

and, by the time she returns, the cancer has advanced considerably, and she dies.

This fictional scenario ends in much the same way as it did in reality, as those familiar with Lacks's story know well (5–7). But rather than getting assessed by a seemingly race-neutral algorithm applied to all patients in a colorblind manner, she was admitted into the Negro wing of Johns Hopkins Hospital during a time when explicit forms of racial discrimination were sanctioned by law and custom—a system commonly known as Jim Crow. However, these are not two distinct processes, but rather Jim Crow practices feed the “New Jim Code”—automated systems that hide, speed, and deepen racial discrimination behind a veneer of technical neutrality (1).

Data used to train automated systems are typically historic and, in the context of health care, this history entails segregated hospital facilities, racist medical curricula, and unequal insurance structures, among other factors. Yet many industries and organizations well beyond health care are incorporating automated tools, from education and banking to policing and housing, with the promise that algorithmic decisions are less biased than their human counterpart. But human decisions comprise the data and shape the design of algorithms, now hidden by the promise of neutrality and with the power to unjustly discriminate at a much larger scale than biased individuals.

For example, although the Fair Housing Act of 1968 sought to protect people from discrimination when they rent or buy a home, today social media platforms allow marketers to explicitly target advertisements by race, excluding racialized groups from the housing market without penalty (8). Although the federal government brought a suit against Facebook for facilitating digital discrimination in this manner, more recently the U.S. Department of Housing and Urban Development introduced a rule that would make it harder to fight algorithmic discrimination by lenders, landlords, and others in the housing industry. And unlike the algorithm studied by Obermeyer *et al.*, which used a proxy for race that produced a racial disparity, targeted ads allow for explicit racial exclusion, which violates Facebook's own policies. Yet investigators found that the company continued approving ads excluding “African Americans, mothers of high school kids, people interested in wheelchair ramps, Jews, expats from Argentina and Spanish speakers,” all within minutes of an ad submission (8). So, whether it is a federal law or a company policy, top-down reform does not by itself dampen discrimination.

Labels matter greatly, not only in algorithm design but also in algorithm analysis. Black patients do not “cost less,” so much as

they are valued less (9). It is not “something about the interactions that Black patients have with the healthcare system” that leads to poor care, but the persistence of structural and interpersonal racism. Even health care providers hold racist ideas, which are passed down to medical students despite an oath to “do no harm” (10). The trope of the “non-compliant (Black) patient” is yet another way that hospital staff stigmatize those who have reason to question medical authority (11, 12). But a “lack of trust” on the part of Black patients is not the issue; instead, it is a lack of trustworthiness on the part of the medical industry (13). The very designation “Tuskegee study” rather than the official name, U.S. Public Health Service Syphilis Study at Tuskegee, continues to hide the agents of harm. Obermeyer *et al.* mention some of this context, but passive and sanitized descriptions continue to hide the very social processes that make their study consequential. Labels matter.

As researchers build on this analysis, it is important that the “bias” of algorithms does not overshadow the discriminatory context that makes automated tools so important in the first place. If individuals and institutions valued Black people more, they would not “cost less,” and thus this tool might work similarly for all. Beyond this case, it is vital to develop tools that move from assessing individual risk to evaluating the production of risk by institutions so that, ultimately, the public can hold them accountable for harmful outcomes. ■

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BATTERY TECHNOLOGY

The coming electric vehicle transformation

A future electric transportation market will depend on battery innovation

By **George Crabtree**^{1,2}

Electric vehicles are poised to transform nearly every aspect of transportation, including fuel, carbon emissions, costs, repairs, and driving habits. The primary impetus now is decarbonization to address the climate change emergency, but it soon may shift to economics because electric vehicles are anticipated to be cheaper and higher-performing than gasoline cars. The questions are not if, but how far, electrification will go. What will its impact be on the energy system and on geoeconomics? What are the challenges of developing better batteries and securing the materials supply chain to support new battery technology?

