Higher labor intensity in US automotive assembly plants after transitioning to electric vehicles

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Abstract

It has been widely suggested that the transition to battery electric vehicles will require 30% fewer assembly workers than those needed for internal combustion engine vehicles. Here, we use publicly available datasets on vehicle production and employment to show that labor intensity has increased at U.S. vehicle assembly plants that have fully transitioned to assembling battery electric vehicles. During the production ramp-up period, labor intensity increases by more than ten-fold compared to historic combustion vehicle assembly labor intensity. For one assembly site studied, labor intensity and total employment remained three times higher despite a decade of electric vehicle production. Our study suggests that it may take longer than 15 years for electric vehicle assembly sites to achieve labor intensity parity with internal combustion vehicle assembly. Thus, widespread loss of employment at vehicle assembly plants is a smaller risk than many fear. Moreover, our study calls for more regionally focused analyses of the transition's effects on labor using data-driven and macro-level surveying approaches.

Introduction

The automotive industry employs 13 million workers in the U.S., including nearly 1 million in the manufacturing sector [1–3] (Fig. 1). Most of these workers are engaged in the production of internal combustion engine vehicles (ICEVs) today, but a rapid shift towards battery electric vehicles (BEVs) is underway as major automakers set ambitious targets to phase out ICEV production within the next two decades [4, 5].

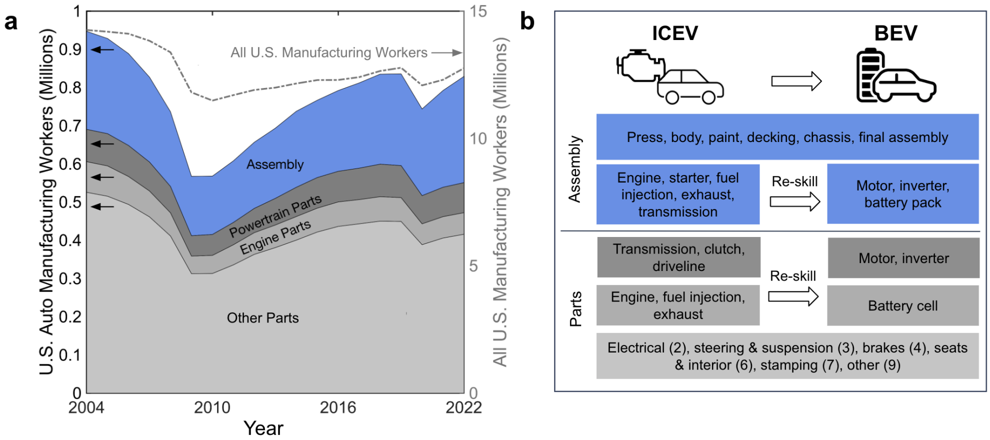

Fig. 1 Overview of U.S. automotive sector employment from 2004 to 2022 and automotive job categories. (a) U.S. automotive sector employment consists of assembly and parts manufacturing jobs, with assembly jobs comprising 33% of total automotive jobs in 2022. During past periods of economic downturn, the percentage of jobs lost in the automotive sector exceeded that of the overall U.S. manufacturing sector, as seen during the recession of 2008 and the pandemic of 2019. (b) The transition from ICEV to BEV production will create shifts in the types and quantities of jobs in both assembly and parts manufacturing. BEVs will require workers to manufacture battery cells and battery packs instead of engines. Shadings in both panels indicate job categories as defined by the North American Industrial Classification System (NAICS) codes. Assembly jobs: NAICS 3361. Engine parts jobs: NAICS 33631. Powertrain parts jobs: NAICS 33635. Other parts: NAICS codes 3363(x) according to the parenthesized values in (b). ICEV: internal combustion engine vehicle. BEV: battery electric vehicle. Source data are provided as a Source Data file.

How will the transition to BEV production affect the overall number of jobs in the automotive sector? The answer to this question is at the core of a Just Transition, which secures the future and livelihoods of workers and their communities in the transition to a low-carbon economy [6–10]. For many U.S. auto workers, the possibility of job loss is not theoretical but experienced. During the 2008 global recession, automotive manufacturing employment declined by 23% within a year (Figure 1a). The overall U.S. manufacturing sector lost 12% of employment over the same period, suggesting that the automotive sector is particularly vulnerable to job losses during periods of economic downturn. Although some industry analysts note the potential for the transition to BEVs to create new U.S. jobs [11], the potential for reduced labor demand in the transition to BEV production has raised concerns among automotive labor groups that the transition may be disruptive for U.S. workers [6].

Despite the importance of understanding the BEV transition's effect on the number of automotive jobs, existing reports have been scarce and contradictory. A common narrative is that BEV powertrains have fewer parts than ICEV powertrains and thus take fewer workers to assemble, so the BEV transition will result in a net loss in automotive jobs. The claim of "30% fewer workers for EV assembly" entered public discourse as early as 2017 [12] and remains a central claim as part of ongoing debates on the effect of the BEV transition on jobs [6, 13–16]. The Economic Policy Institute found that, without policies promoting local production of electric vehicle powertrain components, 75,000 jobs could be lost in the U.S. by 2030. However, the same report also predicted that employment could rise by 150,000 jobs given local production [17]. A study by the Boston Consulting Group found that BEV labor requirements are about 1% less than those for ICEVs after accounting for all production process differences [18]. A study by Cotterman et al. found that the labor intensity required for BEV powertrain manufacturing can be more than twice as high as that for ICEVs if battery cell manufacturing is included and when industry shop floor data is used instead of academic models [19, 20]. The lack of consensus from these existing reports underscores the difficulty of estimating the future trajectory of BEV jobs based solely on technical assumptions [21] and expert judgment [22].

This work studies data from existing vehicle assembly plants based in the U.S. that have already fully transitioned from ICEV production to BEV production. By studying data from existing assembly plants, we show the effect of the ongoing BEV transition on automotive assembly jobs in the U.S. In all three assembly plants studied, we found that BEVs require more workers per vehicle produced than ICEVs.

Results

Identifying BEV transition plants

For this work, we first identified U.S. counties in which there existed a single historic ICEV assembly plant that has since been converted to produce BEVs (Fig. 2a). These sites, termed "transition plants," provide the most direct comparison of labor intensity differences before, during, and after the BEV transition. To systematically identify transition plants, we used vehicle production data from the Automotive News Research & Data Center [23], which details vehicle production volumes by make, model, and plant location (see Methods: Vehicle production data). We used three criteria to identify transition plants. First, the plant must have historically assembled ICEVs. Second, the plant must have fully transitioned from the assembly of ICEVs to BEVs. A full transition ensures that the latest labor intensity figures correspond to BEV production without considering the effect of simultaneous production of BEVs and ICEVs. Third, the plant must have been the sole source of auto assembly activity in its respective county. This exclusivity enabled the use of government employment data, which has county-level resolution, for our study. Based on these three search criteria, three transition plants were identified: Alameda County in California (Fig. 3), Oakland County in Michigan (Fig. 4), and McLean County in Illinois (Fig. 5).

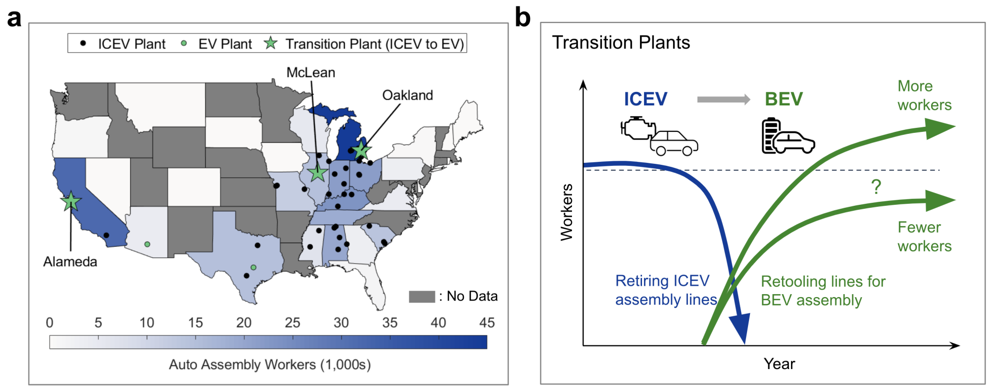

Fig. 2 Fig. 2: Transition plants: vehicle assembly plants that have fully transitioned from assembling internal combustion engine vehicles to battery electric vehicles. (a) Map of U.S. automotive vehicle assembly activity as of 2022. The colormap shows the number of workers classified under "motor vehicle manufacturing" (NAICS code 3361) for each state. Markers highlight major manufacturing plants in each state. Three "transition plants" have been identified as examples of complete ICEV-to-BEV production transformations: (1) Alameda County, CA, representing the transition of the former New United Motors Manufacturing, Inc. (NUMMI) vehicle assembly plant, which assembled ICEV passenger vehicles, to the Tesla plant which assembles BEVs; (2) Oakland County, Michigan, representing the transition from the production of General Motors ICEVs to the Chevy Bolt BEV over six years; and (3) McLean County, Illinois, representing the transition of the former Mitsubishi vehicle assembly plant to the Rivian plant which assembles electric pick-up trucks. (b) Possible trajectories of vehicle assembly workforce size that this work seeks to clarify. ICEV: internal combustion engine vehicle. BEV: battery electric vehicle. Source data are provided as a Source Data file.

