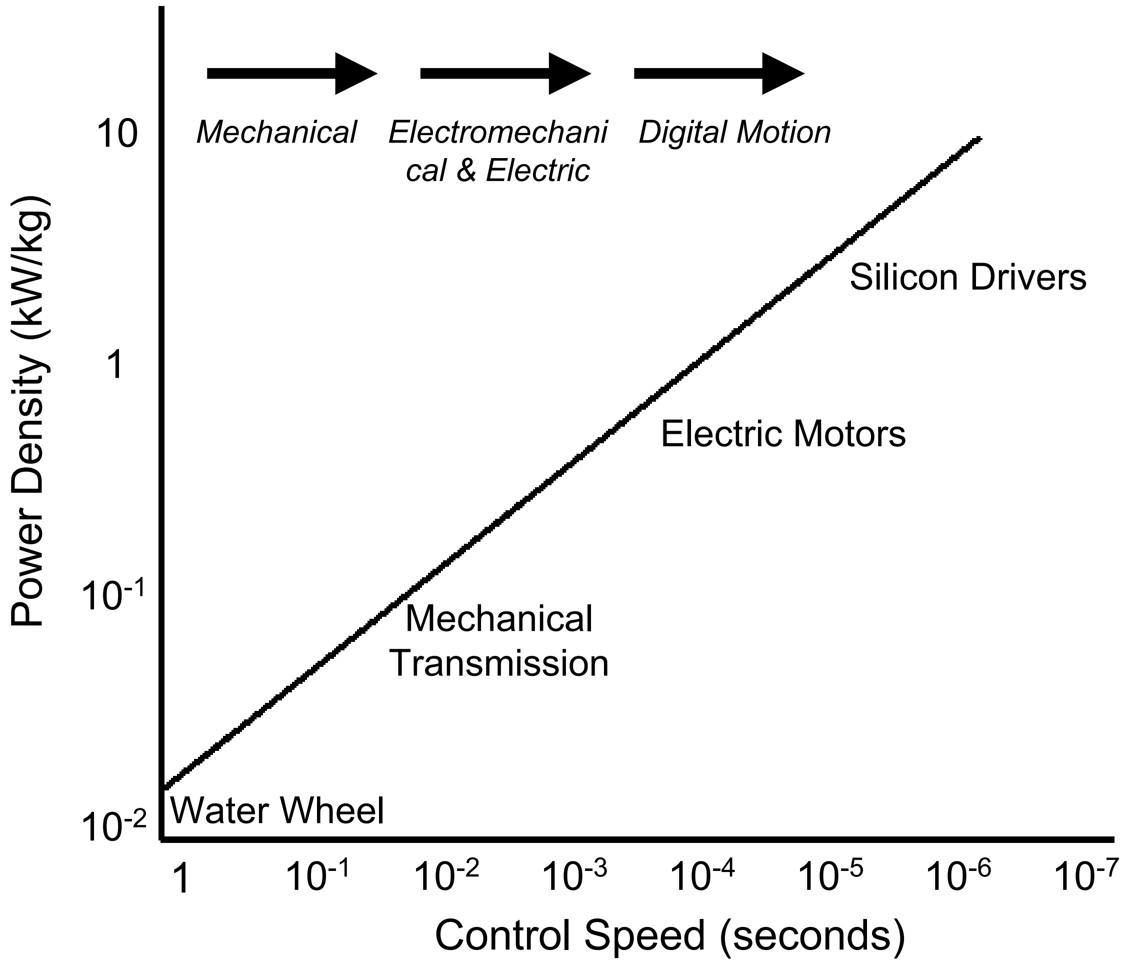
Figure 8.1 Productivity, Energy, and the Economy in the United States



Source: EIA, *Annual Energy Review 2003*; Department of Commerce; Department of Labor, Bureau of Labor Statistics.

Power is one of three fundamental inputs that determine the productivity of labor in every sector of the economy; the other two are material and information. Capital constructs intelligent configurations of concrete, steel, and silicon; power makes these structures run. Power moves the worker to the increasingly distant workplace, drives the intelligent machines that surround him there, and processes the materials and information that he works with.

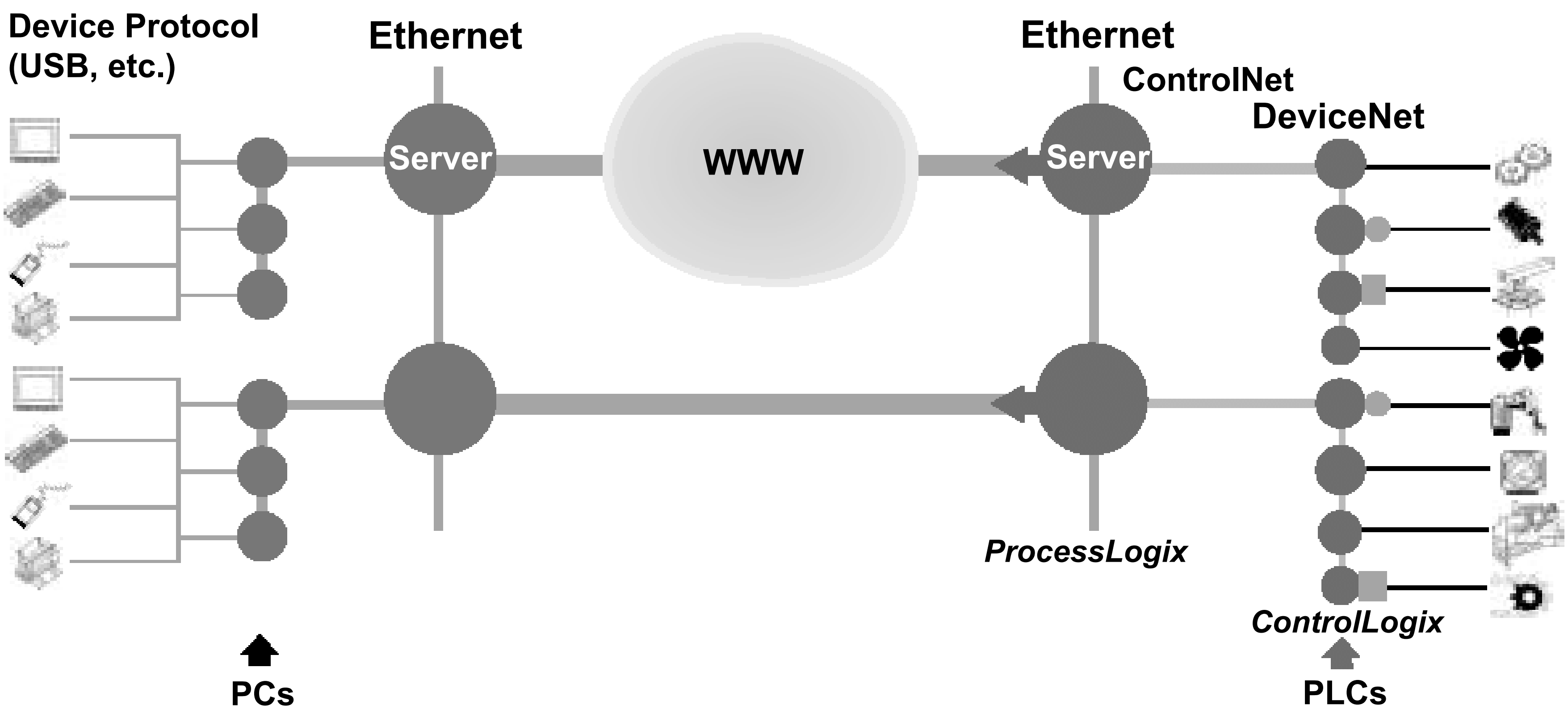
Figure 8.1a Power Conversion and Control



Source: Peter Huber and Mark Mills, "Digital Movers," *Digital Power Report*, February 2002.

From the new classes of power semiconductors, manufacturers can now build ultra-compact and efficient power supplies, capable of shaping voltage and current in any manner desired. Because the functional parts are so small, these devices are extremely fast and efficient. We can now, for the first time ever, speak of *digital power*—power under the control of systems so fast and precise that the power becomes as tractable and ordered as digital logic.