The signs of vehicle electrification are growing. By 2025, Norway aims to have 100% of its cars be either an electric or plug-in hybrid unit, and the Netherlands plans to ban all gasoline and diesel car sales by the same year. By 2030, Germany plans to ban internal combustion engines, and by 2040, France and Great Britain aim to end their gasoline and diesel car sales. The most aggressive electric vehicle targets are those set by China, which has almost half the global electric vehicle stock and where 1.1 million electric vehicles were sold in 2018. Europe and the United States each have just over 20% of the global stock, with electric car sales of 380,000 and 375,000 units, respectively, in 2018 (1, 2).

How far electrification will go depends primarily on a single factor—battery technology. In comparing electric with gasoline vehicles, all the downsides for electric arise from the battery. Purchase price, range, charging time, lifetime, and safety are all battery-driven handicaps. On the upside, electric vehicles have lower greenhouse gas emissions, provided the electricity grid that supports them is powered by renewable energy [the renewable share of global electricity is up from 22% in 2001 to 33% today (3), with Europe at 36%, China at 26%, and



An electric car in Milan, Italy, gets a charge. Grid-connected renewable energy systems, improved energy storage, and new battery technology will accelerate the electrification of transportation.

the United States at 18% (4)]. Moreover, the operation and maintenance costs of electric vehicles are substantially lower than for gasoline cars. Today, for high-mileage cars such as taxis, which typically travel 70,000 miles/year, the total cost of ownership of an electric vehicle, including purchase price, insurance, fuel, and maintenance, is much lower than for a gasoline car. This means that government and commercial fleets used for local service likely will convert to electric to save money, a major step in the electrification trajectory. To reach cost parity with personal gasoline cars, which typically travel 12,000 to 15,000 miles/year, battery prices must decline to near \$100/kWh from the present value of \$180 to \$200/kWh. Projections of the year of cost parity for electric vehicles with gasoline cars globally range from 2022 to 2026 (5, 6). At that point, economics could well take over as the primary impetus for electrification, and electric vehicles would then be on a path to transportation dominance.

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IMPACT ON ENERGY SYSTEM

Electric vehicles will need to be charged from the grid, which may create as much as a 20 to 38% increase in electricity demand by 2050 (7). In developed countries, this should provide revenue for utilities to accelerate transformation to a grid-connected renewable energy system with extensive energy storage and to digital energy management. In developing countries, the increased electricity demand could spur the first-time installation of modern grids that are unencumbered by the legacy of the older, less functional grids of the developed world. Beyond electricity, electric vehicles require a massive rollout of charging stations, which could stimulate local economic and job growth.

Electric vehicles also should bring a welcome flexibility to the energy system. Untied from oil and gasoline, they would run on whatever powers the grid—sunlight, wind, natural gas, nuclear power, or hydropower. This removes a fundamental dependence of transportation on oil, including substantial amounts of foreign oil in many countries. Electricity is fundamentally a local prod-

uct, not amenable to long-distance trade, so domestic economies should reap the economic and job benefits now held by foreign oil interests. The unification of transportation with electricity creates new horizons of opportunity for the grid as well. Electric vehicles are a readily available distributed energy resource of at least 1000 GWh, which represents 10% of the battery capacity of 100 million vehicles, each with a 100-kWh battery. The potential of this distributed energy resource for demand response and for grid storage has not yet been seriously explored.

IMPACT ON GEOECONOMICS

The electrification of transportation is a watershed moment in energy economics. For more than a century, oil has been the lifeblood of transportation, and the oil industry has grown steadily as transportation has expanded with industrialization and rising standards of living. But oil is abundant in relatively few countries, and these countries assume outsized geoeconomic importance because oil for transportation is a critical societal need. By contrast, sunlight and wind are available everywhere, and electric-

ity generation is mostly a domestic enterprise. The electrification of transportation means that oil will lose one of its critical markets—and with it some of its international economic and political power.

What will replace oil as the lifeblood of transportation? The electrification of transportation creates a new commodity—not electricity, which is already established and abundant around the world, but battery technology. The battery is the key to electric transportation, the focal point for progress, and the open opportunity to determine the future of electric vehicles. Battery innovation is needed to achieve lower purchase price, faster charging, longer range, extended lifetime, and greater safety. These challenges do not yet have obvious solutions, but those who discover them will have substantial power in the battery marketplace.