Alameda was chosen as the site of the historic New United Motor Manufacturing Incorporated (NUMMI) plant, a joint venture between General Motors and Toyota, which closed in 2010 and has subsequently been owned and operated by Tesla to produce BEVs. Alameda represents a 'near-steady-state' BEV assembly case: Tesla has now been producing BEVs from this site for over a decade, and its annual production volume of BEVs now exceeds that of the NUMMI plant at its peak. Oakland was next identified as home to the General Motors (GM) Orion assembly plant, which began producing the Chevy Bolt BEV in 2016 concurrently with ICEVs [24]. As of 2021 the plant was exclusively making the Bolt, before ending its production in December 2023 [25]. Oakland thus provides a case study in which the same workforce transitioned from making ICEVs to making BEVs over a period of five years. Finally, McLean was identified as the home to a former ICEV plant owned by Mitsubishi, which has since been taken over by Rivian to produce mass-market electric light-duty trucks. McLean represents the case of a burgeoning BEV manufacturer at the early stages of vehicle production ramp-up.

To understand the effect of the BEV transition on the workforce size at each transition plant, we frame the transition as occurring in several stages, each of which bears consequences for the workforce size at the plant (Fig. 2b). In the first stage, ICEV lines are retired, resulting in lower vehicle production volumes and a reduced workforce. In the second stage, assembly lines are re-tooled for BEV production, renewing the demand for workers. In the third and final stage, the BEV assembly plant approaches a steady state in operational capabilities and production volumes. At this stage, the workforce size is expected to stabilize.

Understanding labor intensity through workers per vehicle

At each transition plant, we study the labor intensity of vehicle assembly before, during, and after the transition to BEVs. Labor intensity is defined by the number of assembly workers needed to produce 1,000 vehicles (WPV) according to Equation (1):

$$\mathrm{WPV}(k) = \frac{W(k)}{V(k)} \times 1000, \tag{1}$$

where $W(k)$ is the number of auto assembly workers employed at the site averaged over four quarters of year k and $V(k)$ is the total number of light-duty vehicles produced at the site during year k. WPV normalizes the workforce size by the production volume and is thus a measure of labor intensity. WPV can be converted to units of hours worked per vehicle by assuming a total annual hours worked per worker. However, since the hours worked are not publicly known at each transition plant, we chose to report labor intensity as WPV for this work (See Methods: Data processing)

Vehicle production data is obtained from Automotive News Research & Data Center [23] (see Methods: Vehicle production data). Automotive assembly worker data reflects employment under the North American Industrial Classification System (NAICS) code 3361, Motor Vehicle Manufacturing. Worker data is corroborated by combining data from two publicly available government databases - Quarterly Census of Employment and Wages (QCEW) and Quarterly Workforce Indicators (QWI) - as well as from local news reports (see Methods: Employment data). National vehicle production and employment data (Supplementary Fig. 1) provide a reference estimate of average ICEV labor intensity since BEV production in the U.S. had not surpassed 7% as of 2022. In the past two decades, national labor intensity has ranged between approximately 17 and 28 WPV. Labor intensity reached its lowest point of 17 WPV in 2015 before steadily climbing toward a high of 28 WPV in 2021.

Alameda: high labor intensity despite a decade of BEV production

Alameda County, California, is home to the vehicle assembly plant historically owned by North America Motor Manufacturing Incorporated (NUMMI) [26]. The plant operated from 1984 to 2010 as a joint venture between General Motors and Toyota, producing ca. 429,000 vehicles per year at its peak. The plant produced midsize economy passenger vehicles (Toyota Corolla and Pontiac Vibe) and light-duty trucks (Toyota Tacoma) (Fig. 3a). The plant closed in 2010 after General Motors pulled out of the partnership in the aftermath of the global recession [27, 28]. The plant closure resulted in the direct loss of 4,700 manufacturing jobs [27] and the closure of 34 businesses in Alameda that supplied parts to the factory [29].

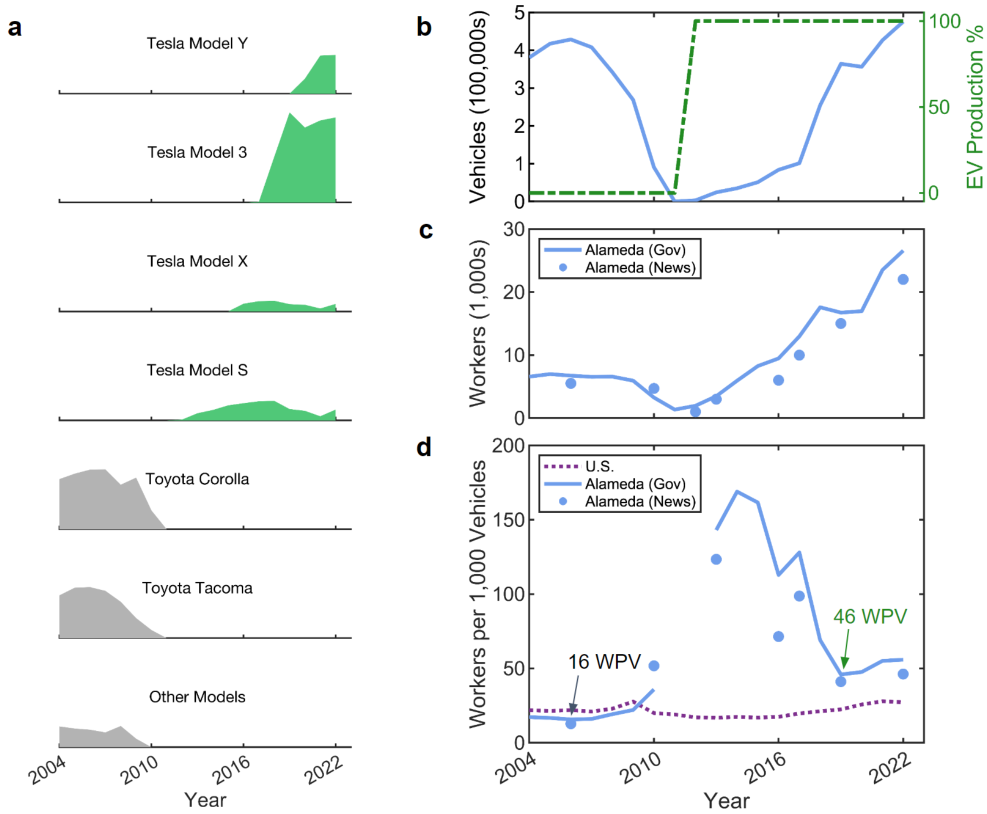

Fig. 3 Vehicle production, workforce size, and labor intensity in Alameda County, California. (a) Before 2010, the New United Motors Manufacturing Incorporated (NUMMI) factory produced ICEVs, including the Corolla and the Tacoma. The factory has since been taken over by Tesla, which has been producing BEVs for over a decade. The green shaded areas indicate BEV production. The gray shaded areas indicate ICEV production. (b) Annual vehicle production volumes. (c) Employment numbers, sourced from government data (U.S. Quarterly Workforce Indicators, NAICS code 3361) and news reports. (d) Labor intensity in Alameda compared to the U.S. average, measured in workers needed to produce 1,000 vehicles per annum (WPV). ICEV: internal combustion engine vehicle. BEV: battery electric vehicle. NAICS: North American Industry Classification System. Source data are provided as a Source Data file.

Following the NUMMI plant closure, Tesla purchased the factory and began to retool the lines, first to produce the Model S sedan and Model X SUV starting in 2012 and 2015, respectively, followed by the Model 3 and Model Y mass-market vehicles starting in 2017 and 2020, respectively. By 2019, the annual vehicle production volume surpassed that of the NUMMI plant at its peak, and by 2022, the plant was producing more than 450,000 units per year (Fig. 3b). In the years between 2012 and 2022, Tesla has maintained a net hiring rate of ca. 2,500 manufacturing workers per year, totaling over 25,000 workers as of 2022 (Fig. 3c). These employment numbers are corroborated by both government data and local news reports (see Methods: Employment data).

