Stranded Assets in the Transition from ICEVs to EVs?
Prospects for Labor Displacement in the Auto Manufacturing Industry

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Introduction: The Future Is Now

Converting light-duty vehicles from internal combustion engines (ICE) to electric motors would be a major achievement in the race to curb climate-changing carbon pollution. But it would also involve a massive shift in auto supply chains, with significant implications for workers, communities, companies, and countries. Many components of ICE vehicles (ICEVs), such as engines, transmissions, and fuel systems, are not needed for electric vehicles (EVs), and the simplification of assembly reduces the labor requirements for that process as well. Many capabilities employed in ICEV manufacturing, both physical and human, could become stranded assets in the EV transition, particularly if it proceeds quickly. Alternatively, the prospect of stranding assets could lead to a backlash that slows or prevents the transition.

This paper briefly reviews the potential role of EVs in reducing carbon emissions. I then provide an overview of projections of the pace of the EV transition and the factors likely to influence it. The core sections of the paper explore the aggregate impact of the transition on labor demand and the more complex question of the uneven distribution of this impact across geographies. The concluding sections set forward four scenarios for the transition in the United States and offer suggestions for policy-makers who desire to make it more likely to proceed smoothly.

Climate Change and the EV Transition

Climate change is harming society and disrupting nature. Temperature extremes and severe storms are increasing in frequency and intensity, and the number of billion-dollar weather- and climate-related disasters has been on an upward trend since the 1980s. What were once considered 100-year floods or heat waves are occurring much more frequently. Ecosystems around the world are under stress. Biologically diverse temperate forests and coral reefs in many regions are already succumbing. The harm will grow increasingly worse as time passes unless carbon dioxide and other greenhouse gas emissions are reduced and ultimately eliminated.[1]

Light-duty vehicles are responsible for about 10 percent of carbon emissions from fossil fuel combustion and industry globally. Their share of emissions is larger in industrialized countries, particularly where measures have been taken to decarbonize electricity, the easiest major sector to tackle. In the United States, for instance, transportation surpassed electricity as the largest source of carbon emissions from fossil fuel combustion in 2017. In California, light-duty

[1] National Oceanic and Atmospheric Administration (NOAA), "Billion-Dollar Weather and Climate Disasters: Time Series," https://www.ncdc.noaa.gov/billions/time-series ; D. J. Wuebbles, *et al*., "Executive Summary" in *Climate Science Special Report: Fourth National Climate Assessment, Volume I* (U.S. Global Change Research Program, 2017), doi: 10.7930/J0DJ5CTG ; Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," in *Global Warming of1.5°C.* (IPCC, 2018), http://www.ipcc.ch/report/sr15/ ; Darryl Fears, "One Million Species Face Extinction, U.N. Report Says," *Washington Post*, May 6, 2019, https://www.washingtonpost.com/climate-environment/2019/05/06/one-million-species-face-extinction-un-panel-says-humans-will-suffer-result/

vehicles alone account for 27 percent of greenhouse gas emissions, far above electricity's 16 percent.[2]

The Paris climate agreement commits signatory nations to work together to limit the average global temperature to no more than 2 degrees Celsius above the pre-industrial level and preferably 1.5 degrees. Decarbonizing electricity supply, and electrifying energy services like light-duty transportation that currently rely on fossil fuels, figure prominently in many of pathways that could achieve these goals while maintaining economic growth and expanding access to energy services for the billion or so people who currently lack them.[3]

The precise impact of an EV transition on global carbon emissions is impossible to predict. It will depend not only on the pace of decarbonization of electricity and the penetration of EVs across diverse new car markets, but also the turnover of the vehicle stock. Perfect synchronization to maximize emissions reduction is unrealistic at this intersection of multiple complex systems. What is imperative is a global push forward along all promising pathways, along with continued investment in the creation of new ones with the potential to scale to meet the climate challenge.[4]

EVs: Evolution or Revolution?

EVs accounted for more than 1 million of the roughly 80 million new light-duty vehicles sold worldwide in 2018.[5] While EVs were a small share of the market, their sales grew by 70 percent, faster than in 2017. In Norway, the market where EV sales have been strongest, their share topped 50 percent for the first time in March 2019. Analysts Alix Partners assessed that "the worldwide automotive industry [has] decisively committed to electrification," while *The Economist* declared the internal combustion engine "roadkill."[6]

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[2] Stephen J. Davis *et al.*, "Net-Zero Emissions Energy Systems," *Science* 360, eaas9793 (29 June 2018); U.S. Environmental Protection Agency, "Fast Facts from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2017," April 2019, https://www.epa.gov/sites/production/files/2019-04/documents/2019_fast_facts_508_0.pdf ; Energy Futures Initiative, *Optionality, Flexibility, and Innovation: Pathways for Deep Decarbonization in California*, May 2019, https://energyfuturesinitiative.org/s/EFI_CA_STUDY_52_FINAL.pdf , 55 and 92.