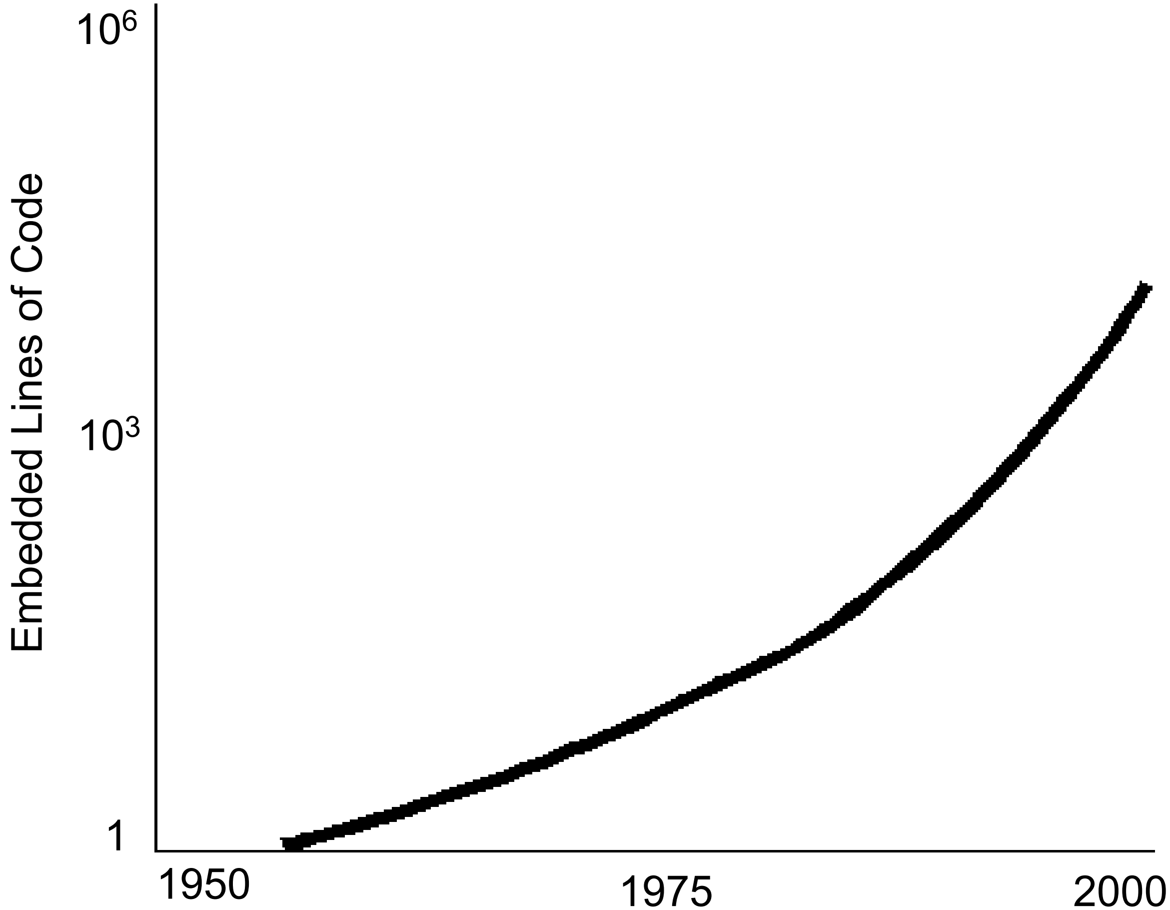
Figure 8.1b The Digital Factory



Source: Peter Huber and Mark Mills, "Networking the Digital Factory," *Digital Power Report,* September 2001.

The newest industrial robots—which are, by and large, complex configurations of electric servomotors—come packed with sensors. And software interfaces now allow their instant reconfiguration to perform new tasks—a dramatic advance over previous systems that required hours of manual rewiring. Digital power, digital logic, programmability, and open standards transform highly specialized, product-specific manufacturing machines into general-purpose, atom-crunching material processors.

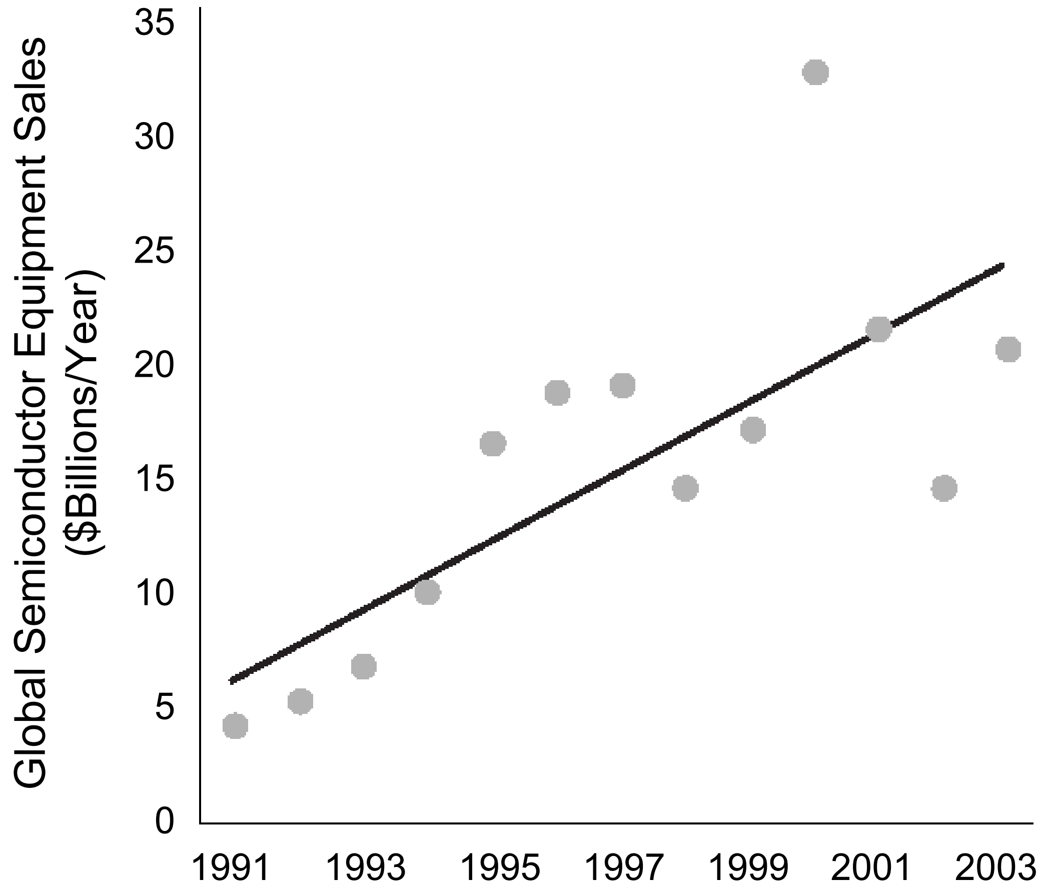
Figure 8.1c Software in Electric Power Supplies



Source: Peter Huber and Mark Mills, "Power Supplies," *Digital Power Report*, August 2002.

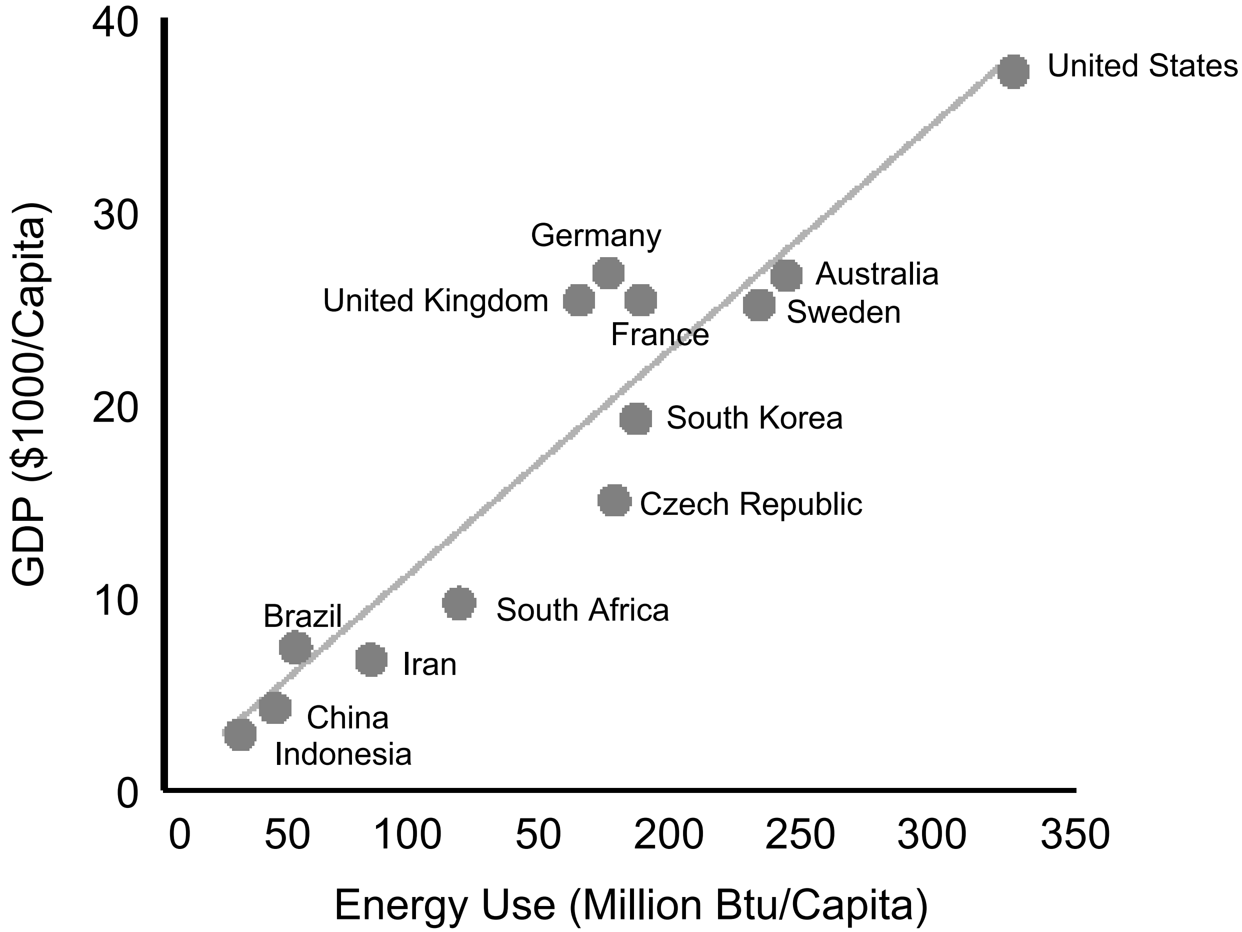
Embedded lines of software code in the ubiquitous ac-dc and dc-dc electric power supplies provide a simple if imperfect measure of the rise of digital power technologies. Until about 1990, few power supplies contained any code at all. Today, they routinely incorporate 10,000-plus lines into the software and firmware. High-end units contain closer to 100,000 lines. And the total is rising geometrically, year by year.

Figure 8.1d Machine Tools of the Digital Age



The first power revolution—James Watt's—transformed industry, and then heavy-duty transportation. The second—Otto's—brought high-speed transportation to the masses. The next great revolution in powered machines is defined by the rise of digital power, dexterous robots, and networked factories. The new machines are nimble, thoughtful, responsive, and intuitively dexterous. They don't move bits, they move stuff—out of the mine and the farm, through the factory, along the assembly line, down the highway, over the water and through the air. The machines are nimble, thoughtful, responsive, and intuitively dexterous.

