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# The rise of electric vehicles—2020 status and future expectations

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ABSTRACT

Electric vehicles (EVs) are experiencing a rise in popularity over the past few years as the technology has matured and costs have declined, and support for clean transportation has promoted awareness, increased charging opportunities, and facilitated EV adoption. Suitably, a vast body of literature has been produced exploring various facets of EVs and their role in transportation and energy systems. This paper provides a timely and comprehensive review of scientific studies looking at various aspects of EVs, including: (a) an overview of the status of the light-duty-EV market and current projections for future adoption; (b) insights on market opportunities beyond light-duty EVs; (c) a review of cost and performance evolution for batteries, power electronics, and electric machines that are key components of EV success; (d) charging-infrastructure status with a focus on modeling and studies that are used to project charging-infrastructure requirements and the economics of public charging; (e) an overview of the impact of EV charging on power systems at multiple scales, ranging from bulk power systems to distribution networks; (f) insights into life-cycle cost and emissions studies focusing on EVs; and (g) future expectations and synergies between EVs and other emerging trends and technologies. The goal of this paper is to provide readers with a snapshot of the current state of the art and help navigate this vast literature by comparing studies critically and comprehensively and synthesizing general insights. This detailed review paints a positive picture for the future of EVs for on-road transportation, and the authors remain hopeful that remaining technology, regulatory, societal, behavioral, and business-model barriers can be addressed over time to support a transition toward cleaner, more efficient, and affordable transportation solutions for all.

Keywords—electrical vehicle

#  INTRODUCTION

 First introduced at the end of the 1800s, electric vehicles (EVs)[12](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adfn2)have been experiencing a rise in popularity over the past few years as the technology has matured and costs (especially of batteries) have declined substantially. Worldwide support for clean transportation options (i.e. low emissions of greenhouse gasses [GHG] to mitigate climate change and criteria pollutants) has promoted awareness, increased charging opportunities, and facilitated adoption of EVs. EVs present numerous advantages compared to fossil-fueled internal-combustion-engine vehicles (ICEVs), inter alia: zero tailpipe emissions, no reliance on petroleum, improved fuel economy, lower maintenance, and improved driving experience (e.g. acceleration, noise reduction, and convenient home and opportunity recharging). Further, when charged with clean electricity, EVs provide a viable pathway to reduce overall GHG emissions and decarbonize on-road transportation. This decarbonization potential is important, given limited alternative options to liquid fossil fuels. The ability of EVs to reduce GHG emissions is dependent, however, upon clean electricity. Therefore, EV success is intertwined closely with the prospect of abundant and affordable renewable electricity (in particular solar and wind electricity) that is poised to transform power systems (Jacobson et al [2015](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib141), Kroposki et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib156), Gielen et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib96), IEA [2020b](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib133)). Coordinated actions can produce beneficial synergies between EVs and power systems and support renewable-energy integration to optimize energy systems of the future to benefit users and offer decarbonization across sectors (CEM [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib43)). A cross-sectoral approach across the entire energy system is required to realise clean future transformation pathways (Hansen et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib111)). EVs are expected to play a critical role in the power system of the future (Muratori and Mai). EV success is increasing rapidly since the mid-2010s. EV sales are breaking previous records every year, especially for light-duty vehicles (LDVs), buses, and smaller vehicles such as three-wheelers, mopeds, kick-scooters, and e-bikes (IEA [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib129), [2018a](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib130), [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib132), [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib134)). To date, global automakers are committing more than $140 billion to transportation electrification, and 50 light-duty EV models are available commercially in the U.S. market (Moore and Bullard [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib199)). Approximately 130 EV models are anticipated by 2023 (AFDC [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib2), Moore and Bullard [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib199)). Future projections of the role of EVs in LDV markets vary widely, with estimates ranging from limited success (∼10% of sales in 2050) to full market dominance, with EVs accounting for 100% of LDV sales well before 2050. Many studies project that EVs will become economically competitive with ICEVs in the near future or that they are already cost-competitive for some applications (Weldon et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib309), Sioshansi and Webb [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib270), Yale E360 [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib322), Kapustin and Grushevenko [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib146)). However, widespread adoption requires more than economic competitiveness, especially for personally owned vehicles. Behavioral and non-financial preferences of individuals on different technologies and mobility options are also important (Lavieri et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib161), Li et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib170), McCollum et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib189), Ramea et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib250)). EV adoption beyond LDVs has been focused on buses, with significant adoption in several regions (especially China). Electric trucks also are receiving great attention, and Bloomberg New Energy Finance (BloombergNEF) projects that by 2025, alternative fuels will compete with, or outcompete, diesel in long-haul trucking applications (Moore and Bullard [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib199)). These recent successes are being driven by technological progress, especially in batteries and power electronics, greater availability of charging infrastructure, policy support driven by environmental benefits, and consumer acceptance. EV adoption is engendering a virtuous circle of technology improvements and cost reductions that is enabled and constrained by positive feedbacks arising from scale and learning by doing, research and development, charging-infrastructure coverage and utilization, and consumer experience and familiarity with EVs.

