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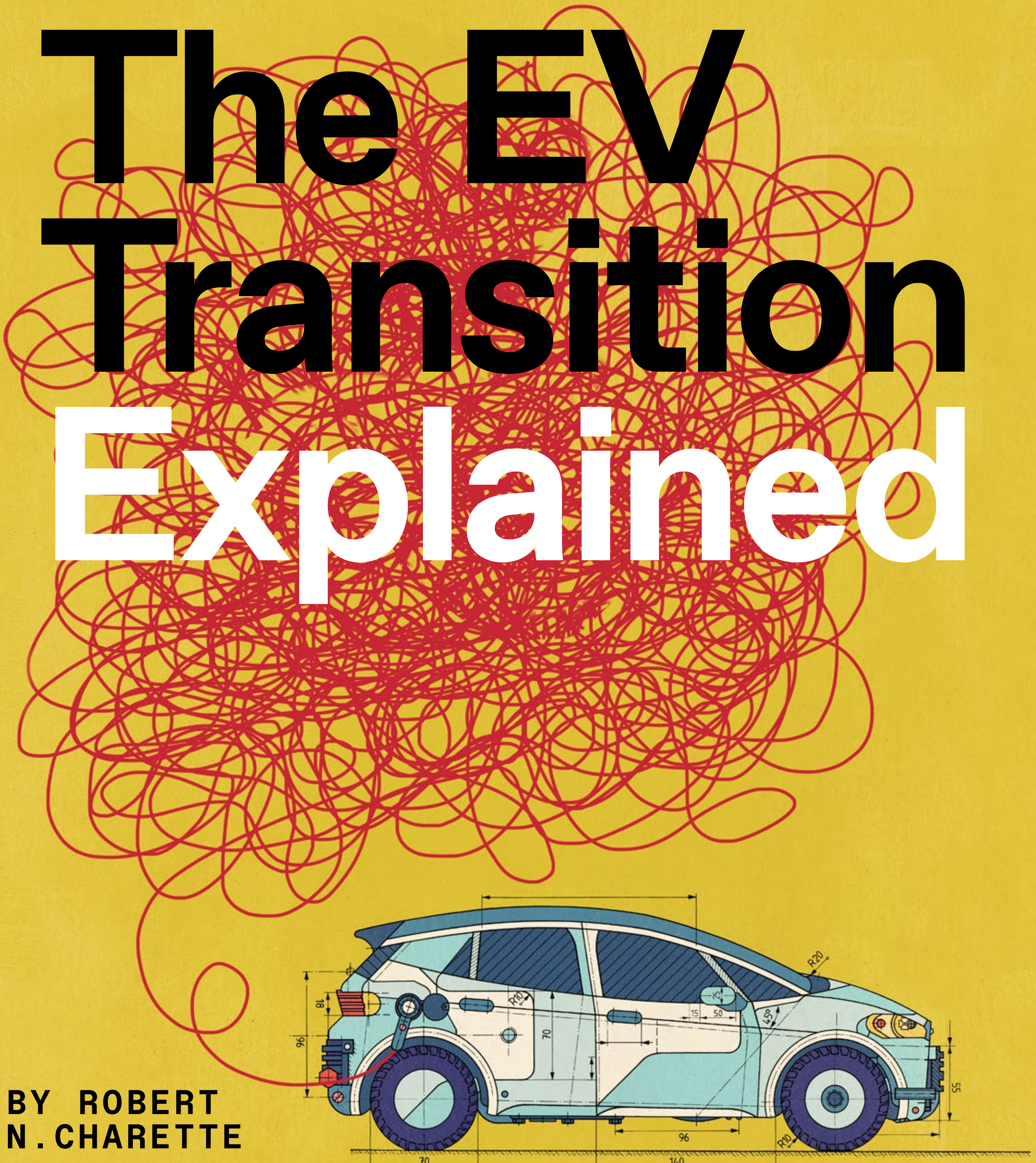
The EV Transition Explained



BY ROBERT N. CHARETTE

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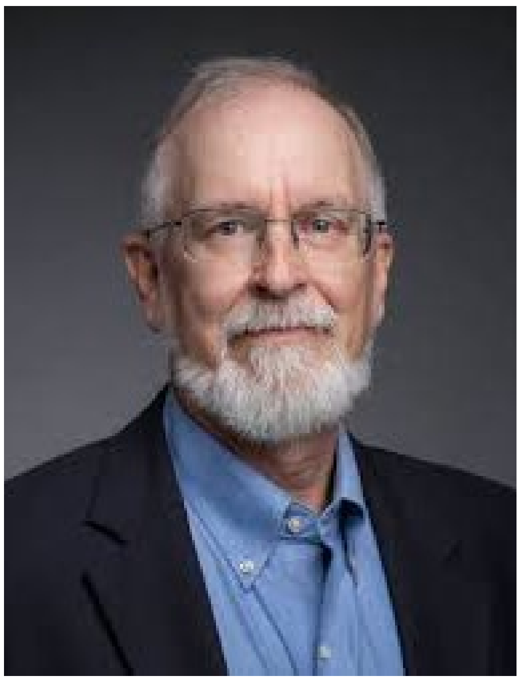
Cover illustration by Christian Gralingen.
This page: Toru Hanai/Bloomberg/Getty Images

Preface: The Staggering Scale of the EV Transition

One engineer's quest to wrap his mind round the challenges ahead

OVER THE LAST 20 OR SO YEARS, contributing editor Robert N. "Bob" Charette has written about some of the thorniest issues facing the planet at large and engineers in particular. For *IEEE Spectrum*, he's dug into software reliability and maintenance, the so-called STEM crisis, and the automation paradox, examining those complex topics through the eyes of a seasoned risk analyst who has consulted for governments and corporations for five decades. I've been fortunate to be Bob's editor for many of his ambitious projects. We often converse on Friday afternoons about what he's hearing from industry insiders and academics on whatever subject he's currently investigating. Our conversations are jovial, sometimes alarming, and always edifying, at least for me.



So when he called me on a Friday afternoon in the summer of 2021 to propose an article delving into the complexities of the global transition to electric vehicles, I knew that he'd do the research at a deeper level than any tech journalist, and that he'd explore angles that wouldn't even occur to them. Take power-grid transformers. These essential voltage-converting components are designed to cool down at night, when power consumption is typically low. But with more people charging their EVs at home at night, the 30-year design life of a transformer will drop—to perhaps no more than three years once mass adoption of EVs takes hold. Transformers can cost more than US $20,000 each, and they're already in short supply in many countries. Bob examined factors like that and dozens of others during the last year and a half. Throughout his research and reporting, Bob focused on the EV transition "at scale": What needs to happen in order for electric vehicles to displace internal-combustion-engine vehicles and have a measurable impact on climate change by midcentury? Quite a lot, it turns out. Humans must change two foundational sectors of modern civilization—energy and transportation—to achieve the targeted reductions in greenhouse gas emissions. These simultaneous global overhauls will involve trillions of dollars in investments, tens of millions of workers, millions of new EVs, tens of thousands of kilometers of new transmission lines to carry electricity from countless new wind and solar farms, and dozens of new battery plants and new mines to feed them. Then there are the lifestyle compromises that most people living in developed countries will have to make.

"As always, Bob approached this tangle of issues from a systems engineering perspective."

As always, Bob approached this tangle of issues from a systems engineering perspective. For a typical assignment, his first draft runs to thousands of words over the assigned length, and we manage to chisel the manuscript down to a single feature article, often leaving a lot of interesting material on the cutting-room floor. This time, we decided to let Bob go long, so he could paint as detailed a picture as possible of a fast-moving and multifaceted target. The process was kind of like building an EV while driving it. As Bob's editor, my job was to help him synthesize his findings into a snapshot of the EV industry at a pivotal moment in history. Every Friday, we'd discuss some new announcement or jaw-dropping data point that needed to find its way into what I came to call The Opus. As Bob talked to more people and read more policy documents, research reports, and public-meeting minutes, the assignment went from two or three articles to twelve, covering the technological hurdles, policy battles, and consumer attitudes surrounding the EV transition. The Opus is now an e-book, *The EV Transition Explained*, the introduction to which you can read on page 40. The e-book itself is available for download exclusively for IEEE members via our website or the QR code at the end of the article. Bob's hope, and ours, is that policymakers, auto-industry executives, engineers, and consumers will use his analysis to inform their discussions and decisions about the best ways to transition to EVs—at scale. ■

Introduction: The EV Transition Is Harder Than Anyone Thinks

Clueless policymakers, skeptical consumers, greedy automakers—and the tech isn't ready either

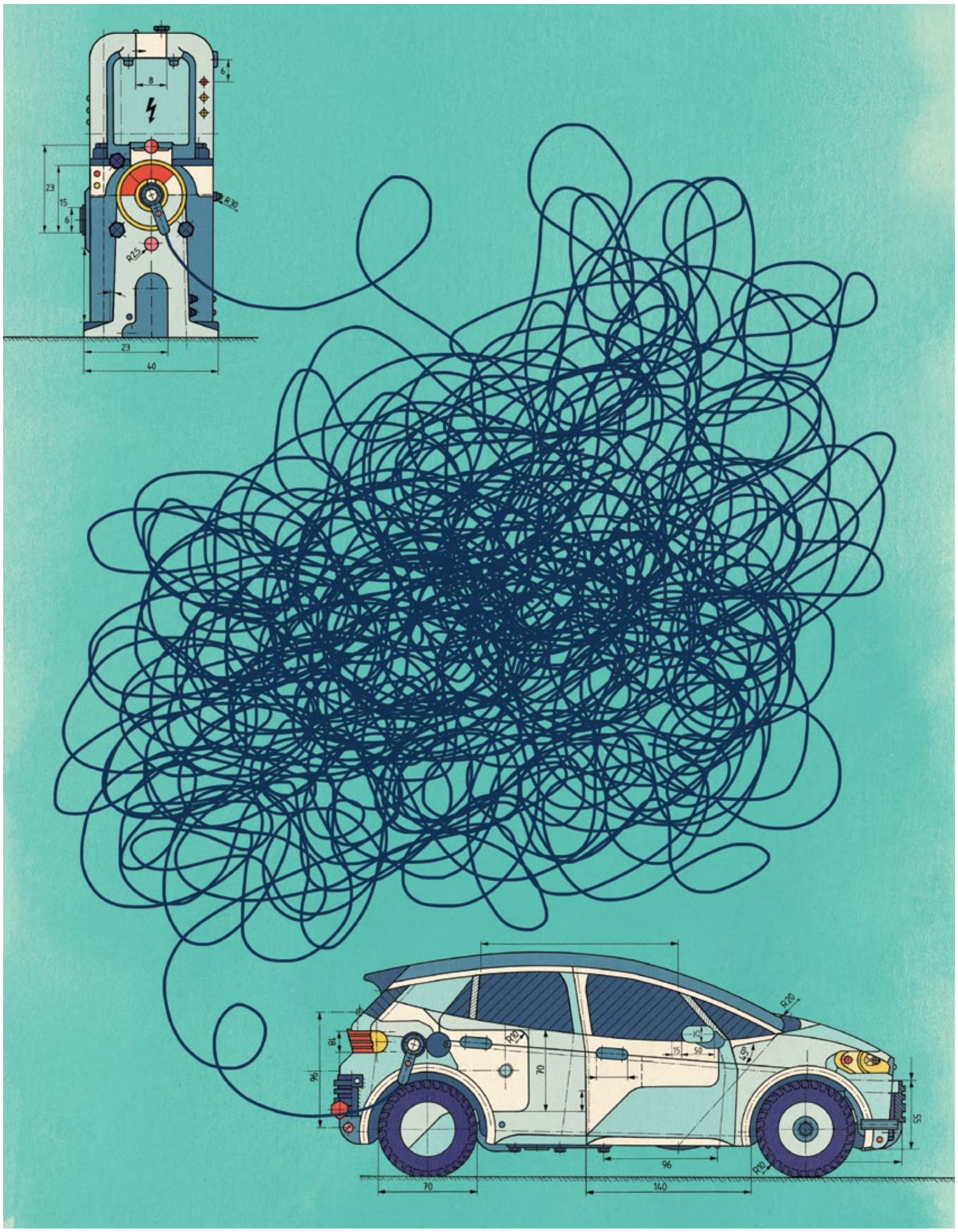


Illustration by Christian Gralingen

VOLVO CARS CEO JIM ROWAN boldly proclaims that electric vehicles will reach price parity with internal-combustion-engine (ICE) vehicles by 2025. Not likely, counter Mercedes-Benz's chief technology officer Markus Schäfer and Renault Group CEO Luca de Meo.

The International Energy Agency predicts that EVs will make up more than 60 percent of vehicles sold globally by 2030. But given the sheer tonnage of lithium, cobalt, and other raw materials needed for EV batteries, that figure is overly optimistic, suggests the mineral market analysis company Benchmark Mineral Intelligence, unless nearly 300 new mines and supporting refineries open by then.

EV owners should be urged to charge at night to save not only money and the power grid but "the world," a news headline cries out. Not so fast, exclaim researchers at Stanford University, who state that charging EVs during the day is actually cheaper, better for the grid, and healthier for the environment.

And so goes the litany of contradictory statements about the transition to EVs:

EVs will/will not collapse the electric grid.

EVs will/will not cause massive unemployment among autoworkers.

EVs will/will not create more pollution than they eliminate.

Confused? Join the crowd.

Sorting through this contradictory rhetoric can make anyone's head spin. My response to each proclamation is often a shrug followed by "It depends."

Two years ago, I began investigating the veracity of claims surrounding the transition to EVs at scale. The result is a 12-part series and e-book, *The EV Transition Explained*, that explores the tightly woven technological, policy, and social issues involved. The articles are based on scores of interviews I conducted with managers and engineers in the auto and energy industries, as well as policy experts, academic researchers, market analysts, historians, and EV owners. I also reviewed hundreds of reports, case studies, and books surrounding EVs and electrical grids.

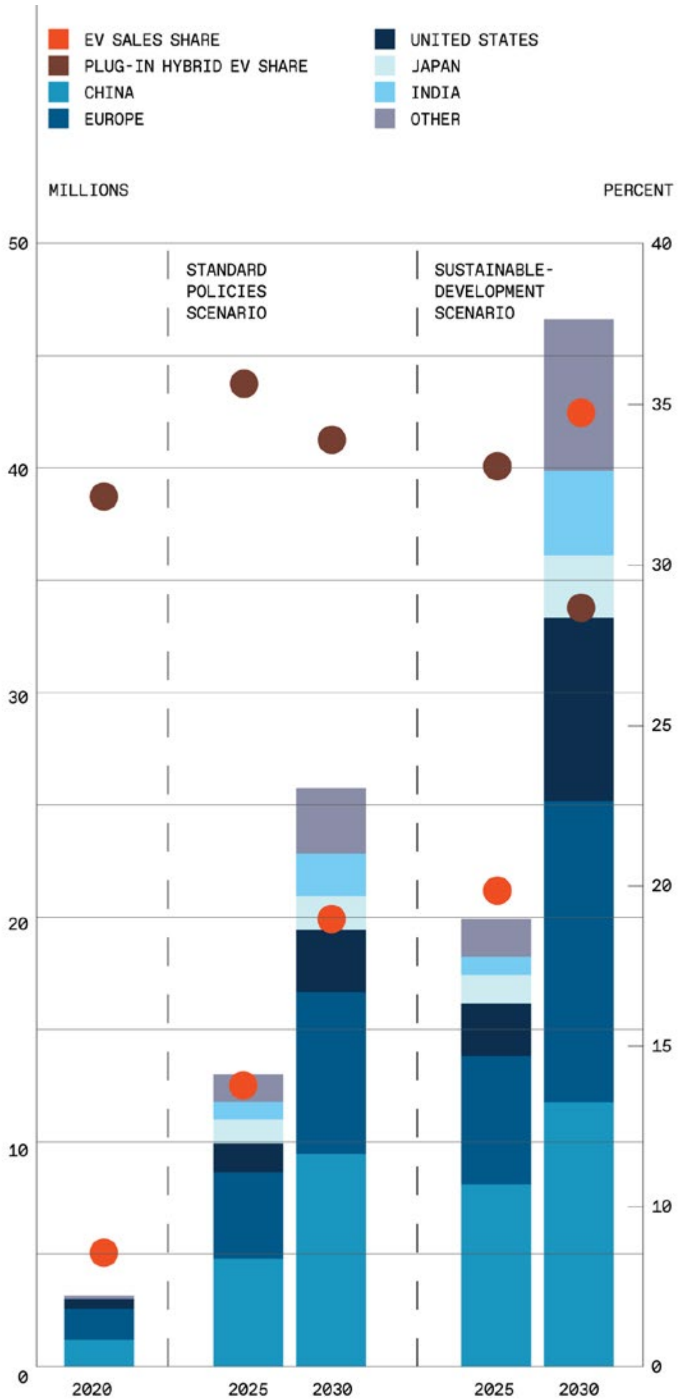
What I found is an intricately tangled web of technological innovation, complexity, and uncertainty, combined with equal amounts of policy optimism and dysfunction. These last two rest on rosy expectations that the public will quietly acquiesce to the considerable disruptions that will inevitably occur in the coming years and decades. The transition to EVs is going to be messier, more expensive, and take far longer than the policymakers who are pushing it believe.

Scaling is hard

LET ME BE VERY CLEAR: Transitioning to electric vehicles and renewable energy to combat climate change are valid goals in themselves. Drastically reducing our fossil-fuel use is key to realizing those goals. However, attempting to make such transitions *at scale* in such a short period is fraught with problems, risks, and unanticipated consequences that need honest and open recognition

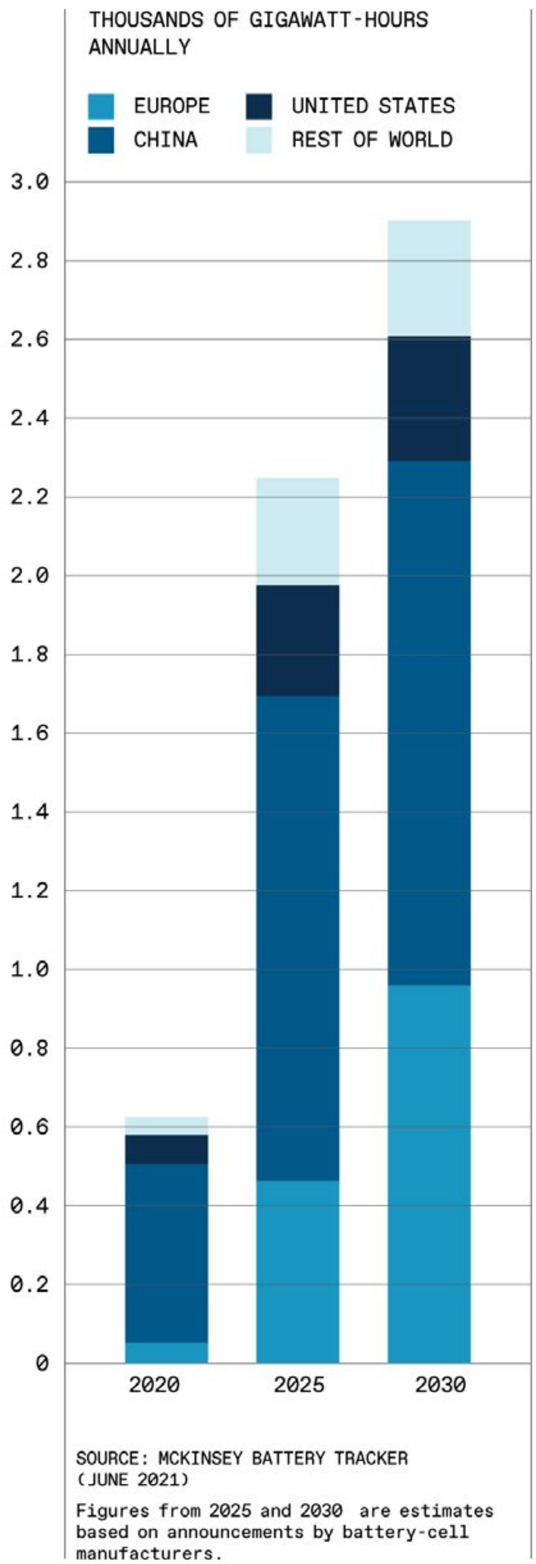
GLOBAL ELECTRIC-VEHICLE SALES BY SCENARIO, 2020-2030

The International Energy Agency's Global EV Outlook 2021 shows 2020 electric-vehicle sales [left column], projected EV sales under current climate-mitigation policies [middle], and projected sales under accelerated climate-mitigation policies [right].



BATTERY-CELL PRODUCTION CAPACITY

This McKinsey & Co. battery tracker from June 2021 shows where batteries are being produced currently and at what volume and where their production is projected to be by the end of the decade. Figures from 2025 and 2030 are estimates based on announcements by battery-cell manufacturers.



Portrait by Christian Gralingen

so they can be actively and realistically addressed. Going to scale means not only manufacturing millions of EVs per year but supporting them from recharging to repair.

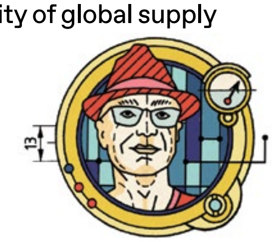
A massive effort will be needed to make this happen. For example, in January 2023 the sales of EVs in the United States reached 7.83 percent of new light-duty vehicle sales, with 66,416 battery-electric vehicles (BEVs) and 14,143 plug-in hybrid vehicles (PHEVs) sold. But consider that also in January, some 950,000 new ICE light-duty vehicles were sold, as well as approximately another 3 million used ICE vehicles.

Transforming the energy and transportation sectors simultaneously will involve a huge number of known and unknown variables, which will subtly interact in complex, unpredictable ways. As EVs and renewable energy scale up, the problems and the solutions will cover ever-expanding populations and geographies. Each proposed solution will probably createnew difficulties. In addition, going to scale threatens people's long-held beliefs, ways of life, and livelihoods, many of which will be altered, if not made obsolete. Technological change is hard, social change even harder.

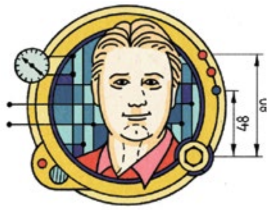
And yet, the rush to transition to EVs is logical. Parts of the world are already experiencing climate-change-related catastrophes, and governments around the world have pledged to act under the Paris Agreement to limit global temperature rise to 1.5 °C above preindustrial levels. This agreement requires the reduction of greenhouse gases across all industrial sectors. Transportation is one of the largest contributors of GHG emissions worldwide, and many experts view replacing ICE vehicles with EVs as being the quickest and easiest way to reach the target of net-zero carbon emissions by 2050.

However, shifting a 125-year-old auto industry that's optimized for ICE-vehicle production to EVs using nascent technology is a monumental challenge in itself. Requiring that automakers do so in 15 years or less is even more daunting, although part of it is their own doing by not recognizing earlier thatEVs might be a threat to their business models. EVs require automakers and their suppliers to reinvent their supply chains, hire employees with new software, battery, and mechatronic skill sets, and retrain or else lay off workers whose outdated skills are no longer needed.

"[GOVERNMENT POLICYMAKERS assume] that they can incentivize the supply and demand of EVs while paying relatively less attention to the capacity of global supply chains to produce them, along with the energy conversion complex needed to power them. Shifting the auto industry, an apex industry supporting a host of others, to meet a new knowledge economy around EVs will be no easy task."

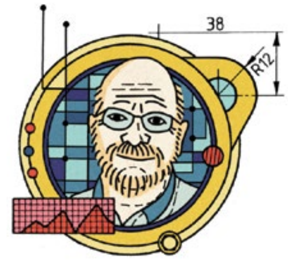


MATTHEW N. EISLER, lecturer at the University of Strathclyde, in Scotland, and a historian and EV expert whose new book is called *Age of Auto Electric*



"WHILE I HAVE often spoken of my concern about the electrical capacity demands required for a significant adoption of EVs, [Charette's] series highlights the many different factors that must change for EVs to be successful. The urgent need to upgrade and increase the number of electric transformers the series discusses, for example, is rarely spoken about."

ALEXANDER EDWARDS, president of Strategic Vision, a research consultancy that analyzes how consumers perceive EVs



"CURRENTLY, THE CADENCE and sequencing of EV policies and engineering activities are out of whack. This creates a concatenation of costly challenges that turns everything you touch into a Pandora's box."

University of Michigan public-policy expert **JOHN LESLIE KING**

Portraits by Christian Gralingen

The articles in the series address different aspects of this transition, including EV-related unemployment, battery issues, the EV charging infrastructure, and affordability. One not entirely surprising finding is that the traditional automakers are electrifying their offerings while also squeezing the last bit of profit from their gas guzzlers. That is, they are introducing less-expensive EV models, but their main thrust is still on producing profitable luxury EV models that are well beyond the means of the average household while also pushing sales of profitable fossil-fuel-powered SUVs.

