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TOPICAL REVIEW

Supply-side challenges and research needs on the road to 100% zero-emissions vehicle sales

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Abstract

In this review paper, we delve into the supply-side challenges and considerations for transitioning to 100% zero-emission vehicles (ZEVs), weaving together an analysis of batteries, vehicle production, charging infrastructure, and relevant supply-side policies. We begin by examining the innovations and environmental impacts of lithium mining and recycling, highlighting the need for robust frameworks to ensure sustainable battery production. Our exploration of vehicle production reveals important issues regarding labor dynamics and global competitiveness. Our investigation into charging infrastructure reveals complexities in deployment models and access, reflecting broader societal and economic considerations. Lastly, a critical evaluation of policies across various jurisdictions provides insights into the effectiveness and potential improvements needed to support the ZEV transition. We emphasize the need for coordinated efforts and further research, particularly in areas such as end-of-life considerations for batteries and the alignment of international production standards. Our findings contribute to a comprehensive understanding of the supply-side landscape for ZEVs and underscore the essential research directions to ensure a responsible and successful electrification of the transportation system.

1. Introduction

Electric vehicles (EVs) are becoming increasingly vital in the global effort to mitigate climate change. Transitioning to EVs offers a promising pathway towards decarbonizing this critical area of our economies as the transport sector accounts for a significant portion of greenhouse gas emissions. The last few years have witnessed a remarkable growth in EV adoption: global sales exceeded 10 million vehicles sold annually with major markets such as California and China exceeding 20% market share. Moreover, several countries have shown strong commitments to accelerating this transition. A total of 28 countries and states have already made pledges to ban gasoline cars, and a further 30 countries (and many more localities) are signatories to reach 100% zero emission vehicle (ZEV) sales by 2040 or earlier [1]. While plug-in EVs are only a subset of

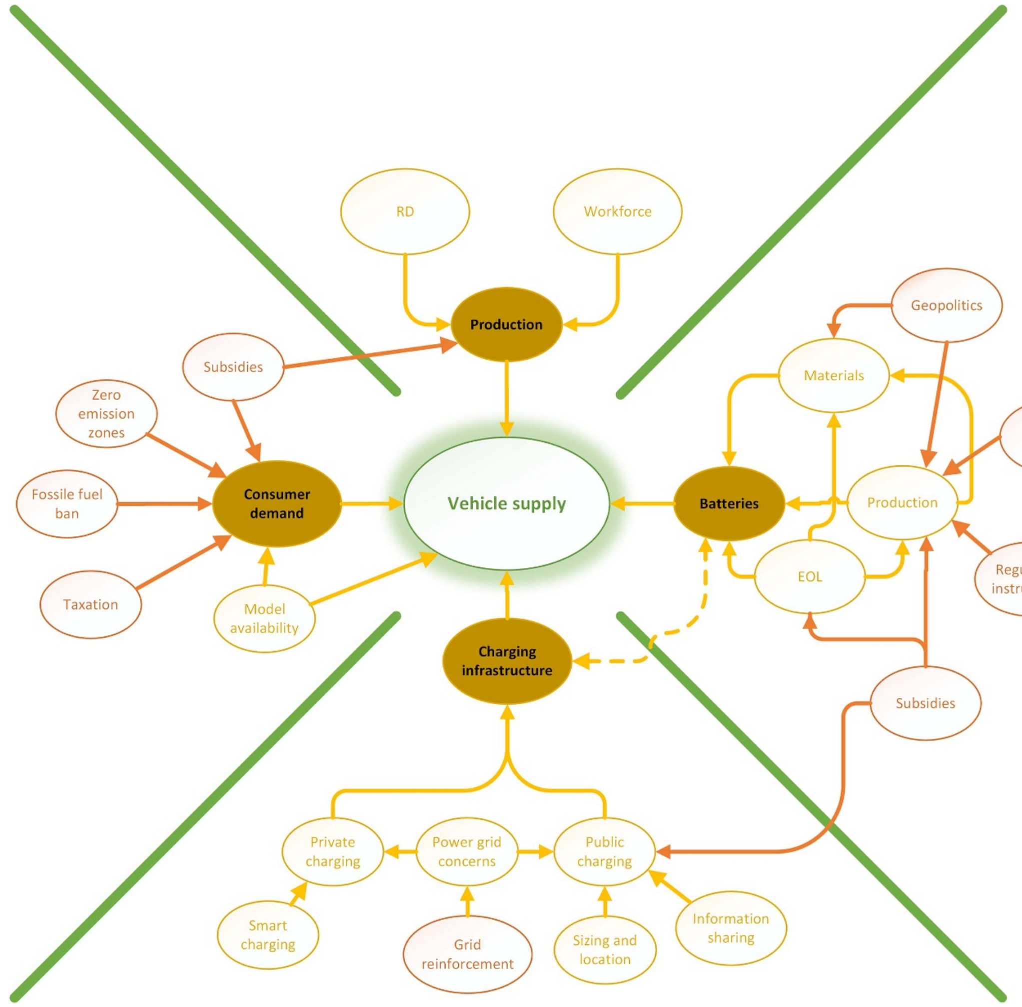

Figure 1. Topical coverage of review paper by category, we proceed through each categories highlighting relevant work that points to challenges in reaching 100% adoption of ZEVs and how they ultimately relate to consumer demand.

