Getting the Most from Energy

Recycling waste heat can keep carbon from going sky high

Thomas R. Casten and Phillip F. Schewe

Energy isn't merely an enabler of things. In a real sense it is the thing itself. The flow of electricity, the digestion of food, the extraction of metal from ore: Energy is perpetually being consumed, transformed and put to new use. Such an intrinsic ingredient in everyday life obviously requires wise management. But setting energy policy gets ever more complicated because even as worldwide energy use skyrockets, we are discovering in greater detail how the deleterious by-products of energy use can foul our habitat and hasten climate change.

Recent studies of three countries—the United States, the United Kingdom and Japan—have found a high correlation between access to useful energy services and growth in income. In other words, energy services—such as the delivery of natural gas for cooking and heating, or the transmission of electricity for processing information or operating motors—make life easier. As the rest of the world strives to reach the levels of income enjoyed in developed economies, efficiency will become ever more important. We must learn to use energy more wisely.

When the Industrial Revolution got under way and the wholesale conversion of fuel into useful work began, the efficiency of this conversion process remained poor. As late as 1900 the U.S. converted only 2.2 percent of potential energy into useful energy services. Thereafter conversion efficiency improved by one percentage point about every 8 years, reaching 13 percent by 1997. Improving these numbers, many would argue, is the key to ensuring a sustainable energy future.

Not all the energy news is bad. For example, in the U.S. it now takes about half as much energy to produce one unit of Gross Domestic Product (GDP) as it did 30 years ago. In that same time span, the energy efficiency of many consumer appliances, such as lightbulbs, refrigerators and air conditioners, has improved two- to four-fold. Nevertheless, we need to concentrate on the dismal prevailing overall energy efficiency of 13 percent. It's an unsustainable habit to convert one unit of energy input into useful work while wasting seven units. We believe that recycling otherwise wasted energy, by recovering useful by-products and reintegrating them in the conversion process, will help to address this problem.

Recycling energy has several immediate benefits: Less fuel is needed, fewer new power plants would be required, and the billows of pollution and greenhouse gases launched into the air would be reduced. The task of recycling energy obviously benefits from improved technology. An even more important factor, however, is the cultivation of an improved way of thinking, one that not only integrates a concern for energy flow at the design stage and includes the cost of environmental impact, but also brings the generation of electric power closer to customers and straightens out the regulatory thickets surrounding power production.

Missing the Point

In a typical fossil-fuel-fired power plant, only one-third of all the energy present in the fuel is turned into usable electricity, whereas two-thirds ends up as cast-off heat. (Even more waste occurs during the use of electricity. For example, an incandescent bulb turns less than 5 percent of power input into light. This is among the reasons why the country's overall energy efficiency is as low as 13 percent.) The prominent

Thomas R. Casten has spent 30 years developing decentralized energy recycling projects. He is currently chairman of Recycled Energy Development (RED). Before that he founded Trigen Energy Corporation and Primary Energy Recycling Corp. He has received numerous awards in the energy field. He is the co-founder and former chairman of the World Alliance for Distributed Energy (WADE) and serves on the Board of Directors and Advisory Boards of the Carnegie Mellon Electric Industry Center, the American Council on Renewable Energy, the Oregon Climate Trust and the Climate Institute. He is a nationally recognized expert on energy and environment issues, and his articles have been widely published, including the book Turning off the Heat *(Prometheus Press, 1998). Phillip F. Schewe works at the American Institute of Physics, where he helps to popularize physics. He is the author of* The Grid *(Joseph Henry Press, 2007), a book about the impact of electricity on society. He has a Ph.D. from Michigan State University in particle physics and has also written plays. Address for Casten: Recycled Energy Development, LLC, 640 Quail Ridge Drive, Westmont, IL 60559. Internet: tcasten@recycled-energy.com*

Figure 1. A power plant in Manhattan supplies both electricity and steam heat to customers of ConEdison, the descendant of Thomas Edison's company from the late 1800s. It's one of the few municipal systems in the United States that still uses its byproduct waste heat for a purpose. Most electrical generation now happens in locations far removed from end users, so heat is simply vented to the air. Figuring out how to recycle this heat back into electrical generation or other useful purposes would go a long way toward improving the efficiency of the energy conversion process in the U.S. Several other countries are also markedly ahead of the U.S. in the use of combined heat-and-power generation.