[3] For the United States, see Daniel Steinberg, *et al*., "Electrification and Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization," (Golden, CO: National Renewable Energy Laboratory, July 2017), NREL/TP-6A20-68214, https://www.nrel.gov/docs/fy17osti/68214.pdf. Carbon-neutral fuels (CNFs) could create alternative pathways to decarbonize light-duty transportation. These pathways might rely on internal combustion engines, avoiding the issues raised in this paper. However, progress has been slow for a variety of reasons, and CNFs appear to be options for emissions reduction only over the very long term.

[4] David Keith and Christopher Knittel, "Why Reducing Carbon Emissions from Cars and Trucks Will Be So Hard," *The Conversation*, May 6, 2019, https://theconversation.com/why-reducing-carbon-emissions-from-cars-and-trucks-will-be-so-hard-113230 ; Anthony Eggert, Jan Mazurek, and Seth Monteith, "2050 Priorities for Climate Action: "Electrify Everything" is Too Simple," climateworks.org, June 13, 2018, https://www.climateworks.org/blog/2050-priorities-for-climate-action-electrify-everything-is-too-simple/ ; Energy Futures Initiative, *Optionality.*

[5] This figure is drawn from the estimate in Bloomberg New Energy Finance, *Electric Vehicle Outlook 2018*, https://bnef.turtl.co/story/evo2018 and includes only battery electric vehicles. Similar figures often include plug-in hybrids, which add about 50 percent to these totals, but do not present the problem of labor displacement with quite the same starkness as battery-only propulsion.

[6] Nic Lutsey and Michael Nicholas, "Update on Electric Vehicle Costs in the United States through 2030," International Council on Clean Transportation, working paper 2019-06, April 2, 2019, https://www.theicct.org/publications/update-US-2030-electric-vehicle-cost ; Associated Press, "Electric Cars Outsell Traditional Ones in Norway," April 2, 2019, https://www.mema.org/electric-cars-outsell-traditional-ones-norway ;

Declarations about the future of technology are, of course, prone to error. Even among those who accept that the EV transition is inevitable, its pace is hotly-debated. Bloomberg New Energy Finance in 2018 raised its projection for EV sales in 2040 to 60 million, a 55 percent market share, up considerably from its 2017 projection of about 40 percent. At the skeptical end of the analytical spectrum, the Organization of Petroleum Exporting Countries also raised its forecast substantially in 2018, but expects EVs' global market share in 2040 to increase only to about 25 percent.[7]

Which of these projections comes closest to predicting the actual diffusion path will depend on complex interactions among technological innovation, consumer behavior, public policy, and corporate strategy. As Benjamin Sovacool of the University of Sussex points out, large-scale transitions are comprised of many smaller ones.[8] The shape of the global "S-curve" of EV adoption – how steep it is and where it levels off – will be influenced by national and even local decisions as well as global processes.

The most commonly-cited variable determining the future of EV adoption is the cost of battery packs. McKinsey's Yeon Baik and colleagues (2019) estimate that the pack accounts for about $10,000 of the $12,000 cost gap between EVs and ICEVs. Lutsey and Nicholas (2019) gather technical analyses and automaker statements about future costs and report an anticipated average unit cost decline (or learning rate) of about 7 percent per year. At that pace, the initial cost of an EV will be below that of an ICEV in the mid- to late 2020s, depending on the model and location. Factoring in lower operating costs for EVs, the study finds that the crossover for the total cost of ownership will occur a year or two earlier.[9]

These projected cost reductions depend on process innovations that in turn depend on economies of scale driven by market growth, but they do not assume new product technologies, such as solid state batteries, that may come into widespread use in the late 2020s or 2030s.[10] However, consumer acceptance of EVs, which will be necessary to achieve the projected economies of scale, will not depend solely on the relative costs of EVs and ICEVs. Buyers will consider other attributes, including driving range, recharge time, and vehicle performance, as well as norms within peer groups and other harder-to-quantify social factors, along with costs. Assessing these factors, EV optimists highlight high satisfaction among EV owners, such as the Norwegians who "don't want to go back" to ICEVs "even at significantly higher costs." EV pessimists note that consumer awareness of EVs in the United States has been stuck at low levels in recent years and that they are often perceived to be expensive luxury products. Accenture research across the

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Alix Partners, "An Inflection Point in Electric Vehicles," July 2018, https://www.alixpartners.com/insights-impact/insights/an-inflection-point-in-electric-vehicles/ ; "Roadkill," *Economist*, August 2, 2017.

[7] BNEF, *Electric Vehicle Outlook 2018*, May 2018, https://bnef.turtl.co/story/evo2018?teaser=true ; OPEC, *World Oil Outlook 2040* (Vienna:OPEC, October 2018), 131, https://www.opec.org/opec_web/flipbook/WOO2017/WOO2017/assets/common/downloads/WOO%202017.pdf

[8] Benjamin Sovacool, "How Long Will It Take? Conceptualizing the Temporal Dynamics of Energy Transitions," *Energy Research and Social Science* 13:202-215 (2016).

[9] Yeon Baik et al., "Making Electric Vehicles Profitable," mckinsey.com, March 2019, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/making-electric-vehicles-profitable (calculation is based on a 50 kWh EV battery) ; Lutsey and Nicholas, "Update."

[10] IEA, *Global EV Outlook 2018*, 66.