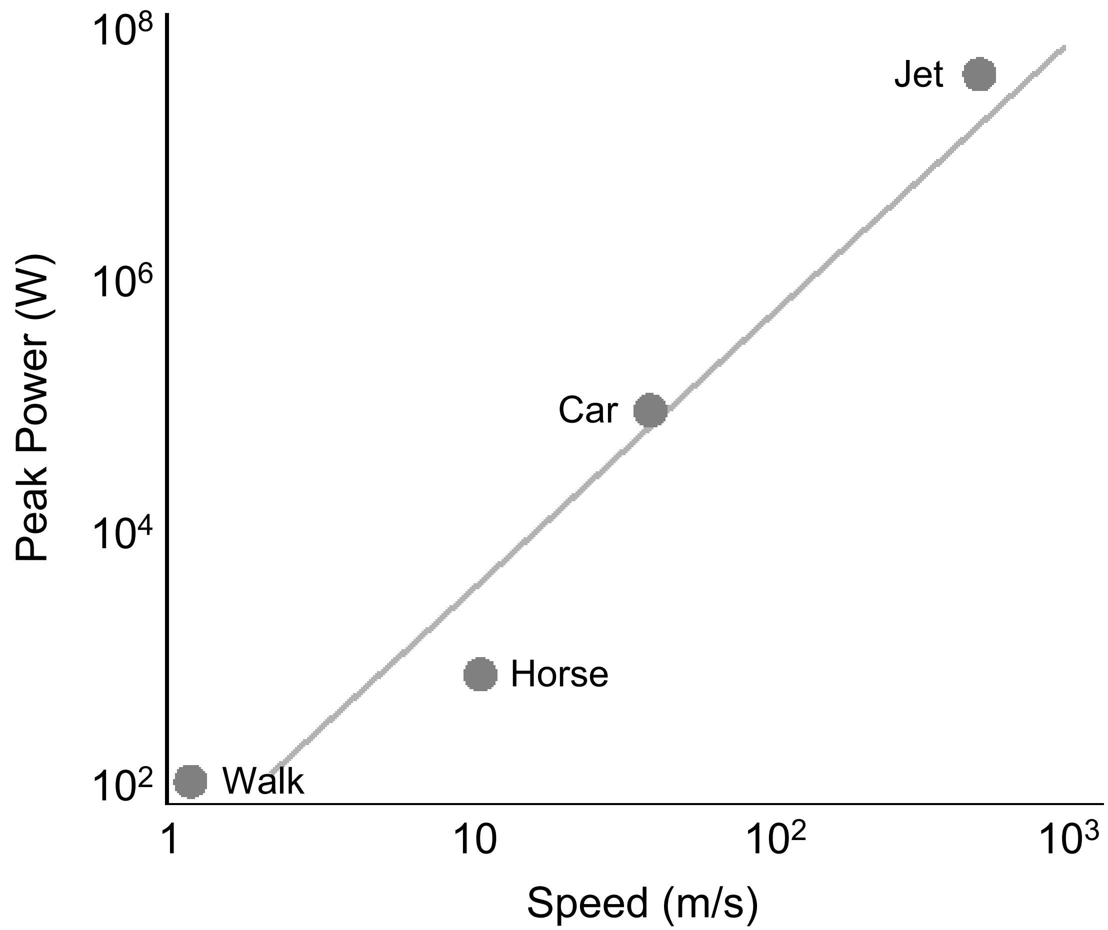
Figure 8.2 Energy and Prosperity



Source: CIA, *World Factbook*; BP p.l.c.

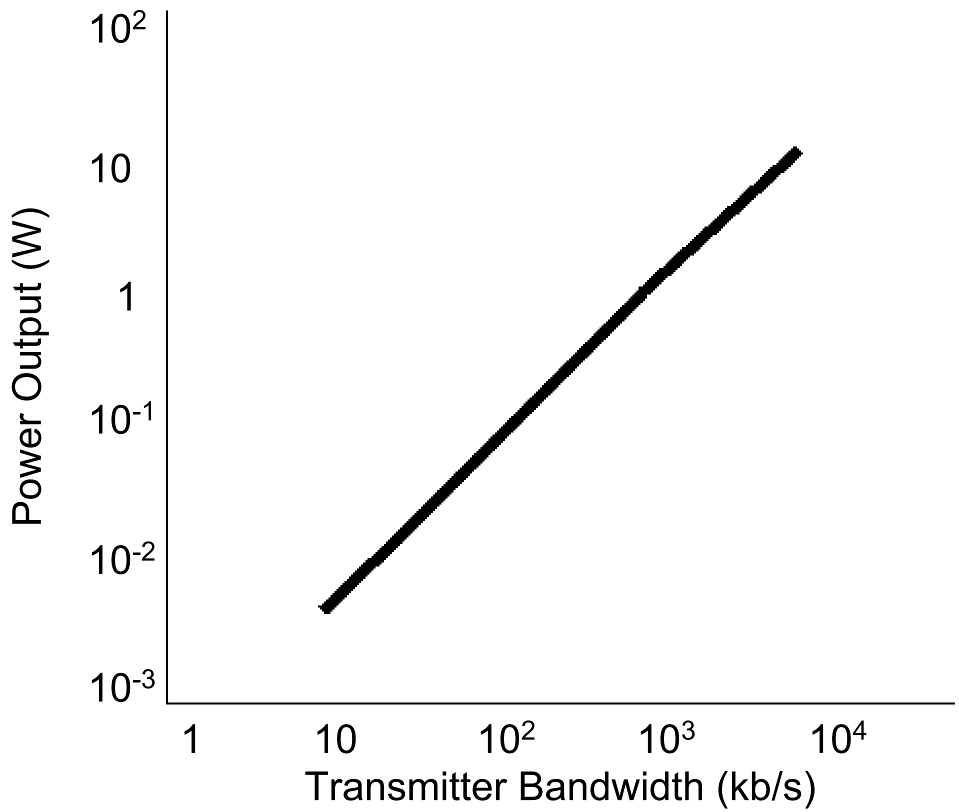
The more energy a nation uses, the richer it gets. Powered machines boost productivity, which boosts wealth.

Figure 9.1 Powering Speed



It takes increasingly pure high-density power to speed up the car, factory, computer, or connection to the Web. We consume more energy to save more time.

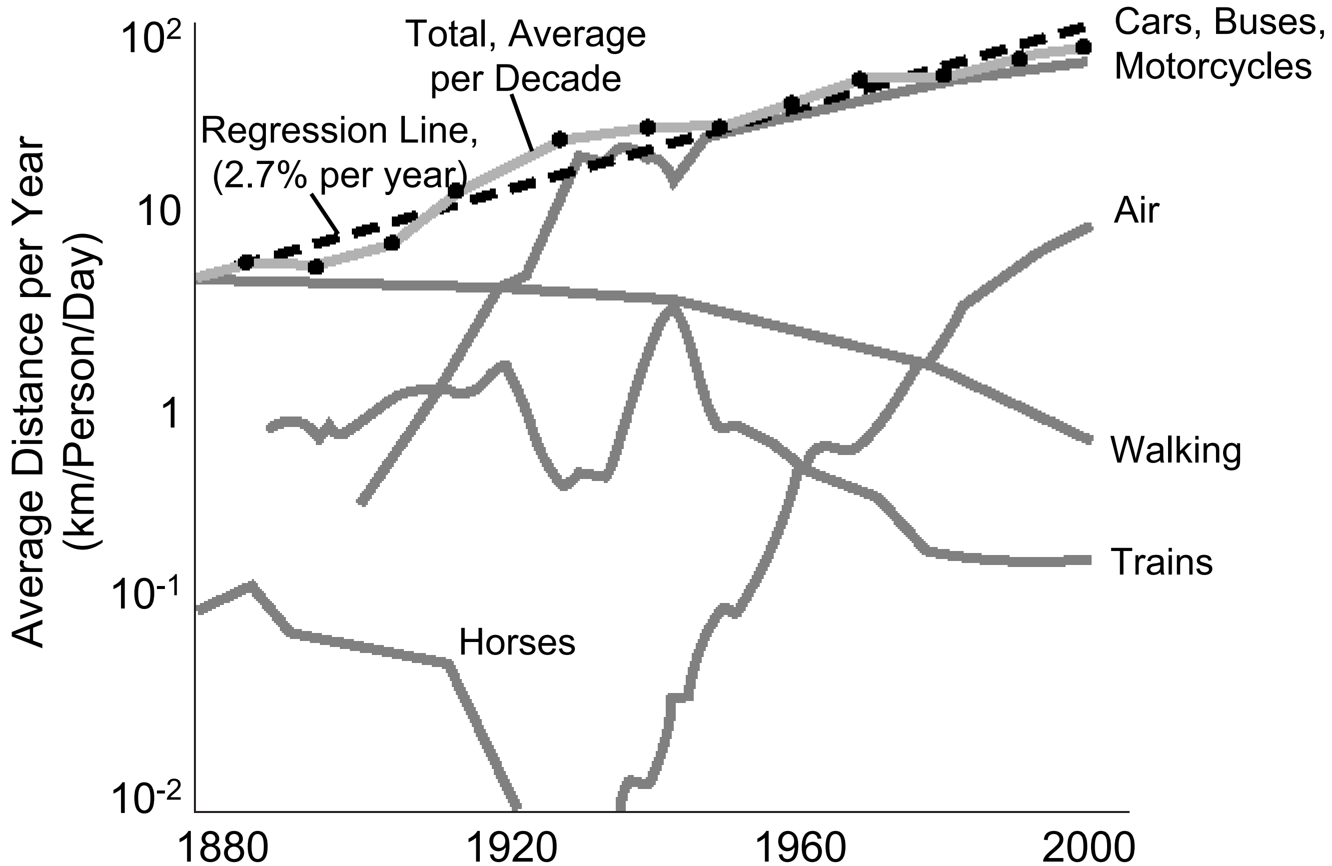
Figure 9.1a Powering Wireless Bandwidth



Source: National Research Council, *Energy-Efficient Technologies for the Dismounted Soldier* (National Academy Press, 1997).

In telecommunications, the maximum capacity—i.e. bandwidth—of a communication channel is directly related to the average signal power: the higher the ratio of the signal power to the background noise, the faster it is possible to transmit data through the channel. All of the private, commercial, and military radio-frequency transmissions together consume about one percent of all our electric power; we thus burn about 10 million tons of coal per year (and the energy equivalent in gas and uranium) to propel weightless photons through space.