The NUMMI factory reached peak labor efficiency, i.e., its lowest labor intensity, in 2006 at 15 WPV (Fig. 3d). Since then, labor intensity has risen year-on-year as vehicle production volume declined. After Tesla acquired the plant in 2012, labor intensity stayed above 50 WPV over the next five years, coinciding with the production of Model S and Model X. Labor intensity then began to decrease starting in 2017, when Tesla began production of the Model 3, its first mass-market BEV. During the period between 2019 and 2022, labor intensity averaged 51 WPV. Overall, during the decade since Tesla began to build BEVs, the labor intensity stayed above 45 WPV.

To the best of our knowledge, the BEV labor force in Alameda includes labor for battery pack assembly for the Model S/X [30] but excludes battery pack assembly for the Model 3/Y which are reportedly manufactured off-site in Sparks, Nevada [31–35]. This BEV labor force further excludes battery cell manufacturing since battery cells for the Model S and X are sourced from Panasonic in Japan [36], and cells for the Tesla Model 3 and Y are reportedly made in Sparks [31–34]. Starting in 2017, Tesla also began to make Model 3 electric motors [35, 37] and battery packs in Sparks. The data after 2017 thus primarily reflects the labor intensity for assembling Model 3 and Y vehicles, excluding electric motor manufacturing, battery cell manufacturing, and battery pack manufacturing, with the exception of Model S/X battery packs which presumably continued to be made on-site. When battery manufacturing workers from Sparks, Nevada, are included, labor intensity further increases to 67 WPV in 2022, reflecting an additional 50% increase in labor intensity (Supplementary Fig. 2).

Overall, Alameda highlights one example of an ICEV to BEV transition in which each BEV took more than twice as many workers to assemble, even before considering the additional labor needed to manufacture battery cells and electric motors. Tesla, now with more than a decade of BEV production, has reached annual production volumes exceeding its former ICEV counterparts. Yet, labor intensity between 2019 and 2022 (51 WPV) remained more than triple that of the NUMMI plant during its peak productivity year in 2006 (16 WPV).

Oakland: same plant owner, similar labor intensity

Oakland County, Michigan, is the home to the Orion Assembly plant owned by General Motors (GM). Before the 2008 recession, the plant produced the Chevy Malibu and Pontiac G6 passenger sedans with a production rate peaking at ca. 456,000 per year in 2004 (Fig. 4a). Production numbers declined in the proceeding years, eventually reaching zero in 2008 when the plant was idled as GM declared bankruptcy [38] (Fig. 4b). As the economy recovered from the recession, the Orion plant re-opened to produce the Buick Verano and Chevy Sonic passenger sedans [39, 40]. In 2016, GM began to convert its assembly lines to produce the Chevy Bolt BEV [24]. By 2021, the plant had transitioned to exclusively assembling the Bolt, with the production rate peaking at ca. 42,000 units per year. GM ended production of the Bolt in December 2023 with plans to renovate the Orion plant to make electric trucks starting in 2025 [25]. Since 2016, vehicle assembly employment in Oakland County mirrored the vehicle production rate: as vehicle production declined, so did employment (Fig. 4c).

Data before 2016 reflects the labor intensity of ICEV assembly, which varied widely (Fig. 4d). Before the 2008 recession, labor intensity varied between 24 WPV and 35

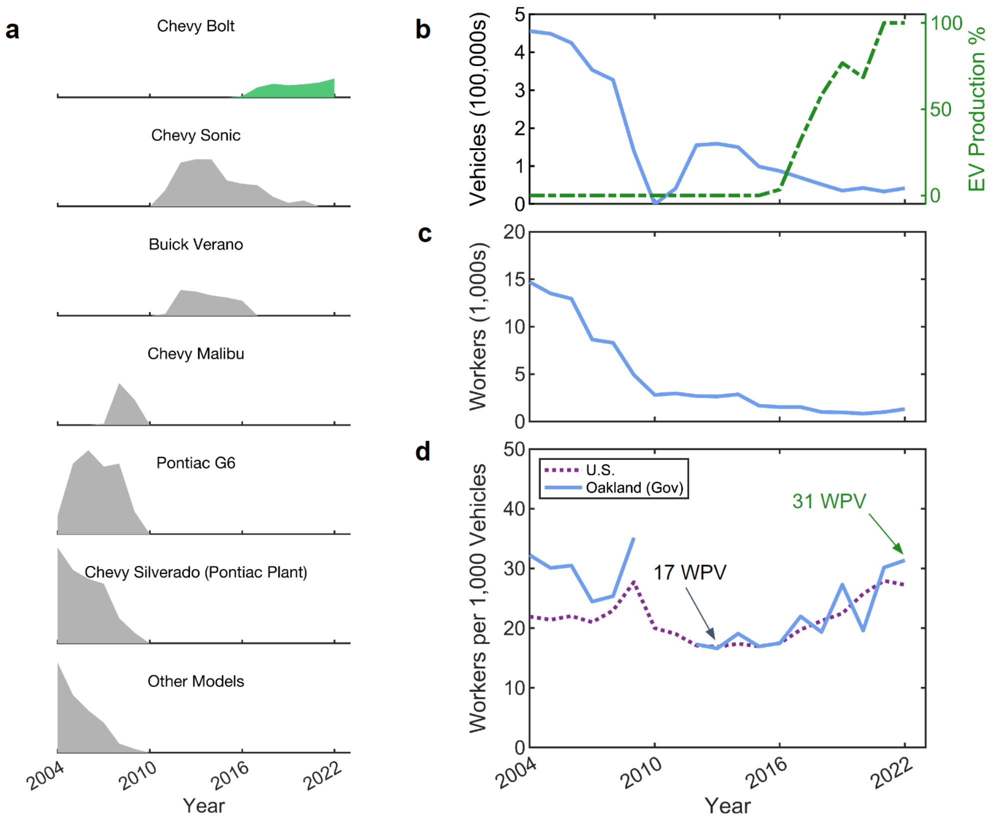

Fig. 4 Vehicle production, workforce size, and labor intensity in Oakland County, Michigan. (a) Oakland County is home to the Orion Township assembly plant owned and operated by General Motors (GM). Before the 2008 recession, plants in the cities of Pontiac and Wixom were also actively producing vehicles, but both plants shut down in 2010, leaving the Orion plant as the sole operating plant in the county. In 2016, Orion began producing the Chevy Bolt BEV alongside GM ICEVs, before exclusively producing the Bolt as of 2021. The green shaded areas indicate BEV production. The gray shaded areas indicate ICEV production. (b) Annual vehicle production volumes. (c) Employment numbers, sourced by averaging two government NAICS 3361 datasets: the U.S. Quarterly Workforce Indicators (QWI) and the U.S. Quarterly Census of Employment and Wages (QCEW). (d) Labor intensity in Oakland compared to the U.S. average, measured in workers needed to produce 1,000 vehicles per annum (WPV). ICEV: internal combustion engine vehicle. BEV: battery electric vehicle. NAICS: North American Industry Classification System. Source data are provided as a Source Data file.

WPV. Following the factory shutdown in 2010, labor intensity decreased to 17 WPV. As the plant began to make the Chevy Bolt BEV in 2016, labor intensity began to rise. However, over the same period, the baseline national labor intensity (i.e., baseline ICEV labor intensity) rose by a similar amount, which we attribute to a general market shift towards larger vehicle types [41].

Oakland thus represents a case in which the transition to BEV assembly did not appreciably change the labor intensity trajectory compared to the rest of the U.S., which continued to assemble mostly ICEVs during the same period. However, while the labor intensity remained similar, the total number of jobs declined due to the reduced vehicle production volumes (Fig. 4b,c). Finally, we note that the labor intensity corresponding to Chevy Bolt BEV assembly excludes battery pack assembly labor to the best of our knowledge. Battery cell manufacturing labor is also excluded since the battery cells are manufactured by LG in South Korea or Holland, Michigan [42, 43]. The labor intensity for the Bolt is expected to increase if either battery pack assembly or cell manufacturing activity is included.

McLean: ten-fold increase in labor intensity during BEV factory production ramp

In this final case study, we turn to McLean County, Illinois, home to the former Mitsubishi vehicle assembly plant [44] (Fig. 5). During Mitsubishi's ownership, vehicles produced included the Eclipse sedan and Outlander sport utility vehicle, with vehicle production plateauing ca. 69,000 vehicles in 2014. In the same year, the plant employed 1,250 workers. In 2015, Mitsubishi shut down operations due to global competitive pressures [45]. The plant was subsequently purchased by Rivian to be re-tooled for assembling electric pickup trucks [46]. In 2022, Rivian produced ca. 18,000 electric vehicles while employing 6,000 workers.