ZEVs, which can include other technologies such as fuel cell vehicles and even internal combustion engine vehicles powered by e-fuels, our study focuses primarily on EVs as they are the dominant technology to help governments achieve ZEV goals in most countries around the world.

The supply-side issues related to EVs constitute a significant part of the story. The term 'supply-side' typically refers to all aspects associated with the production and delivery of EVs to the market, encapsulating the entirety of the supply chains involved and the supply-side effects that are related to the use of EVs. This study aims to delve into these supply-side challenges in reaching 100% ZEVs sales. The focus is to provide a systematic review of the current literature on the subject, offering a holistic perspective on the many issues at play. This study focuses on all aspects of EV supply chains, from batteries to vehicle production, as well as the supply of charging infrastructure and electricity needed to support future demand. By examining these challenges, we aim to contribute to the ongoing discourse about the transition to ZEVs and identify areas where future research is needed. Additionally, we offer a thorough analysis of existing supply-related policies and assess the potential necessity for new regulations to meet the objectives of the EV transition. The knowledge gained from this endeavor can provide valuable insights for stakeholders, from policymakers to industry leaders, to navigate the path towards a fully electrified transportation future. We focus on light-duty vehicles in the present study but believe that many findings can be transferred to heavy-duty ZEVs. Lastly, additional demand from other vehicle and transport segments have the potential to escalate supply-side challenges but are not explicitly included in this review. The outline of the paper is as follows, section 2 describes major supply-side challenges around 100% ZEV sales: battery supply (section 2.1), vehicle production (section 2.2), charging infrastructure (section 2.3), and supply-side policies (section 2.4). Resulting research needs are discussed in section 3 followed by our conclusions in section 4. The conceptual organization of the paper can be found in figure 1.

2. Key supply-side challenges to achieve 100% ZEVs

2.1. Battery supply issues

2.1.1. Battery materials

The production of EVs requires a vastly different set of components compared to traditional fossil fuel vehicles. At the core of these differences lies the battery, a crucial element distinguishing EVs from their fossil fuel counterparts.

If EV adoption reaches ambitious targets, there will be an inevitable surge in demand for batteries, translating to an associated rise in the need for the specific materials used in their manufacture. Lithium-ion batteries, the primary battery technology for EVs, play a pivotal role in the advancement of EVs. However, there are some concerns surrounding lithium's production capacity. Studies indicate that the supply of lithium is less of a concern but there is substantial uncertainty as to whether production can be ramped up quickly enough to meet the burgeoning needs of the EV sector [2]. The demand for lithium batteries has seen a steep rise, with 65% of all lithium supply in 2019 going to batteries, up 30% from 2015. Demand for lithium is further expected to surge by over 300% by 2030 from 2021 levels [3]. As demand escalates, the strategies for lithium extraction must continue to evolve. Today, lithium is primarily obtained from brine operations, and several countries have identified large available resources in lithium-bearing brine deposits [4, 5]. These deposits can further be taken advantage of by employing innovative extraction technologies such as adsorbents, ion exchange, solvent extraction, membrane separation, and electrochemical separation [3, 5]. Moreover, unconventional resources, including non-traditional lithium forms in minerals, or even extracting lithium from seawater [6–8], could help meet the increased demand for the material. Nevertheless, the complexities of lithium production go beyond the material's availability. The process of refining battery grade lithium introduces supply risks from geopolitical factors due to the concentration of material processing in a small number of countries: China (59%), Chile (29%), Argentina (9%), and the US (3%) [9, 10]. The geopolitical questions have recently received more attention as issues of regional technological sovereignty rise following policies supporting technology expansion in this area [11, 12]. Lastly, there is an additional concern linked to the demand for continuously larger batteries over time—smaller batteries can have a substantial impact on the overall demand for battery minerals [13].

Critical materials for lithium-ion batteries extend beyond lithium. Cobalt is one of the most critical materials, vital due to its essential role in battery performance [2, 9, 14, 15]. However, sourcing cobalt presents notable issues as a majority is mined in the Democratic Republic of Congo (DRC), a region associated with labor, humanitarian, and health concerns [14, 16]. The dependence on the geopolitical stability of the DRC for cobalt supply presents potential risks in the EV production process [2]. In response to these challenges, efforts are underway to reduce reliance on cobalt in battery production, albeit with inherent difficulties due to cobalt's unique attributes [17–19]. Attempts to lower cobalt usage in batteries are helpful, but unlikely to alleviate supply issues in the long-term given the rapid growth targets of the EV sector [20]. Recent research and manufacturing efforts have focused on alternate battery chemistries to eliminate cobalt use entirely; BYD, for example, does not use cobalt in their EV batteries, and BMW and Tesla are switching some of their battery chemistries to avoid cobalt. Nickel manganese and lithium iron phosphate cathodes represent solutions that are currently being deployed [21].