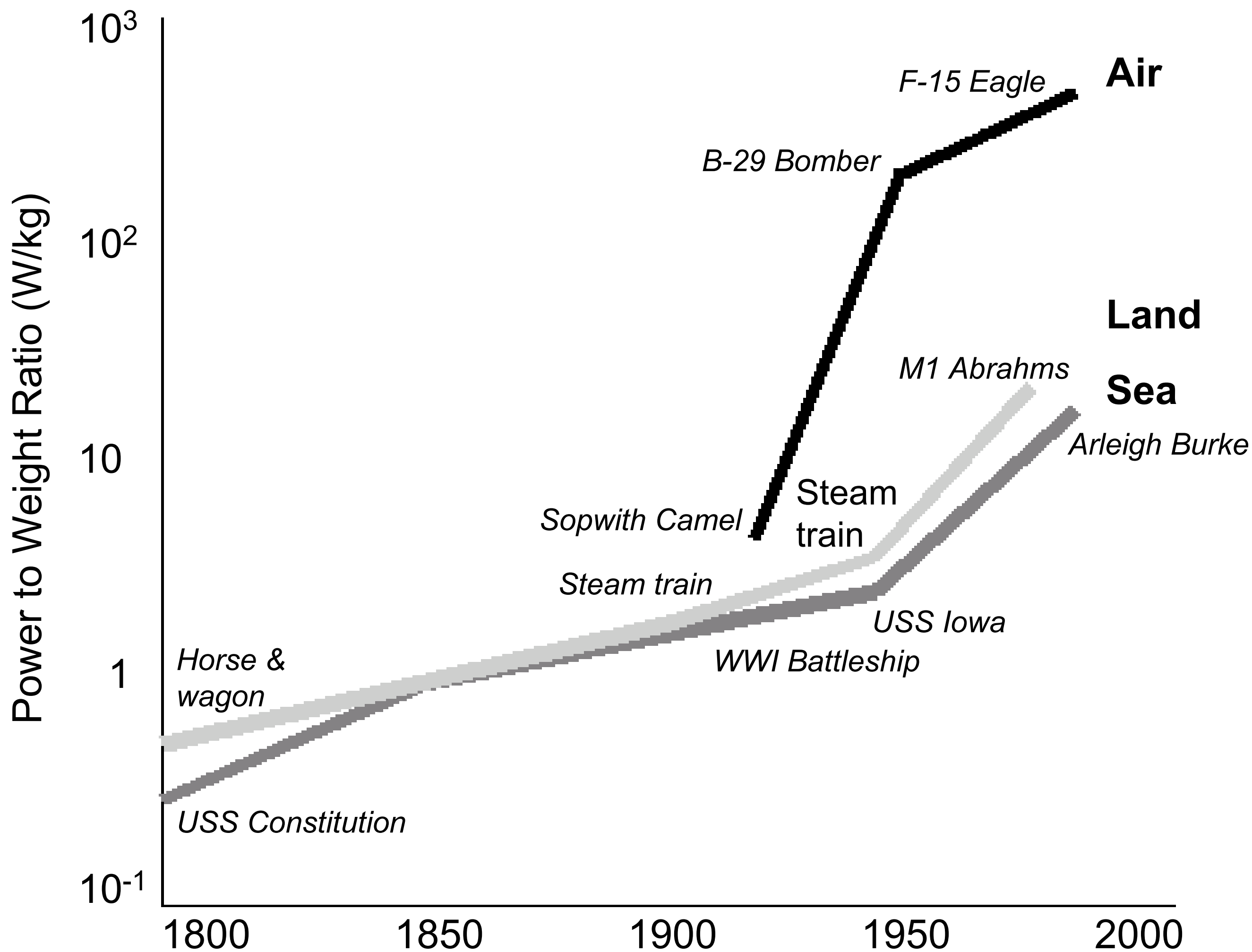
Figure 9.2 Travel



Source: Ausubel and Marchetti, "The Evolution of Transport," *The Industrial Physicist*, April 2001.

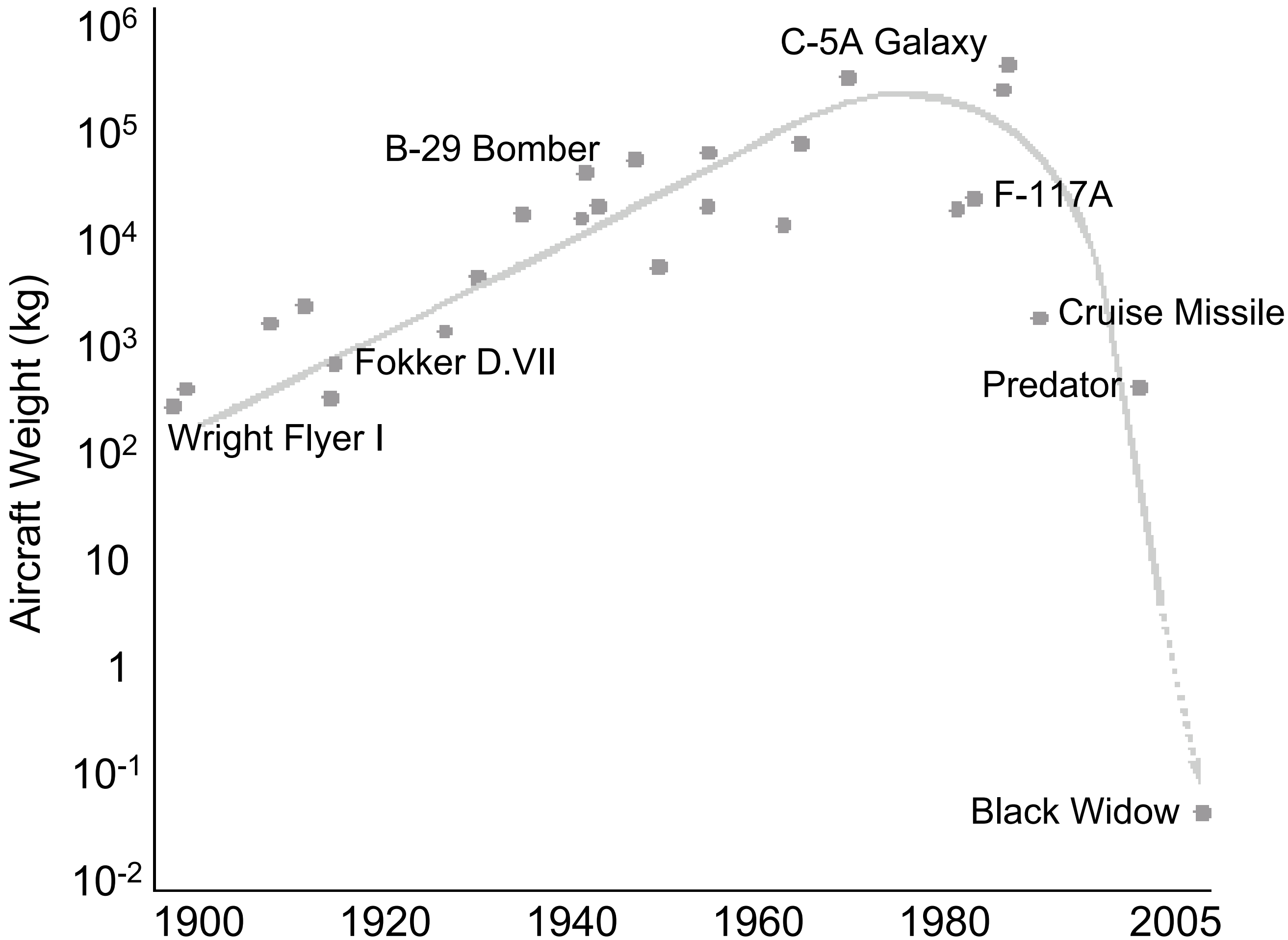
We consume more energy to extend our range. Most of the miles we travel by car today would never have been traveled on horseback; most of the miles we fly would never have been traveled in trains.

Figure 9.2a Platforms for Projecting Military Power



The projection of power is the essence of war. Lighter, faster platforms that project more power prevail.

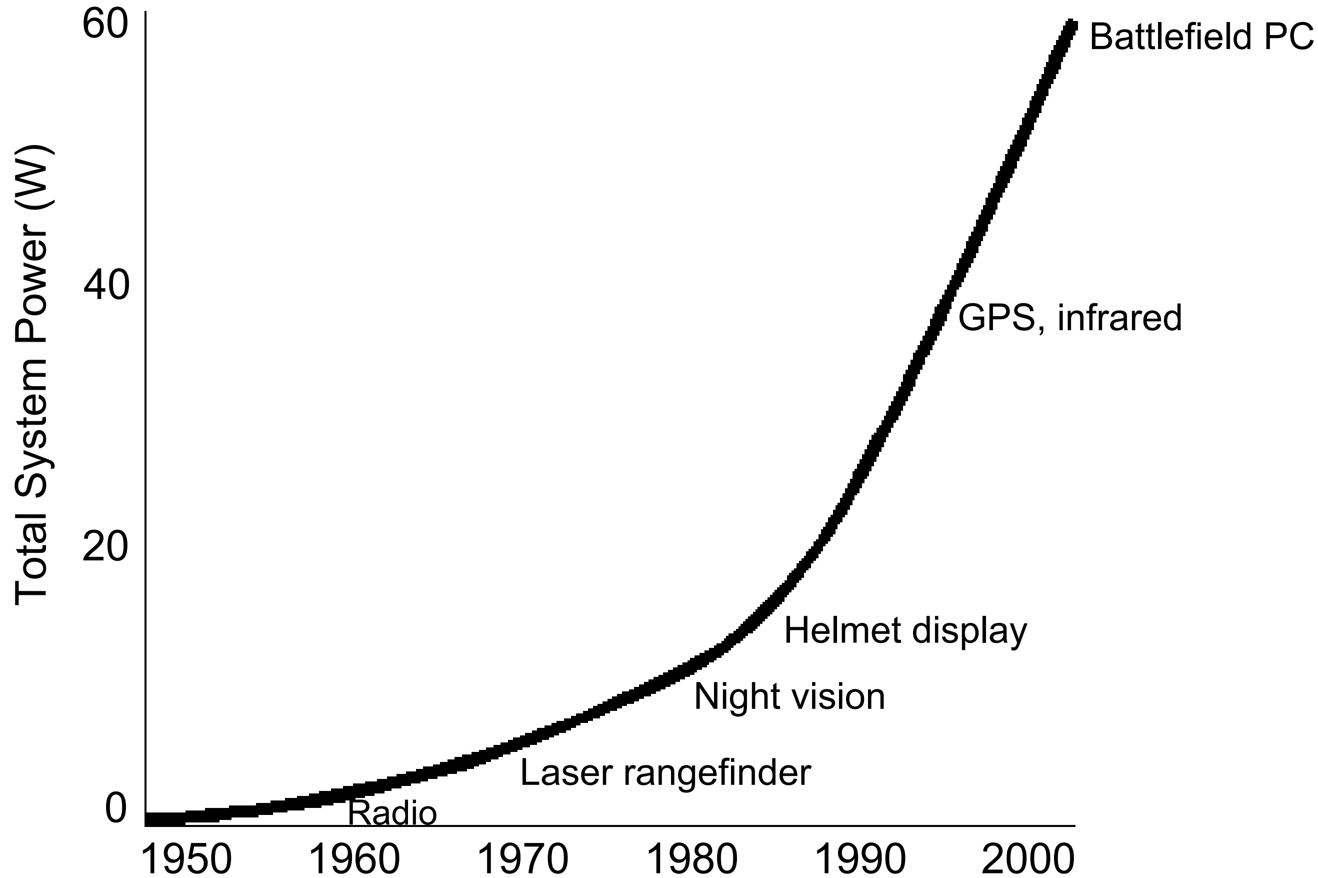
Figure 9.2b Projecting Military Power: Leading Edge Aviation