United States and major European markets in 2018 found that "39 percent of conventional car owners say they would never buy an electric car."[11]

Public policy will shape consumers' behavior as well. Indeed, consumers will not even have a choice if governments forbid ICEVs. China has already started down this path in its largest, most-congested, most-polluted cities by making it virtually impossible for new owners of ICEVs to register their vehicles. India and many large European countries, along with China, have announced that they will phase-out ICEV sales over the next couple of decades. (In the United States, by contrast, the federal government has proposed to freeze fuel economy standards, which include incentives for EVs sales, precipitating a conflict with California and other states that seek to continue tightening the standards.) Subsidies to EV manufacturers and consumers aim to tip the scales further. While such plans and policies are subject to revision and revocation, they send signals to auto producers that must be factored into their investment decisions.[12]

Policy-makers may also influence the pace of uptake by promoting or impeding the development of EV charging infrastructure. Regulators can ease consumer concerns about the convenience of EVs by ensuring widespread availability of high-speed chargers. They may also limit the risks to the grid of charging surges and constrain the cost of grid modernization to accommodate EVs by adopting time-of-use pricing and other measures to shape charging behavior.[13]

For automakers, uncertainty about the pace and scale of the EV transition across diverse markets, combined with the transition's high cost and long lead time, is creating exquisite strategic challenges. As *Automotive News* put it, producers "are placing multibillion-dollar bets with scant evidence to go on." Moving too quickly into EVs risks the creation of idle capacity and lost profits. Deloitte projected in February 2019 that global EV supply will outpace demand by 14 million units in 2030; Daimler stated in 2017 that EVs initially will be half as profitable as ICEVs. Moving too slowly, on the other hand, might mean that newcomers like Tesla overtake incumbents like General Motors, just as the upstart GM overtook the pioneering Ford decades ago.[14]

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[11] Apurba Sakti and Magnus Korpås, "The Lessons of Norway's Rapid Electric Vehicle Adoption," *Axios*, January 30, 2019, https://www.axios.com/the-lessons-of-norways-rapid-electric-vehicle-adoption-76a5c43b-8c6b-4760-9ec8-0b5564153de5.html ; Carla Bailo *et al.*, "The Great Divide: What Consumers Are Buying vs. the Investments Automakers Are Making in Future Technologies, Products, and Business Models," Center for Automotive Research, February 2018, https://www.cargroup.org/publication/great-divide-automotive-consumers-buying-vs-auto-supplier-investments-future-technologies-products-business-models/ , 6-10; Accenture, "Utilities: Lead the Charge in e-Mobility," April 2019, https://www.accenture.com/_acnmedia/PDF-97/Accenture-Utilities-Lead-Charge-eMobility.pdf , 3.

[12] Jonas Meckling and Jonas Nahm, "The Politics of Technology Bans: Industrial Policy Competition and Green Goals for the Auto Industry," *Energy Policy* 126:470-479 (2019); Nic Lutsey et al., "Power Play: How Governments are Spurring the Electric Vehicle Industry," International Council for Clean Transportation, May 2018, https://www.theicct.org/publications/global-electric-vehicle-industry ; Hiroko Tabuchi, "California Strikes Back Against the Trump Administration's Auto Pollution Rollback," *New York Times*, August 7, 2018, https://www.nytimes.com/2018/08/07/climate/california-auto-emissions-trump.html .

[13] Benjamin Leibowicz, "Policy Recommendations for a Transition to Sustainable Mobility Based on Historical Diffusion Dynamics of Transport Systems," *Energy Policy* 119:357-366 (2018).

[14] "Flat Rock Flip-Flop a Sign of the Times," *Automotive News*, March 25, 2019, https://www.mema.org/flat-rock-flip-flop-sign-times ; Deloitte, "New Markets. New Entrants. New Challenges. Battery Electric Vehicles," February 2019, https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/manufacturing/deloitte-uk-battery-electric-vehicles.pdf ; Laurence Frost and Edward Taylor, "Carmakers Face Electric Reality As Combustion Engine Outlook

The continuing evolution of the ICEV, as well as the availability of hybrid vehicles that combine the two forms of propulsion, further complicates the automakers' challenge. The history of technology is replete with cases in which older technologies fended off replacement through a renaissance of innovation. Under regulatory pressure, ICEVs have become considerably cleaner in recent years, the Volkswagen diesel scandal notwithstanding.[15] One can imagine a trajectory on which carbon emissions per unit of transportation services provided by ICEVs decline and some or all of their residual emissions are offset by carbon sinks (or "negative emissions"), limiting the climate rationale for the EV transition.

Finally, electrification is only one of what Daniel Sperling of the University of California – Davis labels "three revolutions" shaking up the auto industry.[16] Autonomy and ride-sharing have the potential to impact carbon emissions from transportation and auto firm competitiveness as massively as electrification. And the three interact. Autonomous systems run on electric power, which would require EVs to have larger batteries; ride-sharing could reduce vehicle sales considerably, slowing the achievement of economies of scale, but speeding stock turnover as fleet sales supplant individual sales.

The auto industry faces greater uncertainty today than it has in many decades. New technologies and growing pressure to reduce carbon emissions are disrupting deeply-ingrained patterns of activity. How these play out, and how quickly, will have significant impacts on the future of auto work.

