powered car the same 560-kilometer range as a 1999 Ford Taurus, says Sims. Rossmeissl and others note that experimental lightweight carbon-fiber tanks and other improvements could extend the driving range of hydrogen-powered cars.

The dominant fuel should emerge in the next few years, say Sims and others. Hydrogen is poised to sprint to an early lead: In the next 2 years the California Fuel Cell Partnership plans to build two hydrogen fueling stations in the state which will pump hydrogen gas into onboard fuel tanks. As for methanol, it could take a few years before reformers are reliable enough to mass-produce. "Until then, we've got this window to prove the [hydrogen] technology" and to devise better ways to make it and store it, says Sigmund Gronich, a DOE hydrogen specialist. But unless hydrogen blows away the field, it is unlikely to conquer the passenger car arena. "As onboard fuel processing reaches maturity in the middle of the next decade, you're probably going to see methanol become a fuel of choice," says Sims.

Whatever version of the technology gets the checkered flag will have a long reign, says Turner. Even if gasoline wins, it could provide a hydrogen source until fossil fuels become scarce decades or even centuries from now. But at that point, Turner predicts, consumers will need to switch to hydrogen, which is easier than methanol to generate from solar power and other renewable energy sources. "Ultimately we will get there," says Turner. "The question is, do we generate an interim infrastructure and then 50 years from now do it all over again?"

–ROBERT F. SERVICE

NEWS

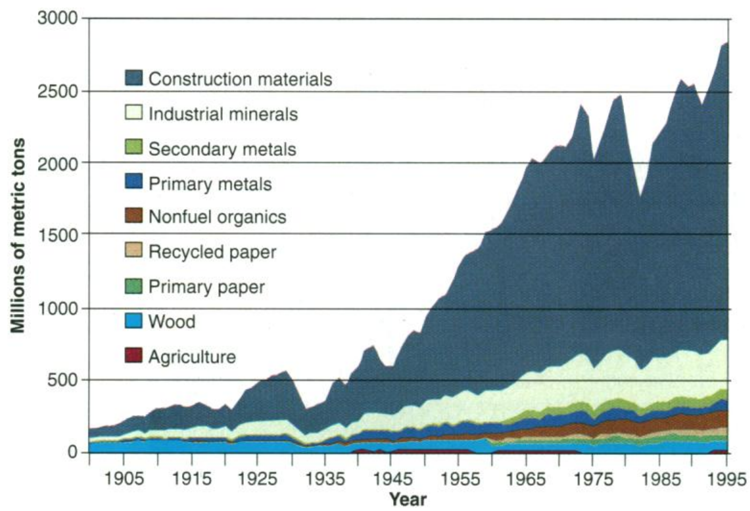
Turning Engineers Into Resource Accountants

A new discipline is trying to persuade companies that tracking the flow of materials and energy over a product's lifetime makes good business sense

To Robert Frosch, a computer is like a frog. Both are made of energy-intensive materials: organic molecules for the amphibian, plastics and metals for the computer. Both use energy as they operate. And, like a dead frog decomposing in a marsh, an obsolete computer will decay somewhere, maybe in a landfill. But Frosch, an industrial ecologist at Harvard University's Kennedy School of Government, believes their life cycles could be made even more similar: Before the computer is junked, he would like to see it picked over by a scrap dealer—someone, he says, "a little like the microorganisms that turn waste into fertilizer."

This view of organisms and consumer goods leading parallel lives is gaining a wider audience thanks to Frosch and like-minded scientists, whose goal is to scrutinize every gram of material and joule of energy going into and out of a product. "It's a way of organizing and systematically studying the built environment," explains Iddo Wernick, a physicist at Columbia University. The philosophy has begun to pay off—mainly in Europe—in everything from appliances designed with reusable parts to schemes for capturing precious metals that may otherwise end up in landfills or riverbeds.