Besides cobalt and lithium, other materials also hold substantial importance in a full transition to EV, including graphite, manganese, and nickel (for batteries), and neodymium and dysprosium (for motors) [22]. Graphite reserves are notably concentrated in a select few countries—Turkey, China, and Brazil—which introduces additional geopolitical considerations regarding its supply. As the industry aims to minimize cobalt usage, both nickel and manganese could see increased demand due to their potential roles in alternative battery chemistries [23, 24]. Beyond these essential materials for battery electrodes, there are also pressing concerns relating to the availability of precious metals used in battery electronics. These metals are critical for components such as the battery management system and various electronic parts, adding another layer of complexity to the supply-side issues associated with EV production [25].

More advanced battery chemistries and technologies such as high-energy electrode materials and solid-state batteries may eventually surpass current chemistries but these technologies are currently in research and development phases and are ready for mass market applications [26, 27].

2.1.2. Battery production

Beyond the raw material procurement and processing, the construction of battery components (from cells to packs) represents another critical bottleneck in the path to vehicle electrification. The sheer infrastructure required to support battery production capacity illustrates the magnitude of this challenge. In the United States, the commitment to battery manufacturing is clear. As of June 2023, over $130 billion in investments have been announced for battery manufacturing and supply chain expansion. This investment includes 170 new or expanded minerals, materials processing, and manufacturing facilities, and is projected to be sufficient for powering 10 million EVs per year, generating over 75 000 new jobs[12]. In North America, battery plant capacity is expected to experience an exponential growth, leaping from 55 GWh yr^{-1} in 2021 to over 800 GWh yr^{-1} by 2025 [28]. This capacity surge has significantly reduced the U.S.' reliance on foreign import of battery cells (primarily from Japan) to less than half in just a few years since the first gigafactories opened in 2018 [29]. In contrast, China's investment in battery manufacturing reached $300 billion through 2019 alone, with a current capacity of over 500 GWh per year[13] [30]. These issues further exacerbate geopolitical factors of technological sovereignty. The implications of certain countries' dominance on the supply chain of batteries will likely lead to strategies including circular economies, supply chain agility, building domestic supplies, and expanding mining operations [31, 32]. This further underlines the global race in battery production, pointing to different strategic approaches across various regions.

2.1.3. Battery end-of-life(EOL) and recycling

The accelerated adoption of EVs and the resulting exponential increase in battery production raises pressing concerns over the handling of batteries at EOL. This issue entails much more than just waste management; it is necessary to satisfy the tremendous resource demand by EVs beyond 2040 and encompasses re-use, recovery of valuable materials, and recycling, along with accordant regulatory frameworks, business viability, and environmental considerations [33–35]. As the world gravitates toward cleaner transportation, the volume of EOL EV batteries is estimated to reach about 4 million tons by 2030 [36]. This area has spawned significant research and debate, and here we explore the two prevailing approaches dominating the discourse on handling EOL batteries: recycling and re-use [36, 37]. Recycling is integral to managing material constraints for lithium-ion batteries and aims to avert the massive waste associated with widespread EV adoption [38, 39]. Concurrently, secondary use strategies emphasize leveraging used batteries primarily within the electricity grid, opening new avenues for energy management [40–43].

The recycling spectrum itself is broad, encompassing the recovery of critical materials such as lithium, nickel, manganese, and cobalt from cathodes [44, 45]. An array of methods is employed for recycling cathodes, including wet and fire recovery processes, mechanochemical techniques, pyrometallurgy, hydrometallurgy, electrochemical treatments, and direct recycling [46, 47]. Yet, the business models for battery recycling remain challenged by economic hurdles, necessitating improvements before wider availability can be realized [47–49]. Despite these obstacles, tangible benefits are evident, with some Chinese enterprises reporting per EV savings of about $470 and a reduction of 4 tons CO_2eq [50]. Another case study highlighted a 5.7% cost decrease alongside a 21.8% reduction in CO_2 [51], underlining the potent potential of recycling.

Regulation, though pivotal to the success of battery recycling, faces ongoing development challenges, complicated by economic, environmental, and technical issues [52–54]. Comprehensive policies must address gaps in material tracking, waste generation, and technology design [55]. The European Union has recently adopted one of the first regulations on minimum requirements for battery recycling: collection of waste portable batteries (63% by 2027 and 73% by 2030), collection of waste batteries for light-duty vehicles (51% by the end of 2028 and 61% by the end of 2031), 50% lithium recovery from waste batteries by 2027 and 80% by 2031, and mandatory minimum levels of recycled content for industrial, SLI, and EV batteries (16% for cobalt, 85% for lead, 6% for lithium, and 6% for nickel)[14]. The considerations surrounding battery EOL are emblematic of the broader challenges faced in the pursuit of 100% electrification. Without addressing these EOL considerations, the supply-side of the electrification equation remains incomplete, potentially hindering progress toward full electrification.

2.2. EV production

The transition to EVs extends beyond the challenges and complexities of battery manufacturing and encompasses a broader transformation of the entire automotive supply chain, including the aftermarkets for repair and maintenance. This shift not only affects production processes but also disrupts current industry dynamics, potentially realigning global competitiveness. Understanding these changes is crucial as we move toward the widespread adoption of EVs.

[12] Department of Energy. 'Investments in American-Made Energy'. www.energy.gov/investments-american-made-energy.