EVs are not just a technology change

ELECTRIC VEHICLES are more than just a new technology for combating climate change. In the United States, for instance, policymakers view EVs as the tip of the spear for a vast program of government-directed economic nationalism—the economic, environmental, and societal change aimed at completely reshaping the nation's US $26 trillion economy away from fossil fuels. They see normal market forces as inadequate to meet the imposed climate deadlines. Hence, with the Biden administration's encouragement, ICE-vehicle sales will be banned in 2035 in California and several other states. In the series, I scrutinize several such EV policies and take a look at the roadblocks that could derail them, such as inadequately sized pole transformers and the failure to issue permits for new electricity transmission lines.

The United States is not alone in seeing EVs as an economic driver, of course. Worldwide, nearly 60 countries are now imposing similar ICE-vehicle sales bans. This has forced EVs into yet another role: as a cudgel to be wielded in the fierce geopolitical competition for economic advantage. For China, Japan, the United Kingdom, the European Union, and the United States, EVs are the vehicle needed to "win the future of transportation and manufacturing." Consider the reactions to the recent change in U.S. EV subsidy policy, which aims to boost domestic EV manufacturing and energy security. The decision deeply angered other countries and is sparking moves to counter it.

EVs alone aren't sufficient to meet carbon-reduction targets, which means enormous lifestyle changes for many of us, as we try to do our part to combat climate change. People will need to drive and fly less, walk and bike more, and take public transportation. We'll need to switch to a more plant-based diet and convert household appliances powered by fossil fuels to electricity, to name only a few looming adjustments. People's willingness to accept these changes and their ability to implement them will be crucial to our success at adapting to climate change and mitigating its impacts.

The introduction of any new system spawns perturbations that create surprises, both wanted and unwanted. We can safely assume that quickly moving to EVs at scale will unleash its fair share of unpleasant surprises, as well as prove the adage of "haste makes waste."

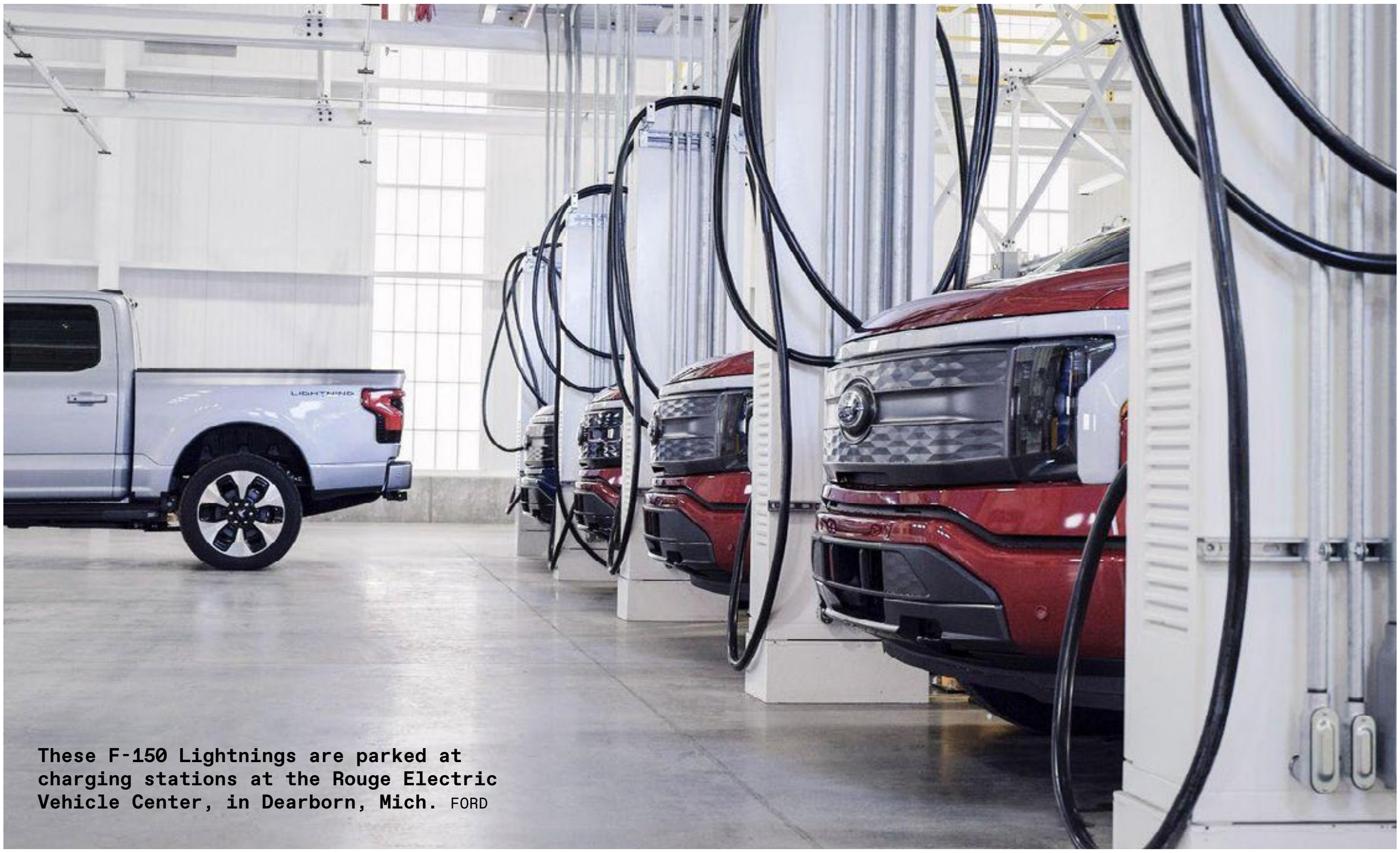
Take a systems-engineering approach

WHAT STRUCK ME most in writing the series was that the EV transition is incredibly fluid. Major changes in transportation and energy policy, battery technology, and automakers' strategies are announced nearly daily, highlighting the many uncertainties. Given the geopolitical nature of the transition, these uncertainties will only increase.

These rapid changes also show the fragility of the transition. The desperate pleas from automakers for more government subsidies is not reassuring. Tesla's recent price cuts, for instance, have thrown the auto industry into turmoil. Neither is a sign of a market that is sure of itself or its future.

This fragility is also obvious when you examine the overly optimistic assumptions and the many caveats buried in EV and energy-policy recommendations. Many things need to go exactly right, and very little can go wrong for the EV transition to transpire as planned. At times like these, I'm reminded of Nobel Prize–winning physicist Richard Feynman's admonishment: "For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."

There is a cacophony of foolishness being spouted by those advocating for the EV transition and by those denouncing it. It is time for the nonsense to stop, and some realistic political and systems thinking to begin. ■



These F-150 Lightnings are parked at charging stations at the Rouge Electric Vehicle Center, in Dearborn, Mich. FORD

Chapter One

Overview

A deep dive into the engineering challenges of making and supporting electric vehicles at scale

FROM THE OUTSIDE, there is little to tell a basic Ford XL ICE F-150 from the electric Ford F-150 Lightning Pro. Exterior changes could pass for a typical model-year refresh. While there are LED headlight and rear-light improvements along with a more streamlined profile, the Lightning's cargo box is identical to that of an ICE F-150, complete with tailgate access steps and a jobsite ruler. The Lightning's interior also has a familiar feel.

But when you pop the Lightning's hood, you find that the internal combustion engine has gone missing. In its place is a front trunk ("frunk"), while concealed beneath is the new skateboard frame with its dual electric motors (one for each axle) and a big 98-kilowatt-hour standard (and 131-kWh extended-range) battery pack. The combination permits the Lightning to travel 230 miles (370 kilometers) without recharging and go from 0 to 60 miles per hour in 4.5 seconds, making it the fastest production F-150 available despite its much heavier weight.

Invisible, too, are the Lightning's sophisticated computing and software systems. The 2016 ICE F-150 reportedly had about 150 million lines of code. The Lightning's software suite may even be larger than its ICE counterpart (Ford will not confirm this). The Lightning replaces the Ford F-150 ICE-related software in the electronic control units (ECUs) with new "intelligent" software and systems that control the main motors, manage the battery system, and provide charging information to the driver.

Ford says the Lightning's software will identify nearby public charging stations and tell drivers when to recharge. To increase the accuracy of the range calculation, the software will draw upon similar operational data communicated from other Lightning owners, which Ford will dynamically capture, analyze, and feed back to the truck.

For executives, however, the Lightning's software is not only a big consumer draw but also among the biggest threats to its success. Ford CEO Jim Farley told *The New York Times* that software bugs worry him most. To mitigate the risk, Ford has incorporated an over-the-air (OTA) software-update capability for both bug fixes and feature upgrades. Yet with an

The F-150 Lightning's front trunk (also known as a "frunk") helps this light-duty electric pickup haul even more. FORD

incorrect setting in the Lightning's tire-pressure monitoring system requiring a software fix only a few weeks after its initial delivery, and with some new Ford Mustang Mach-Es recalled because of "powertrain control module software received as a service update or as an over-the-air update," Farley's worries probably won't be soothed for some time.

Ford calls the Lightning a "Model T moment for the 21st century," and the company's US $50 billion investment in EVs is a bet-the-company proposition. Short-term success looks likely, as Ford closed Lightning preorders after nearly 200,000 were received and with sales expectations of 150,000 a year by 2024.

However, long-term success is not guaranteed. "Ford is walking a tightrope, trying at the same time to convince everyone that EVs are the same as ICE vehicles yet different," says University of Michigan Professor Emeritus John Leslie King, who has long studied the auto industry. Ford and other automakers will need to convince tens of millions of customers to switch to EVs to meet the Biden administration's decarbonization goals of 50 percent new auto sales being non-ICE vehicles by 2030.

King points out that neither Ford nor other automakers can forever act like EVs are merely interchangeable with—but more ecofriendly than—their ICE counterparts. As EVs proliferate at scale, they operate in a vastly different technological, political, and social ecosystem than ICE vehicles. The core technologies and requisite expertise, supply-chain dependencies, and political alliances are different. The expectations of and about EV owners, and their agreement to change their lifestyles, also differ significantly.

Indeed, the challenges posed by the transition from ICE vehicles to EVs at scale are significantly larger in scope and more complex than the policymakers setting the regulatory timeline appreciate. The systems-engineering task alone is enormous, with countless interdependencies that are outside policymakers' control, and resting on optimistic assumptions about promising technologies and wished-for changes in human behavior. The risk of getting it wrong, and the resulting negative environmental and economic consequences created, is high. In this series, we will break down the myriad infrastructure, policy, and social challenges involved, learned from discussions with numerous industry insiders and industry watchers. Let's take a look at some of the elemental challenges blocking the road ahead for EVs.

The soft car

FOR FORD and the other automakers that have shaped the ICE vehicle ecosystem for more than a century, ultimate success is beyond the reach of the traditional political, financial, and technological levers they once controlled. Renault chief executive Luca de Meo, for example, is quoted in the *Financial Times* as saying that automakers must recognize that "the game has changed," and they will "have to play by new rules" dictated by the likes of mining and energy companies.

> "EVERYONE NEEDS TO STOP thinking in silos. It is the adjacency interactions that are going to kill you."
> —DEEPAK DIVAN

One reason for the new rules, observes Professor Deepak Divan, the director of the Center for Distributed Energy at Georgia Tech, is that the EV transition is "a subset of the energy transition" away from fossil fuels. On the other hand, futurist Peter Schwartz contends that the entire electric system is part of the EV supply chain. These alternative framings highlight the strong codependencies involved. Consequently, automakers will be competing against not only other EV manufacturers but also numerous players involved in the energy transition aiming to grab the same scarce resources and talent.

EVs represent a new class of cyberphysical systems that unify the physical with information technology, allowing them to sense, process, act, and communicate in real time within a large transportation ecosystem, as I have noted in detail elsewhere. While computing in ICE vehicles typically optimizes a car's performance at the time of sale, EV-based cyberphysical systems are designed to evolve as they are updated and upgraded, postponing their obsolescence.

"As an automotive company, we've been trained to put vehicles out when they're perfect," Ford's Farley told *The New York Times*. "But with software, you can change it with over-the-air updates." This allows new features to be introduced in existing models instead of waiting for next year's model to appear. Farley sees Ford spending much less effort on changing vehicles' physical properties and devoting more to upgrading their software capabilities in the future.

Systems engineering for holistic solutions

EV SUCCESS AT SCALE depends as much, if not more, on political decisions as technical ones. Government decision-makers in the United States at both the state and federal level, for instance, have created EV market incentives and set increasingly aggressive dates to sunset ICE vehicle sales, regardless of whether the technological infrastructure needed to support EVs at scale actually exists. While passing public policy can set a direction, it does not guarantee that engineering results will be available when needed.

Having committed $1.2 trillion through 2030 so far toward the development and production of millions of EV batteries, automakers are understandably wary not only of the fast reconfiguration of the auto industry but of the concurrent changes required in the energy, telecom, mining, recycling, and transportation industries that must succeed for their investments to pay off.

"FORD IS WALKING A TIGHTROPE, trying at the same time to convince everyone that EVs are the same as ICE vehicles yet different." —JOHN LESLIE KING

The EV transition is part of an unprecedented, planetwide, cyberphysical systems–engineering project with massive potential benefits as well as costs. Considering the sheer magnitude, interconnectedness, and uncertainties presented by the concurrent technological, political, and social changes necessary, the EV transition will undoubtedly be messy.

"There is a lot that has to go right. And it won't all go right," observes Kristin Dziczek, former senior vice president of research at the Center for Automotive Research and now a policy advisor with the Federal Reserve Bank of Chicago. "We will likely stumble forward in some fashion," but, she stresses, "it's not a reason not to move forward."

"A SYSTEMS-ENGINEERING approach toward managing the varied and often conflicting interests of the many stakeholders involved will be necessary to find a workable solution." —CHRIS PAREDIS

How many stumbles and how long the transition will take depend on whether the multitude of challenges involved are fully recognized and realistically addressed.

"A systems-engineering approach toward managing the varied and often conflicting interests of the many stakeholders involved will be necessary to find a workable solution," says Chris Paredis, the BMW Endowed SmartState Chair in Systems Integration at Clemson University. The range of engineering-infrastructure improvements needed to support EVs, for instance, "will need to be coordinated at a national/international level beyond what can be achieved by individual companies," he states.

If the nitty-gritty but hard-to-solve issues are glossed over or ignored, or if EV expectations are hyped beyond the market's capability to deliver, no one should be surprised by a backlash against EVs, making the transition more difficult.

Until Tesla proved otherwise, EVs—especially battery EVs (BEVs)—were not believed by legacy automakers to be a viable, scalable approach to transport decarbonization even a decade ago. Tesla's success at producing more than 3 million vehicles to date has shown that EVs are both technologically and economically feasible, at least for the luxury EV niche.

What has not yet been proven, but is widely assumed, is that BEVs can rapidly replace the majority of the current 1.3 billion-plus light-duty ICE vehicles. The interrelated challenges involving EV engineering infrastructure, policy, and societal acceptance, however, will test how well this assumption holds true.

Therefore, the successful transition to EVs at scale demands a "holistic approach," emphasizes Georgia Tech's Divan. "Everyone needs to stop thinking in silos. It is the adjacency interactions that are going to kill you."

These adjacency issues involve numerous social-infrastructure obstacles that need to be addressed comprehensively along with the engineering issues, including the interactions and contradictions among them. These issues include the value and impacts of government EV incentives, the EV transition impacts on employment, and the public's willingness to change its lifestyle behavior when it realizes converting to EVs will not be enough to reach future decarbonization goals.

"We cannot foresee all the details needed to make the EV transition successful," the University of Michigan's King says. "While there's a reason to believe we will get there, there's less reason to believe we know the way. It is going to be hard." ■

A GMC Hummer EV chassis sits in front of a Hummer EV outside an event where GM CEO Mary Barra announced a US $7 billion investment in EV and battery production in Michigan in January 2022. BILL PUGLIANO/GETTY IMAGES

Chapter 2

Battery Challenges

Batteries expose supply-chain and skills gaps

“ENERGY AND INFORMATION are two basic currencies of organic and social systems,” the economics Nobelist Herbert Simon once observed. “A new technology that alters the terms on which one or the other of these is available to a system can work on it the most profound changes.”

Electric vehicles at scale alter the terms of both basic currencies concurrently. Reliable, secure supplies of minerals and software are core elements for EVs, which represent a “shift from a fuel-intensive to a material-intensive energy system,” according to a report by the International Energy Agency (IEA). For example, the mineral requirements for an EV’s batteries and electric motors are six times those of an internal combustion engine (ICE) vehicle, which can increase the average weight of an EV by 340 kilograms (750 pounds). For something like the Ford Lightning, the weight can be more than twice that amount.

EVs also create a shift from an electromechanical-intensive to an information-intensive vehicle. EVs offer a virtual clean slate from which to accelerate the design of safe, software-defined vehicles, with computing and supporting electronics being the prime enabler of a vehicle’s features, functions, and value. Software also allows for the decoupling of the internal mechanical connections needed in an ICE vehicle, permitting an EV to be controlled remotely or autonomously. An added benefit is that the loss of the ICE powertrain not only reduces the components a vehicle requires but also frees up space for increased passenger comfort and storage.

The effects of Simon’s profound changes are readily apparent, forcing a 120-year-old industry to fundamentally reinvent itself. EVs require automakers to design new manufacturing processes and build plants to make both EVs and their batteries. Ramping up the battery supply chain is the automakers’ current “most challenging topic,” according to VW chief financial officer Arno Antlitz.

These plants are also very expensive. Ford and its Korean battery supplier SK Innovation are spending US $5.6 billion to produce F-Series EVs and batteries in Stanton, Tenn., for example, while GM is spending $2 billion to produce its new Cadillac Lyriq EVs in Spring Hill, Tenn. As automakers expand their lines of EVs, tens of billions more will need to be invested in both manufacturing and battery plants. It is little wonder that Tesla CEO Elon Musk calls EV factories "gigantic money furnaces."

> "ENERGY AND INFORMATION are two basic currencies of organic and social systems. A new technology that alters the terms on which one or the other of these is available to a system can work on it the most profound changes."
> —HERBERT SIMON

Furthermore, Kristin Dziczek, a policy advisor with the Federal Reserve Bank of Chicago, adds, there are scores of new global EV competitors actively seeking to replace the legacy automakers. The "simplicity" of EVs in comparison with ICE vehicles allows these disruptors to compete virtually from scratch with legacy automakers, not only in the car market itself but for the material and labor inputs as well.

Batteries and the supply-chain challenge

ANOTHER CRITICAL question is whether all the planned battery-plant output will support expected EV production demands. For instance, the United States will require 8 million EV batteries annually by 2030 if its target to make EVs half of all new-vehicle sales is met, with that number rising each year after. As IEA Executive Director Fatih Birol observes, "Today, the data shows a looming mismatch between the world's strengthened climate ambitions and the availability of critical minerals that are essential to realizing those ambitions."

This mismatch worries automakers. GM, Ford, Tesla, and others have moved to secure batteries through 2025, but it could be tricky after that. Rivian Automotive Chief Executive RJ Scaringe was recently quoted in *The Wall Street Journal* as saying that "90 to 95 percent of the [battery] supply chain does not exist," and that the current semiconductor chip shortage is "a small appetizer to what we are about to feel on battery cells over the next two decades."

The competition for securing raw materials, along with the increased consumer demand, has caused EV prices to spike. Ford has increased the price of the Lightning by $6,000 to $8,500, and CEO Jim Farley bluntly states that in regard to material shortages in the foreseeable future, "I don't think we should be confident in any other outcomes than an increase in prices."

The underlying reason for the worry: Supplying sufficient raw materials to existing and planned battery plants as well as to the manufacturers of other renewable energy sources and military systems—who are competing for the same materials—has several complications to overcome. Among them is the need for more mines to provide the metals required, which have spiked in price as demand has increased. For example, while demand for lithium is growing rapidly, investment in mines has significantly lagged the investment that has been aimed toward EVs and battery plants. It can take five or more years to get a lithium mine up and going, but operations can start only after it has secured the required permits, a process that itself can take years.

> **5+ YEARS**
> It can take five or more years to get a lithium mine up and going, but operations can start only after it has secured the required permits, a process that itself can take years.

Stiff Competition for Engineering Talent

One critical area of resource competition is over the limited supply of software and systems engineers with the mechatronics and robotics expertise needed for EVs. Major automakers have moved aggressively to bring more software and systems-engineering expertise on board, rather than have it reside at their suppliers, as they have traditionally done. Automakers feel that if they're not in control of the software, they're not in control of their product.

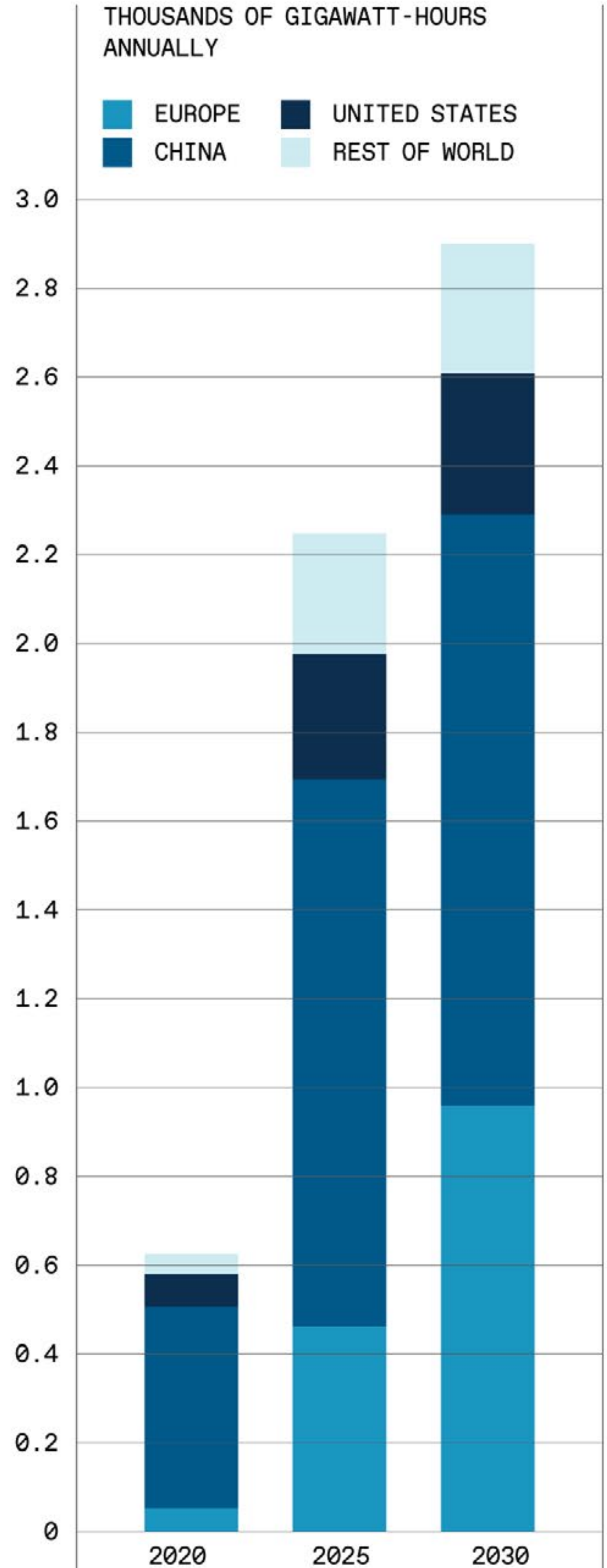
Volvo's CEO Jim Rowan stated earlier this year that increasing the computing power in EVs will be harder and more altering of the automotive industry than switching from ICE vehicles to EVs. This means that EV winners and losers will in great part be separated by their "relative strength in their cyberphysical systems engineering," states Clemson's BMW Endowed SmartState Chair in Systems Integration Chris Paredis.

Even for the large auto suppliers, the transition to EVs will not be an easy road. For instance, automakers are demanding these suppliers absorb more cost cuts because automakers are finding EVs so expensive to build. Not only do automakers want to bring cutting-edge software expertise in house, they want greater inside expertise in critical EV supply-chain components, especially batteries.

Automakers, including Tesla, are all scrambling for battery talent, with bidding wars reportedly breaking out to acquire top candidates. With automakers planning to spend billions to build at least 13 new EV battery plants in North America within the next five to seven years, experienced management and production-line talent will likely be in extremely short supply. Tesla's Texas Gigafactory needs some 10,000 workers alone, for example. With at least 60 new battery plants planned for construction globally by 2030, and scores needed soon afterward, major battery makers are already highlighting their expected skill shortages.

BATTERY-CELL PRODUCTION CAPACITY

This McKinsey & Co. battery tracker from June 2021 shows where batteries are being produced currently and at what volume and where their production is projected to be by the end of the decade. Figures from 2025 and 2030 are estimates based on announcements by battery-cell manufacturers.



