

COMMENT

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An engineer inserts a lithium-ion battery from an electric vehicle into a testing system for recycling.

Ten years left to redesign lithium-ion batteries

Reserves of rare metals used in electric-vehicle cells are dwindling, so boost research on iron and silicon alternatives, urge **Kostiantyn Turcheniuk** and colleagues.

Electric vehicles need powerful, light and affordable batteries. The best bet is commercial lithium-ion cells — they are relatively compact and stable. But they are still too bulky and expensive for widespread use.

The performance of rechargeable lithium-ion batteries has improved steadily for two decades. The amount of energy stored in a litre-sized pack has more than tripled, from around 200 watt hours per litre (Wh l^{-1}) to

more than 700 Wh l^{-1} . Costs have fallen by 30 times, to around US\$150 per kilowatt hour (kWh). But that still exceeds the \$100 per kWh goal for affordability set by the US Department of Energy. And batteries that are powerful enough for an electric car (50–100 kWh) still weigh around 600 kilograms and take up 500 litres of space.

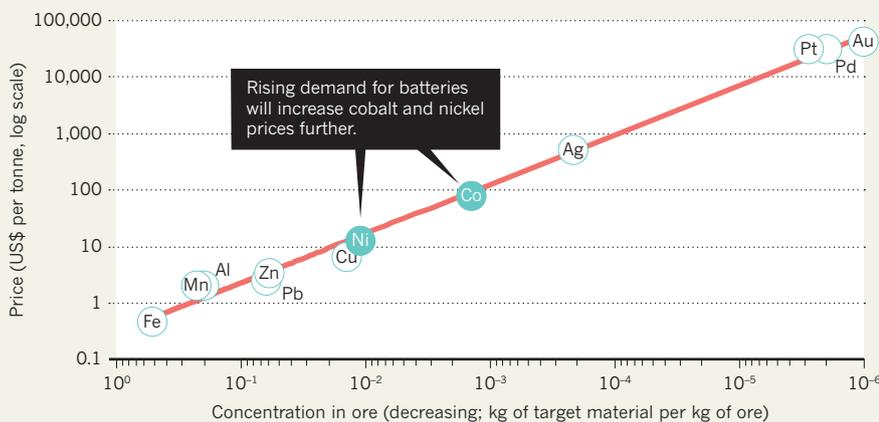
The pace of advance is slowing as conventional technology approaches fundamental limits. The amount of charge that

can be stored in gaps within the crystalline structures of electrode materials is nearing the theoretical maximum. Projected market growth will not lower prices substantially — the markets are already large.

Worse, the materials used in electrodes, notably rare metals such as cobalt and nickel, are scarce and expensive. Surging battery production has almost quadrupled wholesale prices of cobalt over the past two years, from \$22 to \$81 per kilogram. ▶

METAL PRICES

The high cost of extracting metals from low-concentration ores pushes up their market price.



High demand and prices are already encouraging some producers to cut corners and violate environmental and safety regulations. For example, in China, dust released from graphite mines has damaged crops and polluted villages and drinking water¹. In Africa, some mine owners exploit child workers and skimp on protective equipment such as respirators. Small artisanal mines, where ores are extracted by hand, often flout laws. Some companies, including BMW, follow strict policies to verify their cobalt suppliers². Many do not.

Alternative types of electrode based on cheap, common metals such as iron and copper need to be developed urgently. In our view, the most promising candidates involve 'conversion materials,' such as copper or iron fluorides and silicon. These store lithium ions by bonding chemically with them. But the technology is still at an early stage. Problems with stability, charging speed and manufacture must be overcome.

We call on materials scientists, engineers and funding agencies to prioritize the research and development of electrodes based on abundant elements. Otherwise, the roll-out of electric cars will stall within a decade.

SCARCE AND EXPENSIVE

Lithium-ion batteries work by shuffling lithium ions between two electrodes. Ions flowing from the anode to the cathode discharge a current, which powers the car. The lithium ions flow back when the battery is recharged.