[13] 'Investment in battery gigafactories nears $300 billion since 2019 as China extends battery dominance.' *Benchmark Source*. 4 January 2023. https://source.benchmarkminerals.com/article/investment-in-battery-gigafactories-nears-300-billion-since-2019-as-china-extends-battery-dominance.

[14] Regulation (EU) No 2023/1542. https://eur-lex.europa.eu/eli/reg/2023/1542/oj.

2.2.1. Production sites

In recent years, investments in electric mobility have surged globally. By 2021, automaker investments and commitments were on track to total $345 billion through 2030, targeting 22 million EVs by 2025 and 35 million by 2030 [56]. This investment has grown rapidly, from $150 billion in 2018 to $275 billion in December 2020, focusing on 13 million EVs by 2025 [57]. The U.S. alone has investments ranging between $75–$108 billion. However, to meet more ambitious EV sales scenarios, production investments may need to climb as high as $143 billion [58]. It is important to note that these statistics include investments in both vehicle production and battery manufacturing. Specifically, within the U.S., investments in EV components and assembly plants have reached $30 billion as of mid-2023, corresponding to 70 new or expanded EV component and assembly plants, and the creation of 40 000 new jobs[15]. However, this electromobility transition is not uniform across the globe. The shift has already begun to upend the current industry positions, impacting the location of production for EVs and affiliated materials such as batteries and motors. This redistribution has been dramatic in some instances, with specific countries and governments finding themselves either advantageously or disadvantageously positioned [59, 60]. For example, a study has shown that Eastern European countries have begun to lag behind their Western counterparts in the automotive industry, a gap that may widen as the electric transition continues [61]. The technology shift creates an opportunity for new investments for some manufacturing countries based on location and trade agreement while others may remain with manufacturing older ICV technology. Much like the situation with battery manufacturing capacity, there is a conspicuous lack of research in this domain. While there have been efforts to track current numbers, there is very little work on the requirements for a 100% transition. This area is therefore ripe for industrial studies. To gain a comprehensive understanding of the situation, more research is needed to supplement the existing literature and to extend the knowledge to the international level.

2.2.2. Workforce

The transition to EV manufacturing represents not only a technological shift but also a profound change in labor and workforce dynamics. Various studies illuminate different aspects of this complex issue, emphasizing both the opportunities and challenges it presents. The production mix between different powertrains opens up large potential for job creation. Generally, the production process for EVs is more labor-intensive than that for traditional fossil fuel-powered vehicles, while the aftermarket is less labor-intensive [1]. This difference implies that in the short to medium term, the labor intensity for EVs will likely be higher, leading to more jobs in powertrain manufacturing [62, 63] and fewer jobs in the repair and maintenance industry and with a truly different skillset. One study estimates that the increase in economic activity resulting from EV manufacturing could augment state and local tax revenues by $400 to $1500 per vehicle over a ten-year period [64]. This speaks to a broader societal benefit in terms of economic growth and development.

Beyond the production and maintenance workforce, EVs also affect dealer workforces as workers must undergo trainings and retain a different skillset, especially with regards to charging and infrastructure. Additionally, challenges to the traditional dealership business model have been put forth by newer entrants into the vehicle market; Tesla, for example, does not use dealerships and instead sells vehicles directly to buyers. Another proposed model is to sell the vehicle and lease the battery pack, enabling the OEM (or battery dealer) to maintain a central position in the management and replacement of EOL batteries. These disruptions could lead to very different business models requiring different workforces [65].

However, the transition is not without its challenges. While there may be a net benefit for society, the jobs being replaced tend to come from workers with, on average, lower incomes, fewer postsecondary degrees, and lower rates of union membership [66]. This pattern suggests an unequal distribution of impacts as different skills and educational inputs will be needed for the EV industry. Evidence of this has already been found in Thailand's automotive industry, where researchers observed a 10% increase in demand for engineering workforce but a 70% decline in low labor skills [67]. In addition, the physical concentration of production for some conventional vehicle components that may no longer be needed (e.g. transmissions, exhaust systems, etc) may lead to higher levels of employment disruption in some locations. These observations lead to large uncertainties regarding the net effect on employment.

2.3. EV charging infrastructure

2.3.1. Charger deployment

EV battery and vehicle manufacturing are indeed crucial in the supply chain for an EV transition, but an often-overlooked aspect of this transformation is the necessary evolution of 'refueling' infrastructure. It is essential to recognize that the term 'charging infrastructure' encompasses various types of infrastructure,

[15] Department of Energy. 'Investments in American-Made Energy'. www.energy.gov/investments-american-made-energy.

including fast charging systems linked to the medium voltage grid as well as slower public charging stations and land home charging setups connected to the low-voltage grid. In order for consumers to widely adopt EVs, there must be a sufficient number of chargers available to meet the demand for each of these infrastructure types [68]. The fundamental question that emerges is: how many chargers will be required in the future to meet different forecasts of EV adoption across the different infrastructures? Some studies have indicated a structural, long-run relationship between the number of chargers and EV registrations [69–74]. Clearly, this relationship forms the basic premise for understanding the dynamics of charging infrastructure and its impact on EV adoption.

