IF ELECTRONS ARE THE LIFEBLOOD OF A modern economy, copper makes up its blood vessels. In cables, wires, and contacts, copper is at the core of the electrical distribution system, from power stations to the delicate electronics that can display this page of *Science*. A small car has 20 kilograms of copper in everything from its starter motor to the radiator; hybrid cars have twice that. But even in the face of exponentially rising consumption—reaching 17 million metric tons in 2012—miners have for 10,000 years met the world’s demand for copper.

But perhaps not for much longer. A group of resource specialists has taken the first shot at projecting how much more copper miners will wring from the planet. In their model runs, described this month in the journal *Resources, Conservation and Recycling*, production peaks by about midcentury even if copper is more abundant than most geologists believe. That would drive prices sky-high, trigger increased recycling, and force inferior substitutes for copper on the marketplace.

Predicting when production of any natural resource will peak is fraught with uncertainty. Witness the running debate over when world oil production will peak (*Science*, 3 February 2012, p. 522). And the early reception of the copper forecast is mixed. The work gives "a pretty good idea that likely we’ll get a peak somewhere around midcentury," says industrial ecologist Thomas Graedel of Yale University. Technological optimists disagree. "Not that it couldn’t happen, but I don’t think it’s likely to happen," says resource economist John Tilton, research professor emeritus at the Colorado School of Mines in Golden. New and better technology for extracting copper from the earth has always come to the rescue before, he notes, so he expects a much-delayed peak that businesses and consumers will comfortably accommodate by recycling more copper and using copper substitutes.

The copper debate could foreshadow others. The team is applying its depletion model to other mineral resources, from oil to lithium, that also face exponentially escalating demands on a depleting resource.

So far, so good

The techno-optimists were right about copper in the past. From nearly nothing in the mid-18th century, copper production soared along an exponential curve notched only by world wars and economic crises. That’s all the more impressive considering the accompanying decline in the richness, or grade, of the ore being mined. Anyone extracting a
Headed down. Miners must move megatons of low-grade copper ore at the Zijinshan mine in South China. A mineral resource goes for the richest, most easily mined deposits first, so ore grades ran from 10% to 20% copper until late in the 19th century and then plummeted to 2% to 3% in the early 20th century. Since the mid-1990s, the world copper grade has been just below 1% and in slow decline, according to data compiled by resource geologist Gavin Mudd of Monash University, Clayton, in Australia, in a 2013 paper in the International Journal of Sustainable Development.

Even though the available ores have become poorer, forcing miners to claw ever greater volumes of rock from kilometer-deep open pit mines, the price of copper has trended downward since 1900 (with a notable spike since 2005 driven by China’s hunger for raw materials). Multiple factors have driven the price decline. Geologists found a new type of copper deposit—the porphyry ores of buried magma formations—that is now the source of most of the world’s copper. And lately they have been finding extractable porphyry copper faster than it is produced, according to Richard Schodde of MinEx Consulting in Melbourne, Australia. Equipment manufacturers have built humongous shovels and dump trucks to move huge volumes of porphyry ore. And chemical engineers have developed processes such as heap leaching—trickling weak sulfuric acid through piled crushed ore—to get copper out of low-grade ore.

Not so fast
The world’s copper future is not as rosy as a minimum “125-year supply” might suggest, however. For one thing, any future world will have more people in it, perhaps a third more by 2050. And the hope, at least, is that a larger proportion of those people will enjoy a higher standard of living, which today means a higher consumption of copper per person.

Mohr’s model to copper. For their study, the group drew on a database of the extractable copper at all known mine sites that was compiled by Mudd and Weng and published in 2012. The group assumed that per capita demand for mined copper would continue to rise at the historical rate of 1.6% per year and that the world’s population would grow from today’s 7.1 billion people to 10 billion in 2100. They taught the model how to behave realistically by fitting it to past copper production for each country and type of deposit. In the model, increasing demand elicits increased production at existing mines and the opening of new mines. The model delivers some good news, suggesting that production can rise to meet expected demand for the next 2 to 3 decades. “It’s not a story of doom and gloom, of running out tomorrow,” Giurco says, “but rather of needing to be more mindful of use.” But trouble comes in the longer term. With the amount of extractable copper in the Mudd and Weng compilation, the model shows production peaking just before 2040; after that, copper can’t be extracted from depleted mines any faster, no matter how high the price.