Rudy Sulgan/Corbis

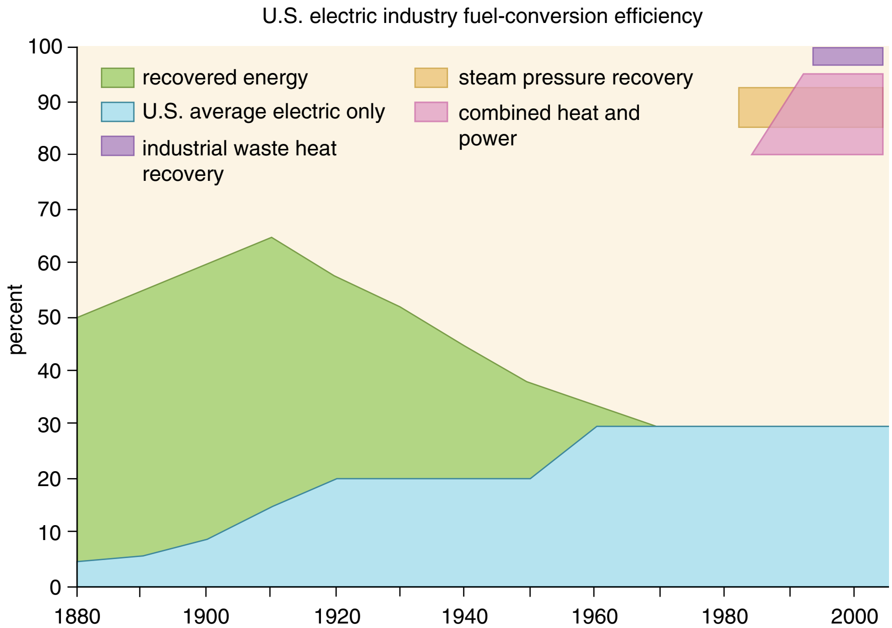

Figure 2. The conversion efficiency of fuel into electricity *(blue)* has remained flat since the 1960s. Simultaneously, the use of recovered energy *(green)*, such as waste heat used to warm buildings, has dwindled to nearly nothing. Energy recycling projects could turn this trend around. The recovery of steam pressure to turn a turbine *(yellow)*, the combined generation of heat and power *(pink)* and industrial waste heat recovery *(purple)* have demonstrated high efficiencies.

plume of steam and other gases coming out of a power plant's exhaust stack is the visible manifestation of its wastage. Energy recycling refers to the rescue of as much of that energy as possible. There are several types of energy waste and energy recovery, but the generation of electricity will necessarily be of central concern owing to its enormous consumption of fuel and production of airborne carbon.

The power industry is peculiar. What other business throws away two-thirds of its input? In what other industrial field has energy efficiency been flat since the Eisenhower administration? Indeed, in terms of total energy usage, Thomas Edison's early power plants in the late 1800s converted more of the input energy to useful work than any of today's electric-only power plants. How can that be? Surely modern electrical generators are better than those used a century ago. Yes, they are, but that isn't the economic point.

Edison used the castoff heat from his generators to warm nearby homes and factories. Consolidated Edison, the descendant company of the one he founded, still delivers heat to thousands of Manhattan buildings via the largest commercial steam system in the world. But few modern fossil-fueled power plants bother to use their heat. They instead vent it into the air. Why throw this valuable thermal energy away? Why burn money? The reasons for this lie in the evolution of the power business, but basically it comes down to one logistical factor: As the years went by, larger plants required more real estate and were built farther from the customer. After all, who wants a sooty coal plant next door? Electricity easily travels many miles, so power plants could be built hundreds of miles away, where they could tap the energy of a river, or where local coal was especially cheap.

Electric customers were happy with this arrangement, but thermal customers were left out in the cold. The heat generated along with electricity does *not* travel far, and so when power plants moved out to the horizon, the steam went to waste. Customers needing heat were forced to build dedicated heating equipment, requiring still more fuel.

This ambivalence over dual heat-and-power production is reflected in grid history. Rapid electrification happened in the early 20th century through a governmental regulated-monopoly scheme, which enabled utilities to earn revenue by expanding electric production. This scaffolding of state and municipal regulations, unfortunately, discouraged the complex integration of thermal and electrical technology needed to utilize the heat made by power plants. The efficient use of heat thus became unprofitable.

There are, of course, fundamental thermodynamic limitations on how much electricity can be wrung from a lump of coal. This fact can be illus-

Figure 3. In a West Virginia plant, electricity, coal and wood chips melt quartz in a large furnace at temperatures around 3,000 degrees Fahrenheit, to produce silicon. The plant is undergoing a conversion process, to be completed in 2010, that will allow it to use much of its byproduct heat to generate power. The recycled heat can produce up to 45 megawatts of electricity, without burning any additional fuel. Image courtesy of Recycled Energy Development.

trated in terms of the Rankine cycle, the name for the multistep process by which heat energy is turned into useful work, in this case the generation of electricity. The cycle shows how a working fluid, usually water, acts as a conveyor belt for energy through a series of devices. First fuel is burned in a furnace to boil the water in pipes lining the furnace walls. This creates steam, now under great pressure, that strikes and turns the blades of a turbine, thereby converting steam pressure into mechanical rotational energy to turn a generator. Wire coils mounted on the generator shaft swivel past a magnetic field created by stationary wire coils, turning the rotational energy into electrical energy.