A comprehensive investigation by Funke *et al* found that generalizations regarding the necessary charging infrastructure cannot be made across different countries. The population density and the housing conditions vary greatly, and this strongly affects the requirements for public charging infrastructure [75, 76]. However, reaching 100% penetration of ZEVs will likely require chargers to be broadly deployed beyond single-family residential locations [77]. Fast chargers are needed in cities for those that lack access to home charging. In more densely populated areas with a high degree of multi-unit dwellings, studies have found that residents of these locations have disproportionately lower adoption of EVs [68, 78–80]. This signifies that the supply of infrastructure in these areas cannot be neglected and will be a critical factor in supporting adoption towards a 100% goal.

As for non-home charging, such as corridor charging [81], destination charging [82], or fast-charging clusters in urban areas [83, 84], there is a wide body of literature that considers deployment strategies. For example, research by Jochem *et al* demonstrated that a minimum of 314 fast charging stations would allow a 150 km range EVs to travel throughout all major highways in the EU [85]. However, while this minimum coverage is suitable for studying early-stage EVs, attention must shift to the long-run needs of high penetrations of EVs. Consumers tend to engage in long-distance trips in similar time intervals, leading to large peaks in demand which needs to be considered when deploying fast chargers for corridor charging. The infrastructure on the motorway system is important because many of these trips represent longer trips, for which 'range-anxiety' is known to have implications for the EV buying and charging preferences [86, 87]. Hence, people are often not overly concerned with most daily trips for which the battery range is sufficient, but for the rare long-distance trips where charging is a concern. In countries with accelerated EV adoption, research has followed in the same vein to consider long-term charging infrastructure deployment and requirements for EV deployment in Norway [71] and China [88]. Like other forms of infrastructure, the state must actively engage in ensuring the timely provision of the right infrastructure. This underlines the need for cost-effectiveness as in Rich *et al*, whose study of the cost-benefit of a state-road charging system suggests that the optimal level of utilization is between 25%–30% if considering waiting time dis-benefits [81]. The study further emphasized that the infrastructure required to meet 'average demand' differs substantially from what is needed to support peak demand during the winter. This once again underscores the significance of addressing range anxiety by subsidizing investments in less densely populated areas. Recent studies have generalized some of these findings to charging infrastructure for heavy-duty vehicles [89–91].

2.3.2. Other infrastructure considerations

While the deployment of charging stations and the quantification of necessary infrastructure form the backbone of the electrification strategy, there are myriad other considerations that must be addressed to ensure a successful and sustainable transition to EVs.

Charging station cost-recovery and profitability are important considerations in the electrification transition [84, 92, 93]. Many chargers are subsidized by the government, but the long-term feasibility of the infrastructure will depend on their ability to turn a profit. In Boston, for example, stations were not found to be profitable, even with the implementation of large user fees [94]. This lack of profitability could hinder the expansion of charging infrastructure. However, there is also a need for stations that are effectively not profitable by definition in the short-term but necessary to make up for structural inequities in the broader transportation system.

An equally crucial consideration is charger reliability. Reliability of charging stations is not merely a matter of convenience, but a pivotal factor in user confidence and adoption rates of EVs. Frequent malfunctions or downtimes [95] not only inconvenience users but also reduce the throughput of the entire charging system, leading to longer waiting times and decreased utilization. This is particularly detrimental in urban areas, where charger availability is already a critical concern. Additionally, charger reliability extends beyond mere operational functionality, encompassing aspects of maintenance, repair, and customer service, which are essential for sustaining long-term user trust and satisfaction. The reliability of charging stations, therefore, is not an ancillary issue but a fundamental component of the charging infrastructure's efficacy, demanding rigorous standards and robust monitoring mechanisms to ensure sustained and reliable service. This underscores the need for robust policy frameworks and industry standards that prioritize and enforce charger reliability, thereby bolstering the resilience and attractiveness of the EV ecosystem.

Another important and often overlooked issue is that 'information sharing' can often mitigate supply problems by providing information about waiting times at the charging stations in real-time. This has been demonstrated in the development of a generic waiting time predictor function for charging stations, which shows that such technology can greatly reduce the need for charging stations because the utilization becomes more efficient across the system [96]. However, this requires that the different commercial operators share information, which might require specific legislation.

Another concern is the challenge of grid infrastructure requirements to support chargers that are connected to low-voltage grids, and the stress they might place on these systems has to be considered [97, 98]. However, the grid impact of EVs varies significantly between each local distribution network area and charging scenario. On higher-voltage grid levels, i.e. the transmission grid, the impact is less severe [99–101]. Careful planning for grid capacity and coordination with utilities will be essential to prevent overloading and ensure that the charging infrastructure's growth does not negatively impact the broader energy system. To this end, policies such as the EU's alternative fuel infrastructure regulation mandating smart charging deployment can be helpful[16]. The rollout of charging infrastructure is further complicated by the need to align a multitude of stakeholders, each with differing objectives. Challenges such as interoperability, standardization, and varying expectations about the future of infrastructure may lead to discrepancies in technology deployment [102]. Governments must work closely with service providers and automakers to ensure optimal cost allocation, maximizing consumer welfare [103]. The success of the charging infrastructure will depend on this effective alignment and collaboration.