In commercial cells used today for electric vehicles, the lithium ions are held in tiny voids within the crystals that make up the electrodes (these are known as intercalation electrodes). The anodes are typically made from graphite and the cathodes from metal oxides. Common oxides include lithium nickel cobalt aluminium oxide (NCA, commonly $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$) or lithium nickel cobalt manganese oxide (NCM, often $\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_2$ or $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$).

A lithium-ion car battery with a 100 kg cathode requires 6–12 kg of cobalt and 36–48 kg of nickel.

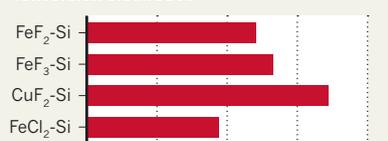
The prices of metals reflect demand, supply and the costs of extracting them from ores. Cobalt is pricey because it is rare and highly sought after. It requires capital-intensive processes to produce it, involving roasting, flash smelting and the consumption of poisonous gases³. Cobalt is often a by-product of copper and nickel mining, and can also need separating from other metals.

Few cobalt mineral deposits are concentrated enough to be worth mining. Most deposits contain just 0.003% of the metal; more than 0.1% is needed to achieve prices of \$100 to \$150 per kg (ref. 4). Production costs jump for poor ores because more rock must be processed (see 'Metal prices'). Thus, only 10⁷ tonnes of cobalt out of 10¹⁵ tonnes potentially available in Earth's crust are profitable to extract⁵. Similarly, only 10⁸ of 10¹⁵ tonnes of nickel reserves are commercially viable⁵.

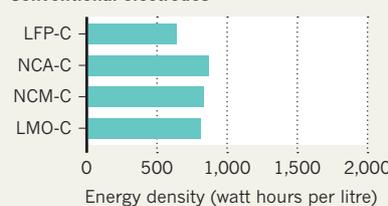
ENERGY ADVANTAGE

Batteries that use conversion electrodes can store more energy in a given unit stack volume than those using conventional electrodes.

Conversion electrodes



Conventional electrodes



C, carbon (graphite); LFP, lithium iron phosphate; NCA, lithium nickel cobalt aluminium oxide; NCM, lithium nickel cobalt manganese oxide; LMO, lithium manganese oxide.

Cobalt-rich minerals are found in just a few places⁶. The Democratic Republic of the Congo (DRC) supplied more than half (56%) of the 148,000 tonnes of the metal mined worldwide in 2015 (ref. 6). Most of this goes to China, which holds stockpiles of 200,000 to 400,000 tonnes⁶. Australia hosts 14% of the world's cobalt reserves but has yet to exploit them fully. Cobalt has been extracted from the deep sea floor, but mining here would be too expensive, ecologically and economically.

Likewise, nickel production is dominated by a dozen nations. In 2017, Indonesia, the Philippines, Canada, New Caledonia, Russia and Australia together supplied 72% of the 2.1 million tonnes mined globally. Of this, less than one-tenth went to batteries; the rest was used mainly in steel and electronics. Nickel is cheaper to extract than cobalt, through a series of reactions with hydrogen and carbon monoxide⁷. Nonetheless, rising demand has boosted nickel prices by about 50% since 2015, from \$9 to \$14 per kg.

Both cobalt and nickel have suffered sudden price hikes and crashes. For example, disrupted Australian supplies, increased demand from China for steel and speculation by hedge-fund managers led to a five-fold surge in the price of nickel and a tripling of that for cobalt in 2008–09.

PROJECTED SHORTFALLS

If nothing changes, demand will outstrip production within 20 years. We expect this to occur for cobalt by 2030 and for nickel by 2037 or sooner.

Car manufacturers and governments project that 10 million to 20 million electric cars will be produced each year by 2025. If each car battery requires 10 kg of cobalt, by 2025, electric vehicles would need 100,000–200,000 tonnes of cobalt per year — most of the world's current production. Similarly, 400,000–800,000 tonnes of nickel would be required annually, or 20–40% of all the metal used today. More would be needed when trucks, buses, aeroplanes and ships become battery-powered.