SOURCE: MCKINSEY BATTERY TRACKER (JUNE 2021)

Figures from 2025 and 2030 are estimates based on announcements by battery-cell manufacturers.

Mining the raw materials, of course, assumes that there is sufficient refining capability to process them, which, outside of China, is limited. This is especially true in the United States, which, according to a Biden administration special supply-chain investigative report, has "limited raw material production capacity and virtually no processing capacity." Consequently, the report states, the United States "exports the limited raw materials produced today to foreign markets." For example, output from the only nickel mine in the United States, the Eagle Mine in Michigan, which is owned by Lundin Mining Co. of Toronto, is sent to Canada for smelting.

One possible solution is to move away from lithium-ion batteries and nickel metal hydride batteries to other battery chemistries such as lithium iron phosphate, lithium-sulfur, lithium-metal, and sodium-ion, among many others, not to mention solid-state batteries, as a way to alleviate some of the material supply and cost problems. Tesla is moving toward the use of lithium iron phosphate batteries, as is Ford, for some of its vehicles. These batteries are cobalt-free, which alleviates several sourcing issues.

Another solution may be recycling both EV batteries as well as the waste and rejects from battery manufacturing, which can run between 5 and 10 percent of production. Effective recycling of EV batteries "has the potential to reduce primary demand compared to total demand in 2040, by approximately 25 percent for lithium, 35 percent for cobalt and nickel, and 55 percent for copper," according to a report by the University of Technology Sydney's Institute for Sustainable Futures.

While investments into creating EV battery recycling facilities have started, there is a looming question of whether there will be enough battery factory scrap and other lithium-ion battery waste for them to remain operational while they wait for sufficient numbers of batteries to make them profitable. Lithium-ion battery-pack recycling is very time-consuming and expensive, making mining lithium often cheaper than recycling it, for example. Recycling low- or no-cobalt lithium batteries, which is the direction many automakers are taking, may also make it unprofitable to recycle them.

An additional concern is that EV batteries, once no longer useful for propelling the EV, have years of life left in them. They can be refurbished, rebuilt, and reused in EVs, or repurposed into energy storage devices for homes, businesses, or the grid. Whether it will make economic sense to do either at scale versus recycling them remains to be seen.

Howard Nusbaum, the administrator of the National Salvage Vehicle Reporting Program (NSVRP), succinctly puts it, "There is no recycling, and no EV-recycling industry, if there is no economic basis for one." ■

Enel's JuiceBox 240-volt Level 2 charger for electric vehicles. ENEL X WAY USA

Chapter 3

Can the Grid Cope?

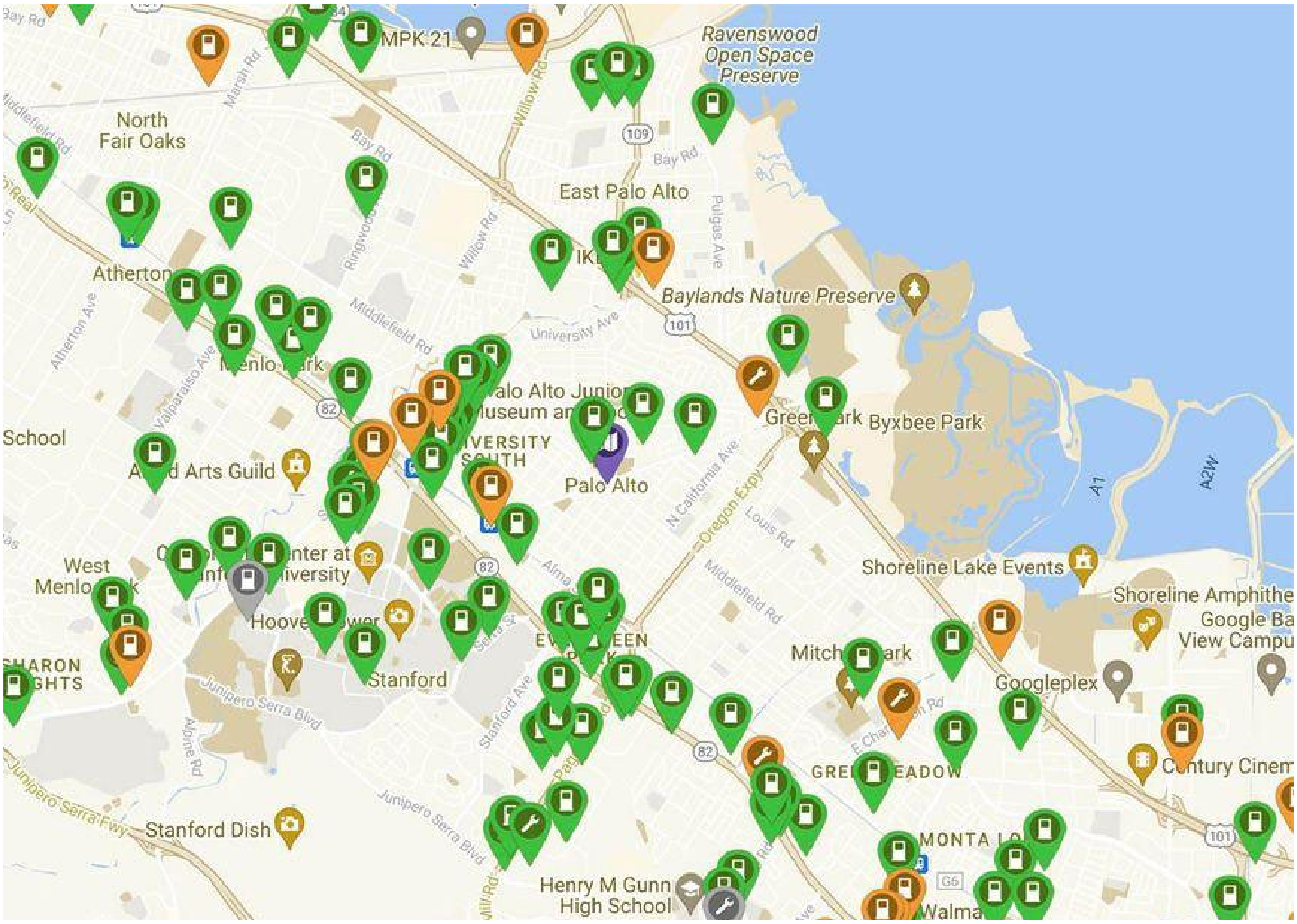
Palo Alto offers a glimpse at the challenges municipalities and utilities face

THERE HAVE BEEN vigorous debates pro and con in the United States and elsewhere over whether electric grids can support EVs at scale. The answer is a nuanced "perhaps." It depends on several factors, including the speed of grid-component modernization, the volume of EV sales, where they occur and when, what kinds of EV charging are being done and when, regulator and political decisions, and, critically, economics.

The city of Palo Alto, Calif., is a microcosm of many of the issues involved. Palo Alto boasts the highest adoption rate of EVs in the United States: One in six of the town's 26,000 households owned an EV. Numbers released by the city in 2019 show that of the 52,000 registered vehicles in the city, 4,500 are EVs. On workdays, commuters drive another 3,000 to 5,000 EVs to enter the city. Residents can access about 1,000 charging ports spread over 312 public charging stations, with another 3,500 or so charging ports located at residences.

Palo Alto's government has set a very aggressive Sustainability and Climate Action Plan with a goal of reducing its greenhouse gas (GHG) emissions to 80 percent below the 1990 level by the year 2030. In comparison, the state's goal is to achieve 85 percent reduction in GHG emissions by 2045. To realize this reduction, Palo Alto must have 80 percent of vehicles within the next seven years registered in (and commuting into) the city be EVs (around 100,000 total). An analysis by the City of Palo Alto's Utilities Advisory Commission projected that the city would "need for 24,200 to 38,300 EV charging ports, up from the estimated 4,300 charging ports currently estimated, to be in place."

To meet Palo Alto's 2030 emission-reduction goals, the city, which owns and operates the electric utility, would like to significantly increase the amount of local renewable energy being used for electricity generation (think rooftop solar), including the ability to use EVs as distributed-energy



A MAP OF EV CHARGING STATIONS IN THE PALO ALTO, CALIF., AREA. PLUGSHARE.COM

resources (vehicle-to-grid (V2G) connections). The city has provided incentives for the purchase of both EVs and charging ports, the installation of heat-pump water heaters, and the installation of solar and battery-storage systems.

There are, however, a few potholes that need to be filled to meet the city's 2030 emission objectives. At a February 2022 meeting of Palo Alto's Utilities Advisory Commission, Tomm Marshall, assistant director of utilities, stated, "There are places even today [in the city] where we can't even take one more heat pump without having to rebuild the portion of the [electrical distribution] system. Or we can't even have one EV charger go in."

"THERE ARE PLACES even today where we can't even take one more heat pump without having to rebuild the portion of the system. Or we can't even have one EV charger go in."
—TOMM MARSHALL

Peak loading is the primary concern. Palo Alto's electrical-distribution system was built for the electric loads of the 1950s and 1960s, when household heating, water, and cooking were running mainly on natural gas. The distribution system does not have the capacity to support EVs and all electric appliances at scale, Marshall suggested. Further, the system was designed for one-way power, not for distributed-renewable-energy devices sending power back into the system.

PALO ALTO'S electrical-distribution system needs a complete upgrade to allow the utility to balance peak loads.

A big problem is the 3,150 distribution transformers in the city, Marshall indicated. A 2020 electrification-impact study found that without improvements, more than 95 percent of residential transformers would be overloaded if Palo Alto hits its EV and electrical-appliance targets by 2030.

For instance, Marshall stated, it is not unusual for a 37.5 kilovolt-ampere transformer to support 15 households, as the distribution system was originally designed for each household to draw 2 kilowatts of power. Converting a gas appliance to a heat pump, for example, would draw 4 to 6 kW, while an L2 charger for EVs would draw 3 to 19 kW; for planning purposes, Palo Alto assumes an L2 charger will draw 12 to 14 kW. A cluster of uncoordinated L2 charging could create an excessive peak load that

“MULTIPLE L2 CHARGERS on one distribution transformer can reduce its life from an expected 30 to 40 years to three years.”
—DEEPAK DIVAN

would overload or blow out a transformer, especially when they are toward the end of their lives, which many already are. Without smart meters—that is, Advanced Metering Infrastructure (AMI), which will be introduced to Palo Alto in 2024—the utility has little to no household peak load insights.

Palo Alto’s electrical-distribution system needs a complete upgrade to allow the utility to balance peak loads, manage two-way power flows, install the requisite number of EV charging ports and electric appliances to support the city’s emission-reduction goals, and deliver power in a safe, reliable, sustainable, and cybersecure manner. The system also must be able to cope in a multihour-outage situation, where future electrical appliances and EV charging will commence all at once when power is restored, placing a heavy peak load on the distribution system.

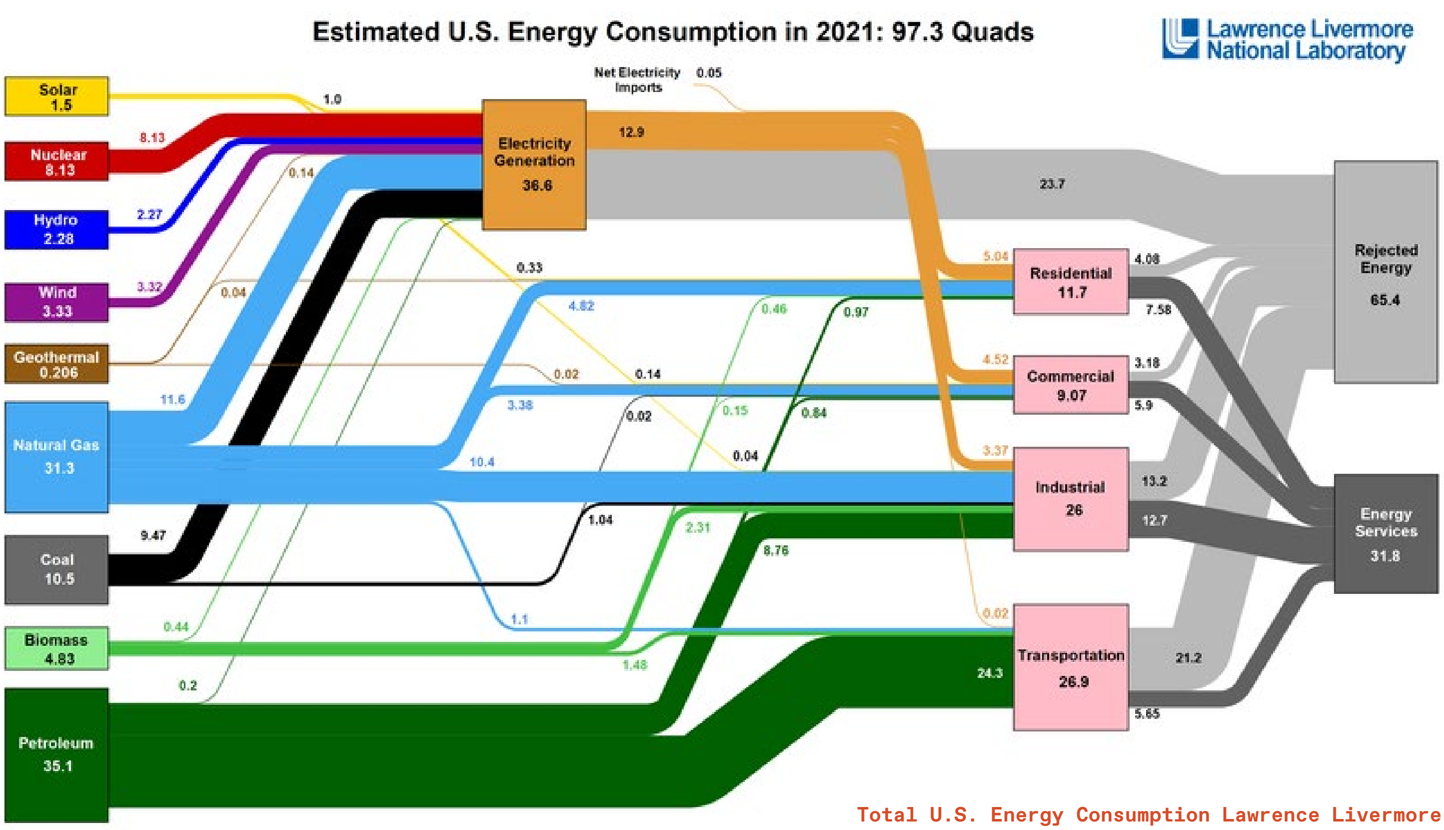
Palo Alto is considering investing US $150 million toward modernizing its distribution system, but that will take a few years of planning plus another few years to perform all the necessary work. And that’s only if the utility can get the engineers, linespeople, and management staff, which continue to be in short supply there and at other utilities across the country. Further, as with other industries, the energy business has become digitized, meaning the skills needed are different from those previously required.

Until it can modernize its distribution network, Marshall conceded that the utility must continue to deal with angry and confused customers who are being encouraged by the city to invest in EVs, charging ports, and electric appliances, only then to be told that they may not be accommodated anytime soon.

Policy Runs Up Against Engineering Reality

THE SITUATION in Palo Alto is not unique. There are some 465 cities in the United States with populations between 50,000 and 100,000 residents, and another 314 that are larger, many facing similar challenges. How many can really support a rapid influx of thousands of new EVs? Phoenix, for example, wants 280,000 EVs plying its streets by 2030, nearly seven times as many as it currently has. Similar mismatches between climate-policy desires and an energy infrastructure incapable of supporting those policies will play out across not only the United States but elsewhere in one form or another over the next two decades as conversion to EVs and electric appliances moves to scale.

As in Palo Alto, it will likely be blown transformers or constantly flickering lights that signal there is an EV charging-load issue. Professor Deepak Divan, the director of the Center for Distributed Energy at Georgia Tech, says his team found that in residential areas “multiple L2 chargers on one



Total U.S. Energy Consumption Lawrence Livermore National Laboratory’s Sankey Diagram of U.S. energy consumption. LAWRENCE LIVERMORE NATIONAL LABORATORY distribution transformer can reduce its life from an expected 30 to 40 years to three years." Given that most of the millions of U.S. transformers are approaching the end of their useful lives, replacing transformers soon could be a major and costly headache for utilities, assuming they can get them.

Supplies for distribution transformers are low, and costs have skyrocketed from a range of $3,000 to $4,000 to $20,000 each. Supporting EVs may require larger, heavier transformers, which means many of the 180 million power poles on which these need to sit will need to be replaced to support the additional weight.

Exacerbating the transformer loading problem, Divan says, is that many utilities "have no visibility beyond the substation" into how and when power is being consumed. His team surveyed "29 utilities for detailed voltage data from their AMI systems, and no one had it."

This situation is not true universally. Xcel Energy in Minnesota, for example, has already started to upgrade distribution transformers because of potential residential EV electrical-load issues. Xcel president Chris Clark told the Minneapolis *Star Tribune* that four or five families buying EVs noticeably affects the transformer load in a neighborhood, with a family buying an EV "adding another half of their house."

Joyce Bodoh, director of energy solutions and clean energy for Virginia's Rappahannock Electric Cooperative (REC), a utility distributor in central Virginia, says that "REC leadership is really, really supportive of electrification, energy efficiency, and electric transportation." However, she adds, "all those things are not a magic wand. You can't make all three things happen at the same time without a lot of forward thinking and planning."

For nearly 50 years, Lawrence Livermore National Laboratory has been publishing a Sankey Diagram of estimated U.S. energy consumption from various generation sources, as shown above. In 2021, the United States consumed 97.3 quadrillion British thermal units (quads) of energy, with the transportation sector using 26.9 quads, 90 percent of it from petroleum. Obviously, as the transportation sector electrifies, electricity generation will need to grow in some reduced proportion of the energy once provided to the transportation section by petroleum, given the higher energy efficiency of EVs.

To achieve the desired reduction in greenhouse gases, renewable-energy generation of electricity will need to replace fossil fuels. The improvements and replacements to the grid's 8,000 power-generation units and 600,000 circuit miles of AC transmission lines (240,000 circuit miles being high-voltage lines) and 70,000 substations to support increased renewable energy and battery storage is estimated to cost more than $2.5 trillion in capital, operations, and maintenance by 2035.

In the short term, it is unlikely that EVs will create power shortfalls in the U.S. grid, but the rising number of EVs will test the local grid's reliability at many of the 3,000 electric-distribution utilities in the United States, which themselves own more than 5.5 million miles of power lines. It is estimated that these utilities need $1 trillion in upgrades by 2035.

As part of this planning effort, Bodoh says that REC has actively been performing "an engineering study that

97.3 QUADRILLION

IN 2021, the United States consumed 97.3 quadrillion British thermal units (quads) of energy, with the transportation sector using 26.9 quads, 90 percent of it from petroleum.

looked at line loss across our systems as well as our transformers, and said, 'If this transformer got one L2 charger, what would happen? If it got two L2s, what would happen, and so on?'" She adds that REC "is trying to do its due diligence, so we don't get surprised when a cul-de-sac gets a bunch of L2 chargers and there's a power outage."

REC also has hourly energy-use data that it can use to find where L2 chargers may be in use because of the load profile of EV charging. However, Bodoh says, REC does not just want to know where the L2 chargers are; it also wants to encourage its EV-owning customers to charge at nonpeak hours—that is, 9 p.m. to 5 a.m. and 10 a.m. to 2 p.m. REC has recently set up an EV-charging pilot program for 200 EV owners that provides a $7 monthly credit if they do off-peak charging. Whether REC or other utilities can convince enough EV owners of L2 chargers to consistently charge during off-peak hours remains to be seen.

Even if EV-owner behavior changes, off-peak charging may not fully solve the peak-load problem once EV ownership really ramps up. "Transformers are passively cooled devices," specifically designed to be cooled at night, says Divan. "When you change the [power] consumption profile by adding several EVs using L2 chargers at night, that transformer is running hot." The risk of transformer failure from uncoordinated overnight charging may be especially aggravated during times of summer heat waves, an issue that concerns Palo Alto's utility managers.

There are technical solutions available to help spread EV-charging peak loads, but utilities will have to make the investments in better transformers and smart metering systems, as well as get regulatory permission to change electricity-rate structures to encourage off-peak charging. Vehicle-to-grid (V2G), which allows an EV to serve as a storage device to smooth out grid loads, may be another solution, but for most utilities in the United States, this is a long-term option.

Numerous issues need to be addressed, such as the updating of millions of household electrical panels and smart meters to accommodate V2G, the creation of agreed-upon national technical standards for the information exchange needed between EVs and local utilities, the development of V2G regulatory policies, and residential and commercial business models, including fair compensation for utilizing an EV's stored energy.

As energy expert Chris Nelder noted at a National Academies of Science, Engineering, and Medicine EV workshop, "Vehicle-to-grid is not really a thing, at least not yet. I don't expect it to be for quite some time until we solve a lot of problems at various utility commissions, state by state, rate by rate. ■

Electric vehicle charging stations in Monterey Park, Calif.
FREDERIC J. BROWN/AFP/GETTY IMAGES

Chapter 4

Charger Infrastructure

How many, where, and who pays?

THE ABILITY TO CONVENIENTLY charge an EV away from home is a top concern for many EV owners. A 2022 survey of EV owners by *Forbes* indicates that 62 percent of respondents are so anxious about their EV range that travel plans have been affected. While "range anxiety" may be overblown, the need for an extensive and reliable external charging infrastructure is not.

Infrastructure terminology can itself be confusing. For clarity, bear in mind that a charging station is a specific physical location that has one or more charging posts. A charging post itself may have one or more ports, where each port can charge a single EV. Each post may have multiple types of service connectors to support different EV-charging connector standards. And a port may supply varying power levels.

The more power delivered, the faster the EV charges. The charging times will vary by model and state of the EV battery. Ford says that an F-150 Lightning "using a 150 kW+ DC fast charger, the standard-range 98 kWh pack can charge from 15-80 percent in about 36 minutes," while Hyundai says its IONIQ 5 EV using a 350 kW DC charger "can charge from 10 percent to 80 percent in just 18 minutes."

Finding a 350-kW charging port is not easy to do. As of this spring, 88 percent of the 46,000 EV public charging stations have some 115,000-plus charging ports, which only support L2 charging, according to *US News & World Report.* Tesla is upgrading its 1,400 Supercharger stations in the United States to 300 kW, as well as opening charging to non-Tesla vehicles, but some 40 percent of DC fast chargers currently operate at only 50 kW or less.

Forecasts concerning how many chargers and the types needed vary greatly, depending on the assumptions about the number and types of EVs in operation in the United States and elsewhere. For example, the International Council on Clean Transportation estimates that there will be 26 million EVs on the road in the United States by 2030, and there will need to be 1.3 million workplace chargers, 900,000 public Level 2 chargers, and 180,000 DC fast-charging ports.

The Edison Electric Institute estimates that there will be 26.4 million EVs on the road by 2030, and it assumes that there will need to be 1.2 million L2 workplace, 2 million public L2, and 140,000 DC fast-charging ports. On the other hand, if the United States meets the Biden administration's goal of making half of all new vehicles sold in 2030 zero-emissions vehicles, including battery electric, plug-in hybrid electric, or fuel-cell electric vehicles—that is 48 million EVs—there will need to be 553,000 L2 workplace, 675,000 public L2, and 533,000 DC fast-charging ports, according to McKinsey & Co.

Regardless of which estimates come closest to reflecting reality, most experts agree that the number of chargers needed in the United States within the decade is at least 20 times as many as exist today. This means installing hundreds of charging ports every day for the next decade, at least. Some countries, like Ireland, estimate that they will need 50 times as many fast-charging ports as they have now, while Australia will need many times more that number given what it currently has in place.

Placement of chargers is critical. The estimates above assume most EV charging will be done at home. The U.S. Department of Energy has long held that some 80 percent of EV charging will be done at an EV owner's residence in the United States. Other studies indicate that this proportion may top out closer to 60 percent, with only about 40 percent of U.S. households having reliable off-street parking at an owned residence. In addition, according to the National Association of Home Builders, some 31.4 percent of households (or 44 million residences) live in multifamily dwellings (apartment buildings, condominiums, townhouses, and mixed-use developments) and may not have convenient charging options. Eliminating "charging deserts" in rural areas and cities, especially in low-income minority areas, is a priority that will need to be addressed. At the very least, tens of millions of L2 EV chargers will need to be installed across all types of residences in the next decade if EVs are going to scale in the United States, which will test the reliability of local electrical distribution systems.

Level 1, 2, and 3 Chargers

Level 1 (L1) chargers plug directly into a standard residential 120-volt AC outlet and supply an average of 1.3 to 2.4 kilowatts. This provides somewhere between 3 and 5 miles of EV range per hour. An empty battery electric vehicle (BEV) battery may take up to 40 to 50 hours to charge, the U.S. Department of Transportation says, and a plug-in hybrid electric vehicle (PHEV) 5 to 6 hours.