The steam, once past the first set of turbine blades, is turned back by fixed blades to hit the next row of spinning turbine blades and thus impart more rotational energy. At each successive stage, the steam gives up temperature and pressure, reducing its ability to perform work. To increase the pressure drop and the subsequent work that can be produced, electric-only plants pump copious quantities of cool water into pipes downstream of the steam turbine to extract low-grade thermal energy and cause the steam to condense into water. A pound of water occupies only one-thousandth of the volume of a pound of low-pressure steam, so condensing the steam creates a vacuum, which maximizes the extraction of mechanical energy. Sophisticated Rankine-cycle plants, even with very cold ocean water for condensers, achieve no better than 42 percent conversion efficiency, a limit effectively reached in the late 1950s. Finally, the condensed steam, as water, must be pumped up and returned to the boiler for another cycle of power making.

The first two steps in this process are reasonably efficient: The boiler converts up to 85 percent of the chemical energy inherent in the fuel into the thermal energy in the steam. It's in the turbine and the condenser that valuable energy is being squandered. To be sure, the laws of thermodynamics dictate that the process of turning fuel into work must generate heat. There will always be heat. But it needn't all be wasted. Besides warming our homes and offices, surplus heat could be, and in some places is, put to good use in heating chemicals, bonding layers of sheetrock, making paper or converting organic matter into biofuel. Nearly spent steam, having given up most of its potential to generate electricity, can even be used to run absorption chillers, which employ heat to produce cooling.

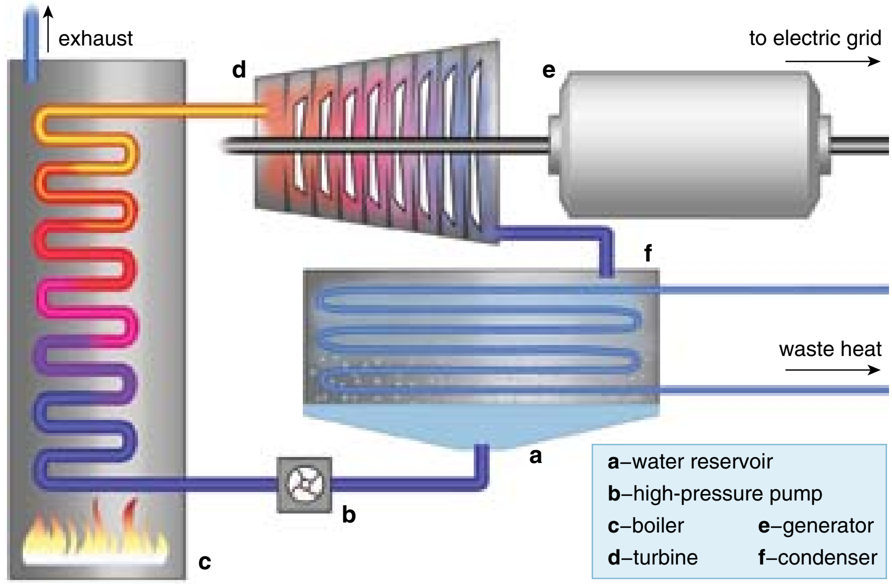

Figure 4. A process called the Rankine cycle generates power from heat. Water from a reservoir *(a)* is pumped to high pressure *(b)* and then piped through the walls of a boiler *(c)* to turn it into steam. The steam expands through a turbine (*d*), turning a series of blades and spinning a shaft attached to an electrical generator *(e)*. Wire coils mounted on the generator shaft swivel past a magnetic field created by stationary wire coils, turning the rotational energy into electrical energy. As steam travels through the turbine, it cools down and then is fed past cold-water pipes in a condenser *(f)* to convert it back into liquid water ready for the next round of the cycle. Adapted from http://en.wikipedia.org/wiki/Rankine_cycle

In the early days of the power industry, so-called combined heat-and-power (CHP) plants like Edison's were common. Now they're rare. Restoring this synergy between heat and power is one of the highest priorities of energy recycling. By changing outmoded rules and upgrading machinery, heat and power could again become inseparable and profitable partners. Where they are combined, the total energy efficiency can reach 90 percent or better.