# Ev adoption

* The global rate of adoption of light-duty EVs (passenger cars) has increased rapidly since the mid-2010s, supported by three key pillars: improvements in battery technologies; a wide range of supportive policies to reduce emissions; and regulations and standards to promote energy efficiency and reduce petroleum consumption.
* Adoption of advanced technologies has been underestimated historically in modeling and analyses; EV adoption is projected to remain limited until 2030, and high uncertainty is shown afterward with widely different projections from different sources. However, EVs hold great promise to replace conventional LDVs affordably.
* Barriers to EV adoption to date include consumer skepticism toward new technology, high purchase prices, limited range and lack of charging infrastructure, and lack of available models and other supply constraints.
* A major challenge facing both manufacturers and end-users of medium- and heavy-duty EVs is the diverse set of operational requirements and duty cycles that the vehicles encounter in real-world operation.
* EVs appear to be well suited for short-haul trucking applications such as regional and local deliveries. The potential for battery-electric models to work well in long-haul on-road applications has yet to be established, with different studies indicating different opportunities.

# Batteries and other EV Technologies

* Over the last 10 years, the price of lithium-ion battery packs has dropped by more than 80% (from over $1000 kWh−1 to $156 kWh−1 at the end of 2019, BloombergNEF [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib23)). Further price reduction is needed to achieve EV purchase-price parity with ICEVs.
* Over the last 10 years, the specific energy of a lithium-ion battery cell has almost doubled, reaching 240 Wh kg−1 (BloombergNEF [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib23)), reducing battery weight significantly.
* Reducing or eliminating cobalt in lithium-ion batteries is an opportunity to lower costs and reduce reliance on a rare material with controversial supply chains.
* While batteries are playing a key role in the rise of EVs, power electronics and electric motors are also key components of an EV powertrain. Recent trends toward integration promise to deliver benefits in terms of increased power density, lower losses, and lower costs.

## **Charging infrastrcuture**

* With a few million light-duty EVs on the road, currently, there is about one public charge point per ten battery electric vehicles (BEVs) in U.S. (although most vehicles have access to a residential charger).
* Given the importance of home charging (and the added convenience compared to traditional refueling at public stations), charging solutions in residential areas comprising attached or multi-unit dwellings is likely to be essential for EVs to be adopted at large scale.
* Although public charging infrastructure is clearly important to EV purchasers, how best to deploy charging infrastructure in terms of numbers, types, locations, and timing remains an active area for research.
* The economics of public charging vary with location and station configuration and depend critically on equipment and installation costs, incentives, non-fuel revenues, and retail electricity prices, which are heavily dependent on station utilization.
* The electrification of medium- and heavy-duty commercial trucks and buses might introduce unique charging and infrastructure requirements compared to those of light-duty passenger vehicles.
* Wireless charging, specifically high-power wireless charging (beyond level-2 power), could play a key role in providing an automated charging solution for tomorrow's automated vehicles.