Level 2 (L2) chargers operate at 208 V (in commercial applications) or 240 V (in residential applications) and deliver from 3 to 19 kW of AC power, with most delivering about 7.6 kW. This provides somewhere between 18 and 28 miles of EV range per hour. An empty BEV battery may take 4 to 10 hours to charge, while a PHEV can take 1 to 2 hours.

Level 3 (L3) or direct current fast chargers (DCFCs) supply between 50 and 350 kW of power and can charge a BEV to 80 percent in 20 to 40 minutes, and to 100 percent in 60 to 90 minutes. Most PHEVs cannot use L3 chargers.

Public charging efforts

MULTIPLE INITIATIVES are underway to provide more public EV charging. GM, EV-charging company EVgo, and Pilot Flying J travel centers have partnered to install 2,000 DC fast chargers across the country by 2025. GM is working with its dealerships to provide 40,000 L2 chargers in communities across the United States and Canada as well. The newly formed National Electric Highway Coalition (NEHC), a collaboration among some 60 utilities in the United States, has pledged to install thousands of fast chargers along U.S. highways by the end of 2030.

The Biden administration has also committed to providing US $5 billion through the federal Infrastructure Investment and Jobs Act (IIJA) to the states to help them create a privately owned EV-charging network of up to 125,000 charging stations with a minimum of four DC fast chargers located approximately every 50 miles near, but not on, U.S. interstate highways. The act will pay for up to 80 percent of the station and help support the business for five years. Under IIJA funding rules, only nonproprietary charging ports can be supported, information about wait times and charging speeds must be publicly available, and the charging infrastructure must also be designed to support future technology advances such as autonomous vehicles and electric semitrailer trucks.

Furthermore, IIJA funding for charging stations is being disbursed over five years. With most construction starting in 2023, it will be 2028 before the interstate charging system is in full operation. It may take even longer, however, as another federal IIJA funding requirement is that the EV charging devices themselves must be American-built. With few EV charging suppliers meeting this requirement, states are already warning of possible delays as all compete for the same resources. EV-station software must also be secure, especially now that stations are becoming the target of hackers.

Another IIJA requirement is that the charging stations must be well maintained. Broken or malfunctioning EV charging ports are becoming a major concern, except at Tesla's Superchargers. A study in California checked out 657 EV service connectors at 181 public DCFC stations in the San Francisco Bay Area and found that more than 20 percent of them were "nonfunctioning." A recent J.D. Power survey supports that study, showing EV owners increasingly frustrated by a "beleaguered public vehicle charging infrastructure…[where] EV owners continue to be faced with charging station equipment that is inoperable."

Ford is so concerned that it is taking it upon itself to check out EV stations, and if it finds nonfunctional service connectors, it will diagnose the issue and tell the station owner. If the problem is not corrected, Ford's EV station location software will remove the station from its charging recommendations.

One common reason for unreliable EV charging stations is the lack of money and skilled maintainers. Installing DC fast chargers is expensive and can cost upward of $470,000 to $725,000 per fast-charging station with four ports built entirely from scratch; such a charging station needs about nine customers a day to cover its operational costs. In rural areas, that number may be very hard to meet. Studies show that it is not unusual for DC fast charging stations to lose money. As a Bloomberg article declares, those in the EV-charging business are doing everything but making a profit. New and highly touted EV-charging startup company Volta is already reportedly in financial trouble.

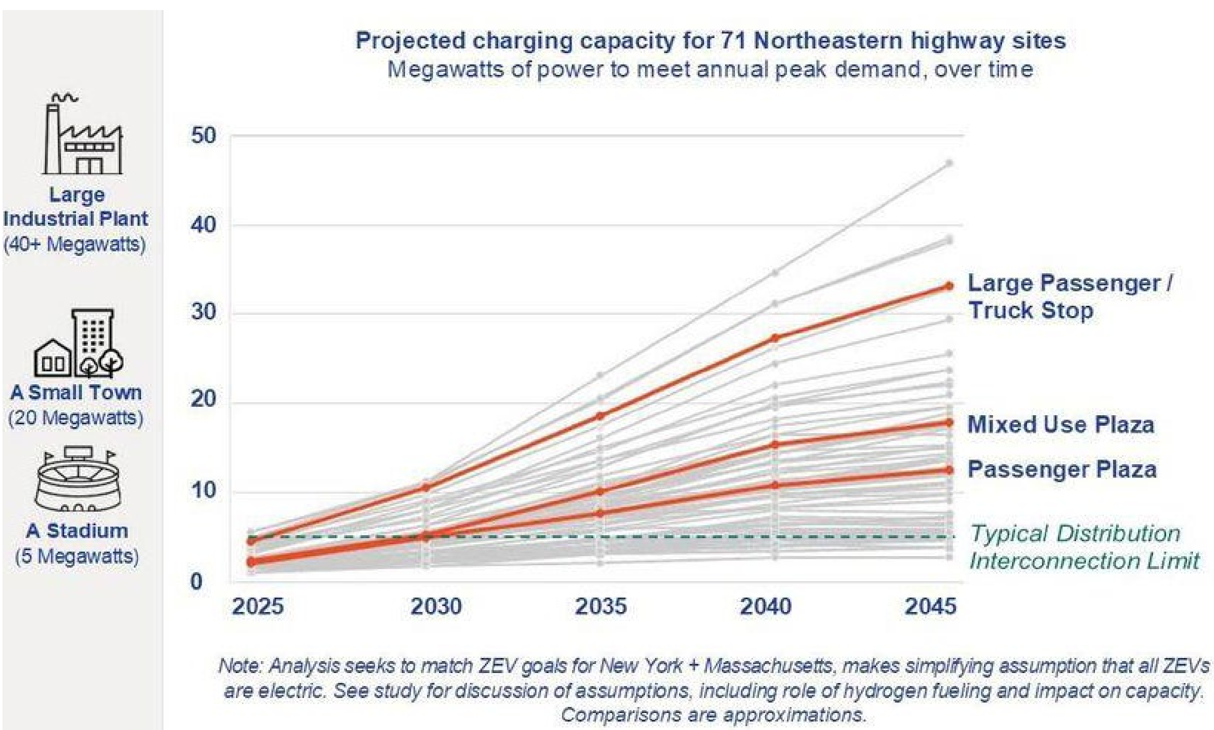
Building an EV station is not easy, either. Getting zoning approval and permits, and dealing with the local utilities—the soft costs—can quickly increase the cost and time needed to build a station. Eight years ago, California passed a state law streamlining EV-station permitting. However, the law is widely ignored by local jurisdictions, which is why the state is next to last in time to get a permit (only New Jersey, another declared EV-friendly state, is slower). Even a company as experienced as Tesla has problems. Rohan Patel, senior global director, public policy and business development, at Tesla, told a National Academies of Science, Engineering, and Medicine EV workshop last year that as Tesla was building a 10-million-square-foot gigafactory in Texas, because of permitting and utility interconnection issues, "We are going to build that thing faster than we can build a Supercharger [station] just down the road."

The study looked into future EV charging station requirements across New York and Massachusetts to understand how they will potentially affect their grid infrastructure. It found that typical highway EV charging sites will need more than 20 fast chargers by 2030 to support passenger EVs, and sites will start reaching the maximum distribution interconnection load limit. After that, many charging sites will need to connect into the high-voltage transmission system as well as see electrical substation upgrades.

The National Grid study states that some existing and planned highway plaza and truck sites will need to start the upgrading process now, before the need exists. The study notes, "While charger installation can be completed in a matter of months, larger transmission interconnections and upgrades can take as long as eight years to construct." Furthermore, it states, its results "show that the minimum site configuration required by the NEVI program formula funding guidance (four 150-kW chargers) will be surpassed by expected demand across many highway sites in the near future." This implies that many of the EV charging sites under the IIJA funding will be undersized almost from the beginning.

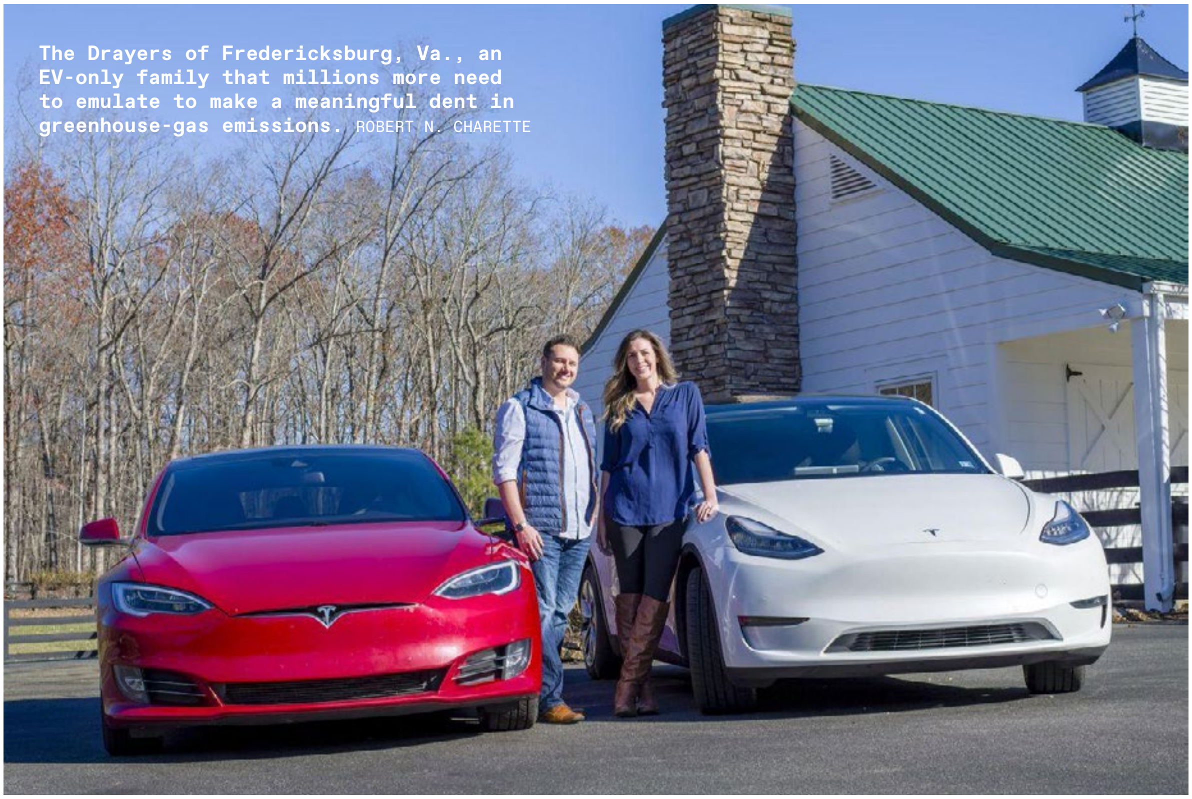
The National Grid study additionally notes that it is "fortunate" that many of the Massachusetts and New York highways and high-voltage transmission lines parallel one another, making it easier to support the future electrical load requirements. Other states may not be so lucky.

As EV charging stations increase, hitting a "Goldilocks" number of them will be important. If too many are built too soon, many stations will not be maintained nor upgraded, or they will be closed for lack of profitability. This is happening in Japan. Too few, and public EV frustration will grow, possibly slowing EV adoption. A wild card is whether economically feasible EV battery-range breakthroughs occur, which could end up dampening the demand for public EV charging stations. ■



Charging stations to support future electric tractor-trailers will be a major challenge, both for supporting warehouse and distribution centers as well as on the road. It is estimated that the power requirement of an EV-friendly highway plaza and truck stop will be equivalent to that of a small town, according to a recent study by the U.S. utility company National Grid.

NATIONAL GRID



The Drayers of Fredericksburg, Va., an EV-only family that millions more need to emulate to make a meaningful dent in greenhouse-gas emissions. ROBERT N. CHARETTE

Chapter 5

Creating a Market for EVs

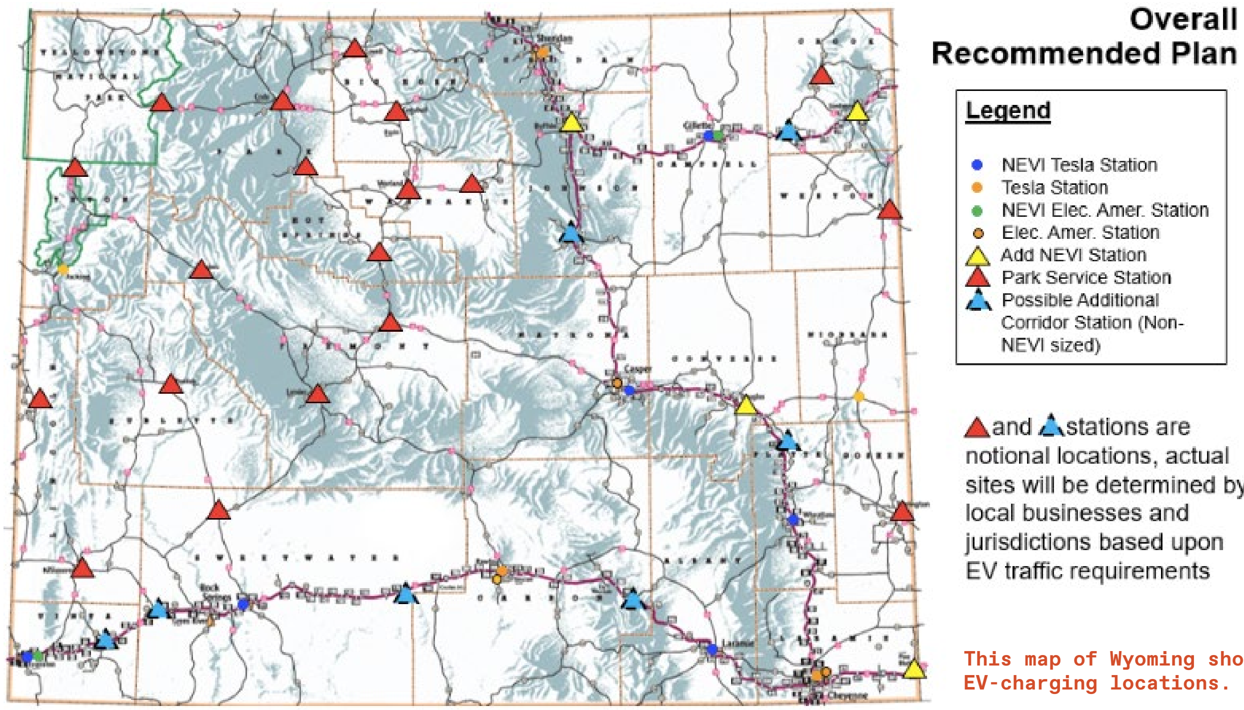
Converting Gasoline Superusers Making chargers ubiquitous is only part of the challenge

"WE'RE NEVER GOING BACK," declare Jonathon and Cory Drayer of Fredericksburg, Va. Both recently traded their respective SUVs for electric vehicles (EVs) and happily swore off ever buying another vehicle powered by an internal combustion engine (ICE). Jonathon and Cory are among the vanguard of a much-hoped-for change: the EV-only family.

Their switch to EVs was also providential. After moving to a home much farther away from their respective workplaces, each would have become part of the gasoline "superusers" club. Club "members" are the 10 percent of U.S. motorists who, according to a study by the environmental group Coltura, drive 30,000 miles or more a year and use an estimated 32 percent of all gasoline. That gasoline consumption is more than the bottom 60 percent of U.S. drivers combined, Coltura says.

Getting these superusers into EVs as soon as possible, Coltura argues, is essential for the United States to reach its 2030 decarbonization objectives. Transportation is a major contributor to greenhouse-gas emissions, accounting for 27 percent of total GHG emissions in the United States and a similar amount in Europe. Passenger cars and light-duty trucks account for about 57 percent of those totals. Transitioning from ICE vehicles to EVs is one important way to reduce these emissions. Therefore, Coltura asserts, instead of offering EV incentives to everyone who purchases an EV, generous incentives should instead be targeted at the estimated 25 million gasoline superusers. As technology historian Melvin Kranzberg has observed, "Although technology might be a prime element in many public issues, nontechnical factors take precedence in technology-policy decisions."

For example, governmental policies and subsidies intended to encourage the use of electric vehicles and discourage ICE vehicles must encompass the 271 million-plus private and commercial vehicles in the United States alone, and eventually the other 1.2 billion vehicles owned worldwide, both numbers that will keep growing. EV offerings from legacy and startup vehicle manufacturers must expand at volume rapidly to meet the policy-driven ICE replacement requirements. Then there is the willingness of hundreds of millions of ICE vehicle drivers the world over to alter their personal behaviors, lifestyles, and, for many,



This map of Wyoming shows proposed EV-charging locations. WYDOT

their livelihoods, to reduce greenhouse-gas emissions.

When 10 percent of drivers use a third of all gasoline, one must consider the mainly rural areas where they reside and the pickup trucks and SUVs they likely drive. For example, with 13 percent of its drivers using 37 percent of the gasoline, Wyoming is second on Coltura's list of states with the highest percentage of gasoline superusers. Consider further that nine out of the 10 most popular Wyoming vehicles are pickup trucks or SUVs, with more than 280,000 pickup trucks and 240,000 SUVs registered in the state.

Getting Wyomingites into EVs, considering there were only 456 electric cars and light trucks registered statewide as of March 2022, with 96 being non-Tesla vehicles, will be tricky. Not surprisingly, nearly all the state's existing 169 public EV charging ports, 75 of which are fast chargers, are part of the Tesla charging network. The lack of EV charging opportunities is endemic across rural areas.

The Wyoming Department of Transportation (WYDOT) submitted its National Electric Vehicle Infrastructure (NEVI) deployment plan to the Federal Highway Administration in early summer 2022. The plan detailed how the state would use its US $24 million allocation from the $5 billion committed in the federal Infrastructure, Investment, and Jobs Act (IIJA) and the $1.2 million from the Volkswagen diesel scandal settlement to place EV charging stations every 50 miles across Wyoming's 913 miles of interstate highway.

WOE IS WYOMING

There is a hitch in the plan, however. Wyoming's NEVI plan states that the detailed IIJA charging-station requirements to receive funding "would not allow any single NEVI-sized station to be profitable in Wyoming until the 2040s." Since the state "has no desire to establish infrastructure that will likely fail," it requested a waiver from the federal requirements to better serve not only Wyomingites' EVs but also tourists' EVs visiting the state's ski resorts and national parks like Yellowstone. Wyoming officials expect tourist attractions to see the most use of any new EV charging stations for at least the next several years.

RURAL AREAS make up 86 percent of U.S. land area and 60 million of the U.S. population. They cannot be ignored in the EV transition.

In September, the Federal Highway Administration approved $9.7 million for Wyoming's plan but refused to grant 8 of the 11 EV station waivers it requested. Wyoming will start developing the seven of its proposed EV charging stations that meet IIJA requirements next year, but it remains to be seen whether any future federal monies will be provided if Wyoming can't get the denied waivers overturned.

The predominance of Teslas in Wyoming mirrors another reality for most gasoline superusers. Coltura found that superusers generally have the same economic status as non-superusers, with a household median income of around $70,000. However, their income lags in relation to EV owners, whose household median income is around $100,000, which makes up about the top 28 percent of U.S. households.

Battery-electric-vehicle owners "earn a lot more than not just the U.S. population but [also] the population of new vehicle buyers," says Alexander Edwards of Strategic Vision, a firm that helps companies understand human behavior and decision-making patterns.

Edwards adds, "They're buying these vehicles not just for their environmental friendliness, although that is a nice thing to have. But they are really buying them for their superior acceleration that outperforms other vehicles."

BATTERY LIFE, reliability, and charging infrastructure are going to be factors in convincing current rural ICE F-150 owners to switch to EVs.

The average Tesla owner's income approaches $150,000, or about the top 20 percent of U.S. households. Wyoming gasoline superusers seeking the capabilities of ICE SUVs and pickups might find these EVs beyond their means, despite generous incentives.

Coltura's analysis further indicates that 9 percent of U.S. gasoline superusers drive Ford's F-Series pickups. Fancifully assuming that only the approximately 3.8 million Ford F-Series gasoline superuser pickup drivers in the United States were allowed to purchase the new Ford electric F-150 Lightnings, it would take more than 20 years at Ford's announced production rates to replace them all. Nor is there an obvious plan for convincing the owners of all the other 12.3 million non-superuser F-Series vehicles on the road to replace them with electric-powered trucks that Ford plans to introduce.

About 200,000 people have placed orders for the Lightning, but Ford CEO Jim Farley revealed that only about "30 percent is [from] F-150 customers....70 percent are new to the brand and new to pickups." Reportedly, some 40 percent of orders are from those who have owned EVs, with a sizable chunk probably being Tesla owners wanting more cargo space. Jonathon, who owns a Tesla, has ordered an electric Chevrolet Silverado RST for that exact reason. Even more gasoline superusers drive General Motors vehicles than Fords—there are 22.1 million current owners of its full-size pickups and SUVs—so GM faces similar challenges persuading its legacy customer base to switch to EVs.

Rural Driving Requirements Are Different

Wyoming gasoline superusers and others in states like Idaho, Montana, and South Dakota are likely to have additional concerns about buying EVs. For instance, a Ford-150 superuser buying a Lightning and driving it the same number of miles will find that their battery warranty will expire in about 3.5 years. High mileage driving in harsh terrain and climate conditions in western states are unknown factors on battery life, as is the eventual cost of replacing a Lightning battery pack, which currently runs from current estimates of $28,556 to $35,960. Even average Wyomingites keep their vehicles for 14 years and drive an average of nearly 17,000 miles a year.

Battery life, reliability, and charging infrastructure are going to be factors in convincing current rural ICE F-150 owners to switch to EVs, especially if they need to tow trailers. Ford's Farley acknowledges that in mountainous states, driving requirements are "different than how we've designed [our EV] vehicles so far."

Another potential bump in the road: EVs are designed for over-the-air software service and feature updates, but cell service can be highly unreliable in rural areas. Lengthy trips to dealers are inevitable given the current poor software reliability of EVs, assuming there are nearby dealers to support them.

Furthermore, rural residents tend to be less supportive of climate action than urban residents, even controlling for political partisanship and other demographics. Appealing to them to convert to EVs for the good of the environment is not likely to be enthusiastically received.

One might object to this analysis on the grounds that Wyoming is an outlier, and that the EV transition will be easier in other states. The issue is not Wyoming per se but rural communities in general, their driving requirements, and the capability of the electrical grid to support EVs at scale in those communities. Rural areas make up 86 percent of U.S. land area and 60 million of the U.S. population. They cannot be ignored in the EV transition.

Besides, getting rural gasoline superusers to give up gasoline-powered SUVs and pickups might be only marginally harder than motivating the driving populace, which also likes to drive SUVs and pickup trucks, to switch. Potential EV owners desire an acceptable level of risk or security when purchasing a vehicle. They want a long-lasting, reliable vehicle that meets their specific needs at an affordable price and can be refueled with minimum concern—as they have now. They may compromise some, says Strategic Vision's Edwards, but not much.

IT'S AN UNDERSTATEMENT to say that it is crucial to coherently manage the totality of the risk ecology associated with...the transition from ICE vehicle to EV ownership.

Without attaining a clear-cut level of EV-purchase risk acceptability, it will be nearly impossible to get the nearly 60 percent of U.S. households with two or more ICE vehicles to feel confident enough to become EV-only families. Even among current EV owners, only about 10 percent are EV-only households.

Can governmental EV policies achieve this level of acceptable risk, given the countless swirling crosscurrents of competing and conflicting interests that EVs at scale present?

The answer to this question is especially important in the United States, given that EV policies underpin the Biden administration's economic transformation plans. EVs at scale are not merely a new technology introduction, like the switchover to HDTV or a new civil-engineering project like building the U.S. interstate highway system. EVs at scale have substantially greater impacts on far more industries, social and political structures, national and global economics, security and political competition, and, of course, the global climate.

It's an understatement to say that it is crucial to coherently manage the totality of the risk ecology associated with the massive social, economic, political, and environmental adjustments initiated by the transition from ICE vehicle to EV ownership.

As Larry Burns, a former GM executive, told *The Wall Street Journal*, there is a "Rubik's Cube of complexity" of policy and its implementation that requires a thoughtful sorting through all of the risks/benefits and trade-offs involved. ■

Four EVs, from economy to luxury, currently for sale in the United States. Clockwise, from top left: the Mercedes-Benz EQE SUV, Hyundai Ioniq 5, Chevrolet Equinox EV 3LT, and Lucid Air. CREDITS: MERCEDES-BENZ GROUP AG; HYUNDAI MOTOR AMERICA; CHEVROLET; LUCID.

Chapter 6

Convincing Consumers to Buy EVs

How range, affordability, reliability, and behavioral changes figure into purchase decisions

WITH THE COMBINATION of requiring all new light-duty vehicles sold in New York State to be zero-emission by 2035, investments in electric vehicle charging stations, and state and federal EV rebates, "You're going to see that you have no more excuses" for not buying an EV, according to New York Governor Kathy Hochul.