Parallel to these challenges, the deployment of charging infrastructure also presents substantial employment opportunities. In California alone, up to 62 400 job-years could be generated to support an announced charger buildout through 2031, with a nationwide workforce need of an additional 28 950 job-years through 2030 [104]. Beyond the practical need for charging infrastructure, this also represents a significant economic opportunity and societal benefit that contributes to the broader picture of the electrification transition.

2.4. Supply-side policy considerations

The path to 100% electrification in the automotive industry is being shaped by the powerful role of policy, regulation, and legislation. As we seek to align the automotive industry with sustainability goals, it becomes imperative to delve deeper into policy's role in achieving 100% ZEV adoption. This section explores these existing initiatives and underscores the need for a more rigorous exploration in this vital area of transformation. In figure 2 we provide several significant examples of supply-side policies in North America, China, and Europe—while our work is not a quantitative assessment of the impacts of the policy, it is perhaps telling that all regions with EV adoption have a plethora of policies promoting the supply of the technology.

2.4.1. ZEV mandate regulations

Despite the prominence and success of California's ZEV mandate, research into its policy impacts is surprisingly sparse [105]. The regulation requires automakers to produce and sell a certain percentage of ZEVs and has been a pioneering force in the automotive industry, with similar policies following in regions such as China[17], South Korea[18], and Canada[19]. Some studies have emphasized the necessity of policy actions like the ZEV mandate for achieving strong electrification. Greene *et al* notably asserted that without such mandates, the goal of full electrification might remain unattainable [106]. Similarly, Axsen *et al* have compared different types of policies to achieve full electrification, such as emissions standards, a feebate system, and a ZEV mandate, concluding that the ZEV mandate is the most cost-effective way of achieving this goal [107].

One distinguishing feature of the California ZEV program is its flexibility to adapt to costs and technological improvements. Despite stringent requirements, McConnell and Leard (2021) highlighted how

16 Regulation (EU) No 2021/0223 (COD). https://data.consilium.europa.eu/doc/document/PE-25-2023-INIT/en/pdf

17 New Energy Vehicle Credit regulation. Ministry of Industry and Information Technology (MIIT). www.transportpolicy.net/standard/china-light-duty-nev/.

18 Korea Zero Emissions Vehicles (ZEV) Dissemination policy. Ministry of Environment. https://korea.influencemap.org/policy/Zero-Emissions-Vehicle-ZEV-Policy-429#:∼:text=In%20December%202021%2C%20President%20Moon,combusition%20engine%20(ICE)%20vehicles.

19 Canada's Zero-Emission Vehicle sales targets. Transport Canada. https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/canada-s-zero-emission-vehicle-zev-sales-targets

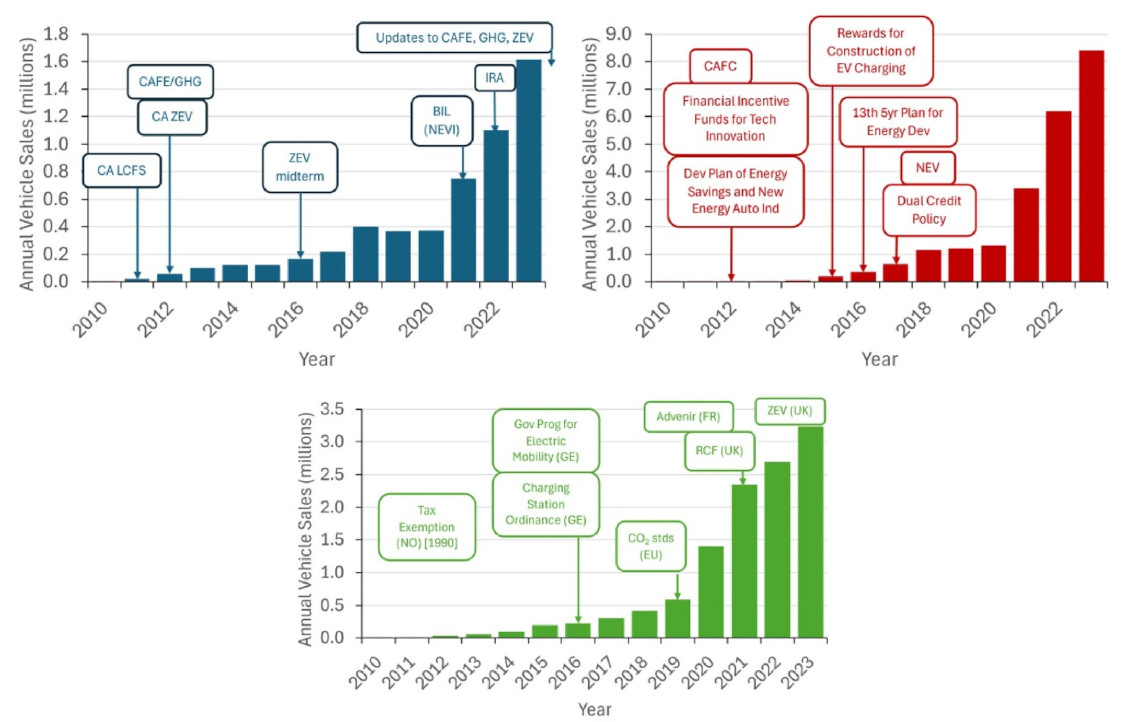

Figure 2. Examples of significant supply-side policies relative to annual sales of electric vehicles in North America (Top-left), China (Top-right), and Europe (Bottom).

the program has continually adjusted over time. They further suggested that, as the regulation approaches periods of greater uncertainty at higher levels of EV adoption, manufacturers should be allowed to purchase credits from the regulatory authority at a set price [108]. This recommendation emphasizes the importance of maintaining flexibility considering potential high costs and the evolving landscape of EV production.