Source: First to Fly.com, USAF Museum, Boeing, Aerovironment.

The pilot of the Predator—a Pterodactyl-sized digitally-powered airship—sits hundreds of miles away from the battlefield, steering a comparative tiny platform that bears digital eyes and digital artillery. Fully functional eagle-sized, bat-sized, then butterfly-sized, autonomous vehicles have already been built. The electric-powered Black Widow typifies the edge of a new family of tiny flyers.

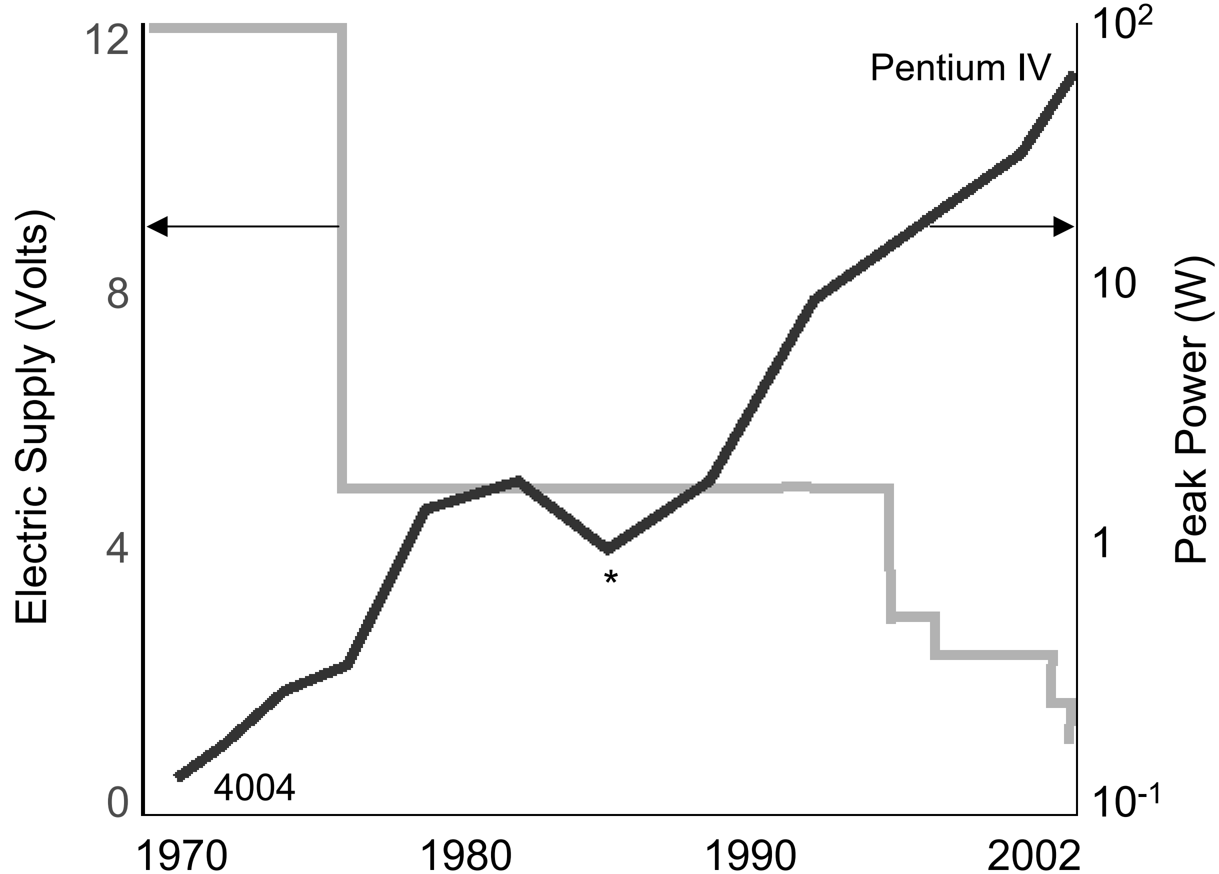
Figure 9.2c Powering the Land Warrior



Source: National Research Council, *Energy-Efficient Technologies for the Dismounted Soldier* (National Academy Press, 1997).

Even the foot soldier now depends on an ever-increasing supply of portable power.

Figure 9.3 Core Microprocessor Trends

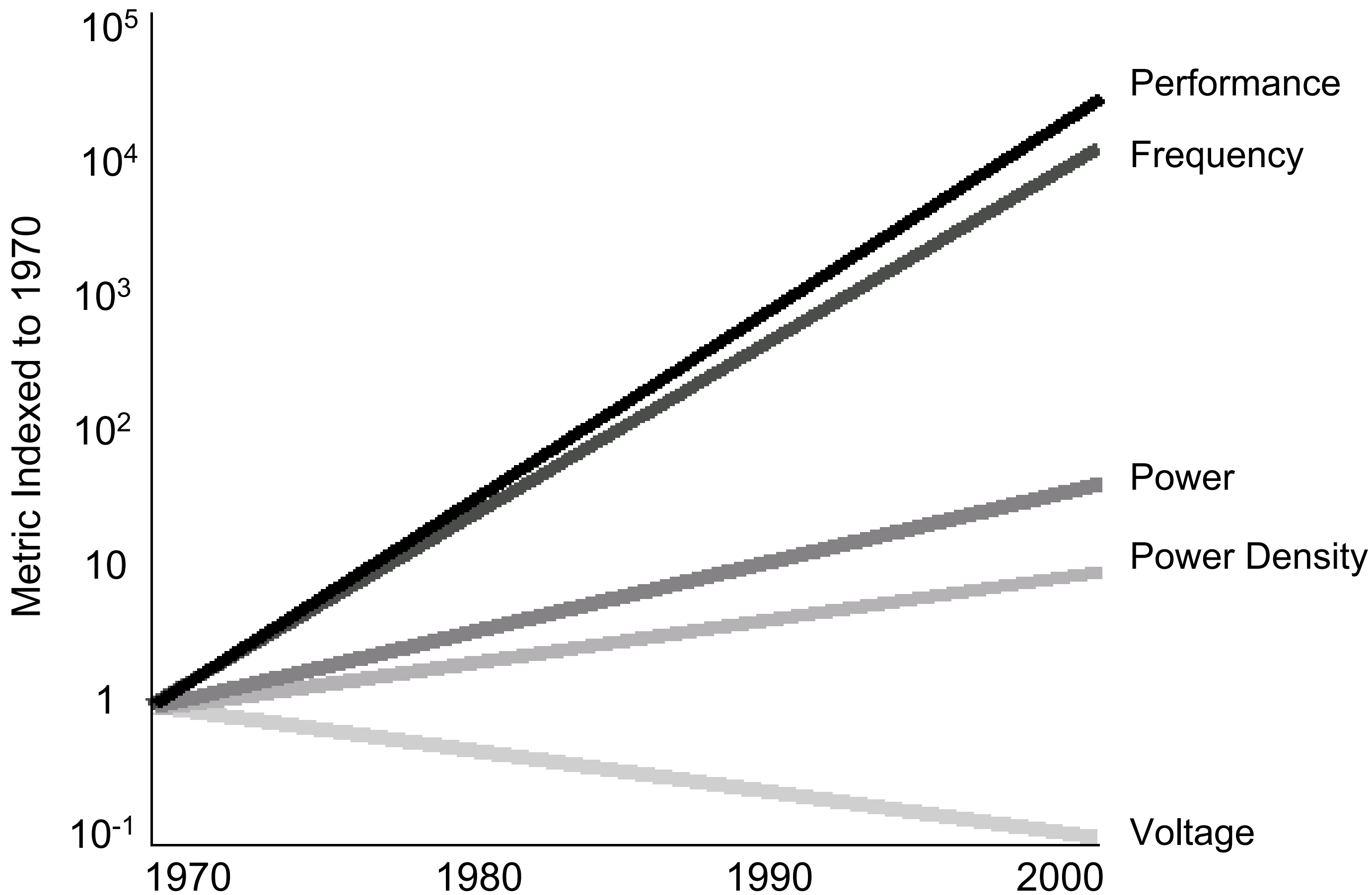


* Introduction of the CMOS transistor architecture

Source: Intel.

As gates on a chip get smaller, operating voltages must be lowered or the insulating layers break down. But as gates get smaller, more get packed on to the chip, power consumption for the chip as a whole goes up, and higher voltages are required to pump in the power.