Perhaps, but getting the vast majority of the 118 million U.S. households in 2023 that own one or more light-duty ICE vehicles to switch to EVs is going to take time. Even if interest in purchasing an EV is increasing, close to 70 percent of Americans are still leaning toward buying an ICE vehicle as their next purchase. In the United Kingdom, only 14 percent of drivers plan to purchase an EV as their next car.

Even when there is an expressed interest in purchasing a battery electric vehicle (BEV) or hybrid, it often does not turn into an actual purchase. A 2022 CarGurus survey found that 35 percent of new car buyers expressed an interest in purchasing a hybrid, but only 13 percent eventually did. Similarly, 22 percent expressed interest in a BEV, but only 5 percent bought one.

Each potential EV buyer assesses their individual needs against the benefits and risks of owning an EV. However, until mainstream public confidence reaches the point where the perceived combination of risks of a BEV purchase (range, affordability, reliability, and behavioral changes) matches that of an ICE vehicle, then EV purchases are going to be the exception rather than the norm.

How Much Range Is Enough?

Studies differ about how far drivers want to be able to go between charges. One Cox Automotive study found 341 miles was the average range desired, while Deloitte's 2022 Global Automotive Consumer Study found U.S.

Peter Rawlinson serves as the CEO and CTO of Lucid. LUCID

Carlos Tavares, CEO of Stellantis. STELLANTIS

consumers want to be able to travel 518 miles on a fully charged battery in a BEV that costs US $50,000 or less.

Arguments over how much range is needed are contentious. There are some who argue that because 95 percent of American car trips are 30 miles or less, a battery range of 250 miles or less is all that is needed. They also point out that this would reduce the price of the EV, since batteries account for about 30 percent of an EV's total cost. In addition, using smaller batteries would allow more EVs to be built and potentially relieve pressure on the battery supply chain. If longer trips are needed, well, "Bring some patience and enjoy the charging experience" seems to be the general advice.

While perhaps logical, these arguments are not going to influence typical buying decisions much. The first question potential EV buyers are going to ask themselves is, "Am I going to be paying more for a compromised version of mobility?" says Alexander Edwards, president of Strategic Vision, a research-based consultancy that aims to understand human behavior and decision-making.

Edwards explains that potential customers do not have range anxiety per se: If they believe they require a vehicle that must go 400 miles before stopping, "even if once a month, once a quarter, or once a year," all vehicles that cannot meet that criteria will be excluded from their buying decision. Range anxiety, therefore, is more a concern for EV owners. Edwards points out that regarding range, most BEV owners have at least one ICE vehicle to meet their long-distance driving needs.

What exactly is the "range" of a BEV is itself becoming a point of contention. While ICE vehicle driving ranges are affected by weather and driving conditions, the effects are well understood after decades of experience. This experience is lacking with non-EV owners. Extreme heat and cold negatively affect EV battery ranges and charging time, as do driving speeds and terrain.

Some automakers are reticent to say how much range is affected under differing conditions. But Ford's CEO Jim Farley freely admits, "If you're pulling 10,000 pounds, an electric truck is not the right solution. And 95 percent of our customers tow more than 10,000 pounds." GM, though, is promising it will meet heavier towing requirements with its 2024 Chevrolet Silverado EV. However, Lucid Motors CEO Peter Rawlinson in a none-too-subtle dig at both Ford and GM said, "The correct solution for an affordable pickup truck today is the internal combustion engine."

Ford's Farley foresees that the heavy-duty truck segment will be sticking with ICE trucks for a while, as "it will probably go hydrogen fuel cell before it goes pure electric." Many in the auto industry are warning that realistic BEV range numbers under varying conditions need to be widely published, or else risk creating a backlash against EVs in general.

Range-risk concerns obviously are tightly coupled to EV-charging availability. Most charging is assumed to take place at home, but this is not an option for many apartment tenants. Even homeowners might have garages that may not be available for EV charging. Scarce and unreliable EV-charging opportunities, as well as publicized EV road-trip horror stories, add to both the potential EV owners' current perceived and real range-satisfaction risk.

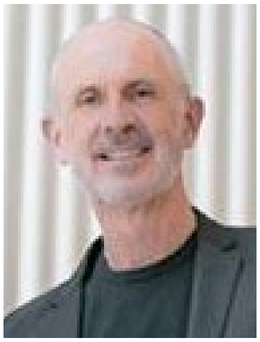
EVs Ain't Cheap

PRICE IS ANOTHER EV purchase risk that is comparable to EV range. Buying a new car is the second-most-expensive purchase a consumer makes behind buying a house. Spending nearly all of an annual U.S. median household income on an unfamiliar technology is not a minor financial ask.

That is one reason why legacy automakers and EV startups are attempting to follow Tesla's success in the luxury vehicle segment, spending much of their effort producing vehicles that are "above the median average annual U.S. household income, let alone buyer in the new car market," Strategic Vision's Edwards says. On top of the 20 or so luxury EVs already or soon to be on the market, Sony and Honda recently announced that they would be introducing yet another luxury EV in 2026.

It is true that there are some EVs that will soon appear in the competitive price range of ICE vehicles like the low-end

The Lucid Air's price ranges from $87,400 to $249,000 depending on options. LUCID



Jim Rowan, Volvo Cars' CEO and President. VOLVO CARS

Chevrolet EV Equinox SUV presently priced around $30,000 with a 280-mile range. How long GM will be able to keep that price in the face of battery cost increases and inflationary pressure is anyone's guess. It has already started to increase the cost of its Chevrolet Bolt EVs, which it had slashed last year "due to ongoing industry-related pricing pressures."

Analysts believe Tesla intends to spark an EV price war before its competitors are ready for one. This could benefit consumers in the short term, but it could also have long-term downside consequences for the EV industry as a whole. Tesla fired its first shot over its competitors' bows with a recently announced price cut from $65,990 to $52,990 for its basic Model Y, with a range of 330 miles. That makes the Model Y cost-competitive with Hyundai's $45,500 IONIQ 5 e-SUV with 303 miles of range.

Tesla's pricing power could be hard to counter, at least in the short term. Ford's cheapest F-150 Lightning Pro is now $57,869 compared to $41,769 a year ago due to what Ford says are "ongoing supply chain constraints, rising material costs, and other market factors." The entry-level F-150 XL with an internal combustion engine has risen in the past year from about $29,990 to $33,695 currently.

Automakers like Stellantis, freely acknowledge that EVs are too expensive for most buyers, with Stellantis CEO Carlos Tavares even warning that if average consumers can't afford EVs as ICE vehicle sales are banned, "There is the potential for social unrest." However, other automakers like BMW are quite unabashed about going after the luxury market, which it terms "white hot." BMW CEO Oliver Zipse does say that the company will not leave the "lower market segment," which includes the battery electric iX1 xDrive30, which retails for AU $82,900 in Australia and slightly higher elsewhere. It is not available in the United States.

Mercedes-Benz CEO Ola Källenius also believes luxury EVs will be a catalyst for greater EV adoption—eventually. But right now, 75 percent of its investment has been redirected at bringing luxury vehicles to market.

The fact that luxury EVs are more profitable than mass-market EVs no doubt helps keep automakers focused on that market. Ford's very popular Mustang Mach-E is having trouble maintaining profitability, for instance, which has forced Ford to raise its base price from $43,895 to $46,895. Even in the Chinese market, where smaller-EV sales are booming, profits are not. Strains on profitability for automakers and their suppliers may increase further as battery metals prices increase, warns data analysis company S&P Global Mobility.

As a result, EVs are unlikely to match ICE vehicle prices (or profits) anytime soon, even for smaller EV models, says Renault Group CEO Luca de Meo, because of the ever-increasing cost of batteries. Mercedes Chief Technology Officer Markus Schäfer agrees and does not see EV/ICE price parity "with the [battery] chemistry we have today." Volvo CEO Jim Rowan disagrees with both of them, however, seeing ICE-EV price parity coming by 2025-2026.

Interestingly, a 2019 MIT study predicted that as EVs became more widespread, battery prices would climb because the demand for lithium and other battery metals would rise sharply. As a result, the study indicated EV/ICE price parity was likely closer to 2030, with the expectation that new battery chemistries would be introduced by then.

Many argue, however, that total cost of ownership (TCO) should be used as the EV purchase decision criterion rather than sticker price. Total cost of ownership of an EV is generally less than an ICE vehicle over its expected life since they have lower maintenance costs and electricity is less expensive per mile than gasoline, and tax incentives and rebates help a lot as well.

However, how long it takes to hit the break-even point depends on many factors, like the cost differential of a comparable ICE vehicle, depreciation, taxes, insurance costs, the cost of electricity/petrol in a region, whether charging takes place at home, etc. And TCO rapidly loses it selling point appeal if electricity prices go up, as is happening in the U.K. and in Germany.

Even if the TCO is lower for an EV, a potential EV customer may not be interested if meeting monthly auto payments is difficult. Extra costs like needing to install a fast charger at home, which can add several thousand dollars more, or higher insurance costs, which could add an extra $500 to $600 a year, may also be seen as a buying impediment and can change the TCO equation.

Reliability and Other Major Tech Risks

TO PERHAPS DISTRACT wary EV buyers from range and affordability issues, the automakers have focused their efforts on highlighting EV performance. Raymond Roth, a director at financial advisory firm Stout Risius Ross, observes among automakers, "There's this arms race right now of best-in-class performance" being the dominant selling point.

This "wow" experience is being pursued by every EV automaker. Mercedes CEO Källenius, for example, says to convince its current luxury vehicle owners to purchase an EV, "the experience for the customer in terms of the torque, the performance, everything [must be] fantastic." Nissan, which seeks a more mass-market buyer, runs commercials exclaiming, "Don't get an EV for the E. Get it because it pins you in your seat and takes your breath away."

EV reliability issues may also take one's breath away. Reliability is "extremely important" to new-car buyers, according to a 2022 report from *Consumer Reports*. Currently, EV reliability is nothing to brag about. *Consumer Reports* says that "on average, EVs have significantly higher problem rates than internal combustion engine (ICE) vehicles across model years 2019 and 2020." BEVs dwell at the bottom of the rankings.

Reliability may prove to be an Achilles' heel to automakers like GM and Ford. GM CEO Mary Barra has very publicly promised that GM would no longer build "crappy cars." The ongoing problems with the Chevy Bolt undercut that promise, and if its new Equinox EV has issues, it could hurt sales.

Ford has reliability problems of its own, paying $4 billion in warranty costs in 2021 alone. Its Mustang Mach-E has been subject to several recalls over the past year. Even perceived quality leader Toyota has been embarrassed by wheels falling off weeks after the introduction of its electric bZ4X SUV, the first in a new series of "bZ"—beyond zero—electric vehicles.

Troubles with vehicle electronics, which have plagued ICE vehicles as well for some time, seem even worse in EVs, according to *Consumer Reports'* data. This should not be surprising, since EVs are packed with the latest electronic and software features to make them attractive—like new biometric capability—but they often do not work. EV startup Lucid is struggling with a range of software woes, and software problems have pushed back launches years for Audi, Porsche, and Bentley EVs, which are part of Volkswagen Group.

Another reliability risk-related issue is getting an EV repaired when something goes awry, or there is an accident. Right now, there is a dearth of EV-certified mechanics and repair shops. According to new analysis from the U.K.'s Institute of the Motor Industry (IMI), 90,000 EV-trained automotive technicians will be required to sufficientlyservice the volume of zero-emissions vehicles predicted to be on U.K. roads by 2030. IMI says that currently only 11 percent of technicians in the U.K. are qualified to work on EVs. The situation is no better in the United States. The National Institute for Automotive Service Excellence (ASE), which certifies auto repair technicians, says the United States has 229,000 ASE-certified technicians. However, there are only some 3,100 certified for electric vehicles. With many automakers moving to reduce their dealership networks, resolving problems that over-the-air (OTA) software updates cannot fix might be troublesome.

Furthermore, the costs and time needed to repair an EV are higher than for ICE vehicles, according to the data analytics company CCC. Reasons include a greater need to use original equipment manufacturer (OEM) parts and the cost of scans/recalibration of the advanced driver assistance systems, which have been rising for ICE vehicles as well. Furthermore, technicians need to ensure battery integrity to prevent potential fires.

And some of the batteries, along with their battery management systems, need work. Two examples: recalls involving the GM Bolt and Hyundai Kona, which are likely to cost GM $1.8 billion and Hyundai $900 million, respectively, to fix, according to "Stout's 2021 Automotive Defect & Recall Report." Furthermore, the battery defect data compiled by Stout indicates "incident rates are rising as production is increasing and incidents commonly occur across global platforms," with both design and manufacturing defects starting to appear.

CCC data indicate that when damaged, battery packs do need replacement after a crash, and more than 50 percent of such vehicles were deemed a total loss by the insurance companies. EVs also need to revisit the repair center more times after they've been repaired than ICE vehicles, hinting at the increased difficulty in repairing them. Additionally, EV tire tread wear needs closer inspection than on ICE vehicles. Lastly, as auto repair centers need to invest in new equipment to handle EVs, these costs will be passed along to customers for some time.

Electric vehicle and charging network cybersecurity is also growing as a perceived risk. A 2021 survey by insurance company HSB found that an increasing number of drivers, not only of EVs but of ICE vehicles, are concerned about their vehicle's security. Some 10 percent reported "a hacking incident or other cyberattack had affected their vehicle," HSB reported. Reports of charging stations being compromised are increasingly common.

The risk has reached the attention of the U.S. Office of the National Cyber Director, which recently held a forum of government leaders, automakers, suppliers, and EV-charging manufacturers focusing on "cybersecurity issues in the electric vehicle (EV) and electric vehicle supply equipment (EVSE) ecosystem." The concern is that EV uptake could falter if EV-charging networks are not perceived as being secure.

A sleeper risk that may explode into a massive problem is an EV owner's right to repair their vehicle. In 2020, Massachusetts passed a right-to-repair law that allows a vehicle owner to have access to the telematics of their vehicle and to take it to whatever repair shop they wish. The law also gave independent repair shops the right to access the real-time vehicle data for diagnosis purposes. Automakers have sued to overturn the law, and some like Subaru and Kia have disabled the advanced telematic systems in cars sold in Massachusetts, often without telling new customers about it. GM and Stellantis have also said they cannot comply with the Massachusetts law and are not planning to do so because it would compromise their vehicles' safety and cybersecurity. The Federal Trade Commission is looking into the right-to-repair issue, and President Biden has come out in support of it.

$20,000,000,000

Ford believes it will earn $20 billion, Stellantis some $22.5 billion, and GM $20 to $25 billion from paid software-enabled vehicle features by 2030.

FOR A TIME in New York City, one had to be a licensed engineer to drive a steam-powered auto. In some aspects, EV drivers return to these roots. This might change over time, but for now it is a serious issue."
—JOHN LESLIE KING

You Expect Me to Do What, Exactly?

FAILURE TO CHANGE consumer behavior poses another major risk to the EV transition. Take charging: It requires a new consumer behavior in terms of understanding how and when to charge, and what to do to keep an EV battery healthy. The information on the care and feeding of a battery, as well as how to maximize vehicle range, can resemble a manual for owning a new exotic pet. It does not help when an automaker like Ford tells its F-150 Lightning owners they can extend their driving range by relying on the heated seats to stay warm instead of the vehicle's climate control system.

The first-ever BMW iX1 xDrive30, Mineral White metallic, 20” BMW Individual Styling 869i. BMW AG

Keeping in mind such issues, and how one might work around them, increases a driver's cognitive load—things that must be remembered in case they need to be acted on. “Automakers spent decades reducing cognitive load with dash lights instead of gauges, or automatic instead of manual transmissions,” says University of Michigan professor emeritus John Leslie King, who has long studied human interactions with machines.

King notes, “In the early days of automobiles, drivers and chauffeurs had to monitor and be able to fix their vehicles. They were like engineers. For a time in New York City, one had to be a licensed engineer to drive a steam-powered auto. In some aspects, EV drivers return to these roots. This might change over time, but for now it is a serious issue.”

This cognitive load keeps changing as well. For instance, “common knowledge” about when EV owners should charge is not set in concrete. The long-standing mantra for charging EV batteries has been do so at home at night, when electricity rates are low and stress on the electric grid is low. Recent research from Stanford University says this is wrong, at least for Western states.

Stanford's research shows that electricity rates should encourage EV charging during the day at work, or at public chargers, to prevent problems during evening grid peak demand, which could increase by as much as 25 percent in a decade. *The Wall Street Journal* quotes the study's lead author, Siobhan Powell, as saying if everyone were charging their EVs at night all at once, “it would cause really big problems.”

Asking EV owners to refrain from charging their vehicles at home during the night is going to be difficult, since EVs are being sold on the convenience of charging at home. Transportation Secretary Pete Buttigieg emphasized this very point when describing how great EVs are to own, “And the main charging infrastructure that we count on is just a plug in the wall.”

EV owners increasingly find public charging unsatisfying and is “one of the compromises battery electric vehicle owners have to make,” says Strategic Vision's Alexander Edwards, “that drives 25 percent of battery electric vehicle owners back to a gas-powered vehicle.” Fixing the multiple problems underlying EV charging will not likely happen anytime soon.

Another behavior change risk relates to automakers' desired EV owner post-purchase buying behavior. Automakers see EV (and ICE vehicle) advanced software and connectivity as a gateway to a software-as-a-service model to generate new, recurring revenue streams across the life of the vehicle. Automakers seem to view EVs as razors through which they can sell software as the razor blades. Monetizing vehicle data and subscriptions could generate $1.5 trillion by 2030, according to McKinsey.

VW thinks that it will generate hundreds of millions in future sales through selling customized subscription services, like offering autonomous driving on a pay-per-use basis. It envisions customers would be willing to pay €7 per hour for the capability. Ford believes it will earn $20 billion, Stellantis some $22.5 billion, and GM $20 to $25 billion from paid software-enabled vehicle features by 2030.

Already for ICE vehicles, BMW is reportedly offering an $18-a-month subscription (or $415 for “unlimited” access) for heated front seats in multiple countries, but not the United States as of yet. GM has started charging $1,500 for a three-year OnStar subscription on all new Buick, Cadillac, and GMC vehicles whether the owner uses it or not. And Sony and Honda have announced their luxury EV will be subscription-based, although they have not defined exactly what this means in terms of standard versus paid-for features. It would not be surprising to see it follow Mercedes's lead. The automaker will increase the acceleration of its EQ series if an owner pays a $1,200-a-year subscription fee.

Essentially, automakers are trying to normalize paying for what used to be offered as standard or even an upgrade option. Whether they will be successful is debatable, especially in the United States. “No one is going to pay for subscriptions,” says Edwards, who points out that microtransactions are absolutely hated in the gaming community. Automakers risk a major consumer backlash by using them.

To get to EV at scale, each of the EV-related range, affordability, reliability, and behavioral change risks will need to be addressed by automakers and policymakers alike. With dozens of new battery electric vehicles becoming available for sale by the end of 2023, potential EV buyers now have a much greater range of options than previously. The automakers who manage EV risks best— along with offering compelling overall platform performance—will be the ones starting to claw back some of their hefty EV investments.

No single risk may be a deal breaker for an early EV adopter, but for skeptical ICE vehicle owners, each risk is another reason not to buy, regardless of perceived benefits offered. If EV-only families are going to be the norm, the benefits of purchasing EVs will need to be above—and the risks associated with owning will need to match or be below—those of today's and future ICE vehicles. ■

U.S. President Joe Biden walks near Chevy vehicles as he arrives to deliver remarks during a visit to the General Motors Factory ZERO electric-vehicle assembly plant in Detroit on 17 November 2021. MANDEL NGAN/AFP/GETTY IMAGES

Chapter 7

Local Policies Shape Global Competition

From Hainan Province to California, cities, states, and regions set an aggressive agenda

THE BIDEN ADMINISTRATION is very clear on what it desires to achieve with its environmental policy: a complete transformation of the nation's US $21 trillion economy away from fossil fuels.

The administration is undertaking multiple actions to place the United States on a path to achieve a 50 to 52 percent reduction in greenhouse-gas emissions by 2030 from a 2005 baseline, and then to achieve net-zero emissions by 2050. This is to try to meet the Paris Agreement of limiting global warming to 1.5 °C, compared to preindustrial levels. Achieving this transformation will be through what *The New York Times* describes as "economic nationalism," with electric vehicles (EVs) as the tip of the spear for economic, environmental, and societal change.

Or, as put in a recent position paper from consultancy Ernst & Young, "Market forces alone won't solve the problem, and the onus is on governments to take a lead."

This controversial government-directed "top-down driven approach" the administration is pursuing is a major break from the past primarily market-driven "bottom-up approach" for encouraging the transition to EVs. This new approach is not merely an incremental subsystem-level change, like setting new vehicle mileage or emission standards, but a whole system change.

As Dave Cooke, senior vehicle analyst at the Union of Concerned Scientists, emphasized at a National Academies EV workshop last year, "This transition isn't just about emissions. That is perhaps the most important point." As the clean-energy transition is made, Cooke says, "we're talking about a massive reshaping of our economy at the same time."

However, Virginia Tech's Lee Vinsel, a technology historian and expert on how regulatory policy has improved auto safety and lowered pollution, warns, "Policy reflected in EVs must be crafted to reduce the risks to hundreds of millions of individuals that feel they're not giving anything up."

Volkswagen's ID.4 compact all-electric SUV advances down an assembly line in VW's new factory in Chattanooga, Tenn. VOLKSWAGEN OF AMERICA, INC.

How massive an economic reshaping is in store? There are roughly 30 million U.S. workers directly employed across the automotive, energy, and transportation industry sectors, as well as tens of millions of other workers dependent upon these industries who are likely to be first affected. A large percentage of U.S. GDP immediately comes into play in the transition to EVs.

To underscore its intent, the administration has set an aggressive goal of 50 percent of all new vehicles sold in the United States to be EVs by 2030. This objective is almost 20 percent greater than the enthusiastic projected sales of the June 2022 Edison Electric Institute's analysis. However, the administration has gained $1.2 trillion in commitments from major automakers toward building EV and battery factories worldwide.

The Biden administration has fully embraced the United Auto Workers (UAW) report "Taking the High Road: Strategies for a Fair EV Future," which argues that "advanced vehicle technology should be treated as a strategic sector to be protected and built in the U.S." The UAW report further asserts that "the economic potential of EVs will be lost if their components are imported." Preventing that outcome, the UAW states, needs a "strong, forward-looking industrial policy" to reap the benefits of fully transitioning to EVs.

EVs as Job Creators

THE ADMINISTRATION has openly supported the UAW conclusions and claims that achieving the EV and clean-energy objectives it has set out will "position America to win the future of transportation and manufacturing and create good-paying union jobs, dramatically expand American manufacturing, make electric vehicles more affordable for families, and export our electric vehicles around the world."

This sets out U.S. government policy objectives not only to decrease greenhouse gases but to be the global EV industrial leader. Through a series of presidential executive orders and legislation, the administration has bolstered its industrial objectives, providing incentives for EV purchases, including clean school buses, battery development and recycling, semiconductor manufacturing, and expanded opportunities for EV charging as well as for improving the electrical grid.

The federal government has also increased mileage standards for new passenger cars and light trucks to a fleet average of 49 miles per gallon in model year 2026, up from 41 mpg today. Even more stringent standards are planned for model years 2027 to 2029. The net effect is to force automakers to sell more EVs and fewer internal combustion engine (ICE) vehicles to meet the fleet average, an approach the Australian government is using, too.

To date, the Biden administration has committed more than $435 billion over the next decade to support the EV transition, and many billions more are likely. Recently, four federal departments and agencies—the departments of Energy, Transportation, Housing and Urban Development, and the Environmental Protection Agency—have signed a Memorandum of Understanding to coordinate their activities to further "decarbonize the transportation sector."

California Sets the Pace

INDIVIDUAL STATES have set out their own EV policies as well. California, for instance, which has possessed the right since 1970 to determine its own vehicle-emission standards, has deliberately set out a more aggressive goal than the federal government. With 11 percent of all U.S. new light-duty vehicles sold in the state annually, or around 2 million vehicles, its environmental policies have market clout.

> "WHO IS looking at the full picture of this transformation?"
> —CARLOS TAVARES, CEO OF STELLANTIS

California has mandated that by 2035 only sales of zero-emission new cars and light trucks (ZEVs) will be allowed. Until then, California is aiming for 35 percent ZEV sales by 2026 and 68 percent by 2030. As of the first half of 2022, California ZEV sales reached more than 16 percent. Some 61 percent of all those ZEV sales to date were Teslas.

California, like nearly every other state, has a wide range of incentives for purchasing EVs and installing chargers. Recently passed legislation would increase to $10 billion the amount the state is committing to support the EV transition over the next five years.