However, a cradle-to-grave approach to doing business hasn't yet caught fire in the United States. Efforts to get U.S. companies to feed off each other's waste, for instance, have sputtered (see sidebar), and only a handful of corporate titans have embraced the concept of scrutinizing their products' material and energy flows. That irks Frosch, who decries the consumption in developed countries, which deplete natural resources at a prodigious rate: about 1000 times the body weight of each inhabitant per year, according to a 1997 study led by the nonprofit World Resources Institute in Washington, D.C. "You find amazing amounts of things being thrown away that are perfectly useful," Frosch says. Industrial ecologists hope to curb this compulsion by convincing companies—and people—to make the most of every iota of energy and substance. But that may happen only if governments end policies that embrace waste, such as cheap landfills and tax subsidies that skew the real costs of virgin materials.



All-consuming. The United States' appetite for many raw materials shows no sign of tapering off.

SOURCE: USGS

What goes in must come out. Industrial ecology was born in the late 1980s, when Frosch and Nicholas Gallopoulos, then at General Motors, described in a *Scientific American* article how to analyze a factory the same way you might an ecosystem, by assessing its energy cycles and decay and reuse. "A key question is, where did this stuff come from and where is it gonna end up?" Frosch says. The budding field, a mix mainly of social scientists, engineers, physicists, and ecologists, got a boost 2 years ago from the debut of the *Journal of Industrial Ecology* (mitpress.mit.edu/JIE).

Fueling the academic push is a wave of regulations and voluntary targets aimed at cutting back on waste. Since the early 1990s, several European countries and Japan have begun to mandate that companies use less packaging and take back old consumer appliances. In the United States, the Clinton Administration has pushed voluntary initiatives, including a program in which the Environmental Protection Agency (EPA) works with companies to help them "design for the environment"—for example, by finding alternatives to lead solder to make computer circuit boards. Some European countries, such as Germany, are even discussing an ambitious goal to curtail their consumption of natural resources by 90% by 2040.

One way to reach these targets might be to employ the principles of industrial ecology. In its most reductionist form, the discipline involves life-cycle assessment—drawing a circle around, say, a television or a toaster, then tallying the materials and energy that go into their parts, manufacture, and use and the waste and pollution that come out. "You go as far back in the chain as the coal coming out of the ground," says H. Scott Matthews of Carnegie Mellon University in Pittsburgh. The next step is to design a

In This Danish Industrial Park, Nothing Goes to Waste

If there's anything that sums up the hopes of industrial ecology (see main text), it's a tiny pipeline-laced town in eastern Denmark called Kalundborg, where companies have been swapping byproducts like gypsum and waste water for up to 25 years. This "industrial symbiosis" is drawing keen interest from policy-makers in the United States, although opinions vary on its odds of success.

Waste not, want not. Almost nothing gets discarded by industries in Kalundborg, Denmark.

The idea behind "ecoparks" is that one company's sludge is another's manna. As five firms that sprang up at Kalundborg over the years encountered new environmental regulations, they forged exchanges. For instance, flare gas from an oil refinery heats other factories; a power plant sends gypsum—produced by scrubbing sulfur dioxide from flue gas—to a drywall factory; and a biotech's fermentation waste gets shipped to farmers for fertilizing fields. Cooling water from the refinery is used by the power plant as boiler water, while the power plant's excess steam heats Kalundborg's 4300 homes. "There basically is no waste generation, and the energy efficiency is quite high," says John Ehrenfeld, an industrial ecologist at the Massachusetts Institute of Technology.

In the United States, the ecopark idea has been pumped by an advisory body called the President's Council on Sustainable Development, which points to at least 15 examples on the drawing board in places like Cape Charles, Virginia, and Londonderry, New Hampshire. The approaches range from making "green" products, like photovoltaic panels, to featuring energy-efficient lighting and nature walks. Few of these projects, however, will exchange waste materials, which some experts say is crucial to making a major dent in resource consumption.

Easier to achieve, and common in the United States and elsewhere, is "green twinning": exchanges between two companies, like a steel mill in Midlothian, Texas, that sends waste slag from its furnaces to a nearby cement plant. Another idea is to set up "virtual" ecoparks, in which far-flung companies can exchange materials. The U.S. Environmental Protection Agency has set up databases and developed software tools to help industries find out what each other is throwing away.