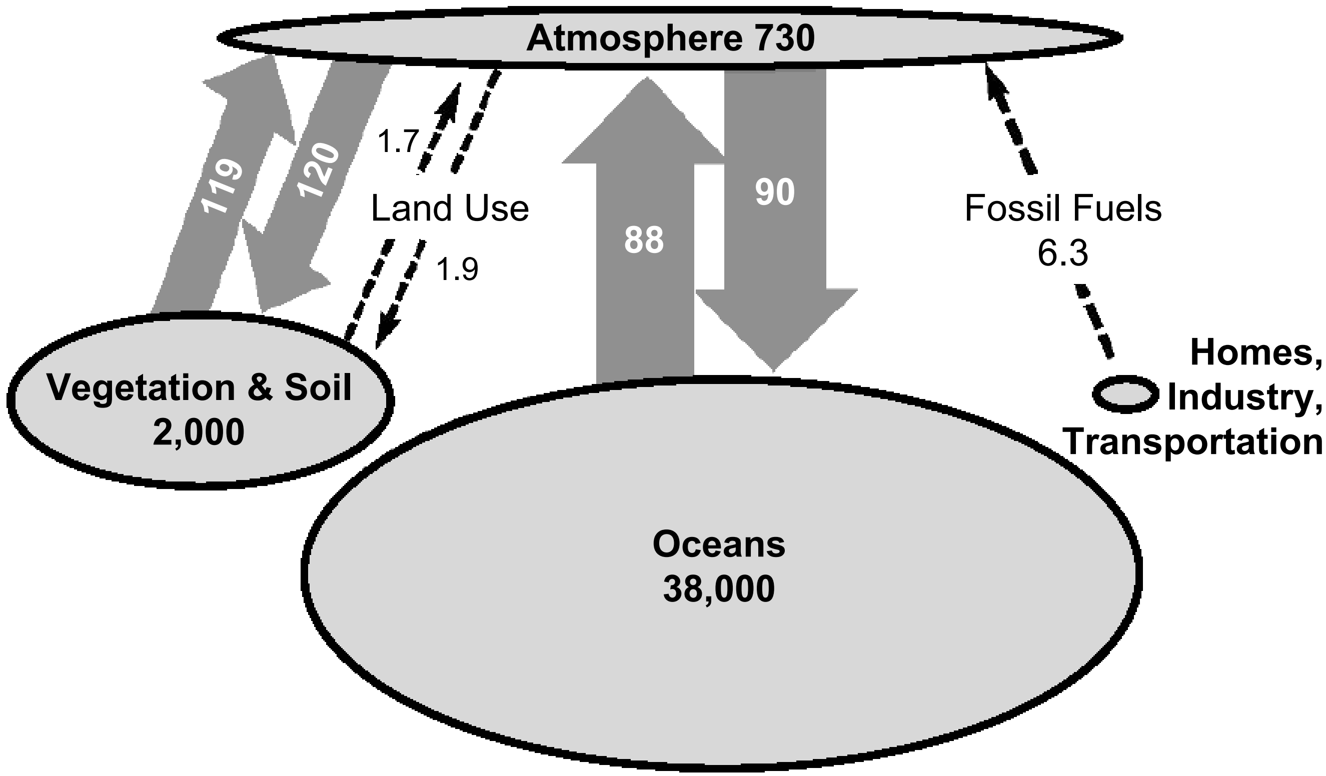
Figure 9.3a Core CPU Trends



More gates and higher speeds mean more power consumption for the device as a whole. Thus, tens to hundreds of watts, fluctuating at gigahertz speeds, have to be pumped into today's microprocessors—and the power requirements keep rising, not falling. The only way to get that much power into that small a space is to use *higher* voltages. But the only way for such a small a gate to survive is to run at *lower* voltages. Thus, the discrete logic element heads south toward zero voltage and power, while the overall power consumption of the intelligent chip heads north toward infinite voltage and power.

Figure 10.1 Global Carbon Flux

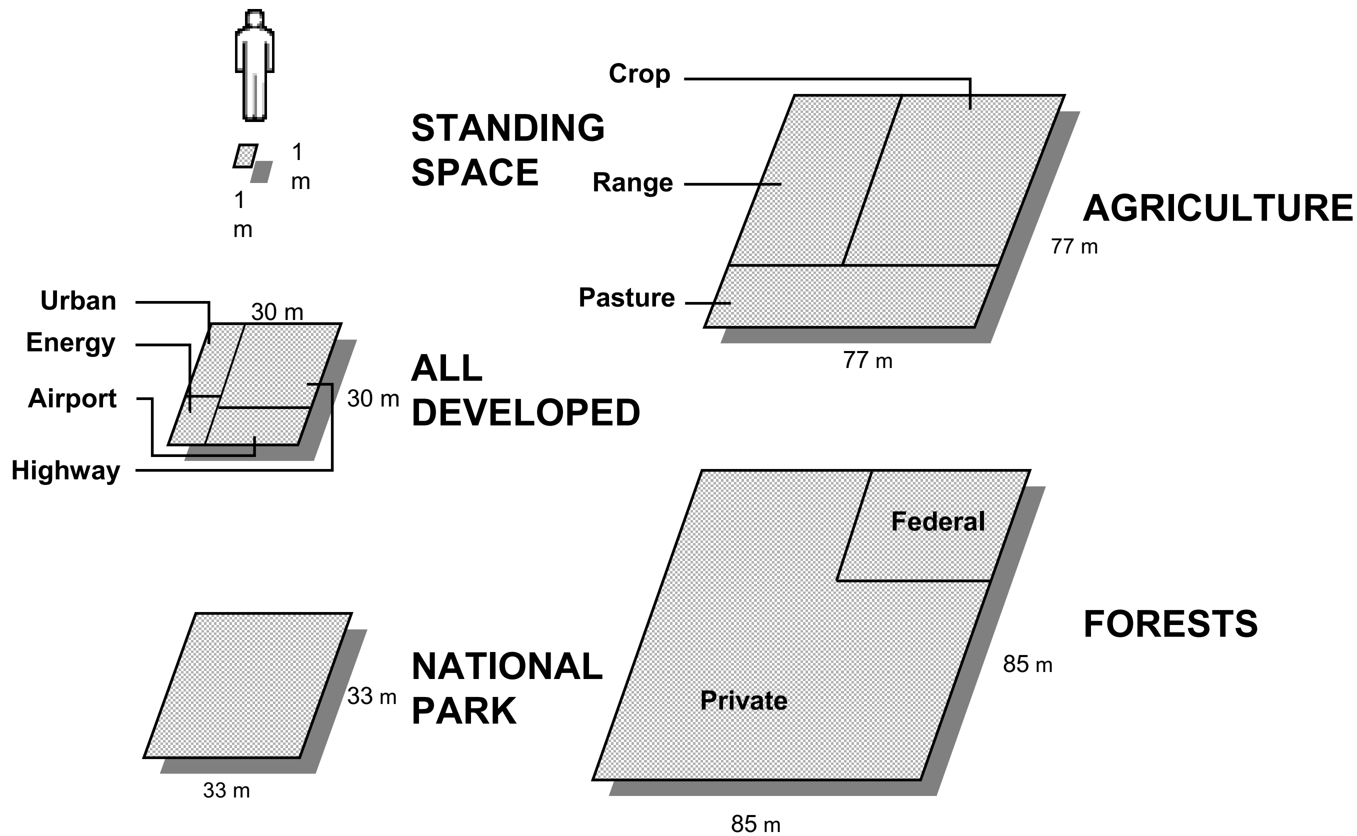
(Billion Metric Tons Carbon)



Source: EIA, International Energy Review 2002 (data are from 1999).

Fossil-fuel combustion and deforestation release carbon into the atmosphere. Human agriculture and forest regeneration remove it. Much larger carbon fluxes are propelled by plant and animal life in the rest of the biosphere, and by the weather over the oceans.

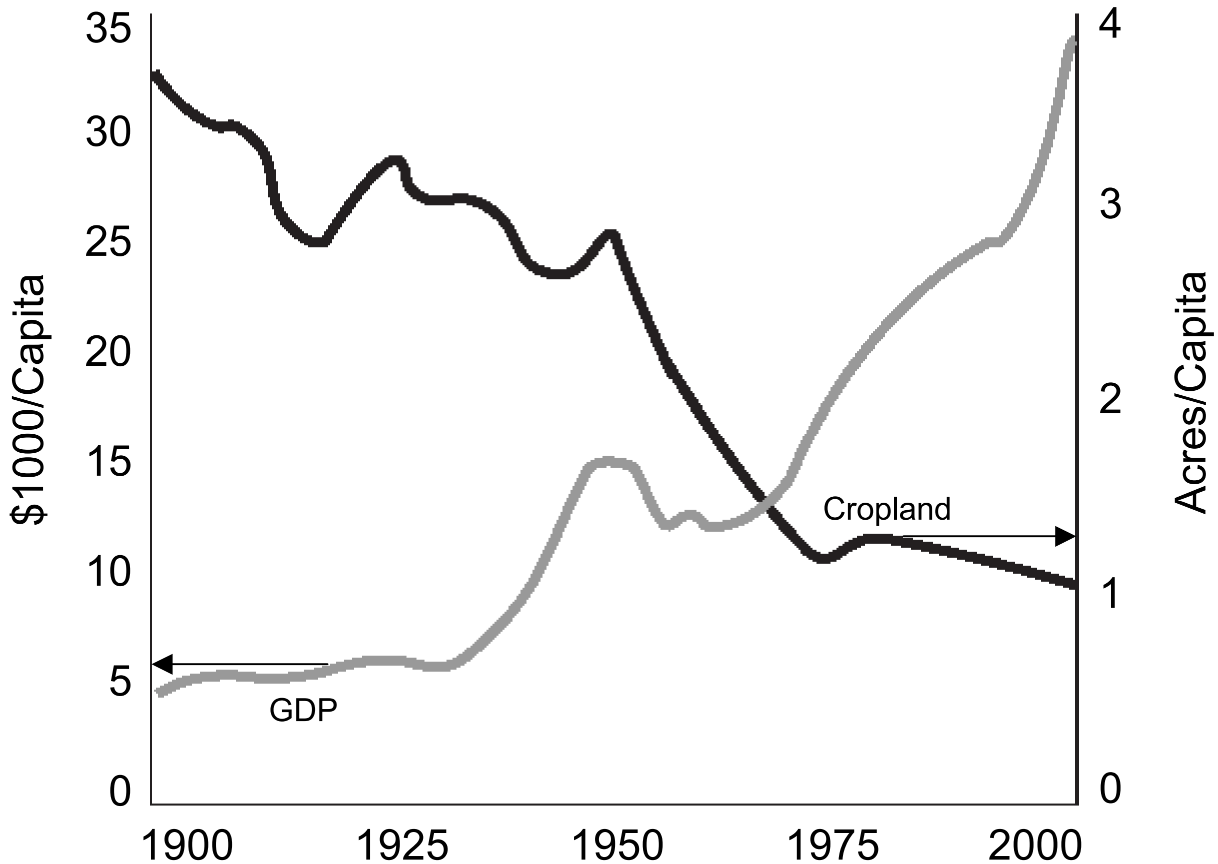
Figure 10.2 Total U.S. Land Use per Capita



Source: Peter Huber and Mark Mills, "From Carbohydrates to Hydrocarbons," *Grenzen ökonomischen Denkens: Auf den Spuren einer dominanten Logik*, ed. Hans A. Wüthrich et al. (Gabler Press, 2001), p. 151. Data for contiguous U.S.