By 2050, producing 50 million to 80 million electric vehicles a year would require 500,000–800,000 tonnes of cobalt. Beyond 2030, this would far exceed current mining capacities. Similarly, 2–3 times more nickel would be needed by 2050. Nickel shortages would be evident by the mid-2030s.

Recycling cannot replenish supplies. Lithium-ion batteries last for 15–20 years, 3 times longer than the 5–7 years for lead-acid batteries. Refiners might exploit poorer quality ores, especially as prices climb. But greater processing costs would push the prices higher. Once supplies peak, we estimate that the price of an electric car battery could leap by more than \$1,000. 'Peak cobalt' might be delayed by a few years if cathodes can be made using less metal. But



A miner enters a copper and cobalt mine in Kawama, Democratic Republic of the Congo.

cathode materials that use less cobalt, which are under development, degrade quicker and would need to be replaced more often.

ABUNDANT MATERIALS

The answer is to make lithium-ion battery electrodes from common metals, such as iron and copper. A kilogram of iron, for example, costs just 6–9 cents. The global iron reserves stand at 76 billion tonnes: easily enough to supply the billions of batteries that could replace today's petroleum car engines.

Already, Chinese electric buses use conventional cathodes made from iron-rich materials such as lithium iron phosphates (LFPs; LiFePO_4), which can survive many cycles of charging. But they are less efficient at holding charge than cobalt- and nickel-based cathodes (see 'Energy advantage'). Twice as many iron-based cells^{8,9}, at nearly twice the cost, are needed to drive the same distance.

Equally inefficient are commercial electrodes made from another common metal, manganese (such as lithium manganese oxide or LMO, commonly as LiMnO_2 or LiMn_2O_4). Earlier this year, a cathode (based on lithium manganese niobium oxyfluoride) was demonstrated in the lab that could almost match the energy storage capacity of cobalt- and nickel-based materials¹⁰. But a

high voltage is needed to charge it, making it unsafe for use in vehicles.

The most promising alternative, in our view, is to use conversion materials in electrodes. Copper and iron fluorides and silicon react with the lithium ions. A transition metal in a conversion cathode can host up to six times more lithium atoms than one in a standard cathode. Such materials swell more to accommodate the extra lithium atoms. Cell designs must allow for this distortion.

Future anodes are likely to be based on silicon. It is produced from sand and stores nearly ten times more lithium ions by mass than graphite does. Combining conversion cathodes with silicon anodes in the next generation of lithium-ion battery cells could allow cells to store more than twice as much energy as the best conventional ones by volume, and more than three times by weight^{8,9}. Half as many cells would be required to power electric vehicles, also halving costs, weight and volume.

Silicon-anode technology is advancing. Tesla already uses small amounts of silicon in anodes made of graphite for lithium-ion cells in its electric vehicles, and BMW announced plans to incorporate silicon-dominant anodes in its future electric vehicle batteries. Other companies, too, are

developing silicon-rich anode materials. These include the Californian firms Enevate in Irvine, Enovix in Fremont and Sila Nanotechnologies in Alameda (G.Y. is a board member, shareholder and chief technology officer of Sila Nanotechnologies).

Metal fluoride cathode technology has yet to move beyond the lab⁹. Conversion-type batteries can take 20 hours to power up; this needs to be reduced to tens of minutes. They also require up to one-third more energy to charge; this should be no more than 10%. And their stability needs to be improved, from 5–500 cycles to 1,000–2,000 cycles.

Undesirable interactions need to be minimized between conversion materials and electrolyte substances. And the microstructures and compositions of electrodes and electrolytes must be optimized. New architectures need to be explored that contain the swelling and shrinkage of electrodes while maintaining their conductivity.

NEXT STEPS

Several technological breakthroughs are needed to secure the future of affordable battery-powered transport.

First, cell performance needs to improve. Materials scientists need to produce high-performance fluoride materials for the ▶

▶ electrodes. Electrochemists should develop more-effective electrolytes. Engineers need to develop tools for manufacturing these materials.