We thus calculate labor intensity in McLean to be 18 WPV during ICEV production in 2014, compared with 316 WPV during BEV production in 2022. The high labor intensity seen in 2022 mirrors the similarly high levels seen during Alameda's first five years of BEV production (Fig. 3d). Both cases represent periods during which fledgling BEV makers undergo rapid production ramp-up and in which production levels have not yet reached a steady state. Rivian also reportedly manufactures battery packs on-site [47], contributing to an additional use of labor which is included in the labor intensity calculation. Note, however, that battery cell manufacturing is not factored into the labor intensity calculation to the best of our knowledge since Rivian is reportedly using cells supplied by Samsung that are not manufactured on-site [47].

More workers for BEV assembly, not fewer

The three case studies in Alameda, Oakland, and McLean counties collectively suggest that each BEV requires just as many, if not more, workers to assemble than each ICEV. We summarize this finding in Table 1, which compares the labor intensity before and after the BEV transition at each transition plant. For each comparison, we report the numbers corresponding to the year with the highest peak labor productivity (the inverse of labor intensity). In Alameda, labor intensity rose three-fold from 16 WPV to 46 WPV after the BEV transition. In Oakland, labor intensity rose two-fold from 17 WPV to 31 WPV. Finally, in McLean, labor intensity rose from 18 WPV to 316 WPV. In all three cases, the labor intensity increased following the BEV transition.

Alameda highlighted a labor scenario for a maturing BEV assembly process. After ten years of BEV production, labor intensity in Alameda remained more than three times higher compared to its ICEV counterparts. McLean showed how labor intensity may increase ten-fold during the early years of vehicle production ramp towards volume production, especially for a new automaker. Oakland highlighted a case in which

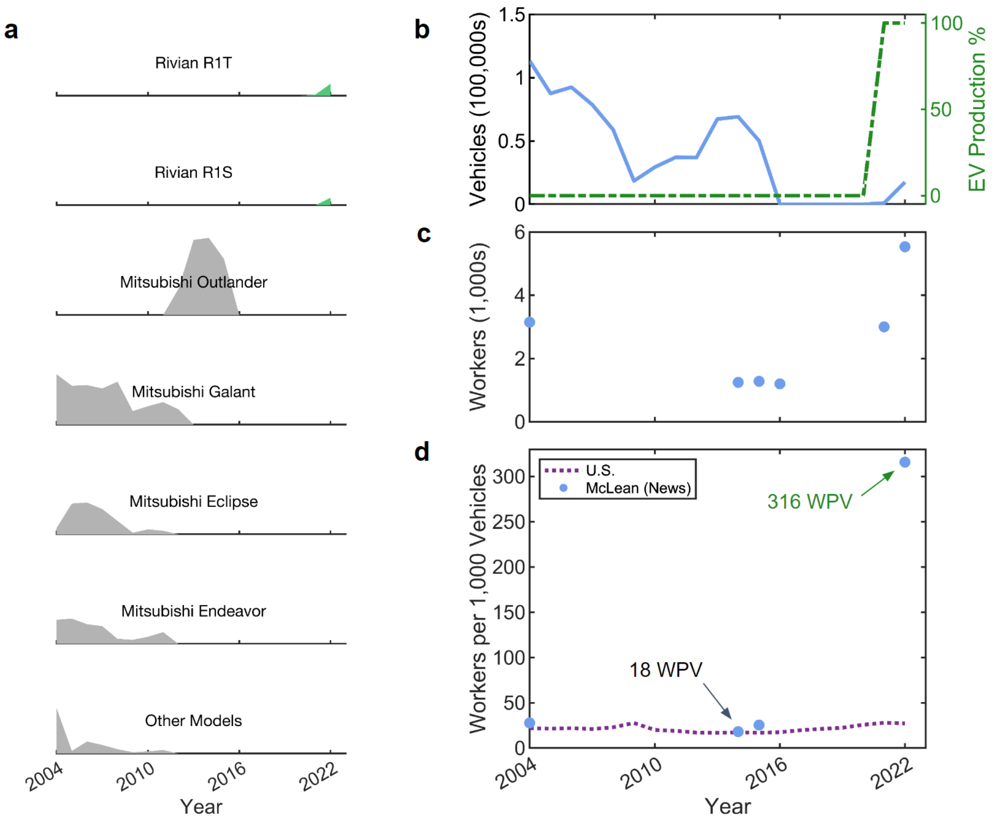

Fig. 5

the labor intensity for making BEVs, while trending higher, was no different from the baseline labor intensity for making ICEVs around the U.S. during the same time period. These three contrasting cases highlight how specific labor intensity outcomes are dependent on the region and automaker.

Explaining higher labor intensity in BEV assembly

We postulate several factors that may influence the labor intensity of BEV assembly: investment in manufacturing technology development, higher vehicle complexity, and vertical integration. These factors may explain why the labor intensity for BEV assembly today exceeds the labor intensity of past ICEV assembly and why labor intensity outcomes are not uniform but vary by region. We discuss each of these factors in turn.

Increased levels of investment in manufacturing technology have the counter-intuitive effect of suppressing near-term labor productivity as companies hire a larger workforce to improve the technology. Such may be the case in Alameda, where Tesla's investment in BEV manufacturing technology [52] has resulted in a workforce of

	ICEV Assembly	BEV Assembly
Alameda, California		
Owner	NUMMI	Tesla
Vehicle models	Tacoma, Corolla, Vibe	Model S/X/3/Y
Peak productivity year	2006	2019
Production volume	429,000	364,000
Employment	6,700	16,700
Labor intensity	16 WPV	46 WPV
Includes engine/transmission production?	No [48, 49]	—
Includes pack assembly?	—	Some* [30–35]
Includes cell manufacturing?	—	No [31–34, 36]
Oakland, Michigan		
Owner	General Motors	General Motors
Vehicle models	Sonic, Verano, Malibu	Chevy Bolt BEV
Peak productivity year	2013	2022
Production volume	159,000	42,000
Employment	2,600	1,200
Labor intensity	17 WPV	31 WPV
Includes engine/transmission production?	No [50]	—
Includes pack assembly?	—	No**
Includes cell manufacturing?	—	No [42, 43]
McLean, Illinois		
Owner	Mitsubishi	Rivian
Vehicle models	Outlander, Galant, Eclipse	R1T, R1S
Peak productivity year	2014	2022
Production volume	69,000	18,000
Employment	1,300	5,500
Labor intensity	18 WPV	316 WPV
Includes engine/transmission production?	No [51]	—
Includes pack assembly?	—	Yes [47]
Includes cell manufacturing?	—	No [47]

Table 1 Higher labor intensity needed for BEV assembly for all three counties studied. Production volume, employment numbers, and labor intensity correspond to the year of minimum labor intensity. The lists of vehicle models highlight certain high-volume production models and are not exhaustive. (*) Battery pack assembly for Model S and X reportedly took place in Alameda [30]; Battery pack assembly for Model 3 and Y reportedly took place offsite in Gigafactory 1 located in Sparks, Nevada [31–35]. (**) Battery pack assembly for the Chevy Bolt occurs at a separate facility in Hazel Park, Michigan. The economic output of the Hazel Park facility is not vehicles and is assumed to be excluded from NAICS code 3361 (motor vehicle manufacturing). ICEV: internal combustion engine vehicle. BEV: battery electric vehicle. NUMMI: New United Motors Manufacturing, Inc. NAICS: North American Industry Classification System. WPV: workers per 1000 vehicles per annum (labor intensity).

salaried engineers who are co-located within the assembly plant [53]. This claim is corroborated by government occupation data, which shows that engineering occupations accounted for 7% of total assembly employment in California in 2021 compared to 5% at the national level and 3% in Michigan (Supplementary Table 1). Wages data tells a similar story: the average income of assembly workers in Alameda, CA, more than doubled from 2013 to 2021, indicating a growing presence of higher-paid engineering occupations. Comparatively, in Oakland, MI, the average income increased by only 20% over the same period. Note, however, that the presence of engineering and other non-production workforce is unlikely to fully account for Alameda's increased labor intensity following the BEV transition: after discounting for non-production workers, Alameda's BEV labor intensity in 2021 would remain over 30 WPV, which is still twice as high as during peak ICEV production in 2006. This calculation assumes that California's statewide average share of production workers in 2021 is a reasonable proxy for Alameda's share of production workers in the same year.