Some experts are skeptical that anything like Kalundborg will ever exist in the United States. "The key difference," says Ehrenfeld, "is that Kalundborg is an open culture. They don't have this notion of the corporation as secretive." Yale industrial ecologist Marian Chertow, however, sees an opportunity in the recent push to deregulate the electric industry. More-efficient power plants are expected to spring up from fiercer competition, and these plants would be ideal anchors for ecoparks, she says. "What we're seeing now is the kernels of their evolution." **–J.K.**

product that uses less raw materials and thus produces less waste.

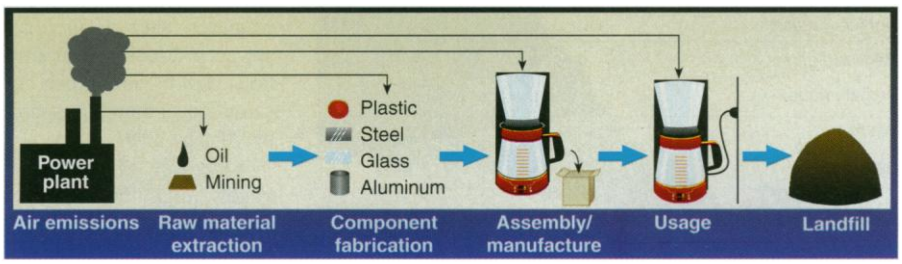
AT&T, a pioneer in this area, in the early 1990s began stamping plastics with ID tags for sorting at recycling centers, assembling phones with snaps instead of glue, and using less packaging. The idea of design with disassembly in mind has since caught on for everything from electric hot water kettles to BMW cars. In Japan, for instance, TV consoles are now often made of a magnesium alloy that, unlike plastic, doesn't degrade with age and can be recycled more easily.

But although most big-name electronics, auto, and personal products firms now do life-cycle assessments, many other companies lack the stomach for it. They are wary of "paralysis by analysis," says Richard Dennison of the Environmental Defense Fund in Washington, D.C., because a detailed assessment can take years and $100,000 or more. Some firms question what's in it for them, says Diana Bendz, director of environmentally conscious products for IBM—"although the more you get into it," she says, "the more you realize you can save money."

A river of waste. Academic industrial ecologists usually get in the game at the next level up, by tracking the flow of materials through whole industries or society. These studies "tend to be assumption busters," says David Rejeski, an EPA policy expert with the White House Council on Environmental Quality. For example, a few years ago researchers at the University of California, Los Angeles, and the California EPA found that silver in San Francisco Bay—blamed for poisoning fish and marine mammals—comes mostly from a commercial solvent used to fix x-ray images in dental offices and hospitals. The study prompted Kaiser Permanente to set up a recycling facility in Berkeley to recover silver in spent fixer from more than 50 medical centers, bringing in about $240,000 a year in profits from silver sales.

"It tends to be a small number of leading-edge companies that are routinely incorporating these practices," says Yale's Reid Lifset, editor-in-chief of the *Journal of Industrial Ecology*. "We've still got a ways to go." Allen Kneese, an economist at Resources for the Future, a Washington, D.C., think tank, argues that more firms will take industrial ecology to heart only if the government revises policies—such as tax breaks for mining companies that make virgin materials cheaper than recycled ones—that obscure the true costs of depleting resources. Like Kneese, environmental scientist Helias Udo de Haes of Leiden University in the Netherlands thinks countries will only "dematerialize" if governments impose a tax on companies for each ton of pollution they emit. "It would be very difficult to do without taxes," he says.

Spreading the gospel will also mean further developing an academic discipline. At least a dozen universities offer industrial ecology programs and courses in Europe and the United States, says Rejeski, but "it's still a pretty small community." Such principles, says Thomas Graedel, chair of Yale's industrial ecology program, "ought to be part of what any technologist does." **–JOCELYN KAISER**



Birth and death of a coffeemaker. Life-cycle assessments aim to track every iota of material and energy over a product's lifetime.

CREDITS: (TOP) JORN BRAENDGAARD; (BOTTOM) J. CAGAN, H. S. MATTHEWS, CARNEGIE MELLON UNIV.