A century ago, a pioneering American family required 40 acres and a mule. Today, allocated per capita, the average American uses far less—about 2 acres in total for dwelling, roads, farm, range, and energy supplies.

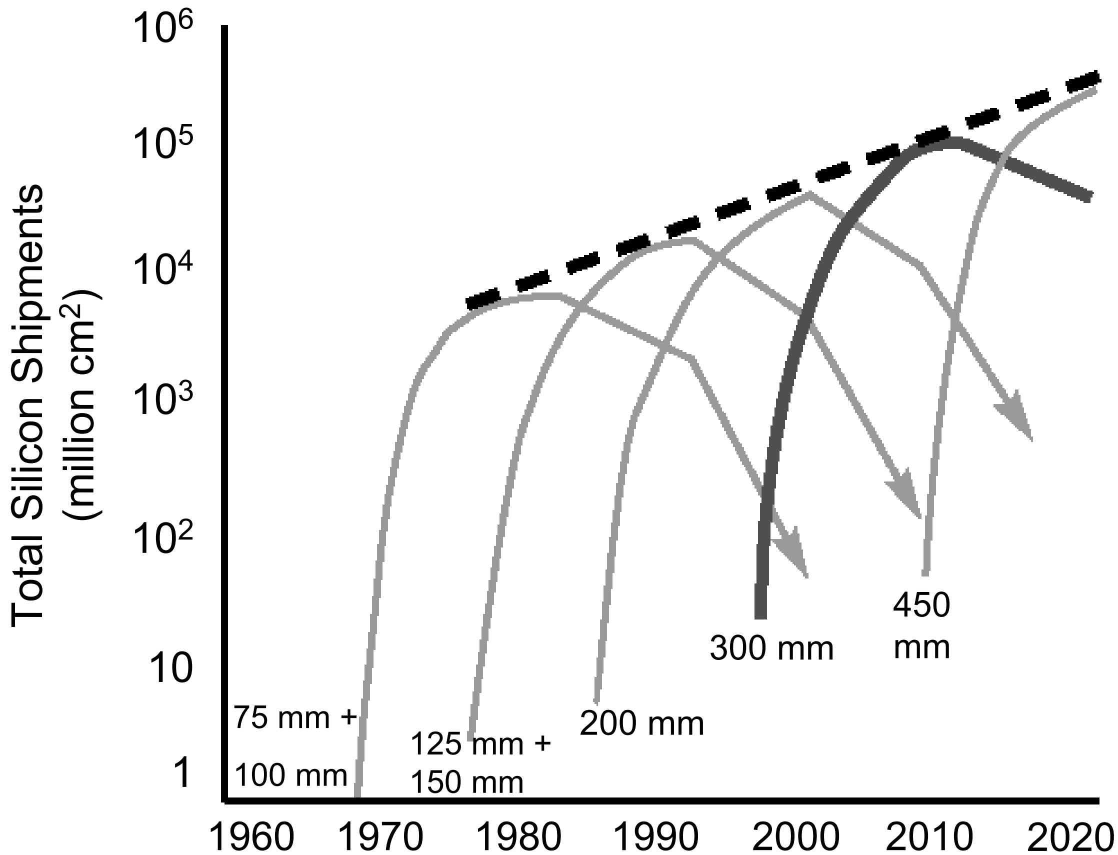
Figure 10.3 U.S. Wealth and Cropland per Capita
Data are for cropland (excluding cattle rangeland)



Source: U.S. Census Bureau, *Historical Statistics of the United States Colonial Times to 1970.*

Per acre of land used, agricultural productivity at least tripled in the twentieth century, in large part because so much less land is now required to power the plow. A horse required 2 acres of pasture to meet its energy needs; the oil wells that fuel a tractor occupy much less space.

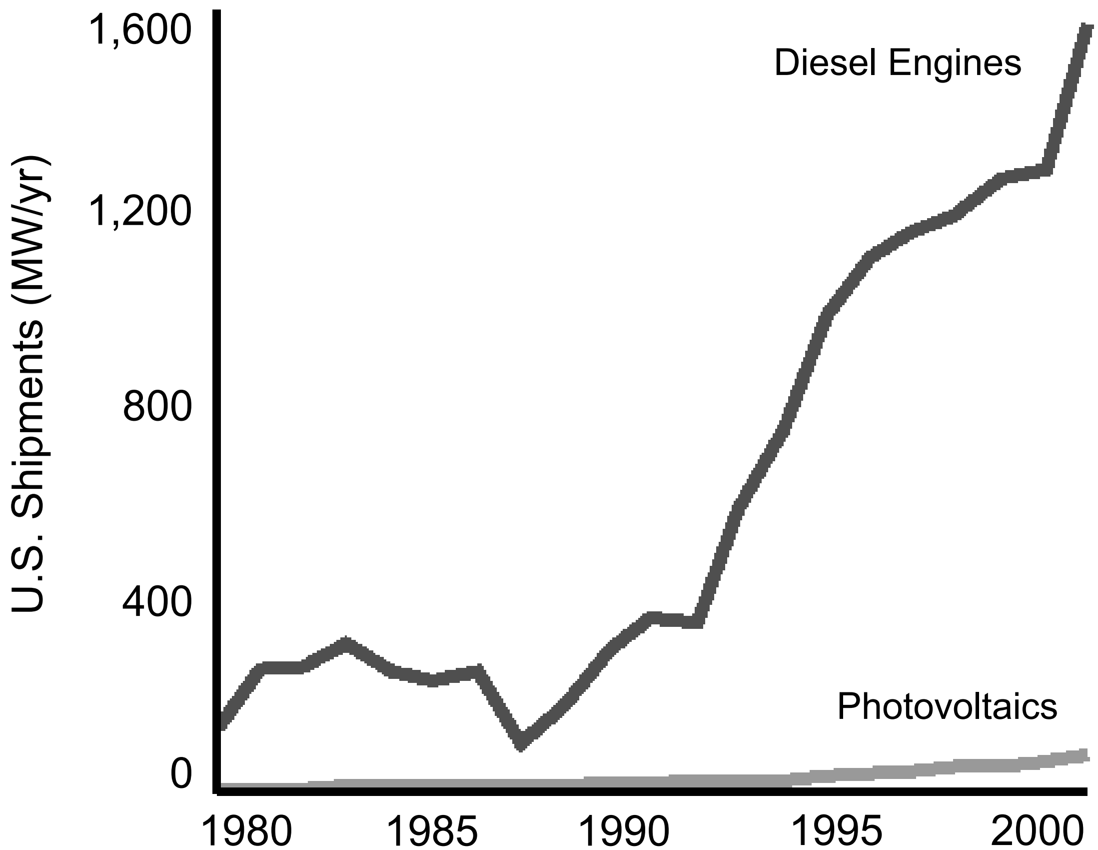
Figure 10.3a Silicon Demand for Logic: Wafer Shipments



Source: R. Doering and Y. Nishi, "Limits of Integrated Circuit Manufacturing," Proceedings of the IEEE (March 2001); Peter Huber and Mark Mills, "Applying Materials in the Perfect Storm," *Digital Power Report*, March 2003.

A Pentium 4 microprocessor consumes about 20 watts per square *centimeter*—ten thousand times more, in power density terms, than a PV solar cell can generate. Semiconductor-grade silicon for digital circuits is currently being shipped ten times faster than silicon destined to make PV cells.