Fewer Parts, Less Labor

EVs use different materials, components, and subsystems and many fewer parts than ICEVs. The most fundamental difference is that EVs are propelled by electrical energy stored in a battery pack and transmitted to the wheels by a simple motor, whereas ICEVs are powered by a gasoline-fueled engine and rely on a complex gearbox and clutch to drive the wheels. ING estimates that a typical ICEV powertrain contains 1400 components, far more than the EV's 200. UBS's teardown finds that the Chevy Bolt's powertrain has 35 moving and wearing parts, compared to the VW Golf's 167. The Bolt's engine has only three moving parts, 110 less than the Golf's.[17]

"Take the gasoline out of the vehicle," writes Lawrence D. Burns, GM's former vice-president for research and development and planning, "and you don't need a heavy engine block to contain

Dims," *Reuters*, September 11, 2017, https://www.reuters.com/article/us-autoshow-frankfurt-electrics/carmakers-face-electric-reality-as-combustion-engine-outlook-dims-idUSKCN1BN00X

[15] "Supply Chain Turns a Deeper Shade of Green," *Automotive News*, September 15, 2018 , https://www.autonews.com/article/20180915/OEM01/180919808/supply-base-turns-a-deeper-shade-of-green

[16] Daniel Sperling, *Three Revolutions: Steering Automated, Shared, and Electric Vehicles to a Better Future* (Washington, D.C.: Island Press, 2018). See also William J. Mitchell *et al.*, *Reinventing the Automobile* (Cambridge: MIT Press, 2010).

[17] UBS, "UBS Evidence Lab Electric Car Teardown: Disruption Ahead," May 18, 2017, https://neo.ubs.com/shared/d1wkuDlEbYPjF/ , 27; ING Economics Department, "Breakthrough of Electric Vehicles Threatens European Car Industry, July 2017, https://www.ing.nl/media/ing_ebz_breakthrough-of-electric-vehicle-threatens-european-car-industry_tcm162-128687.pdf , 13. This paper only considers auto part and assembly. It does not explore the entire value chain, including raw materials and capital goods, including the knotty issue of "ethical supply" of minerals like cobalt. The UBS teardown provides a broader window on the value chain.

any explosions happening within the cylinders. You didn't need an exhaust system with a muffler and a catalytic converter to clean the vehicle's emissions. You didn't need spark plugs or carburetors, or valves or fan belts to cool it. Nor did you require a fuel-injection system or an automatic transmission."[18]

Such differences mean that a complete transition to EVs would eliminate a large portion of the current auto supply chain. The supply chain employs a majority of the workers in the auto industry; in the United States, it is roughly three times as big as final assembly. Engine and transmission parts for light-duty vehicles generate about a fifth of the jobs in the supply chain. Approximately 30 percent of these parts are used for aftermarket repairs, which would be affected more slowly than production for new vehicles. In all, new engines and transmissions alone provide approximately 10 percent of all jobs in the U.S. auto industry.[19]

Battery packs and motors for an equally-sized EV industry would require far fewer workers. Whereas ICEV powertrains contain a diversity of parts, battery packs are mainly uniform arrays of modules, each of which is made up of six to twelve cells. Materials, including metals like cobalt, nickel, and aluminum, rather than capital or labor, account for most of the cost of each cell. Although battery pack design is very important to EV performance and therefore likely to be customized by automakers for each model, the assembly of cells into modules and packs in these designs is relatively easy to automate. A 2018 study by the Fraunhofer Institute commissioned by Germany's IG Metall labor union found that that country's ICEV powertrain workforce would be reduced by 43 percent in a scenario in which EVs gain just 25 percent of the market by 2030, while hybrids, which have more complex drivetrains, gain 15 percent, and ICEVs retain the remaining 60 percent.[20]

The relative simplicity of EVs compared to ICEVs has important implications for final assembly as well as the supply chain. According to Joe Hinrichs, Ford's president of global operations, "EVs will mean auto factories can have a final assembly area that is half the size, requires half the capital investment and 30 percent fewer labor hours per car." McKinsey's Baik and

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[18] Quoted by Daniel Howes, "Self-driving Cars Are 'Not a Science-Fiction Story'," *Detroit News*, March 4, 2019 https://www.detroitnews.com/story/business/columnists/daniel-howes/2019/03/05/self-driving-revolution-imperils-michigan-way/3057731002/

[19] These data are drawn from the U.S. Census Annual Survey of Manufacturers for 2009 to 2016, accessed via factfinder.census.gov on April 9, 2019. NAICS codes are used as follows: 33611 – assembly; 3363 – parts; 33631 – engines and engine parts; 33635 – transmission and powertrain parts. The parts figures are reduced by 15 percent to adjust for heavy vehicle parts, which are also included in these categories. The 30 percent aftermarket estimate is taken from U.S. Department of Commerce, "On the Road: U.S. Automotive Parts Industry Annual Assessment 2011," https://www.trade.gov/td/otm/assets/auto/2011Parts.pdf . These figures may not be representative of other national auto industries, since the composition of vehicles as well as trade in vehicle parts vary across countries. Roughly 25 percent of U.S. auto parts industry jobs are classified as "other." Some jobs outside of the categories counted in the text may also be impacted by the EV transition.