Vehicle complexity is another potential factor. First-time BEV makers tend to produce and sell premium-class vehicles before they produce and sell economy-class vehicles. For example, the first mass-produced BEVs from Tesla (Model S) and Rivian (R1T) are both premium-class vehicles that sell for more than $80,000 USD in 2023 dollars. By comparison, before the BEV transition, the median sales price of ICEVs produced at the same plants was only $28,000 USD since production was dominated by mass-market vehicles such as the Toyota Tacoma and the Mitsubishi Outlander (Supplementary Fig. 3). The present-day bias towards more premium-class BEVs may thus partly explain the higher labor intensity observed for BEV assembly currently. As BEV manufacturers move towards offering more economy-class BEVs, labor intensity may yet decrease. This trend may already be seen in Oakland, where the Chevy Bolt EV's median sales price nearly matched that of its ICEV predecessors, as did labor intensity.

Finally, the rise in BEV labor productivity also parallels a growing industry trend towards consolidating workers who have historically worked off-site, i.e., at the site of parts suppliers, but now work within the assembly plant (Supplementary Fig. 4). This consolidation is most clearly evident in Alameda, where Tesla has chosen to design and manufacture many vehicle components in-house, including electric motors [54], semiconductors [30], and seats [55]. In contrast, legacy automakers, over a period between the late 1990s and early 2000s, have opted for a strategy of outsourcing in which many vehicle components, such as the engine and transmission, are designed and manufactured off-site by parts suppliers [52, 56]. Consequently, parts manufacturing workers (e.g., engine and transmission manufacturing workers) that supported vehicle assembly tended not to be co-located at the vehicle assembly site [57]. A transition to BEVs does not necessarily guarantee that an automaker will move towards greater vertical integration. For example, in the Oakland assembly plant, GM reportedly assembled battery packs off-site, so the workers for battery pack assembly are not included in our measure of labor intensity for the Chevy Bolt.

Parts manufacturing

While this study focused on the trajectory of automotive assembly jobs, the fate of automotive parts manufacturing jobs warrants further study. Parts manufacturing jobs comprised 66% of all auto manufacturing jobs in the U.S. in 2022 (Fig. 1). For some parts manufacturing activities such as electrical, steering, suspension, brakes, seats, and interior trim, worker demand will persist within the context of BEV production. However, disruption in transmission and engine-related parts manufacturing jobs is expected since these components are simplified or absent in BEV powertrains [58]. Engine manufacturing jobs will especially be impacted, considering the lack of combustion engines in BEVs.

In the U.S., engine manufacturing jobs accounted for 7% of all U.S. auto manufacturing jobs in 2022, or 56,486 workers. With the BEV transition, these workers face job losses but also the opportunity for re-employment in other parts of the BEV value chain. The most immediate source of worker re-employment is in battery cell manufacturing which accounts for up to 75% of the total labor intensity for producing a BEV powertrain [19]. Employment data on existing BEV OEMs also suggests that battery cell manufacturing, including pack assembly, can increase labor needed per BEV by over 50% (Supplementary Fig. 2 and Supplementary Table 2). In 2022, Alameda employed 22,000 workers for vehicle assembly, and in the same year, Tesla and Panasonic Energy of North America (the cell supplier) jointly employed 12,000 workers to manufacture cells and assemble battery packs. In other words, for every two workers needed to assemble a BEV, an additional worker is needed to manufacture the battery cells and build the battery pack.

Ultimately, whether new jobs in battery cell manufacturing will replace lost jobs in automotive parts manufacturing depends on the labor intensity needed to make battery cells, the geographical co-location of jobs, and skills [59–62], which should be further investigated (Supplementary Note 1, Supplementary Fig. 5).

Discussion

Our study offers a lens through which the future of BEV labor intensity can be better understood. As an illustrative scenario, Fig. 6 compares the current and future projected trajectory of BEV assembly labor intensity based on data from Alameda. The projected trajectory optimistically assumes that 30% fewer workers is achieved at steady-state (see Methods: Labor intensity projections for details). Four key takeaways are as follows. First, BEV assembly sites demand significantly higher labor intensity during the early stages of factory ramp-up, which can span many years. Second, over the next ten years, labor intensity gradually declines as vehicle production rates increase. Third, if labor intensity improvements continue at their historic pace, then it could take more than 15 years for BEV labor intensity to reach parity with previous ICEV levels. Therefore, even if the common assumption of 30% fewer workers in BEV assembly plants proves accurate in the long run, it will likely take more than 15 years to reach that level of labor intensity, assuming the same vehicle production volume. Finally, the steady-state labor productivity will depend on various techno-economic factors: increased manufacturing R&D investment and vehicle complexity will drive up labor intensity, while higher volume production, robotic automation, and process efficiency improvements will have the opposite effect.

Overall, our study challenges the simplified narrative that BEVs require 30% less labor to assemble than ICEVs. The observed data in three transition plants indicates that BEVs are more labor-intensive to assemble than ICEVs, rather than less. These results suggest that the path towards greater BEV manufacturing will require a workforce size at the assembly plant that matches or exceeds the size of the ICEV workforce. The demand for workers at BEV assembly sites is spurred by a continued need to innovate and improve existing BEV manufacturing technology, a drive

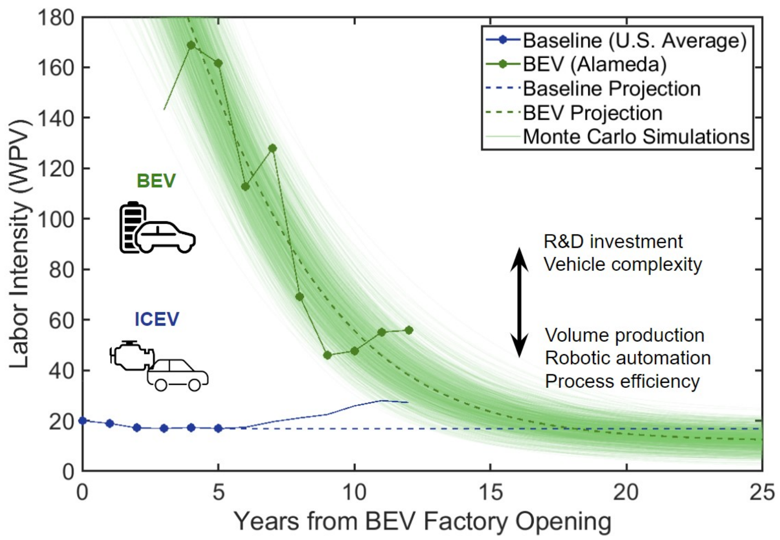

Fig. 6 Illustrative scenario comparing current and future BEV assembly labor productivity. The data compares BEV labor intensity data from Alameda against baseline ICEV data from the U.S. average (Supplementary Fig. 1). Year 0 corresponds to 2010 when Tesla began to retool the factory in Alameda to begin producing the Model S. Baseline WPV is projected based on data from year 5. For the BEV WPV trend, solid markers indicate data points used for the projection. The projected steady-state value assumes that 30% lower labor intensity versus the baseline is eventually realized. Years 0-5: higher labor intensity during the initial period of factory production ramp-up. Years 5-10: gradual decrease in labor intensity as production volume increases. Beyond 15 years: whether BEV labor intensity will reach parity with ICEV labor intensity will depend on various techno-economic factors, including the level of R&D investment, vehicle complexity, production volume, robotic automation, and process efficiency. See Methods: Labor intensity projections for details. ICEV: internal combustion engine vehicle. BEV: battery electric vehicle. WPV: workers per 1000 vehicles per annum (labor intensity). Source data are provided as a Source Data file.

towards greater vertical integration, and the present-day tendency to produce higher-cost BEVs. Our analysis suggests that rapid, widespread job displacement during the BEV transition is a smaller risk than many fear.

Methods

Ethics and Institutional Review Boards approval information

This study conducts a secondary analysis of publicly available datasets and reports, so it does not qualify as human subjects research or require institutional approval.

Vehicle production data

Vehicle production data V was obtained from the Automotive News Research & Data Center [23], which collates North American light-duty (i.e., passenger vehicles and pick-up trucks) vehicle sales, production, and inventory data on a monthly basis and organizes the data by automaker, vehicle make and model, and manufacturing plant location. Only vehicle production in the U.S. was considered for this work. Electric vehicle models were manually identified by cross-referencing publicly available lists of BEV makes and models. The counties in which manufacturing plants reside were manually identified using the counties' Federal Information Processing System (FIPS) codes to enable linking vehicle production data with county-level employment data.

Employment data

County-level automotive manufacturing employment data W was obtained from two government data sources, the Quarterly Census of Employment and Wages (QCEW) and the Quarterly Workforce Indicators (QWI), as well as from local news reports.

