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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.

1. Introduction

First introduced at the end of the 1800s, electric vehicles (EVs)[12] have been experiencing a rise in popularity over the past few years as the technology has matured and costs (especially of batteries) have declined

[12] 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).

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, Kroposki *et al* 2017, Gielen *et al* 2019, IEA 2020b). 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). A cross-sectoral approach across the entire energy system is required to realise clean future transformation pathways (Hansen *et al* 2019). 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, 2018a, 2019, 2020). 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). Approximately 130 EV models are anticipated by 2023 (AFDC 2020, Moore and Bullard 2020). 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, Sioshansi and Webb 2019, Yale E360 2019, Kapustin and Grushevenko 2020). 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, Li *et al* 2017, McCollum *et al* 2018, Ramea *et al* 2018). 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). 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.

Vehicle electrification is a game-changer for the transportation sector due to major energy and environmental implications driven by high vehicle efficiency (EVs are approximately 3–4 times more efficient than comparable ICEVs), zero tailpipe emissions, and reduced petroleum dependency (great fuel diversity and flexibility exist in electricity production). Far-reaching implications for vehicle-grid integration extend to the electricity sector and to the broader energy system. A revealing example of the role of EVs in broader energy-transformation scenarios is provided by Muratori and Mai, who summarize results from 159 scenarios underpinning the special report on Global Warming of 1.5 °C (SR1.5) by Intergovernmental Panel on Climate Change (IPCC). Muratori and Mai also show that transportation represents only ∼2% of global electricity demand currently (with rail responsible for more than two-thirds of this total). They show that electricity is projected to provide 18% of all transportation-energy needs by 2050 for the median IPCC scenario, which would account for 10% of total electricity demand. Most of this electricity use is targeted toward on-road vehicle electrification. These projections are the result of modeling and simulations that are struggling to keep pace with the EV revolution and its role in energy-transformation scenarios as EV technologies and mobility are evolving rapidly (McCollum *et al* 2017, Venturini *et al* 2019, Muratori *et al* 2020). Recent studies explore higher transportation-electrification scenarios: for example, Mai *et al* (2018) report a scenario in which 75% of on-road miles are powered by electricity, and transportation represents almost a quarter of total electricity use during 2050.

Vehicle electrification is a disruptive element in energy-system evolution that radically changes the roles of different sectors, technologies, and fuels in long-term transformation scenarios. Traditionally, energy-system-transformation studies project minimal end-use changes in transportation-energy use over time (limited mode shifting and adoption of alternative fuels), and the sector is portrayed as a 'roadblock' to decarbonization. In many decarbonization scenarios, transportation is seen traditionally as one of the biggest hurdles to achieve emissions reductions (The White House 2016). These scenarios rely on greater changes in the energy supply to reduce emissions and petroleum dependency (e.g. large-scale use of bioenergy, often coupled to carbon capture and sequestration) rather than demand-side transformations (IPCC 2014, Pietzcker *et al* 2014, Creutzig *et al* 2015, Muratori *et al* 2017, Santos 2017). In most of these studies, electrification is limited to some transportation modes (e.g. light-duty), and EVs are not expected to replace ICEVs fully (The White House 2016). More recently, however, major mobility disruptions (e.g. use of ride-hailing and vehicle ride-sharing) and massive EV adoption across multiple applications are proposed (Edelenbosch *et al* 2017, Van Vuuren *et al* 2017, Hill *et al* 2019, E3 2020, Zhang and Fujimori 2020). These mobility disruptions allow for more radical changes and increase the decarbonization role of transportation and highlight the integration opportunities between transportation and energy supply, especially within the electricity sector. For example, Zhang and Fujimori (2020) highlight that for vehicle electrification to contribute to climate-change mitigation, electricity generation needs to transition to clean sources. They note that EVs can reduce mitigation costs, implying a positive impact of transport policies on the economic system (Zhang and Fujimori 2020). In-line with these projections, many countries are establishing increasingly stringent and ambitious targets to support transport electrification and in some cases ban conventional fossil fuel vehicles (Wentland 2016, Dhar *et al* 2017, Coren 2018, CARB 2020, State of California 2020).