[20] Daniel Kupper *et al*., "The Future of Battery Production for Electric Vehicles," Boston Consulting Group, September 11, 2018, https://www.bcg.com/fr-ca/publications/2018/future-battery-production-electric-vehicles.aspx ; Fred Lambert, "Electric Cars Are More Labor Efficient To Make and Will Lead To Job Loss, Says New Study," *Elektrek*, June 5, 2018, https://electrek.co/2018/06/05/electric-cars-labor-efficient-lead-job-loss-new-study/ ; Fraunhofer IAO, "Study Investigates the Effects of Electromobility on Employment in Germany," June 6, 2018, https://www.iao.fraunhofer.de/lang-en/press-and-media/latest-news/1388-mapping-out-the-future-for-the-automotive-industry.html ; Fraunhofer IAO, *ELAB 2.0: The Effects of Vehicle Electrification on Employment in Germany*, preliminary report, June 4, 2018, 7.

colleagues estimate that assembly optimized for a "native EV platform" (that is, a vehicle designed solely for electric propulsion) could lead to savings of $600 per car.[21]

Other differences between EVs and ICEVs may work in the opposite direction. UBS's comparison of the Bolt and the Golf found that the former had six to ten times as much electronic content in its drivetrain: "In a nutshell, the lion's share of mechanical content gets replaced by electr(on)ical content." A study by M Foresight estimated that the electronic content of the auto supply chain would rise from less than 20 percent in 2010 to more than 30 percent in 2030. In the Fraunhofer 2030 scenario referenced above, jobs gained from creating such content, as well as making batteries, offset about 14 percent of those lost.[22]

The skills required for the jobs being gained in the EV transition, however, may be different from those needed for ICEVs. "With electric vehicles, the crucial expertise was no longer going to be mechanical," Burns states. "The crucial expertise in electric vehicles was software." [23] The other two revolutions, autonomy and ride-sharing, will also push skill demand in this direction.

The auto workforce has continually adapted to changing technologies in the past, including robotics in the recent past and continuing today. But the EV transition, particularly if it were to occur quickly, would mark a step change. It is therefore not surprising that Ha Bu-young, the head of South Korea's biggest and most powerful auto union, would say in March 2018: "Electric cars are disasters. They are evil. We are very nervous."[24]

The Geographical Dimension: An Uneven Transition

The nervousness felt by union leaders about electrification as a technological trend is compounded by uncertainty about the location of any labor reallocation and displacement it will cause. Communities and nations are likely to experience the EV transition unevenly. Some places that are heavily-dependent on ICEV manufacturing will be disrupted, while others may thrive. Like the global pace of the transition, its geographical distribution will be shaped by consumer and corporate decisions as well as public policies at multiple levels.

At the national level, China's EV policy reflects export aspirations as well as environmental concerns. China has not yet produced an indigenous global-quality auto firm, despite long-standing efforts to leverage knowledge and capabilities from international firms through joint ventures. By driving EV demand and fostering massive investment, Chinese policy-makers hope to create first-mover advantages that allow Chinese-produced EVs to dominate the domestic market and break into foreign markets. If this strategy proves successful, locations in other

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[21] Joseph White and Paul Lienert, "Ford To Cut Costs $14 Billion, Invest in Trucks, Electric Cars: CEO," *Reuters*, October 3, 2017, https://www.reuters.com/article/us-ford-motor-ceo/ford-to-cut-costs-14-billion-invest-in-trucks-electric-cars-ceo-idUSKCN1C82NL ; Baik *et al.*, "Making Electric Vehicles Profitable."

[22] UBS, "Electric Car Teardown," 24; M Foresight, "Manufacturing Prosperity," June 2018, https://medium.com/@MForesight/manufacturing-prosperity-a-bold-strategy-for-national-wealth-and-security-65d2a97d6d0e , 15; Fraunhofer IAO, "ELAB 2.0," 7.

[23] Quoted in Howes, "Self-Driving Cars."

[24] Fred Lambert, "'Electric Cars Are Disasters and Evil', Says Hyundai's Union Head," *Electrek*, March 27, 2018, https://electrek.co/2018/03/27/electric-cars-disasters-evil-says-hyundai-union-head/

countries where ICEVs are built will suffer. Ford and BMW were reported in April 2019 to be developing models for export from China.[25]

The same thinking applies to auto parts, an industry in which China has had some export success in the ICEV era. Chinese policy-makers have drastically restricted the ability of foreign manufacturers to supply the domestic market for EV batteries, for instance, in order to allow new, indigenously-owned companies to gain scale and improve their technological skills. The most successful of these companies are now competing with incumbent suppliers in overseas markets.[26]

The incumbents targeted by the new Chinese battery giants are headquartered elsewhere in East Asia. Firms like Panasonic, Samsung, and LG leveraged their long-standing capabilities in making electronics into early leadership in EV batteries, which use the same core lithium-ion technology. UBS found that LG alone was responsible for 56 percent of the content of the Bolt. The home countries of these companies, Japan and Korea, run large trade surpluses in batteries.[27]