**Vehicle grid integration**

Connecting millions of EVs to the power system, as may occur in the coming decades in major cities, regions, and countries around the world, introduces two fundamental themes: (a) challenges to meet reliably overall energy and power requirements, considering temporal load variations, and (b) VGI opportunities that leverage flexible vehicle charging ('smart charging') or V2G services to provide power-system services from connected vehicles. Multiple studies, which are reviewed in detail below, investigate the potential load growth, impact on load shapes, and infrastructure implications of increased EV adoption. These works focus especially on impact on distribution systems and opportunities for flexible charging to reshape aggregate power loads. Mai et al ([2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib184)), for example, shows that in a high-electrification scenario, transportation might grow from the current 0.2% to 23% of total U.S. electricity demand by 2050. This growth would impact system peak load and related capacity costs significantly if not controlled properly. In-depth analytics indicate a complex decision framework that requires critical understanding of potential future mobility demands and business models (e.g. ride-hailing, vehicle sharing, and mobility as a service), technology evolution, electricity-market and retail-tariff design, infrastructure planning (including charging), and policy and regulatory design (Codani et al [2016](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib46), Eid et al [2016](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib72), Knezovic et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib153), Borne et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib26), Hoarau and Perez [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib126), Gomes et al [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib99), Muratori and Mai [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib212), Thompson and Perez [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib291)).

While accommodating EV charging at the bulk-power (generation and transmission) level will be different in each region, no major technical challenges or risks have been identified to support a growing EV fleet, especially in the near term (FleetCarma [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib86), U.S. DRIVE [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib299), Doluweera et al [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib66)). At the same time, many studies show that smart charging and V2G create opportunities to reduce system costs and facilitate VRE integration (Sioshansi and Denholm [2010](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib271), Weiller and Sioshansi [2014](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib308), IRENA [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib139), Zhang et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib328)). Therefore, charging infrastructure that enables smart charging (e.g. widespread residential and workplace charging) and alignment with VRE generation and business models and programs to compensate EV owners for providing charging flexibility are critical elements for successful integration of EVs with bulk power systems.

## **Life cycle cost and emissions**

 EVs differ from conventional ICEVs on an emissions basis. While the operation of gasoline- or diesel-powered ICEVs produces GHG and pollutant emissions that are discharged from the vehicle tailpipe, EVs have no tailpipe emissions. In a broader context, EVs still can be associated with so-called 'upstream' emissions from the processes that generate, transmit, and distribute the electricity that is used for their charging. Fueling an ICEV also involves upstream 'fuel-cycle' emissions from the raw-material extraction and transportation, refining, and final-product-delivery processes that make gasoline or diesel fuel available at a retail pump. These fuel-cycle emissions give rise to the colloquial jargon 'well-to-pump' emissions. Accordingly, a 'well-to-wheels' (WTW) life-cycle analysis (LCA) is an appropriate framework for comparing EV and ICEV emissions. WTW considers both upstream emissions from the fuel cycle ('well-to-pump') and direct emissions from vehicle operation ('pump-to-wheels') for a standardized functional unit and temporal period. WTW studies have a history of over three decades of use to evaluate direct and indirect emissions related to fuel production and vehicle operations (Wang [1996](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib307)). WTW analyses typically focus only on fuel production and vehicle operation. Some studies consider broader system boundaries that include vehicle production and decommissioning (i.e. recycling and scrappage) in an LCA framework. This broader system boundary considers what is commonly called the 'vehicle cycle' and provides a so-called 'cradle-to-grave' (or 'C2G') analysis. Vehicle-cycle emissions typically account for 5%–20% of today's ICEV C2G emissions and can be as low as 15% or as high as 80% of today's BEV emissions, depending on the underlying electricity-generation mix. Lower-carbon mixes result in vehicle-cycle emissions accounting for a greater portion of total emissions. As an extreme illustrative example, the case of zero-carbon electricity implies that vehicle-cycle emissions account for 100% of C2G emissions. In general, BEV vehicle-cycle emissions are 25% to 100% higher than their ICEV counterpart (Samaras and Meisterling [2008](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib264), Ambrose and Kendall [2016](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib11), Elgowainy et al [2016](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib76), Hall and Lutsey [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib108), Ricardo [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib257)). As this section explores, higher initial BEV vehicle-cycle emissions almost always are counterbalanced by lower emissions during vehicle operation (with notable exceptions in cases in which BEVs are charged from especially high-emissions electricity).WTW emissions are expressed typically on a per-mile or per-kilometer basis over a vehicle's assumed lifetime.