The QCEW dataset, administered by the U.S. Bureau of Labor Statistics (BLS), comprises a quarterly count of employment and wages for workers covered by unemployment insurance programs, which totals more than 95% of U.S. workers [63]. The data is aggregated and classified by industry according to the North American Industry Classification System (NAICS), and provided for county, metropolitan statistical area (MSA), state, and national levels. This dataset provides employment data at the level of an "establishment", defined as a single physical worksite engaged predominantly in one type of economic activity, e.g., making automotive vehicles.

The QWI dataset, administered by the U.S. Census Bureau, consists of administrative data from the Longitudinal Employer-Household Dynamics program, including Unemployment Insurance Wage Records, data from the Census Bureau, and data from the Office of Personnel Management. This allows the QWI dataset to provide both firm-level and worker-level data. The QWI data covers more than just those eligible for unemployment insurance benefits and includes all employers and their employees for which the administrative records are available. The data provides detailed breakdowns by industry (using NAICS codes) and worker demographics (e.g., gender, age, education, race, and ethnicity), as well as earnings and various measures of job and worker flows. Unlike QCEW, which focuses on the establishment level, QWI produces insights into both the employer side (job creation, destruction, etc.) and employee side (turnover rates, accessions, separations) of labor dynamics.

This work sought national, state-level, and county-level employment data from both QCEW and QWI under NAICS code 3361, which corresponds to Motor Vehicle Manufacturing and encompasses assembly workers. Parts manufacturing labor is excluded from these counts because it has its own distinct NAICS code. Occupation data from the Occupational Employment and Wage Statistics (OEWS) program of BLS was used to confirm that approximately 60-80% of NAICS 3361 workers are in production occupations (Standard Occupational Classification code 51-0000, which includes assemblers and fabricators), depending on the region of the U.S. For reference, Supplementary Table 1 summarizes occupation-industry data for NAICS 3361 in Michigan, California, and the U.S.

The QCEW and QWI databases sometimes suppressed regional (state-level and county-level) employment data under NAICS 3361 to maintain employer anonymity. This most often occurs when a single large employer comprises a majority of the data for a particular industry in a particular region. To circumvent these limitations due to data suppression, local news reports, found via internet searches, provided another independent estimate of employment data for specific automotive factory sites. Using two government databases as well as local news reports ensured a sufficient level of redundancy to circumvent these suppression instances. In most cases, the employment numbers from these data sources agree, improving confidence in the reported numbers. Table 2 summarizes which data sources were used for each of the three counties.

County	QCEW (Gov)	QWI (Gov)	News	Notes
Alameda		✓	✓	QCEW data was suppressed
Oakland	✓	✓		Average of QCEW and QWI data was used
McLean			✓	QCEW and QWI data were both suppressed

Table 2 Summary of data sources used to study employment in the three transition counties. QCEW: U.S. Quarterly Census of Employment and Wages. QWI: U.S. Quarterly Workforce Indicators. Gov: government.

Data processing

Employment data corresponding to NAICS code 3361 covers both light- and heavy-duty vehicle manufacturing employment. The vehicle production data from Automotive News only covers light-duty vehicles, so combining the two datasets requires assuming a negligible volume of heavy-duty vehicle manufacturing presence within the selected counties. While NAICS sub-code 33611 covers employment specifically for light-duty manufacturing, that data is suppressed for the states and counties examined for this work and thus could not be used.

Discontinuities in the WPV calculations shown in Figs. 3 to 5 correspond to periods of zero and extremely low vehicle production. For Alameda and McLean, periods of zero vehicle production occurred during the ownership transition from their respective ICE-making to BEV-making companies. For Oakland, this period occurred during the Great Recession. We also observed that in each county, such a small number of vehicles were produced in the first year resuming production that the WPV metric disproportionately inflated for that year. Thus, for each county, we discard labor intensity calculation for the time period in which zero vehicles were produced, plus the first subsequent year that production resumed.

Another common metric for labor intensity is hours worked per vehicle. While the data on hours worked is available at the national level through surveys such as Current Employment Statistics (CES), county-level data is not made public by government agencies. For this reason, we chose to report labor intensity in units of workers per vehicle. From workers per vehicle, hours worked per vehicle (HPV) can be calculated using Equation (2):

$$\text{HPV} = \frac{W \times t}{V} \tag{2}$$

where W is the number of workers, V is the total vehicles produced, and t is the annualized hours worked per worker. The time input t can be estimated to be 2,236 hours, assuming an average of 43 hours worked per week for vehicle manufacturing workers according to BLS [64].

Labor intensity projections

In Fig. 6, baseline ICEV labor intensity was projected based on U.S. average labor intensity data in 2015, which represented ICEV labor intensity since ICEVs comprised >97% of total vehicle production during that year (Supplementary Fig. 1). BEV labor intensity was projected based on data from Alameda. Data from the two other counties (Oakland and McLean) were not used since neither of these sites has sufficiently ramped up vehicle production to realize a declining trend in labor intensity. The labor intensity trend was projected using a four-parameter sigmoid function according to Equation (3):

$$\mathrm{WPV}(x) = \frac{a}{1 + \exp(-b(x-c))} + \mathrm{WPV}_0, \tag{3}$$

where a, b, c, and WPV_0 are fitting coefficients. WPV_0 corresponds to the steady-state labor intensity value and was fixed to -30% of the baseline WPV to represent the assumption that 30% fewer workers is eventually realized. A least-squares fit to the data points, indicated by solid markers, yielded the optimal values $\{a, b, c, \mathrm{WPV}_0\} = \{448.2, -0.2791, 2012, 16.8977\}$. To visually represent forecasting uncertainty, 1000 additional trendlines were generated via Monte Carlo sampling of the parameters. For each sample, parameters were randomly drawn from Gaussian distributions centered at the optimal values and with standard deviations set to $\{10\%, 10\%, 0\%, 30\%\}$ of the optimal values, e.g., $a = \mathcal{N}(\mu, \sigma) = \mathcal{N}(448.2, 44.8)$.

Software

All data analysis and figure generation were performed using MATLAB R2023a. Geographic maps presented in this work were generated using the Matlab Mapping Toolbox.

Data availability

The employment and vehicle production data compiled for this study have been deposited in the Zenodo repository under DOI: 10.5281/zenodo.13152160.

Code availability

The code used for this work is available at https://github.com/wengandrew/ev-jobs/ and under DOI: 10.5281/zenodo.13152160.

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Author contributions statement

A.W.: conceptualization; methodology; writing - original draft; writing - review and editing; visualization. O.Y.A: methodology; software; investigation; data curation; visualization; writing - original draft; writing - review and editing. G.E.: methodology; writing - review and editing. A.S: conceptualization; writing - review and editing; funding acquisition; project administration.

Competing interests statement

A.W. was employed at Tesla while engaged in the research project; the nature of the employment was unrelated to this project and the project received no funding nor sponsorship from Tesla. The authors declare no other competing interests.

Supplementary Information for

Higher labor intensity in US automotive assembly plants after transitioning to electric vehicles