As EV markets grow, though, Asian-headquartered firms (including the Chinese) are building battery factories closer to the point of use by OEMs. Logistics and associated costs drive these decisions, once a minimum efficient scale of demand has been reached, but politics plays a part as well. Since the 1980s, governments around the world have sought foreign direct investment (FDI) for their auto industries, which are viewed as strategically significant. EV battery manufacturing and assembly plant location decisions will be subject to the same pressures that ICEV plants have been. They will therefore likely be similarly distributed across world regions by producers, regardless of the corporate headquarters location base. Nissan, for example, supplies its Leaf EV to North American customers from assembly and battery plants in Tennessee. Tesla is now building its first overseas factory in Shanghai, China.[28]

These factors may alleviate concerns about massive shifts in the distribution of EV jobs across world regions compared to ICEV jobs. Nonetheless, any shift in national leadership in the auto industry and its supply chain is likely to have at least a modest impact on jobs at this level of aggregation. The "lead factories" in which major innovations are first put into practice by the

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[25] Meckling and Nahm, "Politics of Technology Bans;" Scott Kennedy, "China's Risky Drive into New Energy Vehicles," Center for Strategic and International Studies, November 2018, https://www.csis.org/analysis/chinas-risky-drive-new-energy-vehicles ; Tom Hancock, "Global Automakers Seek To Make China Electric Vehicle Export Hub, *Financial Times*, April 19, 2019.

[26] Nigel Cory, "Worst Mercantilist Policies of 2017," Information Technology and Innovation Foundation, January 22, 2018, https://itif.org/publications/2018/01/22/worst-innovation-mercantilist-policies-2017; Trefor Moss, "China's Road to Electric Car Domination is Driven in Part by Batteries," *Wall Street Journal*, October 21, 2017, https://www.wsj.com/articles/chinas-road-to-electric-car-domination-is-driven-in-part-by-batteries-1508587203 ; Fred Lambert, "BMW Confirms All-Electric Ix3 SUV Will Be Built in China and Exported to Other Markets, Signs Massive Battery Contract," *Electrek*, July 9, 2018, https://electrek.co/2018/07/09/bmw-all-electric-ix3-suv-china-exported-battery-contract/

[27] UBS, "Electric Car Teardown," 1; Lutsey *et al.*, "Power Play," 10.

[28] James Ayer, "Long-Range 2018 Nissan LEAF Production Has Begun In Tennessee," *Clean Technica*, December 6, 2017, https://cleantechnica.com/2017/12/06/long-range-2018-nissan-leaf-production-begun-tennessee/ ; Echo Huang, "Tesla Plans to Hit the Ground Running in China in 2019," *Quartz*, December 28, 2018, https://qz.com/1510091/tesla-cars-could-be-made-in-china-from-2019/

leading firms in an industry are typically in their home countries, along with a large proportion of engineering and R&D jobs.[29]

More significant redistribution of auto industry employment as a result of the EV transition could occur within, rather than across, major nations and world regions. The transition will provide opportunities for OEMs and major suppliers to continue to expand in "greenfield" locations where costs are lower and unions are less powerful. In the United States, for instance, auto industry FDI has been attracted to the South since the 1980s; in Europe, it has tilted to the East from the 1990s on. Public incentives contributed to these decisions and will do so for EV plants as well. Tesla was drawn to the greenfield location of Reno, Nevada, in 2014 in part by a reported $1.25 billion incentive package.[30]

Some places that are highly dependent on ICEV manufacturing will nonetheless remain competitive through the EV transition. The highly-skilled workforces and supplier networks for components that are similar between ICEVs and EVs will allow such places to attract new investment. VW, for instance, has announced that it will build EVs near its existing plant in Chattanooga, Tennessee. In some contexts, incumbent locations may have leverage to retain jobs. In Esslingen, Germany, for example, Mercedes-Benz will begin building batteries and electric motors next to an existing engine factory and has guaranteed jobs through 2029, decisions that were significantly influenced by German labor laws and powerful unions.[31]

But some locations, inevitably, will not be spared. Transportation accounts for 56 percent of the manufactured goods shipped from Japan's Aichi prefecture, which is bracing for a "painful downsizing" as the primary buyer of these goods, Toyota, shifts from ICEVs to EVs. Small towns that are highly dependent on a single ICEV powertrain plant appear to be particularly vulnerable. Bellwood, Illinois, a town of about 20,000 just outside Chicago, for instance, relies on BorgWarner's transmission factory for more than 800 jobs.[32]

Companies like BorgWarner have greater flexibility to adapt to the transition than the communities that depend on them. Those that are bullish on the transition may divest themselves relatively quickly of ICEV assets and acquire EV assets. BorgWarner, which had about $10 billion in sales in 2017, for instance, has already invested well over $1 billion to buy EV parts suppliers. A 2017 study by a former auto-parts-executive-turned-industry-analyst found that "as

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[29] Anna Granlund, *et al.*, "Lead Factory Operationalisation and Challenges," *Production Planning & Control* 30:96-111 (2019), https://www.tandfonline.com/doi/full/10.1080/09537287.2018.1534292

[30] Anjeanette Damon, "Inside Nevada's $1.25 Billion Tesla Tax Deal," *Reno Gazette-Journal*, September 4, 2014, https://www.rgj.com/story/news/2014/09/04/nevada-strikes-billion-tax-break-deal-tesla/15096777/