A Wedge Issue

The Rankine illustration leaves something out: the combustion products. Not of much economic interest, these emissions must nevertheless be considered since they constitute a form of uncollected garbage. They include sulfur compounds (which can precipitate out of the sky as acid rain), nitrous oxides (which can lead to respiratory diseases), particulate matter (which blackens everything when it falls as soot) and carbon dioxide. The first three constitute parts-per-million fractions of typical fuel-combustion exhaust and have been subject to regulation by the Clean Air Act since 1970. Modern power plants emit only 1 to 2 percent of 1970 levels of these three pollutants. The fourth by-product, carbon dioxide, is not a "pollutant" in the normal sense of the word, but it is implicated by the great majority of geoscientists in contributing to ill effects in our climate, such as rising sea levels, intensified droughts and the disappearance of plant species.

We no longer discuss energy and electrical generation without also mentioning the potentially grave effects of CO_2. One of the more notable suggestions advanced in recent years for dealing with this issue is the "wedge" scheme. The team of ecologist Stephen Pacala and physicist Robert Socolow, both at Princeton University, urges that as a first practical step, society reduce CO_2 emissions from the current "business-as-usual" level of increase to a constant level over the next 50 years. The way to do this is to spur many simultaneous approaches to CO_2 emission reduction. In Pacala and Socolow's protocol for achieving stabilization, one layer of reduction, or one "wedge" in the emission-reduction process, comes about by taking 25 billion tons of carbon off the emission menu over the next 50 years. Other

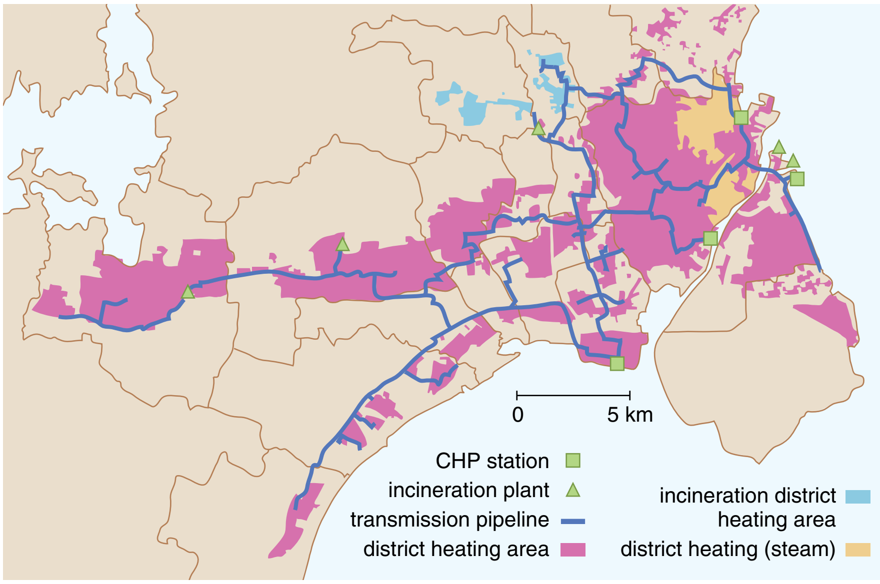

Figure 5. In the region around Copenhagen, Denmark, most homes are warmed by district heating systems, more than 90 percent of which are supplied by co-generation plants. Recycled energy amounts to over 50 percent of all energy used in Denmark. Combined heat-and-power (CHP) stations *(green squares)* and incineration plants *(green triangles)* supply both electricity and heat to most of the region *(pink)*. Some areas receive heat alone from incineration plants *(blue)*, whereas others just receive steam heat from CHP stations *(yellow)*. Data courtesy of Vestegnens Kraftvarmeselskab I/S (VEKS), http://www.veks.dk.

wedge examples include increasing the fuel efficiency of two billion cars from 30 miles per gallon to 60 miles per gallon, cutting electricity use by 25 percent and capturing and storing the CO_2 emissions from 800 large coal-fired power plants.

These steps are all to the good. The more CO_2-reduction wedges that are at work, the better. But much of this discussion has overlooked one of the largest reservoirs of potential CO_2 reduction: redeeming all that heat lifting off of myriad power generators, large and small. The reduction in fossil-fuel burning that is possible from an efficient use of heat and power is enormous.

We believe that one wedge (and as many as two or three) could be derived from a concerted recycled-energy policy. Can't be done? It violates laws of thermodynamics? Well, in the U.S., recycled energy amounts to about 8 percent of all energy used. But in Denmark it's more than 50 percent.

Note that we are addressing the issue of recycled energy, not renewable energy. The use of renewable sources such as wind or solar power will likely, in a forward-looking energy plan, assume a larger role in all energy applications, whether for transportation, electrical generation or industrial processes. Recycled energy, by contrast, is the reemployment of energy that would otherwise be wasted.