Sentiments towards ZEV regulations have varied amongst stakeholders. Though initially defensive against the policy, manufacturers have gradually softened their stance [109]. This evolution is reflected in the gradual increase in patent and sales data, demonstrating a greater emphasis on EVs as manufacturers have responded to policy incentives [110]. In terms of public support, ZEV mandates have a mixed reception. A study by Long *et al* found that in regions like Canada and California, ZEV mandates have a lower level of support compared to emission standards and low carbon fuel standards, though still more favorable than carbon taxes [111]. Nevertheless, from a global perspective, while many emerging vehicle markets provide incentives and demand-oriented policies, no developing countries currently have CO2 standards or ZEV regulations [112]. This highlights an opportunity for an alignment of global strategies for electrification.

2.4.2. Emissions standards

In addition to ZEV mandates, fuel efficiency and emissions standards can be an alternative regulatory instrument for steering manufacturers towards ZEV production. These regulations, if aggressive enough, can act as catalysts for the shift towards full electrification of vehicle fleets. In the United States, previous targets have been relatively mild and have not necessitated a shift to EVs, though they can support the transition [113]. However, recent updates to EPA and NHTSA standards signal a change in this trend, complementing other policies to accelerate the transition towards EVs.

Unlike the US, the European Union's 2019 regulations set ambitious new vehicle CO_2 emission targets estimated to drive EV shares to between 27% and 41% by 2030 [114]. These were the first regulations stringent enough to necessitate the production of EVs to meet the targets (though manufacturers can still choose to not meet the targets and face large non-compliance fines). While promising, some contend that these EU regulations are still embedded within a traditional combustion vehicle framework and recommend supplementation with other measures, like a Bonus–Malus Registration scheme, to maximize emission reduction [115]. Notably, Norway has reached market shares of over 80% by using large incentives—without the requirement of emissions targets. China's approach has been distinctive, weaving together elements of a ZEV program with emissions standard requirements and many local policies that restrict conventional vehicle usage and/or registration [116, 117]. This forceful policy mix has fueled rapid growth in China's EV market, propelling them to global leadership in EV production and sales [118, 119].

2.4.3. Fossil fuel vehicle bans

Gasoline vehicle bans have emerged as a powerful signal of intent in the global effort to shift toward ZEVs. Although typically set as future targets, these bans create regulatory pressure and lay the groundwork for more immediate and stringent regulations, such as aggressive ZEV mandates, as witnessed in California.

In terms of environmental impact, gasoline vehicle bans are likely to expedite transitions towards ZEVs, resulting in substantial energy savings and reductions in greenhouse gas emissions [120, 121]. Despite the apparent effectiveness of gasoline vehicle bans, economists have expressed concerns about their social optimality [122]. Nevertheless, studies indicate specific conditions under which these bans can be implemented effectively [123]. Equity considerations are also paramount in the discussion of gasoline vehicle bans. While they can lead to broad improvements in air quality, there must be consideration of the potential accessibility and affordability challenges for various population segments in transitioning to EVs [124].

2.4.4. Incentives and subsidies for manufacturers

The ZEV mandate, emissions requirements, and gas car bans all serve as regulatory mechanisms with penalties for non-compliance. However, many governments couple these regulations with incentives and subsidies to support the supply chain for production and manufacturing of EVs and their batteries. China has been the most aggressive country in supporting the battery manufacturing industry, with a national policy of becoming a critical piece of the global supply chain—even for non-domestic use, a strategy which has led to their dominance in the battery market [125–128]. More recent efforts to support these industries in the EU (via the European Green Deal) [129, 130] and in the United States (via the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act) [131–133] to boost domestic manufacturing activities in the battery space.

Governments have also assisted in the deployment of charging infrastructure. The Chinese government has provided a massive comprehensive set of subsidies that cover investment in charging providers, flat-rate subsidies for deployment, power-based subsidies depending on charging speeds, and additional investments for operational subsidies [134, 135]. In the United States, the BIL provided $7.5 billion to fund the deployment of chargers across the country [136, 137]. For the EU, unlike the centralized push for battery manufacturing, subsidies and support for charging infrastructure vary from country to country—though most of the Western European countries offer substantial support for the deployment of public charging infrastructure [138].

The deployment of subsidies and incentives has proven essential in jumpstarting the supply chain and infrastructure development necessary to achieve widespread electrification. Without government support, manufacturers and charging providers may face significant economic barriers in scaling production and operations to meet regulatory mandates. As an example, Greaker [139] and Springel [140] suggest that it can be more efficient for governments to subsidize the charging market in terms of prices and market entry, rather than to stimulate EV sales through subsidies.