[31] Larry P. Vellequette, "VW's 2nd Tenn. Plant Could Build EVs for Audi, too: $800 Million Project To Create 1,000 Jobs," *Automotive News*, January 21, 2019, https://www.autonews.com/manufacturing/vws-2nd-tenn-plant-could-build-evs-audi-too ; Fred Lambert, "Mercedes Benz transitioning region from engines to batteries," *Electrek*, April 5, 2019; https://electrek.co/2019/04/05/mercedes-benz-breaks-ground-new-battery-factory/ ; Fred Lambert, "Daimler to Convert Engine Production to Electric at Its Largest Factory," *Electrek*, February 14, 2017, https://electrek.co/2017/02/14/daimler-electric-vehicle-production/

[32] Connor Cislo and Nao Sano, "Electric Cars Could Be a Job Killer for Japan's No. 1 Industry," *Bloomberg Businessweek*, August 13, 2018, https://www.bloomberg.com/news/articles/2018-08-13/electric-cars-could-be-a-job-killer-for-japan-s-no-1-industry ; Buzzfile,"Borgwarner Transmission Systems, Inc.," http://www.buzzfile.com/business/Borg-Warner-Automotive-708-547-2600 accessed April 26, 2019.

many as 75 of the industry's top 100 suppliers will face irrelevance by 2030 unless they establish a niche in the market for electrified cars…"[33]

The same goes for OEMs. Those that make poor decisions about the balance of products that they offer as the EV transition proceeds, how those products are made, and the ways that they interact with their changing supply chain, will be unable to sustain the communities and workers that they now support. But even firms that weather the transition well may choose not to sustain these places and people. The prospect that the transition will leave too many workers and communities behind could, in turn, cause them to oppose it, slowing or even halting it, with perilous consequences for the global climate.

Four Scenarios for the United States

Whether such a backlash emerges and how powerful it becomes will depend on how the various forces described above play out in particular national and subnational contexts. In the United States, the recent history of the coal industry may provide insights into these questions. Like ICEVs, coal faces complete elimination in many climate-change-mitigation scenarios. This existential threat has motivated the industry, supported by its workers and communities, to oppose strong climate policy, with mixed success. While the geographical concentration of coal mining has worked to the industry's benefit at the national level, because of the geographical structure of political representation in the United States, many states without coal mines, empowered by the federal structure of electricity regulation, have taken steps to reduce demand. The U.S. coal industry is in steep decline, but it is not yet spent as a political force, as the Trump administration's continuing efforts to prop it up demonstrate.[34]

This analogy should not be taken too far. There are many differences between the U.S. coal and auto industries. The auto industry is more globally integrated than the coal industry, so its decisions in the United States are more likely to be shaped by international trends. The bridge technology in autos, the hybrid powertrain, is less competitive than its counterpart in electric power, natural gas. Most important, although the auto industry is, like coal, geographically concentrated, it is much bigger, giving it far greater clout in national politics. That clout is amplified by the swing position of auto-intensive states like Ohio and Michigan in national elections.

Four scenarios (see Table 1) help to frame the possibilities. They build on the market and policy dimensions of the analysis above. The "island of SUVs" scenario envisions an EV transition stalled by a weak market and weak climate policies. The "ZEV redux" scenario foresees a transition blocked by consumers despite a push from federal policy-makers. The "resistance is futile" scenario pictures markets shifting toward EVs so strongly that climate policy becomes irrelevant, catalyzing a rapid transition and unmanaged labor displacement. Finally, the "just transition" scenario anticipates the United States actively and deliberately participating in a

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[33] Kurt Nagl, "BorgWarner Creates New Company After Acquiring Specialty Car Shops," *Auto News*, February 20, 2019, https://www.autonews.com/suppliers/borgwarner-creates-new-company-after-acquiring-specialty-car-shops ; David Segwick, "Which Suppliers Will Survive the Electric Era?" *Auto News*, July 30, 2017.
[34] Iulia Gheorghiu, "DOE Policy Chief: 'My Office Is Not Working On Anything To Do With Subsidized Coal," *Utility Dive,* April 30, 2019, https://www.utilitydive.com/news/doe-policy-chief-my-office-is-not-working-on-anything-to-do-with-subsidiz/553668/

global EV transition and taking steps to assist workers and regions who would otherwise suffer as a result. I briefly elaborate each of these scenarios below.