Recycling happens at all scales. At the domestic level, for example, one can recycle food scraps, and even items such as paper and dried leaves, into compost, which delivers nitrogen and minerals to garden plants. This offsets an equivalent amount of artificial fertilizer you might have bought. In another case, automobiles slow themselves when brakes grab hold of the spinning wheels, and this energy of motion is turned into heat, which normally goes to waste. But in a hybrid vehicle, braking is partly achieved by engaging an electrical generator, which charges a battery as it slows the car, storing fuel-free power for the next acceleration cycle.

At the larger industrial level the machinery is bigger, the energy flows are larger and the potential for recycling more impressive. We've already cited the single biggest energy-waste process—the warmth emanating from power production. Natural gas is another major energy commodity, used directly in homes and factories for heating and cooking, and in generating an increasing share of electrical production. Like the electrical grid, the gas grid runs across the countryside and into cities. Gas must be pressurized in order to travel through pipes and re-pressurized every hundred miles or so. At each of these steps heat is generated and usually wasted. Instead it should be recycled.

The heat from the gas turbine driving the compressor, for example, could be used to make steam and then electricity, or piped a few miles to a thermal customer, such as an ethanol plant. At the end of the line the gas is de-pressurized for local use. Even this step, if handled correctly, could generate energy: In its mad dash to expand, the gas could spin a turbine. Moreover, a gas suddenly allowed to expand gets very cold, a process exploited in your kitchen refrigerator. The expansion of natural gas, with clever engineering, could be utilized as a refrigerant in some industrial processes.

We've seen how the by-product heat from generation of power can be exploited for industrial and commercial purposes to displace boiler fuel and electricity. The converse is true too. The exhaust heat from melting metals or from chemical reactions can, when handled in retrofitted generators, produce added heat and power. All this recycled energy—requiring no extra fuel—is as pristine as energy from a solar collector or a wind turbine, but seldom enjoys comparable financial incentives.

Add up rescued energy in many categories and the sum becomes impressive. According to recent reports for the U.S. Environmental Protection Agency and the Department of Energy, the potential for energy recycling in the U.S. alone from wasted industrial energy is 65 gigawatts and from additional CHP power is 135 gigawatts. So the total recycled energy could be 200 gigawatts per year, equaling 20 percent of the power being generated in the U.S. This represents immense avoided costs, as this level is equivalent to 300 to 400 coal plants being closed down or not built, and a 20 percent reduction in current U.S. CO_2 emissions (which would cover 1 to 3 wedges in Pacala and Socolow's protocol).

Recycling Success Stories

Inescapably, recycling means localizing energy generation. This is because the energy to be redeemed—such as turbine heat, tail fumes or expanding gases—cannot travel far and is available only in proximity to the primary electrical or manufacturing process. Also, to successfully integrate thermal