Sixteen other states have agreed to follow California auto-emission rules, with 13 indicating they will embrace its ZEV requirements. Together, the 17 states represent almost 40 percent new light-duty vehicles sold, worth close to $500 million in new-car sales in 2021, according to data from the National Automobile Dealers Association.

There is, however, some question of how prepared some of these states are to support these ZEV requirements. Massachusetts, for example, has set a goal of at least 750,000 to 1 million EVs on the road by 2030; as of mid-2022, it has only about 51,000 EVs, of which 31,000 are battery electric.

The state also wants 15,000 public charging stations by 2025 and 75,000 by 2030; it currently has about 4,800.

The Geopolitics of EVs

THE UNITED STATES is far from alone in wanting to use EVs to "win the future of transportation and manufacturing." The European Union, China, and Japan, as well as the United Kingdom and South Korea, all have announced the same intention. Each has set its own environmental policies to push the countries toward transition to EVs at scale. For example, the U.K. will stop the sales of new diesel and petrol-fueled cars and vans by 2030. All new vehicles sold will be ZEVs from 2035 on. The EU has also banned the sale of new diesel and petrol-fueled cars by 2035, while Japan, with 24.5 percent of new car sales being (mostly hybrid) EVs, says all new car sales in 2035 will be electric.

China is the acknowledged leader in EV production. From mining to EV charging stations and everything in between, China has secured its EV supply chain and infrastructure. Like the United States, China also expects to become the undisputed global leader in EVs. In 2014, President Xi Jinping defined China's intent, stating, "Developing new-energy vehicles is the only way for China to move from a big automobile country to a powerful automobile hub." The Chinese government long ago realized that if ICE vehicles were to be eliminated, China could effectively compete with Western automakers.

By 2025, China aims to have 20 percent of new vehicles sold be new-energy vehicles (NEVs), which include battery electric (BEV), plug-in hybrid electric (PHEV), and fuel-cell electric vehicles (FCEV). The NEV goal goes up to 50 percent by 2035, with the other 50 percent being (non-plug-in) hybrids. In other words, no conventional ICE vehicles will be sold after 2035. This ban goes into effect even sooner in the Hainan Province, whose government has decreed that no fossil-fueled automobiles will be sold after 2030. Other provinces may follow suit.

The scale China brings to the EV transition is truly stunning: There are already some 300 companies making EVs there. In September 2022 alone, more than 675,000 NEV passenger cars were sold in China— more than the number sold in the United States in 2021. It exported 500,000 EVs in 2021, as well. Some 5.8 percent of European EVs on the road today are Chinese-made, with predictions of 12 to 20 percent being Chinese brands by 2030.

The Chinese government has also made known that it will protect the country's EV leadership position. Chinese Ambassador Qin Gang recently made it very clear at the 2022 Detroit Auto Show that the country would not take kindly to any efforts by the United States or other countries to remove it from the EV supply chain or markets. "To decouple with China means to disconnect from the world's largest market as well as the biggest opportunity," Qin Gang stated. He added that "the industry chain has been relatively well established over past years, and there would be no winner if anybody wanted to intervene or even destroy [it]."

Australian Minister for Resources Madeleine King tacitly agrees with this sentiment, saying that it was a "pipe dream" that any Western country could end its EV mineral dependence on China. King is quoted in an interview with Bloomberg News as saying that China saw "this need coming and made the most of it." Australia, she said, will provide a second source of needed minerals but is not looking to replace China.

Employees work on the assembly line of the T03 electric small crossover at a factory of Chinese EV startup Leapmotor, on 26 April 2022, in Jinhua, Zhejiang Province, of China. HU XIAOFEI/VCG/GETTY IMAGES

China, along with the EU, Japan, and South Korea, has also voiced unhappiness with the United States' EV tax-credit incentives that now require certain percentages of EV components to be manufactured or assembled in North America. South Korean auto companies Hyundai and Kia are already blaming drops in their U.S. electric vehicle sales to the new law. These countries undoubtedly see the content requirement as a foreign policy shot across the bow. Given the Biden administration's lukewarm response to the complaints, it would not be surprising for other countries to enact retaliatory policies.

The wide swath of policies supporting EVs across the globe combined with the financial commitments of automakers makes the EV transition seem inevitable. The policies also reflect the tremendous number of industrial activities that need to occur to bring EVs to scale, and governments' outsize role and risks in making it happen. However, as Virginia Tech's Vinsel observes, "Policymakers often only weigh the benefits [of their policies] and not their other outcomes."

As a result, the question of how quickly EV policies must— or can—be implemented has spawned vociferous debates.

According to a report by Reuters, the questions that will fuel those debates were posed by Stellantis CEO Carlos Tavares this past May at the FT Future of the Car 2022 conference in London. While delivering remarks on near-term battery supply-chain issues and the substantially increased amount of raw materials required for each new EV as compared with ICE vehicles, Tavares asked, "What's next? Where is the clean energy? Where is the charging infrastructure? Where are the raw materials? Where are the geopolitical risks of sourcing those raw materials? Who is looking at the full picture of this transformation?" ■

Heavy traffic moves along the 101 freeway in Los Angeles.
MARIO TAMA/GETTY IMAGES

Chapter 8

The Carrot or the Stick?

Policymakers differ on how to incentivize automakers and consumers

WITH LESS THAN eight years for the United States to meet the objective of a 50 percent reduction in greenhouse-gas emissions from 2005 levels, many environmental advocacy groups argue that an even faster transition to EVs is mandatory. For instance, the Rocky Mountain Institute (RMI) estimates that 70 million EVs must be on U.S. roads by 2030 to meet the GHG reduction target. The latest Edison Electric Institute projection is that only about 26.4 million EVs will likely be on the roads by then, although some others estimate the number could be as high as 35 million. However, that is still far short of RMI's target.

To accelerate EV uptake, the Zero Emission Transportation Association, a lobbying group formed by Tesla, Lucid, and Rivian along with some EV-charging suppliers among others, asserts that sales of new internal combustion vehicles must be banned by 2030. Greenpeace agrees and argues that sales of all diesel and petrol vehicles, including hybrids, must end by 2030. In addition, as is happening in some Indian cities, many environmentalists believe gasoline vehicles 15 years or older and diesel trucks over 10 years old should not be allowed on U.S. roads.

There is also a push to make those who own heavy SUVs pay a steep annual registration fee to discourage their ownership, as is happening in Washington, D.C. Furthermore, there are demands that policies should be enacted to cease construction or upgrades of gasoline stations as is happening now in some California cities.

The 50 percent GHG-emission reduction target by 2030 is indeed entirely possible, according to a report from Lawrence Berkeley National Laboratory. This can be accomplished by building upon the above EV and ICE vehicle policy recommendations, coupled with 100 percent methane capture, retiring all coal-fired electric generation, as well as converting the U.S. electric grid to 80 percent clean energy by 2030. A coordinated effort by U.S. policymakers is all that is preventing this from happening, the report states.

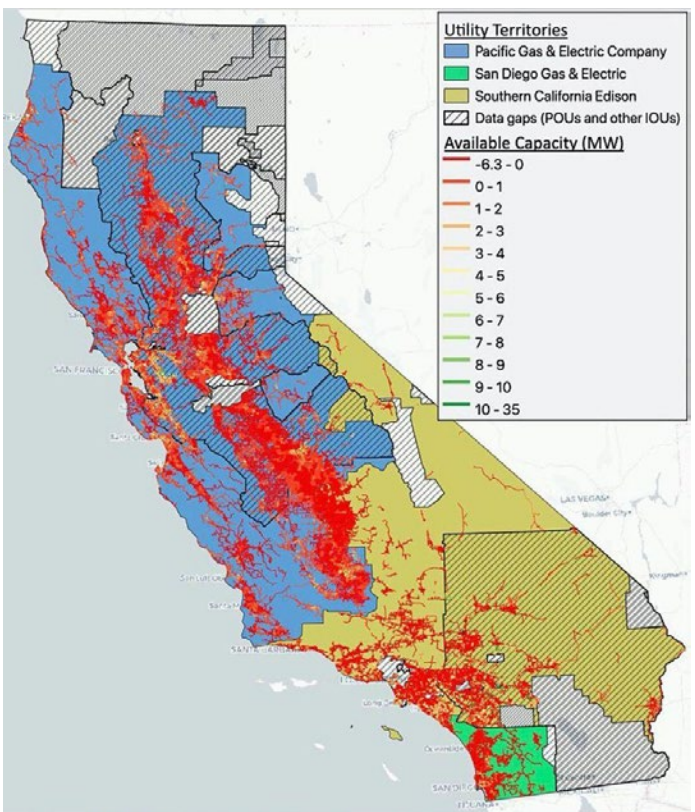
Recommendations on how to complete the numerous global and domestic systems engineering efforts across multiple industries required to carry out such policies in such a short time frame is conspicuously absent from LBL's report, however.

California Dreaming

Even for California, the approach outlined above is an EV too far. California Air Resources Board (CARB) Chair Liane Randolph told Reuters that its 2035 EV mandate was the "sweet spot," given "where the automakers are, where the supply chains are, and where the production facilities are." Not all CARB members are so confident, however, with some questioning whether the board had enough information to set such an aggressive mandate.

One reason to be skeptical about the state's ability to meet that mandate is that California's EV infrastructure support is a bit fraught. For instance, the California Energy Commission (CEC) projects that the state will need 1.2 million public and shared EV charging ports at workplaces, multiunit dwellings, and other public spots by 2030. However, the state, with 79,000 EV charging ports installed as of October 2022 (up from 73,000 in 2021) is unlikely to meet its 2025 target of 250,000 charging ports. The number also assumes that most charging stations will be in good working order, something that EV drivers unhappily have not found.

Yet even if California does meet its 2025 mark, more than 520 charging ports would still have to be installed every day to meet the 2030 objective. It is uncertain whether, given the rapidly rising demand for charging stations across the U.S. and elsewhere, enough can even be manufactured to meet California's need in time.



Red lines indicate areas where the grid cannot accommodate additional load without any thermal or voltage violations. Grey hatched areas indicate regions where gaps in utility grid data exist. Colored lines, keyed in the legend, indicate the available circuit capacity in megawatts. CALIFORNIA AIR RESOURCES BOARD

EVEN IF California does meet its 2025 mark, more than 520 charging ports would still have to be installed every day to meet the 2030 objective.

Further, CARB states in its environmental analysis of transitioning to EVs by 2035 that "special attention" and "investment in transformers, meters, breakers, wires, conduit, and associated civil engineering work will be necessary." California's electricity distribution grid, especially in the rural areas, the report states, will need to be upgraded to handle the increased electricity demand by up to 20 percent in the morning and 25 percent in the evening.

Automakers Divided

AUTOMAKERS ARE also split over governmental EV policies in the United States and elsewhere. As mentioned, pure EV automakers and EV charging companies would like ICE vehicles to be banned by 2030 in the United States, for obvious reasons. GM, too, is in favor of an accelerated EV mandate, believing this gives the automaker a commercial advantage over its rivals. GM wants the U.S. Environmental Protection Agency (EPA) to make the administration's aspirational 50 percent EV sales goal by 2030 a national mandate instead.

However, automakers like Stellantis and Toyota are not enthralled with current EV mandates nor the proposed outright bans of ICE vehicle sales. Stellantis CEO Carlos Tavares has been very vocal in saying the speed demanded for the transition to EVs by politicians is "beyond the limits" of what the auto industry can support and worries it could end up being counterproductive.

Toyota President Akio Toyoda, who has been receiving strident criticism for not committing the company to an all-battery EV strategy, reportedly stated about meeting the California EV requirements: "Realistically speaking, it seems rather difficult to really achieve them." He also believes that like autonomous vehicles, BEVs will take longer to become the dominant everyday vehicle than "the mainstream media would like us to believe." Toyoda also argues that only selling EV powertrains would not serve Toyota's customers well in other countries, a similar argument made by automakers BMW, Mazda, and VW.

One issue that all automakers can agree on is that the new U.S. electric vehicle incentives need revision. For example, to receive the full $7,500 tax credit available, 40 percent of a battery's critical minerals must be extracted from or processed in the United States or a U.S. free-trade-agreement partner, or be recycled in North America; 50 percent of the battery components must be manufactured or assembled in North America before 2024. Thereafter, the percentages go up by 10 percentage points each year. Additionally, there are also price caps on the EVs that are eligible—$55,000 for autos and $80,000 for SUVs, vans, or pickup trucks.

There are also income caps. Even if a U.S. taxpayer buys an EV that meets the credit, but their tax

"I DON'T THINK that you can transform the mineral production and extraction within the next two to three years. You cannot change the sources from Congo, China, and other places within two to three years." —PABLO DI SI

liability is not at least $7,500 in the year they purchase the vehicle, they do not reap the full benefit. An individual using the standard tax deduction would have to earn around $70,000 to get the full federal tax benefit. So the value of the credit means little to the less well-off.

Automakers had previously agreed they could meet the Biden administration's 2030 EV sales objectives, providing there are substantial subsidies given to potential EV buyers. However, under the current incentive scheme, automakers say it will be nearly impossible to meet the content requirements. The Alliance for Automotive Innovation, which represents GM, VW, and other major automakers, warns that the credit structure likely will "jeopardize our collective target of 40-50 percent electric vehicle sales by 2030."

President and CEO of Volkswagen Group of America Pablo Di Si adds, "I don't think that you can transform the mineral production and extraction within the next two to three years. You cannot change the sources from Congo, China, and other places within two to three years."

The automakers do have a point. Only about 20 EVs on the market today are currently eligible for the tax credits. The U.S. Congressional Budget Office (CBO) further estimates that only about 11,000 new EVs will be sold in 2023 that meet the component requirements. The CBO further states that only 237,000 incentive-meeting EVs will be sold between 2022 and 2026. Automakers were hoping to sell at least 6 million mostly subsidized EVs over that period.

GM's CEO Mary Barra says she expects that its EVs will qualify for the full $7,500 tax credit within the next two to three years. If they do not, GM's $50 billion in projected revenue by 2025 and healthy profit margins from EVs will be at risk. Ford, which has previously stated before the new content rules that it did not expect its EV business to be fully profitable until model year 2025, may also need to redo its profitability calculations. Rising EV battery prices do not help. It is undoubtedly one reason that Ford, along with other automakers, is lobbying fervently for a liberal interpretation of the EV content requirements.

Consumer Subsidies, Industry Incentives, or Both?

HOWEVER, NOT EVERYONE is sympathetic to the automakers' plight. Some believe, as U.S. Senator Joe Manchin (D-W.Va.) famously stated, that EV incentives are "ludicrous": If EVs are so much better than ICE vehicles, and there are yearlong waiting lists to buy them, why do automakers need incentives to sell them?

Manchin, chief architect of the current consumer-oriented EV subsidy regime, has recently cautioned that he will not favorably look upon efforts to weaken it, because, he reasons, it's the best way for the United States to develop its own EV supply chain capability. However, the U.S. Treasury Department has delayed its final ruling on which electric vehicles might qualify for subsidies for a few months, setting up a potential political firestorm in early 2023 if more are added than Manchin believes should be.

Other observers contend that EV incentives are misdirected or misplaced altogether. For instance, a National Bureau of Economic Research (NBER) study indicates past incentives seemed to cannibalize fuel-efficient vehicles, leading to overestimating emissions benefits supposedly gained by EVs by almost 40 percent. A Massachusetts government–sponsored study of the effects of the more than $50 million of EV subsidies the state doled out found that they did not influence EV buyers—they would most likely have bought one anyway.

World Bank data indicate that funding EV charging station expansion is more cost-effective than EV purchasing subsidies to get people into EVs. The U.K. has gone this route, stopping its decade-long EV subsidy program to improve EV charging across the country instead.

Still other EV advocates contend that some form of EV purchasing subsidies will be needed probably until 2050 but paid through "feebates" rather than by taxpayers. A feebate comes out of the transaction costs of buying a vehicle. For instance, if you were buying an ICE vehicle, you might pay a fee that goes into a fund to incentivize others to purchase EVs. Taxpayers themselves, however, want immediate rebates at the conclusion of the sale, instead of having to file their taxes to receive it.

THE MULTITUDE of arguments and counterarguments over EV subsidies and incentives, their focus, efficacy, and fairness, illustrate just a small part of the conflicts, uncertainty, and politics involved in EV policymaking.

Other EV advocates acknowledge consumer desire for rebates, but emphasize that whatever subsidies or rebates are provided, they need to be targeted to support the less-affluent EV buyer and not reward the well-off, which Massachusetts is now trying to do with its subsidies.

There are also concerns of what happens to EV demand if subsidies are stopped. China, which originally planned to stop EV subsidies at the end of 2020, extended the program to the end of 2022 based on a drop-off in EV sales. The U.K. decision to end subsidies has not gone without complaint, either.

The ending of government EV subsidies altogether is applauded by other groups, because they can distort the competitive landscape. Still others believe that with EV-ICE parity by 2025 or 2026, they are no longer needed anyway. Volvo CEO Jim Rowan recently claimed that parity in that time frame is entirely possible.

The multitude of arguments and counterarguments over EV subsidies and incentives, their focus, efficacy, and fairness, illustrate just a small part of the conflicts, uncertainty, and politics involved in EV policymaking. The conflicts get even more complicated and fraught when EV policies must be put into engineering practice. ■

Chapter 9

Policy Roadblocks

How Bureaucracy and Public Opposition Could Stymie Efforts to Support EVs at Scale

Wind turbines near Northwood, Iowa, stand over a farmhouse, 2 February 2018. Opponents of wind power are successfully stalling or rejecting wind-farm projects across the country. Criticism of wind turbines is nothing new, but this latest rebellion is raising a host of issues and halting developments. CHARLIE NEIBERGALL/AP

"PUBLIC POLICY implementation is hard even if everyone supports a policy," says University of Michigan professor emeritus John Leslie King, who has studied policy management and administration for decades.

It becomes infinitely harder when the technology is complex and depends on several other equally complex technologies; where the stakes are huge; where there is a myriad of players involved, each with competing missions, interests, and policymaking boundaries to protect; and when time is short.

Such is the case with the Biden administration's attempted transition of the U.S. economy away from dependence on fossil fuels like petroleum, coal, and natural gas to 100 percent carbon pollution–free electricity by 2035. Driving that timeline is the shift to electric vehicles, which the administration wants to account for 50 percent of all new cars sold by 2030.

Implementing a national EV policy that aims to transform the economy is an exercise in mind-boggling complexity. Not only are several federal departments and agencies directly involved, including the Departments of Agriculture, Commerce, Energy, the Interior, Labor and Transportation; the Environmental Protection Agency, the Small Business Administration, the Federal Energy Regulatory Commission, and the Federal Trade Commission, but the different and often competing policy objectives and statutory regulations covering multiple industries must be coordinated, agreed on, and implemented across all 50 state governments, some 3,000 local counties, and 19,000 municipalities.

The U.S. electrical power industry alone "is influenced by a variety of decision-makers, including over 200 investor-owned utilities, 10 federal power authorities, over 2,000 publicly owned utilities, about 900 rural electric cooperatives, seven RTOs [Regional Transmission Organizations], 48 state regulatory bodies [e.g., Public Utility Commissions (PUCs)], and many state and federal agencies," states a report by the nonprofit group Americans for a Clean Energy Grid. Reproduce that across the numerous EV-involved industries, from mining to recycling, and the complexity involved becomes clearer.

1,000,000

BY 2050, as many as 1 million circuit miles of new transmission lines may be needed, with some 140,000 miles required just for the replacement of existing aging transmission lines.

Typically, each governmental body has some number of elected, appointed, and full-time staff that can affect how well, or even whether, a policy is implemented. State PUCs, for instance, have a major role in ensuring the electrical infrastructure needed to support EVs exists. Affordability is expected to be just one highly contentious issue: Who, exactly, is going to pay for grid upgrades? In Kansas, the average customer paid $4 per month on their utility bill for transmission costs 10 years ago, but that has climbed to $20 per month today, and is likely to go higher as billions are spent on new transmission lines to support renewable energy. Increasing electricity rates is politically fraught for elected members of public utility commissions. The fight over how to implement EV charging networks in Minnesota is another example of the tricky politics PUCs are involved with.

Tricky politics are one thing; having enough expertise on hand to accomplish policy goals is another altogether. Utility commissioners and their staffs are now dealing with "rising workloads with limited staff, limited resources, and growing gaps in internal expertise due to the increasingly specialized needs of today's energy system," states the Rocky Mountain Institute. In addition, the lack of relevant legal or industry expertise is increasingly worrisome. This may become a major operational and legal problem at the federal level as thousands of new employees are hired across multiple federal departments and agencies to carry out the Biden administration's environmental policies.

Staggering Number of New Transmission Lines Needed

A **CONSEQUENCE** of the multitude of constituencies involved is that the "decision friction" involved in getting any decision approved is white hot. To cool it down requires coordinated communications and joint action among all the participants involved. Given the increased future dependency on renewables, the grid as a whole needs to be much more reliable and flexible than it is today. How to achieve that still requires quite a bit of research, according to the U.S. Department of Energy's National Renewable Energy Laboratory.

Yet, as noted in a Clean Air Task Force report, "To date...there has been hardly any conversation among policy analysts, let alone high-level policymakers, about how such a massive [energy] infrastructure initiative should be undertaken." When there is conversation, it is frequently combative, with local, state, and federal officials fighting among themselves over who has the final say on what is going to be done, where, and when.

To have any hope of reaching a carbon-free electricity grid, tens of thousands of miles of new transmission lines must be added by 2035 to add to the more than 600,000 circuit miles of existing alternating current (AC) transmission lines (240,000 operating at more than 230 kilovolts). By 2050, as many as 1 million circuit miles of new transmission lines may be needed, with some 140,000 miles required just for the replacement of existing aging transmission lines.

Unfortunately, between 2010 and 2020, only 18,000 miles of new transmission lines were added to the U.S. grid. Worse, in 2021, just 386 miles were added, according to the American Clean Power (ACP) organization's "2021 Annual Market Report." The ACP report further notes that "only 5,000 miles is on-track for delivery between now and 2025."

The proximate causes for the slow installation of transmission lines are the numerous competing federal and state interagency statutory requirements that must be followed. As a result, new transmission-line projects take a decade or more to complete and often double or more in cost, if they get built at all. The longer the transmission line, generally the more time it takes to overcome all the statutory hurdles as well as possible landowner objections.

Take the SunZia transmission line project, which was started in 2006 to send enough renewable power via transmission lines 520 miles across federal, state, and private lands between New Mexico and central Arizona. If no final hurdles appear, that project might begin construction in 2023 and be completed in 2025. The U.S. Bureau of Land Management alone spent more than six years reviewing the project. This does not include the numerous other reviews performed by individual state regulators, other regulatory stakeholders, and public entities. The project owners also had to strike multiple deals with the private landowners to run the lines through their properties.

Every major transmission-line project in the United States faces similar challenges to overcome. The public backlash over the proposed transmission line in Maine and the recently canceled California Colusa-Sutter Transmission Line Project illustrates the contentious issues involved. With many more transmission lines needed to support renewable energy projects, the public fights are expected to get even more cantankerous.

It is little wonder that Alison Silverstein, a former senior advisor to the U.S. Federal Energy Regulatory Commission, exclaimed in regard to getting energy infrastructure built, "The politics are a freakin' nightmare."

Nightmares for Everyone

THE SAME KINDS of political and legal nightmares are replicated for every other EV infrastructure challenge. That includes gaining the necessary mining permits for the critical minerals needed for EVs. Both Ford and Rivian are pushing the U.S. Department of the Interior to speed up mining permits in the United States and limit the permitting process to last no more than three years, as in Canada and Australia. Currently, permitting takes up to 10 years in the

Mike Love of Toyota is at the podium at a meeting of the California Air Resources Board, with former chair Mary D. Nichols projected on the screen, in Los Angeles, 26 January 2012. REED SAXON/AP

"[T]HERE HAS been hardly any conversation among policy analysts, let alone high-level policymakers, about how such a massive [energy] infrastructure initiative should be undertaken."
—CLEAN AIR TASK FORCE

United States. Even after permits have been approved, however, there is no guarantee that a mine will become fully operational, as Nevada's Thacker Pass lithium mine's ongoing controversy shows.

Permitting issues also bedevil wind power projects. For example, Iowa is one of the best states for wind power farms. In 2022, Iowa generated more than 57 percent of its electricity from wind power, a larger share than any other state. However, as wind turbine farms have increased, so has local opposition to them. As a result, 49 to 77 percent of potential Iowa wind turbine sites are no longer available. In addition, there is also strong opposition to building the high-voltage transmission lines needed to connect wind farms to the Midcontinent Independent System Operator and Southwest Power Pool grids. Public opposition to wind turbine projects is growing in Illinois, Indiana, and Ohio as well.

Yet even when a popular EV-friendly policy is passed, that doesn't mean it will be implemented without difficulty. For instance, eight years ago, California passed a state law streamlining EV charging-station permitting. However, the law is widely ignored by local jurisdictions that want to have their own say. This helps explain why California is next to last for the time it takes to get a permit for a direct-current fast charger approved. Equally, the state has long had a subsidy plan to help low-income residents buy EVs. Unfortunately, applications for the subsidies take months to get approved if they are at all. The fund often runs out of money, discouraging future EV purchasers.