## **Synergies with other technologies, macro trends, and future expectations**

Vehicle electrification fits within broader electrification trends, including power-system decarbonization and mobility changes. The latter include micro-mobility in urban areas, new mobility business models revolving around 'shared' services as opposed to vehicle ownership (e.g. ride-hailing and car-sharing), ride pooling, and automation. These trends are driven partially by the larger availability of efficient and cost-effective electrified technologies (Mai et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib184)) and the prospect of abundant and affordable renewable electricity and by other technological and behavioral changes (e.g. real-time communication). Abundant and affordable renewable electricity is a conditio sine qua non for EVs to provide a pathway to decarbonize road transportation. Direct use of PV on-board vehicles (i.e. PV-powered or solar vehicles) also is being considered. However, this concept still faces many challenges (Rizzo [2010](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib258), Aghaei et al [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib3)). Yamaguchi et al ([2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib323)) show potential synergies for integration but also highlight that for this technology to be successful, the development of high-efficiency (>30%), low‐cost, and flexible PV modules is essential.

Urban micro-mobility is emerging recently as an alternative to traditional mobility modes providing consumers in most metropolitan areas worldwide with convenient options for last-mile transportation (Clewlow [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib44), Zarif et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib326), Tuncer and Brown [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib296)). Virtually all micro-mobility solutions use all-electric powertrains. Shared electric scooters and bikes (often dockless), e.g. those pioneered by Lime and Bird in the U.S., are experiencing rapid success and are 'the fastest-ever U.S. companies to reach billion-USD valuations, with each achieving this milestone within a year of inception' (Ajao [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib8)). Future expectations for micro-mobility remain uncertain due to issues related to sidewalk congestion, safety, and vandalism (heavily impacting the business case for these technologies). However, the nexus with EVs has not been questioned.

Similarly, ride-hailing—matching drivers with passengers at short notice for one-off rides through a smartphone application, which date back to Uber's introducing the concept in 2009—is an attractive alternative to traditional transportation solutions. These mobility-as-a-service solutions cater to the consumer's need for quick, convenient, and cost-effective transportation and may lead to drops in car-ownership and driver-licensure rates (Garikapati et al [2016](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib91), Clewlow and Mishra [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib45), Movmi [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib205), Walmsley [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib305), Henao and Marshall [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib123), Arevalo [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib15)). After just over 10 years, ride-hailing is widely available and extremely successful, with hundreds of millions of consumers worldwide and 36% of U.S. consumers having used ride-hailing services (Mazareanu [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib187)). While most ride-hailing vehicles today are ICEVs (in line with the existing LDV stock), many ride-hailing companies are exploring electrification opportunities (Slowik et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib272)). EVs offer a number of potential advantages as high vehicle usage promotes a more favorable business model for recovering the higher EV purchase price by leveraging cheaper fuel costs (Borlaug et al [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib24)). At the same time, long-range vehicles and effective charging solutions are required for ride-hailing companies to transition to EVs (Tu et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib295)). Moreover, EVs can mitigate additional fuel use and emissions related to increased travel, mostly due to deadheading, which is estimated to be ∼85% (Henao and Marshall [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib123)). EVs also provide access to restricted areas in some cities (driving some regional goals for ride-hailing electrification). For example, Uber aims for half of its London fleet to be electric by 2021 and 100% electric by 2025 (Slowik et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib272)).

# footnotes

* EVs are defined as vehicles that are powered with an on-board battery that can be charged from an external source of electricity. This definition includes plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). EVs often are referred to as plug-in electric vehicles (PEVs).
* Transport electrification is confined not only to electric LDVs. Transport electrification includes a widerange of other vehicles, spanning from small vehicles that are used for urban mobility, such as three-wheelers, mopeds, kick-scooters, and e-bikes, to large urban buses and delivery vehicles. In 2019, the number of electric two-wheelers on the road exceeded 300 million and buses approached 0.6 million (IEA [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib132), Business Wire [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib312)), with new deliveries in 2019 close to 100 thousand units (EVVolumes [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib81)).
* Just over 10% of the U.S. heavy-duty truck (Class 7–8) population requires an operating range of 500 miles (805 km) or more, while nearly 80% operate within a 200 mile (322 km) range and around 70% within 100 miles (161 km). Only ∼25% of heavy truck VMT require an operating range of over 500 miles (805 km) (Borlaug et al [Forthcoming](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib25)).
* As a counterargument, Tesla states that 'all new Tesla cars come standard with advanced hardware capable of providing Autopilot features today, and full self-driving capabilities in the future—through software updates designed to improve functionality over time'.

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