EV charging undoubtedly will impact the electricity sector in terms of overall energy use, demand profiles, and synergies with electricity supply. Mai *et al* (2018) show that in a high-electrification scenario, transportation might grow from the current 0.2% to 23% of total U.S. electricity demand in 2050 and significantly impact system peak load and related capacity costs if not controlled properly. Widespread vehicle electrification will impact the electricity system across the board, including generation, transmission, and distribution. However, expected changes in U.S. electricity demand as a result of vehicle electrification are not greater than historical growth in load and peak demand. This finding suggests that bulk-generation capacity is expected to be available to support a growing EV fleet as it evolves over time, even with high EV-market growth (U.S. DRIVE 2019). At the same time, many studies have shown that 'smart charging' and vehicle-to-grid (V2G) services create opportunities to reduce system costs and facilitate the integration of variable renewable energy (VRE). Charging infrastructure that enables smart charging and alignment with VRE generation, as well as business models and programs to compensate EV owners for providing charging flexibility, are the most pressing required elements for successfully integrating EVs with bulk power systems. At the local level, EV charging could increase and change electricity loads significantly, which could impact distribution networks and power quality and reliability (FleetCarma 2019). Distribution-network impacts can be particularly critical for high-power charging and in cases in which many EVs are concentrated in a specific location, such as clusters of residential LDV charging and possibly fleet depots for commercial vehicles (Muratori 2018).

This paper provides a timely status of the literature on several aspects of EV markets, technologies, and future projections. The paper focuses on multiple facets that characterize technology status and the role of EVs in transportation decarbonization and broader energy-transformation pathways focusing on the U.S. context. As appropriate, global context is provided as well. Hybrid EVs (for which liquid fuel is the only source of energy) and fuel cell EVs (that power an electric powertrain with a fuel cell and on-board hydrogen storage) have some similarities with EVs and could complement them for many applications. However, these technologies are not reviewed in detail here. The remainder of this paper is structured as follows. Section 2 focuses on the status of the light-duty-EV market and provides a comparison of projections for future adoption. Section 3 provides insights on market opportunities beyond LDVs. Section 4 offers a review of cost and performance evolution for batteries, power electronics, and electric machines that are key components of EV success. Section 5 reviews charging-infrastructure status and focuses on modeling and analysis studies used to project charging-infrastructure requirements, the economics of public charging, and some considerations on cybersecurity and future technologies (e.g. wireless charging). Section 6 provides an overview of the impact of EV charging on power systems at multiple scales, ranging from bulk power systems to distribution networks. Section 7 provides insights into life-cycle cost and emissions studies focusing on EVs. Finally, section 8 touches on future expectations.

1.1. Summary of take-away points

1.1.1. 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.

1.1.2. 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). 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), 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.

1.1.3. Charging infrastructure

- 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.

1.1.4. Power system integration

- Accommodating EV charging at the bulk power-system level (generation and transmission) is different in each region, but there are no major known technical challenges or risks to support a growing EV fleet, especially in the near term (approximately one decade).
- At the local level, however, EV charging can increase and change electricity loads significantly, causing possible negative impacts on distribution networks, especially for high-power charging.
- The integration of EVs into power systems presents opportunities for synergistic improvement of the efficiency and economics of electromobility and electric power systems, and EVs can support grid planning and operations in several ways.
- There are still many challenges for effective EV-grid integration at large scale, linked not only to the technical aspects of vehicle-grid-integration (VGI) technology but also to societal, economic, business model, security, and regulatory aspects.
- VGI offers many opportunities that justify the efforts required to overcome these challenges. In addition to its services to the power system, VGI offers interesting perspectives for the full exploitation of synergies between EVs and VRE as both technologies promise large-scale deployment in the future.