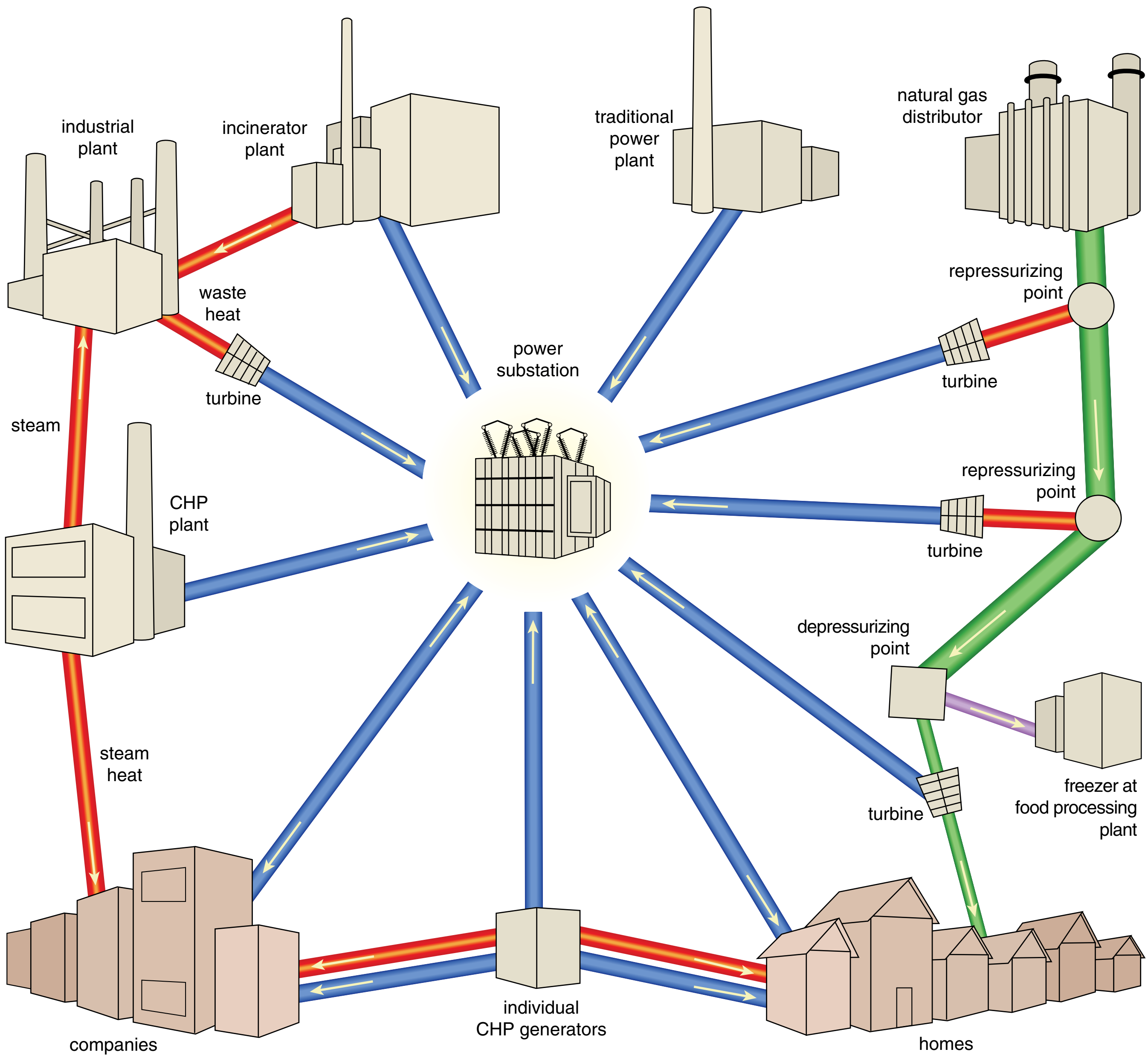

Figure 6. In an ideal system of recycled-energy use, the generation of electricity *(blue lines)* and steam heat *(red lines)* would come from multiple sources. Besides traditional power plants that supply electricity to substations for distribution, incineration plants and combined heat-and-power (CHP) plants would play a larger role in energy production. Both of these plants could also supply steam for heat and for industrial processes. In turn, the waste heat from industrial plants can be run through turbines to create additional electricity. Small, individual CHP generators are now available and can be installed into homes and offices to provide both heat and power and to feed any excess electricity back into the grid. In addition, waste heat from other processes, such as the repressurizing of natural gas pipelines *(green lines)*, could be converted into power. The expansion of natural gas *(purple line)* could be used as another source of energy, to chill instead of heat, such as might occur in a freezer at a food-processing plant.

energy and electrical energy, a sort of role reversal will have to take place.

Rather than regarding heat as an afterthought, one should, if anything, put it foremost: Design a local CHP plant to make as much heat as you need locally (in a house or factory) and then export whatever extra electricity you make into the main electrical grid, just as from a central electricity-only plant. The host retains the advantages of being connected to the grid while benefiting from recycling by-product heat. Meanwhile, society gains the advantages of more efficient generation from multiple locations close to customers.

Could this work on a small scale? Well, in the 1980s personal computers displaced mainframe computers. This came about because of new technology (microelectronics and versatile software), new thinking (decentralized computation was feasible) and new services (Internet, e-mail, computer-assisted design, etc.). Could the same thing happen with energy?

There could be such a thing as personal electricity. In an experimental venture, Honda has marketed a home-sized turbine (called a micro-CHP) that can make up to 3.3 kilowatts of heat and 1.2 kilowatts of electricity. Currently being tried out chiefly in the northeastern U.S., where winters are hard, the units are able to send power not needed by the home into the main grid.