Making policy implementation harder still is that some regulatory bodies assume that other regulatory bodies will implement their policies for them. For instance, the California Air Resource Board, in setting the state's 2026, 2030, and 2035 EV sales mandates, assumed that the California Public Utilities Commission (CPUC) would be able to mandate the requisite EV-supporting electrical infrastructure. As one CARB member has stated, their concern is climate, whereas solving power generation is the responsibility of the CPUC.

This highlights something that seems to be a critical weakness in EV policymaking, says Virginia Tech's Lee Vinsel, a technology historian and expert on how regulatory policy has improved auto safety and lowered pollution. Historically, auto regulation has dealt with "the negative externalities associated with the auto itself," he explained. "Issues like auto safety and pollution were the chief concerns. These issues are self-contained to the auto itself."

However, Vinsel points out that with EVs, "the negative externalities are generally outside the auto. EVs are part of a larger system that involves the electric grid, mining, and so on, increasing dramatically the regulatory scale involved."

It is not surprising, therefore, that John Bozzella, president of the industry trade group Alliance for Automotive Innovation, questions the feasibility of California's mandates. "Whether or not these requirements are realistic or achievable is directly linked to external factors like inflation, charging and fuel infrastructure, supply chains, labor, critical mineral availability and pricing, and the ongoing semiconductor shortage," Bozzella says. "These are complex, intertwined, and global issues well beyond the control of either CARB or the auto industry."

Vinsel further notes, "Successful regulation is fragile." It depends acutely, he says, upon the government possessing "reliable knowledge, substantial expertise, and organizational capabilities." EVs are a different regulatory beast from ICE vehicle regulation, needing regulatory expertise that may not exist across government at the depth and breadth needed across so many different industries, Vinsel observes.

As a result, Vinsel warns, "I do think there are real social risks if the government messes this transition up." ■

Employees work at the assembly line of the Volkswagen ID.4 electric car in Emden, Germany, last year. DAVID HECKER/AFP/GETTY IMAGES

Chapter 10

Reshaping Labor Markets

Millions of automotive, energy, and mining jobs will be created… and destroyed

ONE OF THE MOST vexing social challenges confronting the transition to EVs at scale is dealing with the effects that governmental EV transition policies will have on millions of jobs across a wide swath of industries. For example, the Biden administration has proudly proclaimed that moving to EVs will be the source of new, high-paying jobs. President Biden says his EV policies will result in "one million new jobs in the American automobile industry. One million."

The President's "fuzzy math," as the Associated Press termed it, however, fails to calculate how many jobs will be lost by his policies.

As does the U.S. 2050 net-zero strategy document, which explains how America will get to net-zero greenhouse-gas emissions by 2050. It has 60 pages of detail selling the myriad benefits and assumptions of new "good-paying jobs" accruing by getting to net-zero, but a mere three sentences are devoted to the "difficult transition" getting to net-zero will entail over the next three decades.

But the effects of the transition are already being felt by workers. Ford, for example, recently cut 3,000 salaried and contract workers as a down payment to help fund the transition to EVs. Ford CEO Jim Farley has said that employee cuts are necessary, as Ford has "too many places in some places, no doubt about it. We have skills that don't work anymore, and we have jobs that need to change."

Ford is not alone. Stellantis is offering certain higher-salaried U.S. employees separation packages to help its "transformation to become a sustainable tech mobility company and the market leader in low-emission vehicles," a company spokesperson said. The automaker has already begun idling auto plants and is warning of future closures to pay for its transition to EVs and to try to keep EV prices affordable.

By some estimates, upward of 80,000 autoworkers and a similar number in the auto supply chain have

80,000 BY SOME estimates, upward of 80,000 autoworkers and a similar number in the auto supply chain have already been laid off globally to support the EV transition.

already been laid off globally to support the EV transition. For example, Daimler and Audi reportedly eliminated 20,000 jobs, while auto supplier Bosch will be laying off 1,000 workers in a move to support vehicle electrification.

It is not surprising that policymakers tout the benefits of their policy decisions while ignoring the downsides. Michigan Governor Gretchen Whitmer, for example, claimed that since she took office in 2019, 25,000 new auto jobs were added to the state through her leadership in "the future of mobility and electrification." However, a more accurate number is a net loss of 1,600 jobs as internal combustion engine (ICE) jobs were cut and EV jobs moved elsewhere.

Knowing how many net jobs the transition to EVs and related renewable energy will create, change, or eliminate—and over what time period—is critical to determining the impacts of governmental policies and whether they need revision. However, accurate job figures are exceedingly hard to determine.

Counting Jobs

IN MANY WAYS, it is easiest to determine how many new EV-related jobs are needed. An obvious example involves the making of millions of EV batteries. For example, Secretary of Energy Jennifer Granholm has stated that the United States "needs over 100 battery cell manufacturing locations by 2035" to meet the projected EV demand. Currently, 21 battery factories are in operation or will be within five years.

If each factory employs 2,000 to 3,000 workers, then 200,000 to 300,000 new battery-related jobs will likely be created, along with thousands of factory construction jobs. For their part, European Commission officials predict EVs will lead to major job growth across the 27 EU countries, with up to 4 million battery-related new jobs being created by 2025 because of its formation of the European Battery Alliance.

Workers lower an R1T truck body onto a chassis in the assembly line at the Rivian electric vehicle plant in Normal, Ill., on 11 April 2022.
BRIAN CASSELLA/CHICAGO TRIBUNE/TRIBUNE NEWS SERVICE/GETTY IMAGES

BY ONE ESTIMATE, at least 74 lithium, 62 cobalt, 76 nickel, and 97 graphite mines, as well as 54 new synthetic graphite factories, will be needed by 2035 to meet the demand for EV and renewable-energy storage batteries.

Of course, more EV battery factories creates more demand for raw materials. Mineral market analysis company Benchmark estimates that at least 74 lithium, 62 cobalt, 76 nickel, and 97 graphite mines, as well as 54 new synthetic graphite factories, will be needed by 2035 to meet the global demand for EV and renewable-energy storage batteries. Each mine and factory will need hundreds of workers to operate it.

The impact of EVs on auto manufacturing and supplier jobs is harder to assess. Electric vehicles require new or retooled factories, with each needing thousands of employees. How many will be new hires versus existing workers who are retrained is not clear. BMW, for example, claims it will not cut jobs in the transition to EVs, but it is likely that it will still reduce its workforce by both attrition and reskilling into other areas like battery manufacturing, as other German automakers are contemplating. Further, given that EVs are said to need 30 percent less labor to produce than ICE vehicles, coupled with more automation that will be used for their manufacturing, many assembly-line jobs may disappear.

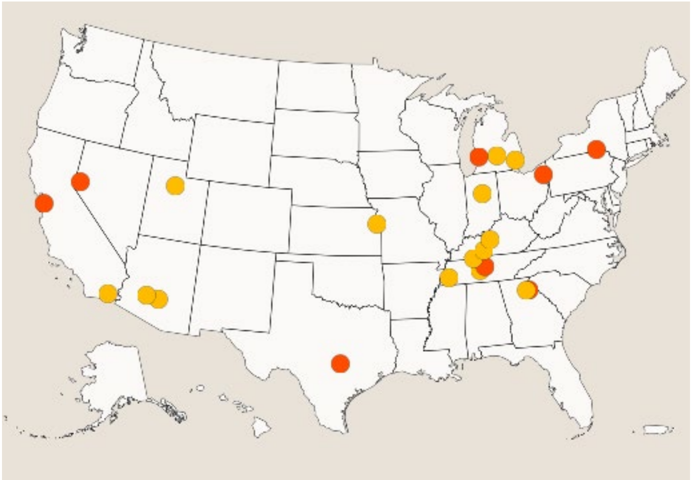
In addition, the elimination of the power train required in ICE vehicles means all those related auto-part manufacturing jobs in the auto-supplier community will disappear. The Congressional Research Service estimates, "Of the nearly 590,000 U.S. employees engaged in motor vehicle parts manufacturing, about one-quarter—nearly 150,000—make components for internal combustion power trains."

High-end engineering and computer software and systems jobs at auto suppliers are also at risk, as auto manufacturers are moving to shift those jobs in-house. Former Volkswagen CEO Herbert Diess said in 2019, for example, that he expected by 2030 that software "will account for half of our development costs." VW, like every other automaker, wants to control those costs.

A recent analysis by the Economic Policy Institute (EPI) finds that U.S. auto-industry jobs could rise by 150,000 by 2030 if battery electric vehicle sales reach 50 percent by 2030 and the vehicle market share of U.S.-assembled vehicles increases to 60 percent from today's 50 percent. As a data point, the 15 major automakers in the United States employ about 388,000 workers, according to the American Automotive Policy Council. Including such employers as suppliers, dealers, and service centers, there are nearly 8 million people employed in the industry at large, or about 5 percent of the U.S. workforce.

However, EPI concedes, it would take even more governmental policy intervention to make these goals happen. Without additional government involvement in the EV market, EPI states, the industry could lose 75,000 jobs instead.

NEW GIGAFACTORIES CLUSTER IN THE MIDWEST, SOUTH AND NEAR TESLA FACILITIES
This map of the United States shows operational factories (yellow dots), and planned factories (orange dots).



A Boston Consulting Group (BCG) analysis of the European auto industry posits that about 930,000 existing auto manufacturing and supplier jobs will disappear with the introduction of EVs by 2030, but another 895,000 new jobs will be added. So, BCG says, the transition to EVs will basically be a net job wash. The European Association of Automotive Suppliers, however, is more pessimistic. It believes that there will be a net loss of 275,000 auto-industry jobs by 2040, with most of the drop-off coming between 2030 and 2035. It's unknown how many existing workers will find comparably paying jobs. There are also concerns in Japan, or at least at Toyota, over the potential for job losses from the transition to EVs. Toyota CEO Akio Toyoda has stated that moving solely to battery electric vehicles would "risk losing the majority of 5.5 million jobs" in the Japanese auto industry.

However, another study by consulting group Arthur D. Little Japan cast doubts on that number. It estimates that out of the current 686,000 auto-part supplier jobs in the country, about 84,000 will be lost by 2050.

Fossil-Fuel Job Impacts

EVS WILL OBVIOUSLY have an impact on jobs in the fossil-fuel and biofuel industries as well. Again, determining how much impact will be directly attributed to EVs versus the change to renewable energy is hard to unravel. For instance, an in-depth study by Princeton University's Andlinger Center for Energy and the Environment assessed different U.S. policy scenarios from conservative to aggressive for achieving net-zero by 2050. The Princeton analysis estimates that by 2030 net fossil fuel energy jobs in the United States could decrease by 209,000 positions. On the other hand, the study estimates that somewhere between 777,000 to 5.1 million new energy-related jobs could be created in the United States by 2050.

300,000,000
There will likely still be 300 million ICE vehicles on the road in the United States alone in 2030, up from 280 million in 2020.

Other job impacts are likely as well. California estimates that some 32,000 auto mechanics would lose their jobs in that state alone by 2040, while thousands working for family-owned service and fueling stations across the country would also be at risk.

There are also worries in dozens of states that depend on fossil-fuel sales to fund schools, public health, and infrastructure that they will not be able to replace those funds, or the jobs they create.

Canada's federal Natural Resources Minister Jonathan Wilkinson, on the other hand, believes the transition to EVs and renewable energy will create so many "good, well-paying jobs and economic prosperity in every region of the country" that there will not be enough workers to fill them all.

Wilkinson told the Canadian Broadcasting Corporation News, "I said it many times publicly that I do not believe that the challenge we are going to face is that there are workers who are displaced that will not find other good-paying jobs.

"I am actually quite worried that there are so many opportunities...we will not have enough workers to fill the jobs."

All these numbers should be taken with a heavy dose of skepticism, however. It is useful to remember that even as EV sales increase, even in optimistic scenarios, there will likely still be 300 million ICE vehicles on the road in the United States alone in 2030, up from 280 million in 2020. There will still be jobs needed to support tens of millions of ICE vehicles for two decades or more after that. One study shows that even in 2050, some 44 percent of all vehicle sales globally will still have internal combustion engines, albeit perhaps using biofuels.

This is not to say there is not going to be intense personal and economic pain faced by tens of thousands of workers across multiple industries during the transition to EVs at scale. It will be easy to view these figures as abstract statistics, unfortunately, and not as actual individuals whose livelihoods are disrupted.

While there has been some consideration to helping those who are going to lose their jobs, it is not nearly enough. Furthermore, government retraining programs have a long history of being expensive failures.

The bottom line is that no one really knows how many jobs will be added or lost or how rapidly in the EV transition. Better statistics are needed. However, the increasing number of EVs and their increasing job disruption across multiple industries do point toward one important need: workers with new skills.

The Insatiable Need for Talent

THE RAPID AND largely unforeseen shift in global governmental policies since 2010 in strongly promoting EVs and renewable energy has left the industries involved short on the technical and managerial skills needed to make the transition.

For instance, the EV-battery industry has grown from three gigafactories in 2015 to more than 285 currently being built or planned globally. Not surprisingly, this has exposed

800,000 ATTEMPTING TO FILL in its battery talent shortfall, the EU is setting out to retrain or upskill 800,000 workers by 2025.

a massive skills gap spanning workers to managers that may last for years, with leading battery manufacturers engaged in spirited fights over talent. South Korean battery manufacturers, for example, are short some 3,000 new hires with graduate degrees to work in battery research and design. Attempting to fill in its battery talent shortfall, the EU is setting out to retrain or upskill 800,000 workers by 2025.

GM announced in an investors call that it was pushing back its target of making 400,000 EVs in North America by the end of 2023 to mid-2024. One reason for the delay, according to GM CEO Mary Barra, was that the company was taking "longer than expected" to hire and train staff for its new Warren, Ohio, battery plant. Another reason: "battery pack assembly" issues that need to be corrected.

Skill shortages are hitting the mining, energy, and auto industries, too, especially regarding workers with advanced engineering and digital skills. Even traditional jobs, like qualified electrical lineman, are in short supply across the United States, affecting even small utilities. Some 29,000 linesman need to be hired by 2023, along with tens of thousands of others, including technicians, plant/field operators, and engineers.

A PRINCETON UNIVERSITY study estimates that somewhere between 777,000 and 5.1 million new energy-related jobs could be created in the United States by 2050.

The auto industry is spending hundreds of millions of dollars to also upskill its workforce. Ford, for example, has pledged to spend US $525 million in the United States over the next five years to train technicians to service EVs. Mercedes-Benz says it will be investing €1.3 billion ($1.4 billion) by 2030 in Germany alone to train all its staff from production to administration in vehicle electrification and digitalization. Auto supplier Bosch says it will be spending another €1 billion reskilling its workforce in EV-related technology over the next five years on top of the €1 billion it has already spent.

The EV-battery startup company Sparkz is going to fill its worker needs in its planned West Virginia plant by recruiting and retraining laid-off coal miners. It says the new plant will employ at least 350 people and could grow to 3,000 workers.

How much the coal miners will earn in wages and benefits compared to what they earned previously will be interesting to see. As mentioned, a point of contention in the transition to EVs is whether the new jobs will, in fact, be "good, high-paying jobs" as is frequently promised. Fossil-fuel industries are traditionally where a worker can earn a large paycheck without needing a college degree. While energy employment generally pays more than the average, the International Energy Agency data also indicate that renewable-energy jobs pay less than those in the fossil-fuel industry.

Brad Markell, the executive director of the AFL-CIO Industrial Union Council, told a National Academies EV workshop last year, "Since 2000, real wages for nonsupervisory production workers in the auto industry are down 20 percent." Unions are concerned that automakers and battery manufacturers will aim to further reduce worker wages and benefits at new EV and battery factories.

Indeed, new factories by Ford and GM that are being built in lower-cost, right-to-work states like Kentucky and Tennessee will be staffed by thousands of nonunion workers earning significantly less than their union counterparts. Subaru recently announced it will not build an EV factory in the United States because the wage it pays at its U.S. auto plants cannot compete with what McDonald's pays. The UAW is trying to unionize GM battery plants like the one in Lordstown, Ohio, to increase worker wages and benefits in line with its unionized autoworkers.

Exacerbating this trend is the fact that autoworker jobs are leaving their traditional locales in Michigan and Ohio because of the EV-subsidy death-cage-match bidding wars among state governors hypercharged by billions of dollars in federal aid to have EV and battery factories, and the jobs they bring, locate in their state. Tennessee provided Ford $884 million in incentives to locate in the state, while Kentucky provided a loan of up to $250 million. North Carolina has provided $1.2 billion in incentives to the Vietnamese EV startup VinFast to locate there, while Georgia has provided incentives worth $1.8 billion to South Korean company Hyundai and $1.5 billion to Rivian.

The state of Michigan has been the epicenter of the U.S. auto industry for the past century with 11 assembly plants, 2,200 auto-research or design facilities, and 26 automaker and supplier headquarters. However, Michigan is finding the auto industry center of gravity moving away, as EV-battery factories pop up across the Midwest "battery belt." Automakers like to colocate EV factories near their battery factories, meaning the auto industry will not be the job creator in Michigan it once was.

Michigan has countered out-of-state financial carrots by providing nearly $2 billion of its own to Ford and another $1 billion to GM to stay in the state, with hundreds of millions more in incentives likely. Whether it will be enough to keep auto jobs in the state is unlikely, and the long-term impact on Michigan's economy and middle-class jobs could be severe.

More state EV incentive deals can be expected over the next few years. Whether they are a good idea is debatable. Every job being brought in or saved is costing hundreds of thousands of dollars in subsidies, and automakers have been known to take the money and run. States, however, continue to view them as good investments that will, at the very least, bring better-paying jobs than exist there today.

As North Carolina's Commerce Secretary Machelle Baker Sanders has gushed over VinFast's decision to locate in the state, "Automotive assembly plants are incredible engines for economic growth, due to the positive ripple effects they create across a region's economy." ■

Chapter 11

Why EVs Aren't a Climate Change Panacea

Unless people change their behaviors, we won't hit 2050 net-zero emissions targets

Teslas in a parking lot after arriving at a port in Yokohama, Japan.

TORU HANAI/BLOOMBERG/GETTY IMAGES

"ELECTRIC CARS will not save the climate. It is completely wrong," Fatih Birol, executive director of the International Energy Agency (IEA), has stated.

If Birol were from Maine, he might have simply observed, "You can't get there from here."

This is not to imply in any way that electric vehicles are worthless. Analysis by the International Council on Clean Transportation argues that EVs are the quickest means to decarbonize motorized transport. However, EVs are not by themselves in any way going to achieve the goal of net-zero by 2050.

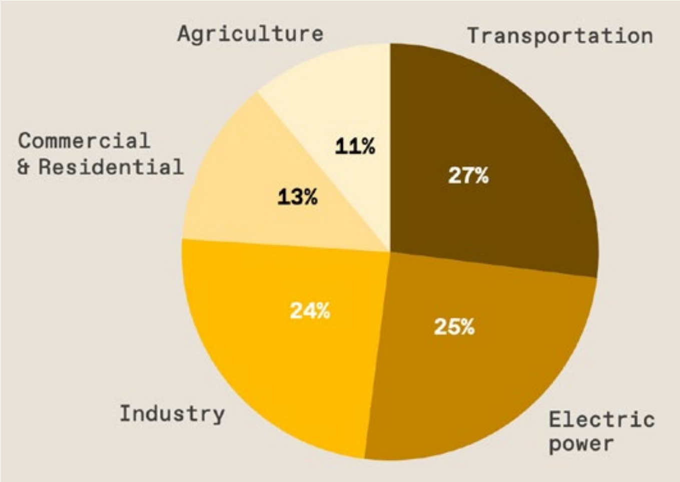
There are two major reasons for this: First, EVs are not going to reach the numbers required by 2050 to hit their needed contribution to net-zero goals. Second, even if there are the requisite number of EVs on the road, a host of other personal, social, and economic activities must be modified to reach the total net-zero mark.

For instance, Alexandre Milovanoff, formerly at the University of Toronto and currently a policy analyst with the Canadian government, demonstrated in his research that the United States must have 90 percent of its vehicles, or some 350 million EVs, on the road by 2050 in order to hit its emission targets. The likelihood of this occurring is infinitesimal. Some estimates indicate that about 40 percent of vehicles on U.S. roads will be ICE vehicles in 2050, while others are less than half that figure.

For the United States to hit the 90 percent EV target, sales of all new ICE vehicles across the United States must cease by 2038 at the latest, according to research company BloombergNEF. Greenpeace, on the other hand, argues that sales of all diesel and petrol vehicles, including hybrids, must end by 2030 to meet such a target. However, achieving either goal would likely require governments offering hundreds of billions of dollars, if not trillions, in EV subsidies to ICE owners over the next decade, not to mention significant investments in EV charging infrastructure and the electrical grid. ICE vehicle households would also have to be convinced that they would not be giving up activities by becoming EV-only households.

As a reality check, current estimates for the number of ICE vehicles still on the road worldwide in 2050 range from a low of 1.25 billion to more than 2 billion. Even assuming that the required EV targets were met in the

TOTAL U.S. GREENHOUSE GAS EMISSIONS BY ECONOMIC SECTOR IN 2020



United States and elsewhere, it still will not be sufficient to meet net-zero 2050 emission targets. Transportation accounts for only 27 percent of greenhouse-gas emissions (GHG) in the United States; the sources of the other 73 percent of GHG emissions must be reduced as well. Even in the transportation sector, more than 12 percent of the GHG emissions are created by air and rail travel and shipping. These will also have to be decarbonized.

Nevertheless, for EVs themselves to become true zero-emission vehicles, everything in their supply chain, from mining to electricity production, must be nearly net-zero emission as well. Today, depending on the EV model, where it charges, and assuming it is a battery electric and not a hybrid vehicle, it may need to be driven anywhere from 8,400 to 13,500 miles, or, controversially, significantly more to generate less GHG emissions than an ICE vehicle. This is due to the 30 to 40 percent increase in emissions EVs create in comparison to manufacturing an ICE vehicle, mainly from its battery production.

In states (or countries) with a high proportion of coal-generated electricity, the miles needed to break even climb more. In Poland and China, for example, an EV would need to be driven 78,700 miles to break even. Just accounting for miles driven, however, BEV cars and trucks appear cleaner than ICE equivalents nearly everywhere in the United States today. As electricity increasingly comes from renewables, total electric vehicle GHG emissions will continue downward, but that will take at least a decade or more to happen everywhere across the United States (assuming policy roadblocks disappear), and even longer elsewhere.

If EVs Aren't Enough, What Else Is Needed?

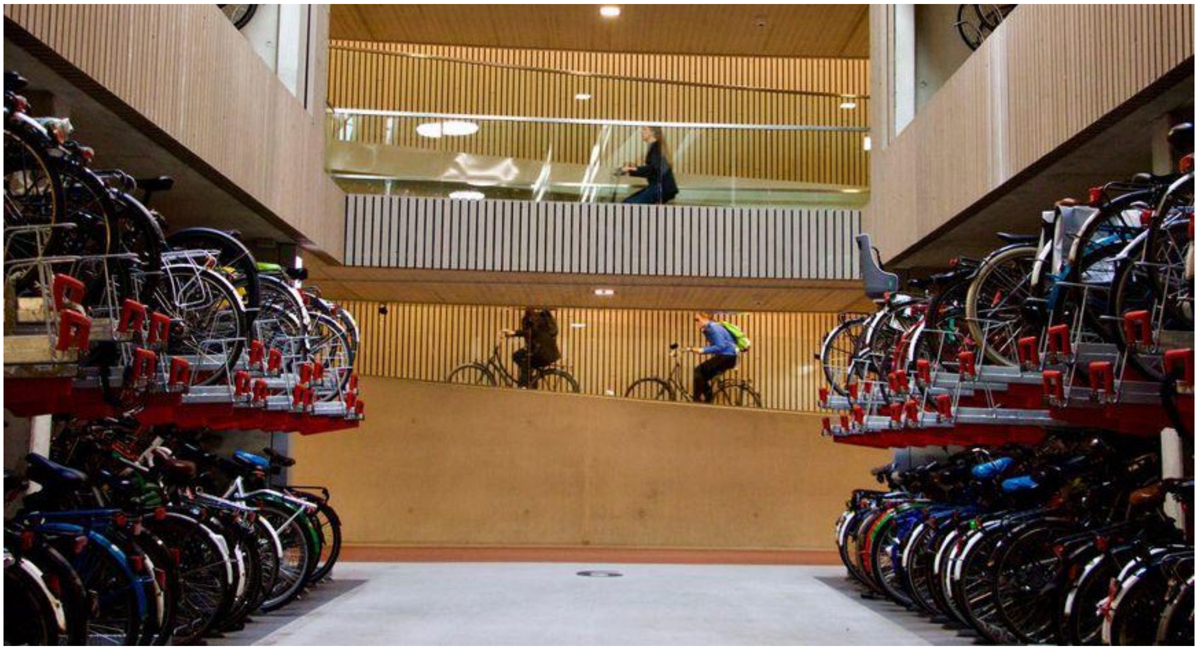
GIVEN THAT EVs, let alone the rest of the transportation sector, likely won't hit net-zero 2050 targets, what additional actions are being advanced to reduce GHG emissions?