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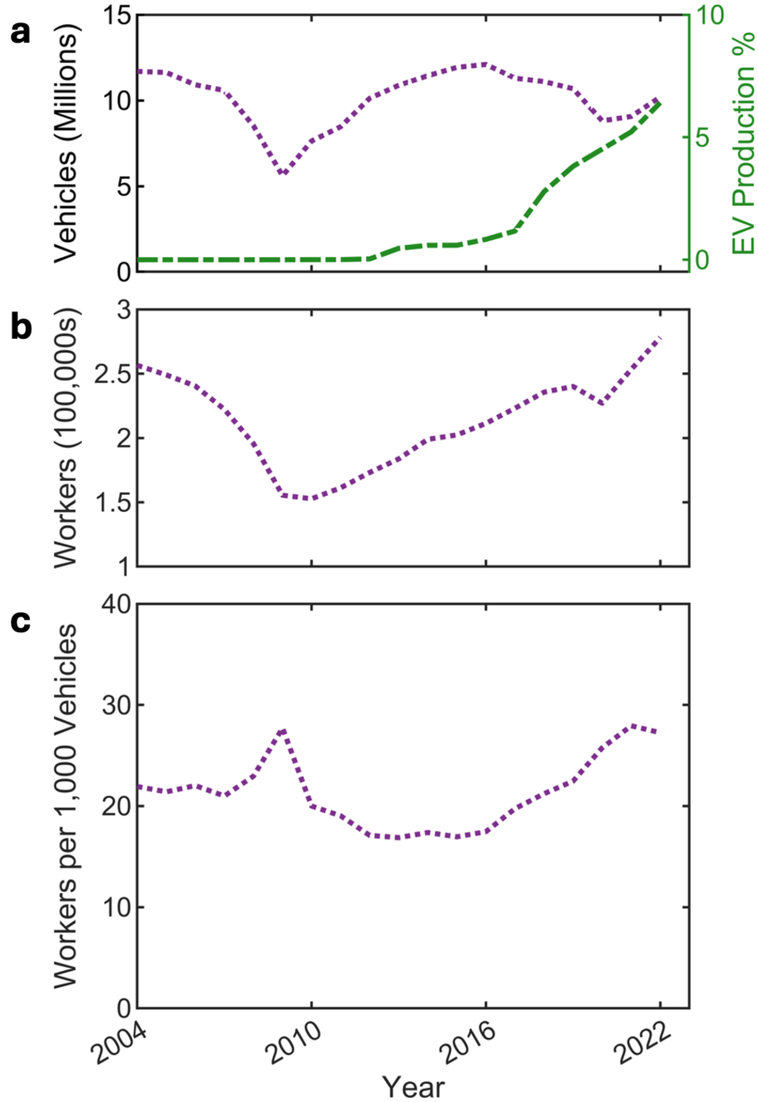
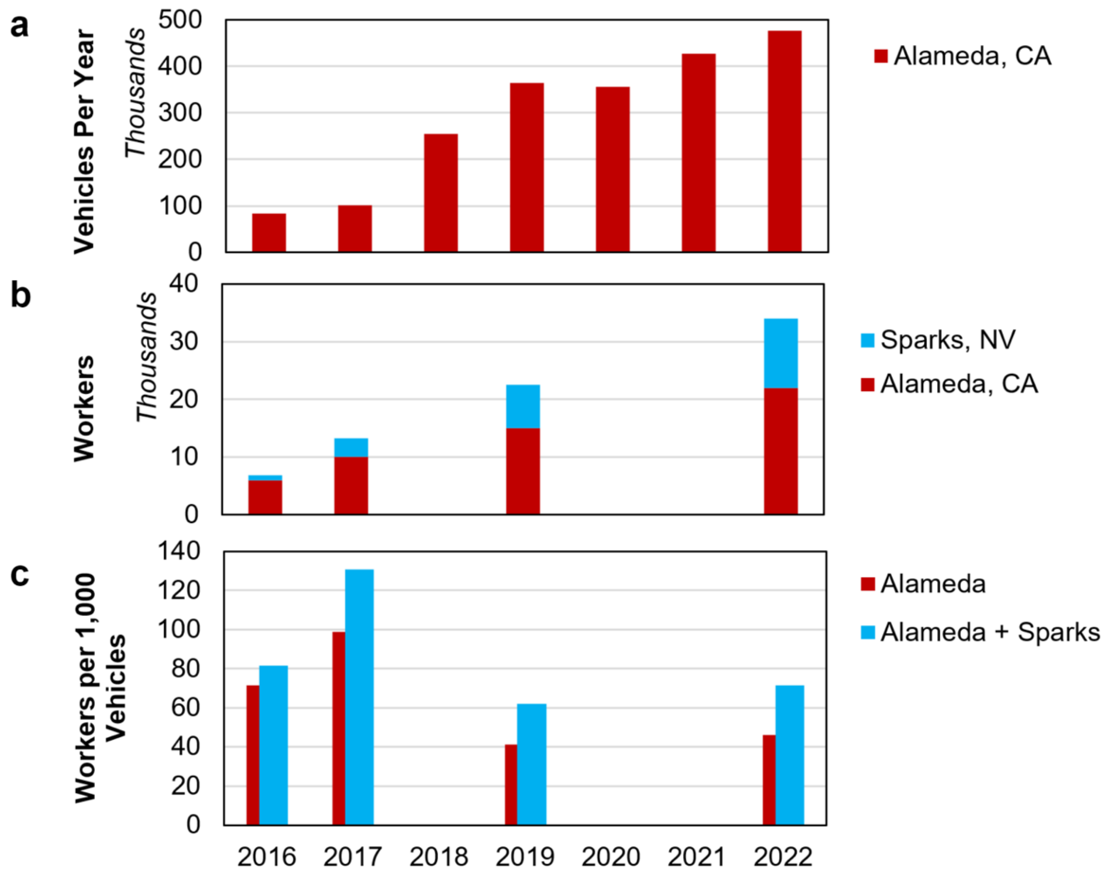
Table of Contents

Supplementary Figure 1: US-level production, employment, and labor intensity



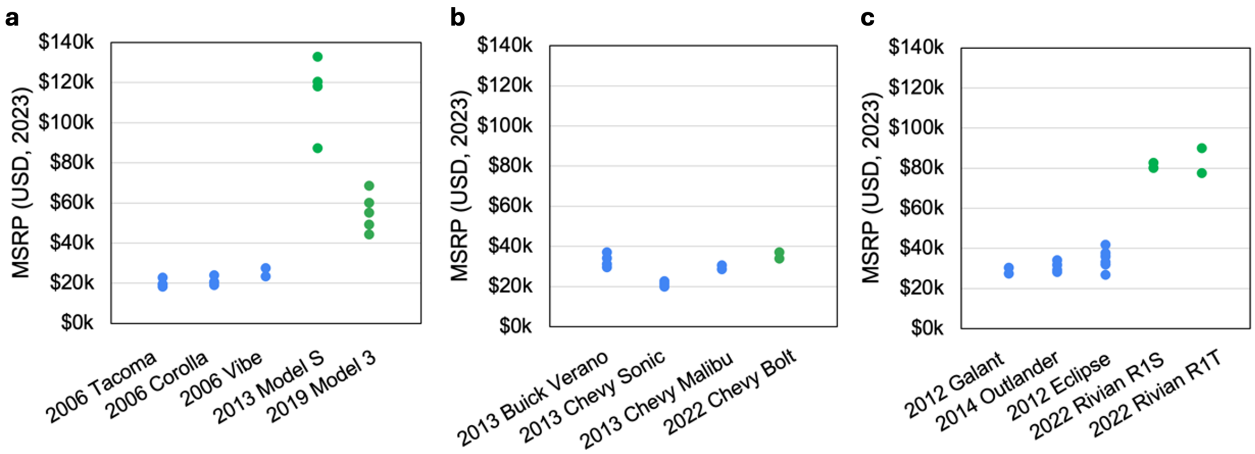
(a) U.S.-level vehicle production volume, (b) assembly worker employment, and (c) labor intensity. Vehicle production data were obtained from the Automotive News Research & Data Center, while employment data was obtained from the Quarterly Census of Employment and Wages (QCEW); see Methods section.

Supplementary Figure 2: Battery cell and pack manufacturing labor intensity



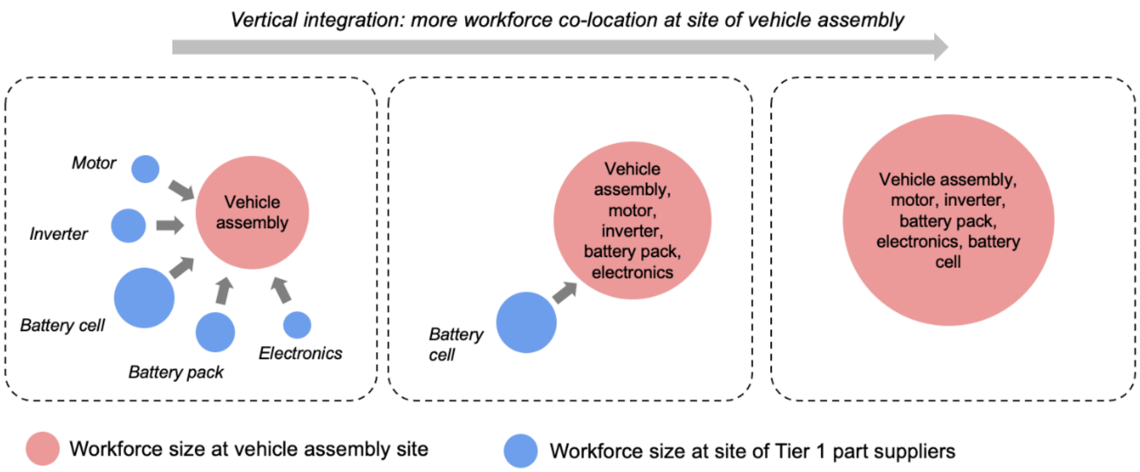
Battery cell and pack manufacturing adds to the labor intensity of making BEVs. (a) Annual vehicle production volume in Alameda, California. (b) Employment in Alameda, California (CA), and Sparks, Nevada (NV), based on news reports (see Supplementary Table 2). Employment in Sparks reflects additional workers for battery cell and pack manufacturing at Tesla Gigafactory 1. Data is shown only when Alameda and Sparks data are available for the same production year. (c) Comparison of labor intensity, i.e., workers per 1000 vehicles per annum, with and without including workers from Sparks. BEV: battery electric vehicle.