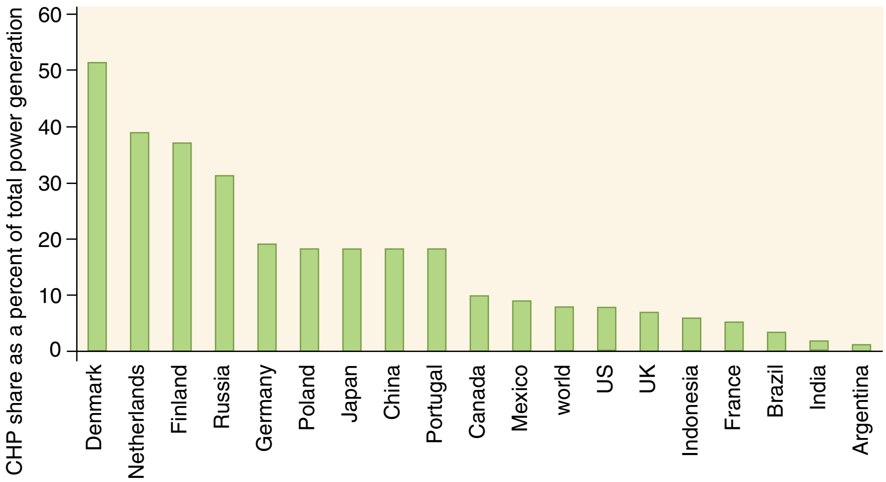

Figure 7. As of 2005, combined heat-and-power production (CHP) amounted to only about 8 percent of the total energy used in the United States. In other countries, it reaches much higher percentages. The current world leader is Denmark, with more than 50 percent of all energy used coming from recycled sources. In the United States, some states do better than others. California and Hawaii produce more than 20 percent of their power using combined heat-and-power sources. But three U.S. states report having no CHP plants whatsoever. On average, worldwide electrical generation provided by CHP plants is 7.5 percent. Data courtesy of the World Alliance for Decentralized Energy.

Figure 8. Combined heat-and-power (CHP) generation can now take place in the home. This micro-CHP system, manufactured by Honda, produces 3.26 kilowatts of heat and 1.2 kilowatts of electric power. The electricity is generated as a byproduct of heating, which also leads to reductions in the generation of carbon dioxide from heating. In certain states, homeowners are allowed to sell any unused power generated back to the electrical grid in their community. A similar micro-CHP system has been on the market in Japan since 2003, with more than 45,000 units sold there to date. Image courtesy of American Honda Motor Corporation.

Of more practical and immediate value are the many opportunities for the coordinated use of heat and power production at the industrial level. Dow Chemical, for example, began an intensive CHP program in the mid-1990s. Since then they have recycled an amount of energy equivalent to a year's worth of household consumption in a city the size of New York.

An additional benefit of the localization of power, besides pushing energy efficiency from 30 percent up to 90 percent, would be shorter transmission paths. Typically 6 to 10 percent of the electrical power running over wires is lost. Shortening the path saves energy. Furthermore, since most large electrical blackouts originate in the grid itself and not because of generator problems, shortening transmission journeys should mitigate the blackout threat, which currently imposes an estimated annual business cost of 70 to 100 billion dollars in the U.S. alone.

There are some success stories already for the efficient recycling of waste heat. At a steel mill in northwestern Indiana, the exhaust heat from making blast-furnace coke (pure carbon made porous to increase access to oxygen, allowing it to burn hotter) was previously vented into the air. Now the heat is used to make steam to generate 95 megawatts of electricity; one million pounds of the steam is also used industrially. At the same steel mill, normally flared gas emerging from three blast furnaces is burned to make an additional 130 megawatts of power. The total recycled electrical power from this one steel mill is thus 225 megawatts. This is equivalent to a modest coal-fired power plant, but one that requires no fuel and that costs about one-tenth of the price of clean power from a photovoltaic setup. In addition, almost a million tons of CO_2 per year, the same as emissions from 170,000 cars, is no longer sent into the air.

Here is a sampling of additional recycled-energy success stories from just the past few years. A factory in Brattleboro, Vermont, reuses the heat from drying wood products to make 380 kilowatts of power. A factory in Kallo, Belgium, running on bio-oil, dries manure into fertilizer pellets using a CHP plant that makes 9 megawatts of electricity and 8 megawatts of heat. A natural gas compressor in Kern River, California, uses cast-off heat to make steam to generate 6 megawatts of power. And again in Copenhagen, Denmark, most homes are warmed by district heating systems, more than 90 percent of which are supplied by co-generation plants.

In addition, a furnace in West Virginia separating silicon from its ore, generating lots of heat in the process, will use the heat to make steam and 44 megawatts of electricity starting in 2010. In Shanghai, China, a CHP plant generates 315 kilowatts of electricity and all the heat needed for the Jinqiao Sports Center, including its swimming pool. And back in Oxnard, California, a lettuce and vegetable processing factory uses the byproduct heat from a 49-megawatt CHP plant to drive an ammonia refrigeration plant that chills produce and freezes strawberries.

Prospects for Recycled Energy

In our society, the market is expected to drive production towards optimal use of available technology. The French economist Jean-Baptiste Say defined "entrepreneur" as a person who transferred resources from less productive areas to more productive areas. Policymakers, assuming that the generation of heat and power has been subject to these free market forces, see new technology as the answer. For example, President George Bush, addressing global warming, said, "Technology is the ticket."

However, power markets are not fully free, but are subject to numerous inhibitions and have mostly failed to deploy new technology unless it is consistent with the existing paradigm of big, regulation-encumbered, largely electric-only power plants. Utility and environmental regulations essentially ban much potential entrepreneurial behavior in the electric-generation arena. It is often illegal to transfer resources from less-productive approaches to more-productive ones. How then can market forces bring heat and electricity back together again?