BATTERY DEVELOPMENT

One of the most promising and disruptive battery innovations is the combination of lithium metal anodes and solid-state electrolytes. Every atom of a lithium metal anode can store and release energy during the charge-discharge cycle, whereas in graphite anodes now used in lithium-ion batteries, only 14% of the atoms (one lithium for every six carbons) can store or release energy. The greater capacity of the lithium metal anode could approximately double the energy density of the lithium-ion battery, extending the driving range of electric vehicles to compete with gasoline cars.

Solid-state electrolytes bring several advantages to lithium-ion batteries (8). They are not flammable, eliminating the primary safety hazard of lithium-ion batteries—the thermal runaway reaction that causes batteries to burst into flames if their temperature exceeds about 150°C. Some solid-state electrolytes, including sulfides such as $\text{Li}_2\text{S-P}_2\text{S}_5$ (LPS) and garnets such as $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ (LLZO), have high lithium-ion conductivity at room temperature, enabling the high-power performance needed for fast charging. Solid-state electrolytes conduct heat better than liquid electrolytes, protecting against the development of “hot spots” that trigger degradation and shorten battery life. In addition, the mechanical rigidity of solid-state electrolytes can block the growth of dendrites that form on the lithium metal anode surface and grow across liquid electrolytes to the cathode, shorting out the battery. These benefits of solid-state electrolytes are balanced by still-unresolved research challenges, including narrow working voltage windows, high reactivity with lithium anodes, and long-term stability.

There is now an intense drive to develop lithium metal anodes and solid-state

electrolytes spanning academic, government, and industrial laboratories. Toyota announced its intention to have batteries with lithium anodes and solid-state electrolytes ready for electric vehicles by the early 2020s (9). The combination of lithium metal anodes with solid-state electrolytes would mark the first disruptive step in lithium-ion battery development, breaking a three-decade pattern of steady incremental advances in performance and cost (10).

MATERIAL SUPPLY CHAINS

Lithium, cobalt, manganese, nickel, and graphite are essential for battery technology, and some of these elements are found in only a few places in the world, not unlike oil (11, 12). The expected rapid increase in electric vehicle sales could threaten the supply chains for lithium, cobalt, and graphite in the short term because of the time required to ramp up new materials production and the relative scarcity of geographic sources. In the longer term, there are adequate resources in Earth's crust if lithium-ion batteries are recycled. Currently, less than 5% of Li-ion batteries are recycled, compared to more than 99.5% of lead-acid batteries. (13) Research and development to develop Li-ion battery recycling technology is an urgent need.

Batteries and their supply chains are the new oil; leadership in the battery and electric vehicle market requires strategically securing not only battery technology but also the battery materials supply chain. Recycling can play a substantial role in securing the supply chain for lithium-ion batteries, lowering costs by as much as 20% and supplying as much as 50% of the required materials (12). The nation or region that leads battery technology and secures its supply chain will have outsized influence on geoeconomics and world development.

GLOBAL LANDSCAPE

Europe has grasped the electric vehicle opportunity, driven by its strict carbon emission requirements for future vehicles. The United States, by contrast, has proposed weakening its carbon emission requirements, and target dates for electrification of transportation are correspondingly farther out. In the International Energy Agency's New Policy Scenario (1), electric vehicles are projected to reach 26% of new car sales in Europe by 2030, but only 8% in the United States. China slightly leads Europe, with a 28% share of electric vehicles in 2030. In addition, China has moved strategically to secure its battery supply chain (11, 12). China now has the largest electrical vehicle market and the largest battery manufacturing enterprise in the world, amounting to 60% of the global capacity (14). It is well posi-

tioned to benefit economically and politically from the coming global electrification of transportation.

The electrification of transportation is far from complete. Buses, long-haul trucking, air taxis, and regional flight (15) remain relatively untapped opportunities. Batteries still must overcome challenges in cost, range, charging speed, safety, and lifetime for electric vehicles to dominate the market. Recycling is critical to sustainable supply chains but is still in its infancy. There are enormous opportunities for innovation in discovering solutions to these fundamental challenges. The innovating countries and regions will reap enduring economic and geopolitical benefits. ■

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