A high priority, says IEA's Birol, is investment in across-the-board energy-related technology research and development and their placement into practice. According to Birol, "IEA analysis shows that about half the reductions to get to net-zero emissions in 2050 will need to come from technologies that are not yet ready for market."

Many of these new technologies will be aimed at improving the efficient use of fossil fuels, which will not be disappearing anytime soon. The IEA expects that energy-efficiency improvement, such as the increased use of variable-speed electric motors, will lead to a 40 percent reduction in energy-related GHG emissions over the next 20 years.

But even if these hoped-for technological improvements arrive, and most certainly if they do not, the public and businesses are expected to make more energy-conscious decisions to close what the United Nations says is the expected 2050 "emissions gap." Environmental groups foresee the public needing to use electrified mass transit, reduce long-haul flights

Dronning Louise's Bro (Queen Louise's Bridge) connects inner Copenhagen and Nørrebro and is frequented by many cyclists and pedestrians every day.
FRÉDÉRIC SOLTAN/ CORBIS/GETTY IMAGES



The world's largest bike parking facility, Stationsplein Bicycle Parking, near Utrecht Central Station, in Utrecht, Netherlands, has 12,500 parking places. ABDULLAH ASIRAN/ANADOLU AGENCY/GETTY IMAGES

for business (as well as pleasure), increase telework, walk and cycle to work or stores, change their diet to eat more vegetables, or, if absolutely needed, drive only smaller, shorter-range EVs. Another expectation is that homeowners and businesses will become "fully electrified" by replacing gas-fired stoves and oil, propane, and gas furnaces with electric heat pumps, as well as by installing solar power and battery systems.

Underpinning the behavioral changes being urged (or encouraged by legislation) is the notion of rejecting the current carcentric culture and completely rethinking what personal mobility means. For example, researchers at University of Oxford in the U.K. argue that "focusing solely on electric vehicles is slowing down the race to zero emissions." Their study found "emissions from cycling can be more than 30 times lower for each trip than driving a fossil-fuel car, and about 10 times lower than driving an electric one." If just one out of five urban residents in Europe permanently changed from driving to cycling, emissions from automobiles would be cut by 8 percent, the study reports.

Even then, Oxford researchers concede, breaking the car's mental grip on people is not going to be easy, given the generally poor state of public transportation across much of the globe.

Behavioral Change Is Hard

HOW WILLING are people to break their car dependency and other energy-related behaviors to address climate change? The answer is perhaps some, but maybe not too much. A Pew Research Center survey taken in late 2021 of 17 countries with advanced economies indicated that 80 percent of those surveyed were willing to alter how they live and work to combat climate change.

However, a Kantar Public survey of 10 of the same countries taken at about the same time gives a less positive view, with only 51 percent of those polled stating they would alter their lifestyles. In fact, some 74 percent of those polled indicated they were already "proud of what [they are] currently doing" to combat climate change.

What both polls failed to explore are what behaviors specifically would respondents be willing to permanently change or give up in their lives to combat climate change?

For instance, how many urban dwellers, if told that they must forever give up their cars and instead walk, cycle, or take public transportation, would willingly agree to do so? And how many of those who agreed would also consent to go vegetarian, telework, and forsake trips abroad for vacation?

It is one thing to answer a poll indicating a willingness to change, and quite another to "walk the talk," especially if there are personal, social, or economic inconveniences or costs involved. For instance, recent U.S. survey information shows that while 22 percent of new car buyers expressed interest in a battery electric vehicle, only 5 percent actually bought one.

Granted, there are several cities where living without a vehicle is doable, like Utrecht in the Netherlands, where in 2019 48 percent of resident trips were done by cycling, or London, where nearly two-thirds of all trips taken that same year were made by walking, cycling, or public transportation. Even a few U.S. cities might be livable without a car.

However, in countless other urban areas, especially across most of the United States, even those wishing to forsake owning a car would find it very difficult to do so without a massive influx of investment into all forms of public transport and personal mobility to eliminate the scores of U.S. transit deserts.

As Tony Dutzik of the environmental advocacy group Frontier Group has written, in the United States, "the price of admission to jobs, education, and recreation is owning a car." That's especially true if you are a poor urbanite. Owning a reliable automobile has long been one of the only successful means of getting out of poverty.

Tim Kuniskis, CEO of Dodge Brand, Stellantis, introduces the Dodge Charger Daytona SRT Concept all-electric muscle car on August 17, 2022, in Pontiac, Mich.

BILL PUGLIANO/GETTY IMAGES

Massive investment in new public transportation in the United States is unlikely, given its unpopularity with politicians and the public alike. This unpopularity has translated into aging and poorly maintained bus, train, and transit systems that few look forward to using. The American Society of Civil Engineers gives the current state of American public transportation a grade of D- and says today's $176 billion investment backlog is expected to grow to $270 billion through 2029.

While the $89 billion targeted for public transportation in the recently passed Infrastructure Investment and Jobs Act will help, it also contains more than $351 billion for highways over the next five years. Hundreds of billions in annual investment are needed not only to fix the current public transport system but to build new ones to significantly reduce car dependency in America. Doing so would still take decades to complete.

Yet even if such an investment were made in public transportation, unless its service is competitive with an EV or ICE vehicle in terms of cost, reliability, and convenience, it will not be used. With EVs costing less to operate than ICE vehicles, the competitive hurdle will increase, despite the moves to offer free transit rides. Then there is the social stigma attached to riding public transportation that needs to be overcome as well.

A few experts proclaim that ride-sharing using autonomous vehicles will separate people from their cars. Some even claim such AV sharing signals both the end of individual car ownership as well as the need to invest in public transportation. Both outcomes are far from likely.

Other suggestions include redesigning cities to be more compact and more electrified, which would eliminate most of the need for personal vehicles to meet basic transportation needs. Again, this would take decades and untold billions of dollars to do so at the scale needed. The San Diego, California, region has decided to spend $160 billion as a way to meet California's net-zero objectives to create "a collection of walkable villages serviced by bustling (fee-free) train stations and on-demand shuttles" by 2050. However, there has been public pushback over how to pay for the plan and its push to decrease personal driving by imposing a mileage tax.

According to University of Michigan public policy expert John Leslie King, the challenge of getting to net-zero by 2050 is that each decarbonization proposal being made is only part of the overall solution. He notes, "You must achieve all the goals, or you don't win. The cost of doing each is daunting, and the total cost goes up as you concatenate them."

Concatenated costs also include changing multiple personal behaviors. It is unlikely that automakers, having committed more than a trillion dollars so far to EVs and charging infrastructure, are going to support depriving the public of the activities they enjoy today as a price they pay to shift to EVs. A war on EVs will be hard fought.

Should Policies Nudge or Shove?

THE COST CONCATENATION problem arises not only at a national level, but at countless local levels as well. Massachusetts's new governor, Maura Healey, for example, has set ambitious goals of having at least 1 million EVs on the road, converting 1 million fossil-fuel-burning furnaces in homes and buildings to heat-pump systems, and the state achieving a 100 percent clean electricity supply by 2030.

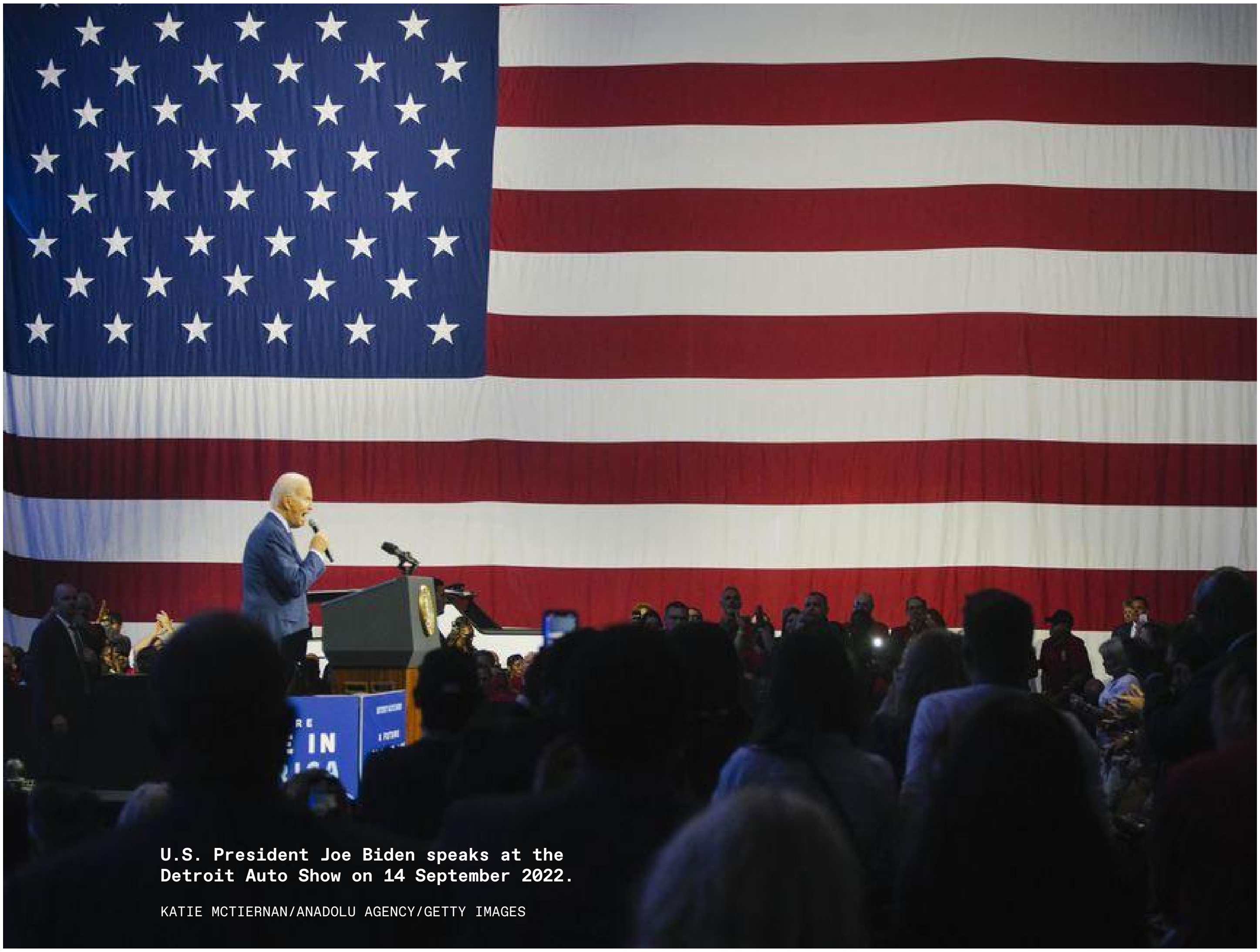
The number of Massachusetts households that can afford or are willing to buy an EV and/or convert their homes to a heat-pump system in the next eight years, even with a current state median household income of $89,000 and subsidies, is likely significantly smaller than the targets set. So what happens if by 2030 the numbers are well below target, not only in Massachusetts, but in other states like California, New York, or Illinois that also have aggressive GHG-emission-reduction targets?

Will governments move from encouraging behavioral changes to combat climate change or, in frustration or desperation, begin mandating them? And if they do, will there be a tipping point that spurs massive social resistance?

For example, dairy farmers in the Netherlands have been protesting plans by the government to force them to cut their nitrogen emissions. This will require dairy farms to reduce their livestock, which will make it difficult or impossible to stay in business. The Dutch government estimates 11,200 farms must close, and another 17,600 must reduce their livestock numbers. The government says farmers who do not comply will have their farms taken away by forced buyouts starting in 2023.

California admits that getting to a zero-carbon transportation system by 2045 means car owners must travel 25 percent below 1990 levels by 2030 and even more by 2045. If drivers fail to do so, will California impose weekly or monthly driving quotas, or punitive per-mile driving taxes, along with mandating mileage data from vehicles ever more connected to the Internet? The San Diego backlash over a mileage tax may be just the beginning.

"EVs," notes King, "pull an invisible trailer filled with required major lifestyle changes that the public is not yet aware of." When it does, do not expect the public to acquiesce quietly ■.



U.S. President Joe Biden speaks at the Detroit Auto Show on 14 September 2022.

KATIE MCTIERNAN/ANADOLU AGENCY/GETTY IMAGES

Chapter 12

The Aftershocks of the EV Transition Could Be Ugly

To avoid unintended consequences, bring realism to the table

THE INTRODUCTION OF any new system causes perturbations within the current operating environment, which, in turn, create behavioral responses, some predictable, many not. As University of Michigan professor emeritus and scholar of system-human interactions John Leslie King observes, "People find ways to use systems for their own benefit not anticipated by designers and developers. Their behavior might even be contradictory to hoped-for outcomes."

"Change rides on the rails of what doesn't change," King notes, "including people being self-serving."

As we noted early in the series, EVs are a new class of cyberphysical system that dynamically interacts with and intimately depends upon both energy and information systems of systems to function. When used as the catalyst to fundamentally transform an economy in a decade, as the Biden administration desires, EVs profoundly change both concurrently, affecting society on the scale of a magnitude

8.3 earthquake followed by the 1,700-foot mega-tsunami it creates.

Nothing in modern society operates without reliable access to both energy and information, and they are connected in ways we do not fully understand. Agitate one or the other, let alone both simultaneously, without comprehending or actively planning contingencies for how the countless and frequently fragile interactions between them will be affected, is asking to be unpleasantly surprised by the aftershocks created. Creating far-reaching technology policy first and then figuring out the myriad of engineering details needed to implement it second is always going to be a high-risk strategy that needs an appropriate level of wariness.

The perturbations caused by transitioning EVs to scale are not market-driven but government policy–driven to meet a climate emergency. This need to act creates even more uncertain socioeconomic and technological perturbations, disruptions, and distortions to be dealt with.

How, or even whether, EVs would have transitioned to scale without the forcing function of government actions to decarbonize transportation and energy is an interesting one to ponder. EVs may have eventually replaced internal combustion engine (ICE) vehicles without government policy mandates, incentives, and subsidies, but not in the time frame they are projected to do so today. A critical unanswered question is whether both society and government can successfully adjust to such a rapidly imposed change.

EV Transition Won't Happen Based on Hope

THE WORLDWIDE governmental ambitions to transition to EVs in a very short period risk creating many more consequential anticipated and unanticipated effects than if the transition were primarily market-driven. Even market-driven technological transformations can have surprising societal impacts and perturbations that no one predicts, like what has happened with the home microwave oven, mobile telecommunications, and social media. Even relatively straightforward technologies are no different (see sidebar).

When embarking on transforming the U.S. economy, policymakers should not underestimate the resulting ramifications to the current intertwined national and global technological, societal, political, and economic risk ecology.

The EV political network effects can be especially difficult to contain and can spill over into other arenas. Late political scientist Robert Jervis has observed, "Politics, like nature, rarely settles down as each dispute, policy, or action affects others and reshapes the political landscape, inhibiting some behaviors and enabling others."

For example, the European Union (EU) is counting on EV-battery plants to create new employment opportunities for tens of thousands of autoworkers who are expected to be laid off as European legacy automakers transition to EVs, as well as help ensure European EVs' cost competitiveness in international markets. However, high energy prices may make it economically unfeasible to build plants in Europe, according to Volkswagen COO

What Smart Thermostats Augur for EVs

Smart home thermostats are popular because they control heating and cooling remotely, lower energy costs, and are good for the environment. However, recent studies suggest that some of these benefits come with unexpected downsides.

Researchers at the Harris School of Public Policy at the University of Chicago found that energy use varied little among homes with smart thermostats versus those with conventional ones. The fault lay not in the smart thermostats but in their owners, who keep overriding their settings via their phone apps to prioritize their comfort level over energy savings.

Cornell University researchers independently observed this result as well, with smart thermostat energy savings only ranging at about 5 to 8 percent instead of the advertised 25 to 30 percent. More concerning, however, was they also found that smart thermostat use is causing morning energy-usage spikes because thousands of users are commanding their homes' air-conditioning or heating systems to come on at the same time, around 6 a.m. This load-synchronization problem is beginning to heavily tax local utility distribution networks, with the risk promising to increase as more residential energy systems are converted from fossil fuels to electricity.

ECOBEE

One solution is to allow utility companies to control customer thermostats to smooth out the demand. However, as Colorado utility Xcel discovered last summer, customers who voluntarily gave Xcel control to lower their utility bills were not entirely happy when they found themselves locked out of their thermostats during a heat wave. Excessive demand and equipment issues created an "energy emergency" that caused Xcel to set those 22,000 customer thermostats to 4 degrees Fahrenheit above their current temperature setting. As their homes rapidly heated up, those customers complained when they found out they could not lower their thermostat.

In response to the complaints, Xcel noted that it was clear about this always being a possibility and went on to thank those affected customers for helping to stabilize the grid. It will be interesting to see how many customers who allow their thermostats to remain in Xcel's control will, in a future heat wave, set their thermostats to 4 or more degrees below their usual temperature in case they get locked out again.

"SCIENCE-FICTION MOVIES can help us think about and prepare for the social consequences of technologies we don't yet have but are coming faster than we can imagine."
—ANDREW MAYNARD, Physicist

The Lexus 2054 concept car designed for the 2002 film *Minority Report*.
ICE MAN FROM FRANCE/WIKIPEDIA

Thomas Schäfer. As a result, the EU's "social harmony" may be jeopardized if such new job opportunities are not available to those made unemployed by EVs, or EV prices are too high, warns Carlos Tavares, CEO of Stellantis.

The Biden administration, however, has sought to exploit the EU's high energy costs by actively enticing European automakers to build their plants in the United States, which would also help them meet the administration's new U.S. content requirements to qualify for EV purchasing subsidies. EU leaders are understandably angry over both actions that undercut their EV strategic plans. EU leaders are now warning of retaliation and are planning counter-policies of their own. These mutual actions could spark a U.S.-EU trade war and potentially spill over into policy arenas having nothing to do with EVs, which could end up undercutting cooperation in policy areas of mutual benefit.

The same political tit-for-tat may happen with Asian countries, who are also unhappy with U.S. EV subsidy policy. For instance, Professor Matthew Eisler, a historian at the University of Strathclyde, in Scotland, who studies the relationship between environmental and energy policy and industrial science and technology, notes, "Much of the added value of new [EV] technology and employment has been offshored, along with the most damaging environmental effects of the industries of the electric automobile."

"Another way of expressing this relationship is that improving air quality of the U.S. and especially California," he says, "has come at the cost of exacerbating the air, water, and soil pollution of Asian societies." He believes that, at some point, U.S. foreign policy will likely be held accountable for U.S. EV industrial policy.

This, again, shows that EVs have become not just a means to combat climate change but also a geopolitical weapon. Trying to predict where EV policy decisions having global ramifications might eventually lead is nigh impossible.

Get Experts in the Room, Stat

THIS LEVEL OF uncertainty has not kept politicians in all countries from confidently trying to attempt to shape EV and allied markets to meet their economic as well as political objectives. This confidence is not undercut by any lack of expertise, either. For instance, U.S. National Security Advisor Jake Sullivan, who has recently been in the midst of tense discussions with U.S. allies like South Korea over subsidies, once candidly admitted to the MinnPost what goes on behind the scenes during critical policy decision meetings.

"There must be another room, somewhere down the hall, where the real meeting is happening, where the real experts are, making the real decisions," Sullivan related. "Because it can't just be us. It can't just be this. You know what? Turns out that it is."

EV policy is more likely to produce unanticipated consequences if there is a dearth of engineering and risk-management expertise to draw upon. Professor Deepak Divan, the director of the Center for Distributed Energy at Georgia Tech and one deeply involved in the issues of the EV transition, wryly observes that "while the number of EV users has exploded over the past few years, the number of experts who really understand all the nuances [of EVs] has not exploded." People do not fully understand what needs to be done or the consequences of not understanding what needs to be done, he says.

"THERE MUST BE another room, somewhere down the hall, where the real meeting is happening, where the real experts are, making the real decisions."
—JAKE SULLIVAN

University of Michigan's King notes that it often takes longer than the planning process allows for unanticipated consequences to appear. When that happens, policymakers end up playing "whack-a-mole" trying to deal with the negative effects from their earlier policies. If played long enough, policies end up contradicting themselves.

Film Clips From the Future

THERE IS A fascinating book titled Films From the Future, by physicist Andrew Maynard, that dives deep into the subjects of a host of science-fiction films. He focuses on how these films tell "stories about our relationship with the future, and like all good storytelling, they sometimes play around with reality to reveal deeper truths."

Maynard goes on to write that the creative freedom that sci-fi filmmakers have "can be surprisingly powerful when it comes to thinking about the social benefits and consequences of new technologies....Science-fiction movies can help us think about and prepare for the social consequences of technologies we don't yet have but are coming faster than we can imagine."

Sci-fi films are excellent, too, at illustrating Amara's Law, which will no doubt apply to EVs going to scale, i.e., "We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run," especially

POLICYMAKERS would be wise to follow the risk-management adage "Master the details to master the risks."

the unanticipated societal consequences (aka unknown unknowns) of a technology.

Without the sci-fi writer's luxury of playing around with reality, we too have tried through this Spectrum series to help readers think about the relationships among EV technology, society, and the future, and the scale of change needed to address climate change and role of electric vehicles in doing so.

We have also discussed just a small set of the myriad technical, political, social, and economic obstacles that must be overcome to gain the full benefits of transitioning to EVs at scale. Most of these can be called "anticipated but not desirable" consequences of the transition. These include raw material and skill shortages; energy transmission and distribution line shortfalls; loss of employment from fossil-fuel retirement; the societal restrictions imposed by carcentricity and dependency; the difficulties of expanding EV charging, mass transit, and battery recycling; as well as the rampant EV and energy policy dysfunction and politicization, to name but a few. Each obstacle presents unique challenges whose solutions can be counted on to spawn yet more challenges.

And the list above is hardly complete. Other challenges, large and small, include eliminating EV opportunity disparities for the economically disadvantaged; safety risks created by the heavier weights of EVs both in crashes as well as on parking decks; the risk of more bicycling injuries and deaths in the United States as more bike lanes are created to help reduce driving; the risk of EVs being driven even more than ICE vehicles and causing worse traffic jams because of the rebound effect; the risk of social and economic harm caused by lithium and other mineral mining on the ocean floor; the economic risk of fossil fuel–stranded assets; the risk of used ICE vehicles being exported to underdeveloped nations; the risks from environmental litigation, and many, many, many more, as EVs go to scale.

Any of the above can slow, delay, or even derail the transition to EVs if not thoughtfully addressed. Adding to the mix, of course, are all the other technological and societal changes that will be simultaneously occurring regardless of EVs. There are ongoing social problems that also are competing with EVs for major governmental attention and funding, such as poverty, health care, education, immigration, and defense, to name just a few.

In addition, who knows what advances in artificial intelligence, quantum computing, 6G telecommunications, autonomous vehicles, or some other yet-to-be-discovered technology, let alone a war, pandemic, natural disaster, recession, or change of government by election or coup d'état will have on the uptake of EVs over the next few decades? And if climate change targets are not being reached, will policymakers resort to something like geoengineering? Let us not forget, either, that EVs are only part of the climate change fight: There are also many other behavior changes the public is being asked to embrace, too, that will likely influence EV uptake.

The transition to EVs does not operate in a vacuum, as many policymakers like to pretend. As political scientist Robert Jervis has also noted, "Regulators [like to] believe that controlling one element will allow them to change behavior as desired. In fact, this would be the case only if everything else in the system were constrained."

California Governor Gavin Newsom, for example, is learning the limits of his span of control. Because of state budgetary shortfalls, Newsom is confronted with having to cut US $6 billion in investments toward combating climate change and moving the state to zero-emission vehicles in 2035. What these cuts and potential future budgetary shortfalls mean for California's ability over the next few years to build the infrastructure required to support its aggressive decision to ban ICE vehicles sales in 2035 is worth contemplating. If California cannot afford it, can the other 16 states that have pledged to follow California's EV lead afford it, either?

Now, multiply budgetary cuts across multiple countries if a global recession occurs, and the transition to EVs at scale does not look nearly so secure.

Policymakers would be wise to follow the risk-management adage "Master the details to master the risks." There will be many consequences to EVs at scale, and not all are going to be foreseen. While unanticipated consequences happen with any new technology, more should be expected with EVs. Many of them, given the rush to make EV policy based on optimistic assumptions, will be much more troublesome than they might, or should, have been. Promising opportunities that could be exploited may also be overlooked because of the unwillingness to reexamine those assumptions or the rush to "do something." ■