When President Jimmy Carter sought to improve energy efficiency in the 1970s, Congress passed the Public Utility Regulatory Polices Act, or PURPA. It allowed generation by nonutilities, if the independent power plants recycled some heat and achieved an overall efficiency of 45 percent. Utilities were forced to purchase the excess power at their "avoided costs." State regulatory commissions were left to determine these avoided costs, and a variety of approaches created a patchwork system. In California, CHP came to account for 20 percent of total power. By contrast, several states had no CHP at all. Some utilities fought to maintain their monopoly control of generation, and even more to maintain their control over the distribution of power.

Subsequently, the generation part of the power industry was largely deregulated, with many states using various approaches to have the market determine which plants generate at any given time. However, all states have largely continued to enfranchise monopoly distribution of electricity. And so it remains illegal to sell power through a private electric wire across any public street in the U.S., a power-delivery approach that is common in the rest of the world.

Policymakers, seeking to reduce dependence on fossil fuel and on fuel imports, have offered various incentives for the development of renewable energy from solar, wind, geothermal and certain types of biomass generation. Renewable energy has become sexy, use of it is growing and this will benefit society. But energy recycling, with just as great a potential impact on energy policy, has not yet received comparable favor. Many well-intentioned energy analysts have essentially prescribed a path—renewable energy—instead of a goal—clean energy.

Another major policy impediment to energy recycling, and another issue also shaped by the unforeseen consequences of good intentions, is the force of environmental regulations. To win the consensus needed for passage, the Clean Air Act in effect "grandfathered" existing plants, allowing them to continue polluting at historic levels, and requiring only new plants to meet new, higher standards. This concession makes it ever more expensive to construct a new power plant, which then must compete with a grandfathered dirty plant when selling power. In addition, if modifications are made to use waste heat in an older plant, it will lose its grandfathered status and would be subject to current regulations. These factors discourage transition to a high-efficiency heat-and-power approach.

It doesn't have to be this way. Several policy changes would induce rapid efficiency gains in the production of heat and power, and would unlock both energy recycling and profitable reduction of greenhouse-gas emissions.

First, the policies in a wide variety of protocols designed to promote renewable energy should be broadened to promote all clean energy, recognizing that waste-energy recycling and good CHP plants deliver useful energy without the use of additional fuel.

Second, governments and agencies at every level could initiate clean-energy programs that ensure profitable reduction of greenhouse gases. This approach would determine the delivered cost of new power from the best new electric-only plant and then offer long-term contracts for power from clean–energy plants providing that the clean plants deliver power at a price below (say, 15 percent below) that provided by electric-only plants. Providing long-term contracts for clean energy will induce entrepreneurs to develop and build such projects. To be eligible for a "clean energy" designation, a plant should have to achieve at least 60-percent efficiency (rather than the old 45-percent standard). These are the true goals of energy recycling: profitable operation, less fuel consumption and cleaner skies.

Rising fuel costs (as rates are likely to remain on an upward swing, despite recent price plummets at the gas pump) and the need to mitigate severe climate change will eventually force this sort of regulatory reformation. There is another reason for embracing energy recycling: The sheer intellectual satisfaction of knowing that every last bit of energy that can be wrung from our consumption of fuel is put to good use. Nations compete for scarce resources, legislators compete for political advantage and businesses compete for sales and profits. More inexorable by far is the combat we all do with the Second Law of Thermodynamics, which decrees that everything will eventually be reduced to useless heat. Even here, though, engineers and scientists likely will, if they're clever enough, find additional ways to tap still more energy from the environment—from the chemical potential locked in vented gases, from steam as it comes down in temperature (below 400 degrees Fahrenheit, it's possible to replace water with propane, which has a much lower boiling temperature), from pressurized natural gas as it expands to atmospheric pressure, and from water as it comes down off the mountain and returns to sea.

The chief energy challenges of our age are to reduce the use of fossil fuel and to reduce harmful emissions, even as we maintain our standard of living. To achieve these goals, we must embrace energy recycling. We must extract more useful work from the energy at our disposal, especially in manufacturing, processing and power generation. We can't afford to send the large majority of our energy, unused, into the sky.

Bibliography

Ayers, R., and B. Warr. 2002. *Useful Work and Information as Drivers of Growth.* Fontainebleau, France: Center for the Management of Environmental Resources.

Bailey, O., and E. Worrell. 2005. *Clean Energy Technologies: A Preliminary Inventory of the Potential for Electricity Generation.* Berkeley, Calif.: Energy Analysis Department, Lawrence Berkeley National Laboratory.

Casten, T. 1998. *Turning Off the Heat.* Amherst, NY: Prometheus Books.

Pacala, S., and R. Socolow. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* 305:968.

For relevant Web links, consult this issue of *American Scientist Online:*

http://www.americanscientist.org/issues/id.76/past.aspx