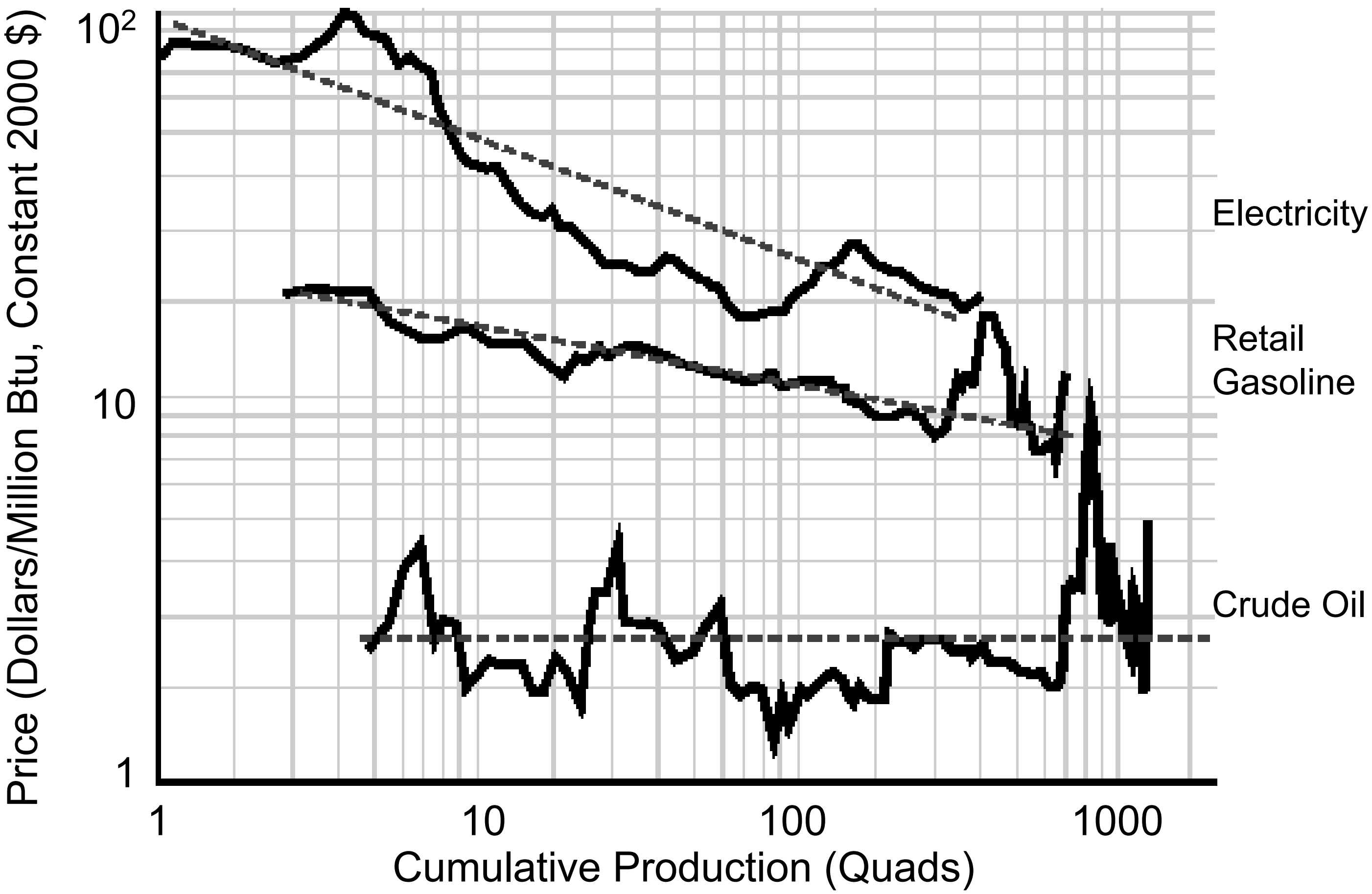
Figure 10.3b Distributed Power: Silicon and Diesel



Source: Peter Huber and Mark Mills, "Transmission and Distribution," *Digital Power Report*, October 2002.

Boron- or phosphorus-doped silicon wafers mounted in glass or plastic can currently capture about 30 watts per square meter on a round-the-clock average in the United States—making photovoltaics (PV) about forty times better than the typical leaf of a green plant. A small diesel-fueled electric generation can pump out nearly one million times the power in the same square meter. Diesel-electrics dominate the shipments of small distributed generators.

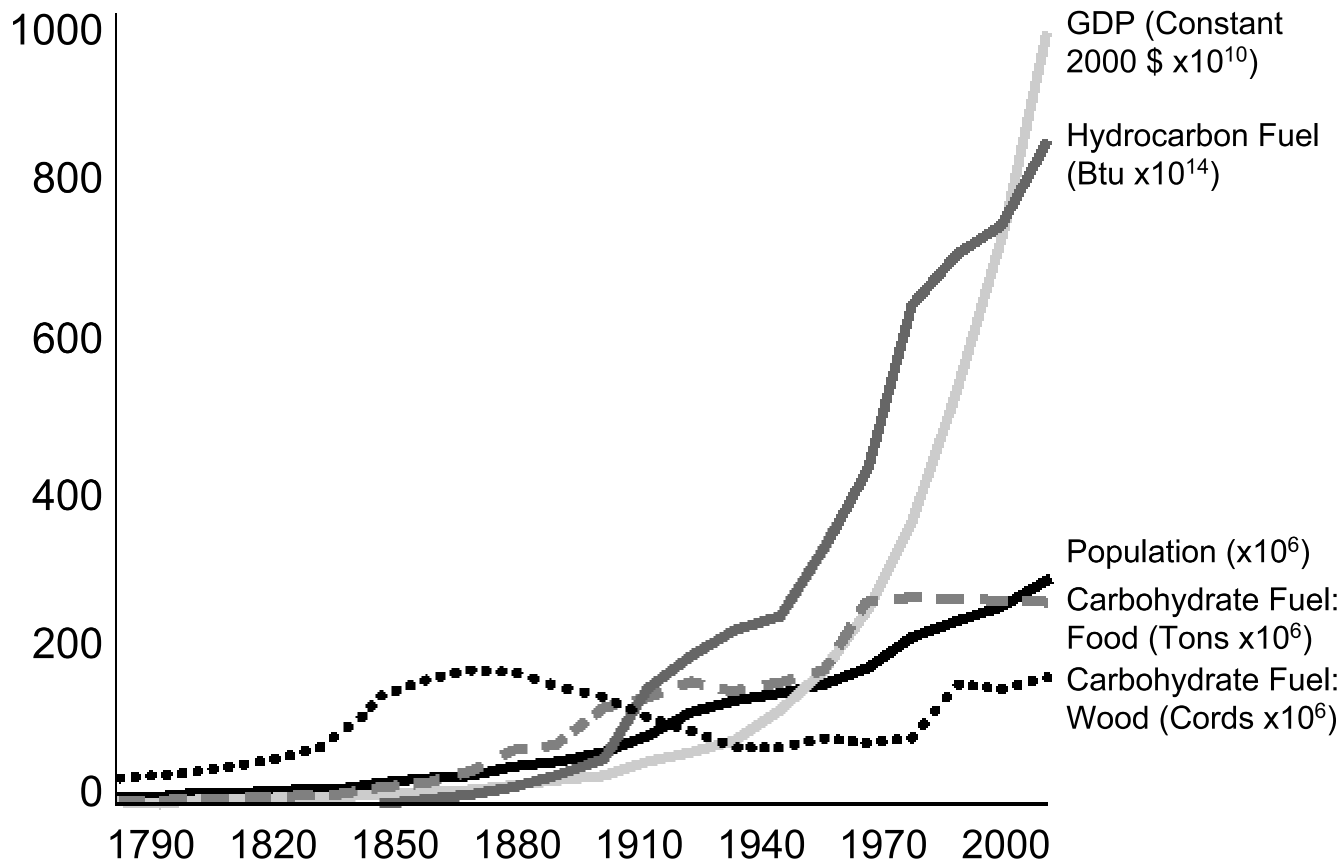
Figure 11.1 U.S. Energy Production and Cost



Source: EIA, *Annual Energy Review 2003*; American Petroleum Institute; John Fisher, *Energy Crises in Perspective* (Wiley, 1974).

Continuous improvement in the energy-consuming technologies that find and retrieve energy has kept energy prices stable—or falling—over the long term. 1 million Btu of electricity is a 60 W light bulb running for 6 months; 1 million Btu of gasoline is about 8.1 gallons, and 1 million Btu of crude oil is about 7.1 gallons.

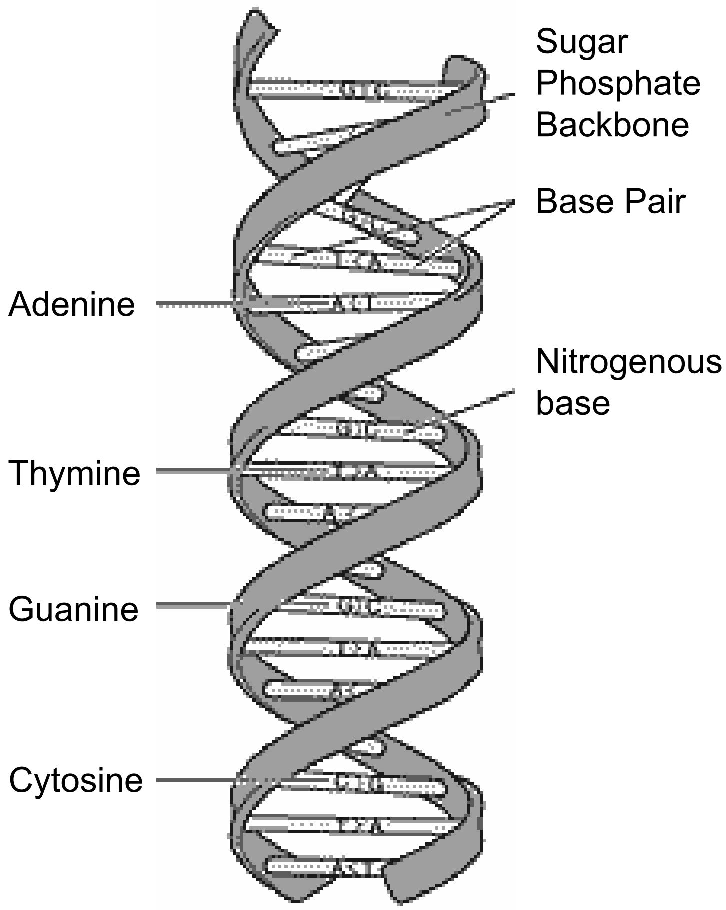
Figure 11.2 U.S. Agriculture, Population, and Energy



Source: EIA, *Annual Energy Review 2003*; U.S. Census Bureau, *Historical Statistics of the United States Colonial Times to 1970*; Bureau of Economic Analysis; Louis Johnston and Samuel H. Williamson, "The Annual Real and Nominal GDP for the United States, 1789 - Present," Economic History Services, April 2002.

James Watt's coal-fired steam engine was invented to mine more coal. In short order, humanity was harvesting billions of tons of plants that had grown in the Cretaceous and Carboniferous periods some 65 to 360 million years ago. Energy consumption and wealth have since risen exponentially.

Figure 12.1 DNA



Source: The Why Files, www.whyfiles.org.

Life is a confluence of energy and information. Stored chemical energy—a sugar, basically—makes up the backbone of Deoxyribose Nucleic Acid (DNA). The cross-bars of the helix store information—the genetic code.