Table 1: Four Scenarios for the United States

	Weak Climate Policy	Strong Climate Policy
Weak EV Market	Island of SUVs	ZEV Redux
Strong EV Market	Resistance Is Futile	Just Transition

Island of SUVs: This scenario is perhaps closest to the path that the United States is on under the Trump administration and would likely be sustained in the event of a reelection in 2020. U.S. consumers continue to prefer large ICEVs, and the rollback of federal fuel economy standards, along with protectionist trade policy, helps incumbent manufacturers to accommodate this demand. Tesla's continuing production challenges prevent it from broadening its product line-up, while other newcomers like Rivian, which has received acclaim and investment with its electric pickup truck, suffer a similar fate. No backlash arises in this scenario, because EVs never disrupt the U.S. industry. Instead, ICEV sales in the United States provide resources to fund EV investments in the rest of the world.[35]

ZEV Redux: This scenario recalls the past, specifically California's early attempts to implement a zero emission vehicle (ZEV) mandate in the 1990s. An aggressive ICEV phase-out policy is enacted by a left-leaning Democratic president and Congress elected in 2020. Consumers rebel, egged on not only by the petroleum industry, but also by a preemptive backlash from the auto industry. The phase-out is delayed, diluted (like the ZEV mandate was with PZEVs, AT-PZEVs, and other not-quite-ZEVs), or overturned by the courts, Congress, or subsequent presidents. Compared to "Island of SUVs," the U.S. auto industry is less successful in "ZEV Redux," whipsawed by shifts in policy that induce investments that are later stranded.[36]

Resistance Is Futile This scenario fulfills the vision of Silicon Valley futurists like Tony Seba.[37] Although the U.S. government does not adopt policies intended to drive down carbon emissions in the transportation sector, global automakers follow through on their commitments to electrification because other governments do adopt strong policies, leading EV prices to decline more rapidly than expected. Early adopters, attracted by the EV's value proposition, rave about its performance, inducing a massive shift in U.S. consumer psychology and unleashing a tsunami

[35] Ian Thibodeau, Ford Invests $500M in Rivian; Companies Plan Electric Vehicle, Detroit News, April 24, 2019, https://www.detroitnews.com/story/business/autos/ford/2019/04/24/ford-invests-500-rivan-companies-plan-electric-vehicle/3559658002/ ; Bailo *et al.*, "The Great Divide," 10-12.
[36] Louise Wells Bedsworth and Margaret R. Taylor, "Learning from California's Zero-Emission Vehicle Program," *California Economic Policy*, vol. 3, no. 4, pp. 1-19, September 2007.
[37] See James Arbib and Tony Seba, *Rethinking Transportation 2020-2030*, ReThinkX, May 2017. This paper notes the importance of mitigating the impacts of these disruptive trends on workers, but is optimistic about the overall economic impact of the transition. It does not consider the location of EV production.

of follow-on adoption. Rapid growth of ride-sharing and autonomy displaces a significant fraction of individual purchasing and accelerates stock turnover as well. China's planners are proven right, and their EV and battery companies supply a large fraction of the U.S. market. While these developments spark a backlash among U.S. auto workers and communities, it has no impact, and they are left to fend for themselves.

Just Transition This scenario realizes the hopes of Green New Dealers. The federal government enacts ambitious carbon emissions reduction policy and works with other countries to encourage a predictably-paced and globally-consistent EV transition. The auto industry responds with process innovation that brings down costs and product innovation that meets consumer demand. Innovative U.S.-based producers successfully compete in the transformed market, but some incumbent workers and communities lose out in the process of creative destruction. Anticipating these consequences, policy-makers foster economic redevelopment, invest in retraining, and encourage worker mobility to avert some impacts, while providing pensions, health insurance, and other services to mitigate other impacts.

Three of these four scenarios are failures. "Island of SUVs" and "ZEV Redux" fail to address the energy end-use that is making the United States' biggest contribution to climate change. They would require greater reliance on "negative emissions" technologies that are not yet available at scale or, more plausibly, lead emissions reductions to plateau. "Resistance Is Futile" fails as a matter of social justice. The United States' largest manufacturing industry would undergo a severe shock that might have been softened, if not wholly avoided, with negative consequences that can be inferred from the job destruction that manufacturing as a whole suffered in the decade after China entered the World Trade Organization in 2000.

Conclusion: Rocky Road Ahead

The dilemma facing the United States is shared around the world (including in China's ICEV manufacturing hubs). Helping the climate means harming the auto industry as we have known it. The likelihood that some production locations will weather the EV transition better than others makes the dilemma more acute for each nation. Strategic behavior in the face of such a negative-sum game could lead to very unequal outcomes. The road ahead is likely to be rocky.

To make it somewhat smoother, the two-pronged strategy sketched in the "Just Transition" scenario may provide some guidance for policy-makers. First, climate policy should move light-duty transportation toward electrification. But it should provide a push, not a shove. The impact of the EV transition on emissions will be muted in any case by the pace of electricity decarbonization and vehicle stock turnover, so the gains to the climate from a crash program to shift to EVs would be limited. A measured pace would also reduce the risks of backlash and reversal and provide time for workers, communities, and companies to adjust.

Second, policy-makers should support the adjustment process. Auto workers who are unable to retain their jobs should be enabled to retrain for new positions within the industry or outside it, or to retire with pension and other benefits they have been promised. National governments should make appropriate public investments and exert leverage to encourage private investment in affected regions, including through trade policy and domestic content rules, within the constraints of globally-agreed limits on such controls and subsidies.

In this early phase of the EV transition, there are few visible signs of backlash, at least in the United States. In fact, the United Autoworkers has called instead for "[a] strong, forward-looking industrial policy…to use the EV disruption as an opportunity to create high-quality manufacturing jobs making the vehicles of the future." Given the long lead time, high stakes, and complex global playing field, it is not too early to heed their call.