Increasing the amount of accessible cop-
per in the model by 50% to account for what might yet be discovered moves the production peak back only a few years, to about 2045. It just takes a lot of copper to satisfy exponentially growing demand, Mohr says. In additional model runs performed at the request of Science, Mohr found that even doubling the available extractable copper pushes peak production back only to about 2050. And quadrupling it—an optimistic projection indeed—would mean the world would run short of copper by about 2075.

Copper trouble spots

So far, so bad—but technological optimists are quick to note that human ingenuity has confounded the gloom-sayers before. “As a society, we have tended to underestimate how much copper is out there, and how cre-ative society can be about extracting it,” Tilton says. He points out that in the 1970s, USGS estimated that about 1.6 billion tons of copper could be extracted with current technology. Today, the equivalent USGS figure is 3.1 billion tons. “And it’s very likely to double again,” Tilton says, even without including the copper on the ocean floor along midocean ridges. “We know the copper’s there—it’s a matter of resolving technical problems allowing extraction,” he says.

Graedel doesn’t go that far, saying the world has been so thoroughly explored for copper that most of the big deposits have probably already been found. Although there will be plenty of discoveries, they will likely be on the small side, he says. As for technological breakthroughs on a par with those in the past, he says, “you can’t tell.”

Furthermore, the models don’t take into account constraints on copper mining that could make things worse. “The critical issues already constraining the copper industry are social, environmental, and economic issues,” Mudd writes in an e-mail. Any process intended to extract a kilogram of metal locked in a ton of rock buried hundreds of meters down inevitably raises issues of energy and water consumption, pollution, and local community concerns. And such “environmental and societal constraints are getting stronger,” Mudd says.

Mudd has a long list of copper mining trouble spots. The Reko Diq deposit in northwestern Pakistan close to both Iran and Afghanistan holds $232 billion of copper, but it is tantalizingly out of reach, with

After the peak

Whenever it comes, the copper peak will bring change. Alternative materials can replace copper in many uses, but substitution in some is easier than in others. In 1982, the U.S. copper penny—at least 88% copper since 1793—became 97.5% zinc and just 2.5% copper, mostly as copper plating, to discourage people from melting down the coins for their copper. But Graedel and his Yale colleagues reported in a paper published on 2 December 2013 in the Proceedings of the National Academy of Sciences that copper is one of four metals—chromium, manganese, and lead being the others—for which “no good substitutes are presently available for their major uses.”

Recycling is more promising. Copper is already the third most recycled metal after iron and aluminum. Roughly 50% of the copper that goes out of service is returned to use, Graedel says. Governments could increase that figure by requiring product designs that, say, made recovery of copper wiring from cars easier and less expensive. Scarcity-driven price hikes will also boost recycling, Graedel notes.

Copper is far from the only mineral resource in a race between depletion—which pushes up costs—and new technology, which can increase supply and push costs down. Gold production has been flat for the past decade despite a soaring price (Science, 2 March 2012, p. 1038). Much crystal ball-gazing has considered the fate of world oil production. “Peakists” think the world may be at or near the peak now, pointing to the long run of $100-a-barrel oil as evidence that the squeeze is already on. Mohr’s model is only slightly less pessimistic: It forecasts an oil peak in the late 2030s or early 2040s.

Coal will begin to falter soon after, his model suggests, with production most likely peaking in 2034. The production of all fossil fuels, the bottom line of his dissertation, will peak by 2030, according to Mohr’s best estimate. In the studies Mohr has had a hand in publishing, only lithium, the essential element of electric and hybrid vehicle batteries, looks to offer a sufficient supply through this century. So keep an eye on oil and gold the next few years; copper may peak close behind.

—RICHARD A. KERR

Postpeak options. The price spike at peak copper will drive even more recycling of scrap (above). U.S. pennies used to be pure copper (far left), but now they are copper-plated zinc; substitutions in major uses of copper will be far less satisfactory.