Government agencies and leading car manufacturers should fund this research, which will require billion-dollar investments. In our view, the best way to apportion this money is by targeting projects addressing key battery challenges, as the US Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) does. Developing batteries free from cobalt and nickel should be one priority.

As promising battery materials and cell technologies emerge, funding should be refocused towards improving their characteristics and viability. Production processes and costs must be addressed. We expect that synthesizing conversion electrode materials will require different steps, including forming certain nanoscale structures. Treatments involving series of solutions and gases, for example, might be borrowed from other sectors such as food, pharmaceuticals, filtration and composite manufacturing.

Lithium-ion battery manufacturers have already invested billions of dollars in dozens of 'giga-factories' to boost the electric-vehicle market. With co-ordination, thought and planning, these can be set on a new path to deliver the next generation of affordable batteries. ■

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Pet genomics medicine runs wild

Genetic testing for dogs is big business. It is too easy for companies to sell false hope, warn **Lisa Moses, Steve Niemi** and **Elinor Karlsson**. They call for regulation.

Last year, a 13-year-old dog, let's call her Petunia, started having trouble walking and controlling her bladder and bowels. Distressed, her owners bought a US\$65 genetic test through a direct-to-consumer (DTC) company. It suggested that the pug carried a mutation that is linked to a neurodegenerative condition similar to the human disease amyotrophic lateral sclerosis (ALS, or motor neurone disease).

What published data there are^{1,2} suggest that as few as 1 in 100 dogs that test positive for this common mutation will develop the very rare disease, and Petunia's condition was also consistent with more-treatable spinal disorders. But her owners chose to put her to sleep, convinced that she would otherwise suffer progressive and irreversible paralysis and eventual death.

Genetic testing for pets is expanding. Hundreds of thousands of dogs have now been genetically screened, as Petunia was, and companies are beginning to offer tests for cats. But the science is lagging. Most of these tests are based on small, underpowered studies. Neither their accuracy nor their ability to predict health outcomes has been validated. Most vets don't know enough about the limitations of the studies, or about genetics in general, to be able to advise worried owners.

Pet genetics must be reined in. If not, some companies will continue to profit by selling potentially misleading and often inaccurate information; pets and their owners will suffer needlessly; and opportunities to improve pet health and even to leverage studies in dogs and cats to benefit human health might be lost. Ultimately, people will become more distrustful of science and medicine.

WEAK SCIENCE

Global spending on pets has grown by 14% over the past 5 years (see 'Animal lovers'), and worldwide annual spending on pet care is currently estimated to be about \$109 billion.

Genetics is one of the newest additions to this booming industry. Worldwide, at least 19 laboratories are now marketing genetic-testing products. Some vets use the results to help to diagnose sick pets, or to recommend that healthy ones be subject to expensive and sometimes invasive tests, such as bone-marrow biopsies. Some dog breeders use the tests to try to reduce the incidence of inherited diseases. At least one US veterinary hospital chain is now recommending genetic testing for all dogs, saying that the results allow "individualized healthcare" and can guide behavioural training.

We believe that three major problems plague pet genetic testing in its current state.

Lack of validation. In both humans and animals, mapping genetic variants to risk of disease is incredibly challenging. But most dog genetic tests are based on studies of candidate genes, which is a problematic approach. In such studies, researchers test a handful of human or animal genes for mutations that both match an expected inheritance pattern and seem likely to be pathogenic, for instance because they affect the structure of an expressed protein.

In humans, fewer than 2% of candidate-gene studies have stood up³ to further investigations using more-advanced methods, such as genome-wide association studies. As a result of these shortcomings, geneticists who study humans must now bring more evidence to designate a genetic variant as 'disease-causing'. Through collaborative efforts involving industry, academia, physicians and patients, every clinical variant identified is now scored on a five-point scale, from 'pathogenic' to 'benign'^{4,5}. (Clinical variants are those that are linked to medically important phenotypes.)

No such careful reassessment has occurred in veterinary medicine. Many of the 200 tests offered by companies are based on only a single small candidate-gene study (see, for example, go.nature.com/2nqntx).