However, while these interventions are vital in the early stages of market development, long-term sustainability requires a gradual shift towards self-sustaining market conditions. As economies of scale are realized, costs decline, and technological advancements are achieved, market forces should increasingly drive EV production and infrastructure deployment. The challenge for policymakers lies in creating a strategic exit plan for subsidies that fosters innovation and competition without undermining the progress made toward 100% electrification targets.

3. Future research needs

Here we outline some research questions identified from our review, emphasizing the global intricacies and interconnectedness of the supply-side issues necessary for 100% vehicle electrification. First, there is a pronounced need to investigate the international context of supply-side production. We were able to identify several regional approaches but found limited comprehensive analyses that encompass the global complexity of EV production, material sourcing, standardization, and policy coordination. More studies that provide an international perspective may help understand the alignment and disparities between various regions, inform how global policies and regulations can be crafted for consistency and effectiveness, anticipate potential geopolitical barriers, and chart a cohesive path towards the goal of 100% ZEV sales. Finally, there is a continuous need for studies that track the evolving dynamics of the international supply chain, technology, and market trends.

3.1. Vehicle production and manufacturing

- How can production capacity be scaled to meet adoption targets and what are the implications on global supply chains?

- What investments and innovations are required in battery and vehicle factories to align with electrification objectives?
- How do manufacturing processes need to adapt to the specific demands and technological shifts associated with full electrification?
- How do supply-side issues, e.g. EV model availability, interact with demand-side aspects?

3.2. Geopolitics of EV production

- What are the geopolitical challenges in sourcing essential materials for EV production, and how might they impact the goal of 100% ZEVs?
- How can international collaboration facilitate a more stable supply chain that supports the global ambition of full electrification while ensuring regional technological sovereignty?
- What policies and agreements, including the increase of recycling rates, can help mitigate potential conflicts over raw materials and production facilities crucial for achieving 100% ZEVs?

3.3. Charging infrastructure

- What role do governments and regulatory bodies play in harmonizing charging standards across regions as supply of infrastructure deployment accelerates?
- How can policy ensure and accelerate offers for smart charging, vehicle-to-grid, and renewable integration?
- How to channel charging infrastructure subsidies to less attractive areas to mitigate range anxiety issues on EV uptake and avoid 'black holes' in the fueling infrastructure of the future?
- How should profitability and equity considerations be balanced?

3.4. EV policy

- What specific policies have been effective in different regions, and how can they be adapted to accelerate progress towards 100% ZEV sales?
- How to reach 100% ZEV stock after 100% ZEV sales?
- What lessons can be transferred from passenger vehicle ZEV policies to heavy-duty and other commercial vehicles?
- What mechanisms can facilitate cross-border policy coordination and learning to streamline policy development?

3.5. Economic and social impacts

- How do local revenue considerations and labor impacts fit into the broader strategy of achieving electrification?
- How can economic incentives be structured to encourage both industry investment and consumer adoption, in alignment with the goal of 100% electrification?
- How and to what extent can societies leverage V2G capabilities to mitigate temporary electricity supply shortages?

4. Conclusions

In this paper, we explore the landscape of supply-side issues, as well as the policies and regulatory pressures necessary to reach the ambitious goal of 100% ZEV sale. Unlike most studies focusing on demand, our investigation delves into the supply-side dynamics, shedding light on the fundamental aspects that could drive or hinder the complete transition to ZEVs.

Our research highlights key areas that require more attention, such as the implications of investments in manufacturing, geopolitical considerations of EV production, standardization of charging, labor effects, and local revenue impacts. We also recognize the necessity of having strong, targeted policies in place to ensure the realization of full electrification, such as California's ZEV mandate, China's New Energy Vehicles policy, EU's CO2 standards, fuel efficiency/emissions standards, and gasoline car bans. Despite the strides made in some regions, reaching the goal of 100% ZEV sales remains a complex and distant target. The present landscape still exhibits a patchwork of regulations and standards, with developing countries lagging behind in implementing stringent CO2 or ZEV regulations. This implies, among others, that there is a risk for leakage of fossil fuel vehicles from EU, possibly delaying the transition. There is a continuous need for further research to refine policies, ensuring that they are not only robust but also flexible, adapting to technological advances and the evolving economic landscape.

While automakers may initially resist stringent policies, evidence shows that a shift is occurring. Continued emphasis on strong regulatory measures can catalyze change, with automakers embracing the transition. However, careful consideration of the social impacts, including labor implications and equity concerns, must be at the forefront of policy decisions.

The global transition to 100% ZEV sales requires more than aspirational targets and isolated regional efforts. It demands a concerted, international push, guided by meticulous research and effective policy-making. For countries that do not manufacture their own vehicles, but predominantly rely on the import of vehicles from major suppliers like the US, China, or Germany, governments must begin considering strategic policies that can secure a steady supply of EV technologies. While the focus of this review has been on supplier countries, more research and policy action are needed in non-supplier countries to ensure a worldwide transition to electric mobility. By understanding and addressing the unique challenges and opportunities of the supply-side, we can foster an environment conducive to innovation, equity, and sustainability, bringing the vision of a fully electrified automotive future closer to reality. Policymakers must act thoughtfully, seeking the broader support needed to ensure that the transition to ZEVs becomes a shared global success, rather than a disjointed series of regional accomplishments.

Data availability statement

No new data were created or analysed in this study.

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