Supplementary Figure 3: Comparison of vehicle sales prices



Comparison of vehicle sales prices (MSRP) in (a) Alameda, (b) Oakland, and (c) McLean counties. Dollar values are inflation-adjusted to 2023 dollars based on the Consumer Price Index (CPI) for U.S. new vehicles [1]. MSRPs for all available vehicle trims are shown.

Supplementary Figure 4: Illustrating the effect of vertical integration on workforce co-location



This illustrative example shows how vertical integration creates more workforce co-location at the vehicle assembly site. The area of each circle represents workforce size. Moving from left to right of the image represents a greater degree of vertical integration, leading to a larger workforce size at the vehicle assembly site. Left: a vertically disintegrated vehicle manufacturer will source vehicle parts from off-site suppliers. Middle: as the manufacturer moves towards full vertical integration, nearly all vehicle parts (e.g., motor, inverter, battery pack, electronics), except battery cell manufacturing, are made at the vehicle assembly site. Right: a fully vertically integrated vehicle manufacturer may have all vehicle components, including cell manufacturing, under one roof.

Supplementary Table 1: Breakdown of occupation types and wages

	Location	2013	2021
% of NAICS 3361 workers in production	California (State)	66%	62%
	Michigan (State)	74%	81%
	U.S.	74%	76%
% of NAICS 3361 workers in engineering	California (State)	4%	7%
	Michigan (State)	5%	3%
	U.S.	5%	5%
NAICS 3361 average monthly pay	Alameda, CA	$6,243	$16,462
	Oakland, MI	$7,557	$8,907
	U.S.	$6,660	$6,864

The proportion of NAICS 3361 workers in production (SOC code 51-0000) and architecture/engineering occupations (SOC code 17-0000), compared with the average monthly pay of NAICS 3361 workers. The comparison is given for California, Michigan, and the US. Occupation data was obtained from OEWS. Income data for Alameda, CA, was obtained from QWI. Income data for Oakland, MI, was obtained by averaging QWI and QCEW data. Income data for the U.S. was obtained from QCEW. NAICS: North American Industry Classification System. SOC: Standard Occupational Classification. QWI: Quarterly Census of Employment and Wages. QWI: Quarterly Workforce Indicators. OEWS: Occupational Employment and Wage Statistics. CA: California. MI: Michigan.

Supplementary Table 2: Employment numbers from news reports

Location (County)	Date	News Source	Reported Employment
Tesla (Alameda)	Jun 2012	1	1,000
	Jul 2013	2	3,000
	Jun 2016	3	6,000
	Oct 2017	4	10,000
	Mar 2019	5	15,000
	Jun 2022	6	22,000
Tesla/PENA (Sparks)	2016	7	850
	2017	8	3,249
	2018	9	7,059
	2022	10	12,000
NUMMI (Alameda)	Jan 2002	11	5,739
	Mar 2006	12	5,500
	Apr 2010	13	4,700
Rivian (Normal)	Oct 2021	14	3,000
	Apr 2022	15	5,000
	Jun 2022	16	5,600
	Jul 2022	17	6,000
	Mar 2023	18	7,400
Mitsubishi (Normal)	2004	19	3,150
	2014	20	1,250
	2015	21	1,280
	2016	22	1,200
GM (Oakland)	2013	23	2,561
	2022	24	1,238
	2023	25	1,270

List of news reports used to corroborate factory employment numbers. News sources: 1. SFGATE, 2. Wired, 3. TheCountryCaller, 4. The Mercury News, 5. Forbes, 6. Tesla, 7. Electrek, 8. Electrek, 9. The Associated Press, 10. Tesla, 11. SFGATE, 12. East Bay Times, 13. Recordnet.com, 14. WGLT, 15. CIPROUD, 16. Energy News Network, 17. CIPROUD, 18. SGLT, 19. Chicago Tribune, 20. Local Wiki, 21. Chicago Tribune, 22. WQAD8, 23. CarGroup.org, 24. GM, 25. Wards Auto. PENA: Panasonic Energy of North America. NUMMI: New United Motors Manufacturing, Inc. GM: General Motors.

Supplementary Note 1: Jobs per GWh

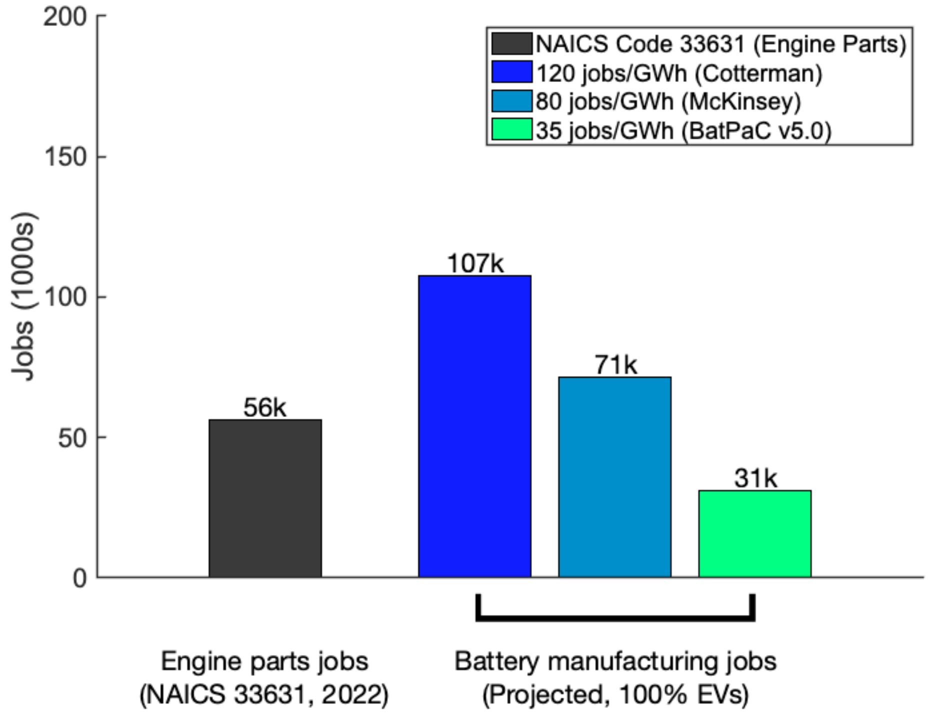
McKinsey reported that, on average, new battery factories add approximately 80 jobs for every GWh of capacity, i.e., **80 workers per GWh** [2]. This number carries high uncertainty since differences in value-chain coverage, e.g., battery-cell production only versus local module/pack production and co-location of R&D facilities, are unclear.

Tesla's Gigafactory 1 reportedly employed 3,249 people when the factory produced 20 GWh of annual output [3]. Among these workers, 1,201 were employed by Panasonic, the main battery cell manufacturer; 93 were employed by Heitkamp & Thumann Group (H&T), a battery cell can supplier; and 1,955 were employed by Tesla. Assuming those employed by Panasonic and H&T are responsible for battery cell manufacturing, it is inferred that 1,294 workers produced 20 GWh of annual output, equaling **65 workers per GWh**. If Tesla employees are additionally included, the calculation yields **162 workers per GWh**.

The BatPaC v5.0 baseline factory model reported an annual labor of 3,876,000 hours per year to produce 50 GWh of output [4]. Assuming each worker works 2,236 hours per year (equivalent to a 43-hour workweek, the U.S. average for automotive manufacturing [5]), this corresponds to **35 workers per GWh**.

Cotterman et al. [6] reported labor intensity per BEV powertrain assuming a 60kWh battery pack, which varied depending on the data source and whether the labor was broken down between cell and pack/module assembly. For data sources where this breakdown was available, labor intensity ranged between 11 to 16 hours per 60kWh for industry data sources and 6 to 15 hours per 60kWh for public data sources. Assuming again 2,236 hours per year worked per worker [5], the range of labor demand is calculated to be **44 to 119 workers per GWh**.

Supplementary Figure 5: Comparing parts manufacturing jobs



This comparison of engine manufacturing parts jobs in 2022 against projected battery cell manufacturing jobs makes the conservative assumption of 100% BEV uptake and under various assumptions of jobs per GWh. The extent to which battery manufacturing jobs can replace all engine parts jobs lost depends largely on the assumption of jobs per GWh, which varies by the data source. BEV: battery electric vehicle. NAICS: North American Industry Classification Code.

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