1.1.5. Life-cycle cost and emissions

- Many factors contribute to variability in EV life-cycle emissions, mostly the carbon intensity of electricity, charging patterns, vehicle characteristics, and even local climate. Grid decarbonization is a prerequisite for EVs to provide major GHG-emissions reductions.
- Existing literature suggests that future EVs can offer 70%–90% lower GHG emissions compared to today's ICEVs, most obviously due to broad expectations for continued grid decarbonization.
- Operational costs of EVs (fuel and maintenance) are typically lower than those of ICEVs, largely because EVs are more efficient than ICEVs and have fewer moving parts.

1.1.6. Synergies with other technologies and future expectations

- Vehicle electrification fits in broader electrification and mobility macro-trends, including micro-mobility in urban areas, new mobility business models regarding ride-hailing and car-sharing, and automation that complement well with EVs.
- While EVs are a relatively new technology and automated vehicles are not readily available to the general public, the implications and potential synergies of these technologies operating in conjunction are significant.
- The coronavirus pandemic is impacting transportation markets negatively, including those for EVs, but long-term prospects remain undiminished.
- Several studies project major roles for EVs in the future, which is reflected in massive investment in vehicle development and commercialization, charging infrastructure, and further technology improvement. Consumer adoption and acceptance and technology progress form a virtuous self-reinforcing circle of technology-component improvements and cost reductions.
- EVs hold great promise to replace ICEVs affordably for a number of on-road applications, eliminating petroleum dependence, improving local air quality and enabling GHG-emissions reductions, and improving driving experiences.
- Forecasting the future, including technology adoption, remains a daunting task. However, this detailed review paints a positive picture for the future of EVs across a number of on-road applications.

2. Status of electric-LDV market and future projections

This section provides a current snapshot of the electric-LDV market in a global and U.S. context, but focuses on the latter. The global rate of adoption of electric LDVs has increased rapidly since the mid-2010s[13]. By the end of 2019, the global EV fleet reached 7.3 million units—up by more than 40% from 2018—with more than 1.25 million electric LDVs in the U.S. market alone (IEA 2020). EV sales totaled more than 2.2 million in 2019, exceeding the record level that was attained in 2018, despite mixed performances in different markets. Electric-LDV sales increased in Europe and stagnated or declined in other major markets, particularly in China (with a significant slowdown due to changes in Chinese subsidy policy in July 2019), Japan, and U.S. U.S. EV adoption varies greatly geographically—nine counties in California currently see EVs accounting for more than 10% of sales (8% on average for California as a whole), but national-level sales remain at less than 3% (Bowermaster 2019). BEV sales exceeded those of plug-in hybrid electric vehicles (PHEVs) in all regions.

The rapid increase in EV adoption is underpinned by three key pillars:

(a) Improvements and cost reductions in battery technologies, which were enabled initially by the large-scale application of lithium-ion batteries in consumer electronics and smaller vehicles (e.g. scooters, especially in China, IEA 2017). These developments offer clear and growing opportunities for EVs and HEVs to deliver a reduced total cost of ownership (TCO) in comparison with ICEVs.

(b) A wide range of supportive policy instruments for clean transportation solutions in major global markets (Axsen *et al* 2020), which are mirrored by private-sector investment. These developments are driven by environmental goals (IPCC 2014), including reduction of local air pollution. These policy instruments support charging-infrastructure deployment (Bedir *et al* 2018) and provide monetary (e.g. rebates and vehicle-registration discounts) and non-monetary (e.g. access to high-occupancy-vehicle lanes and preferred parking) incentives to support EV adoption (IEA 2018a, AFDC 2020).

[13] Transport electrification is confined not only to electric LDVs. Transport electrification includes a wide range 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, Business Wire 2020), with new deliveries in 2019 close to 100 thousand units (EV Volumes 2020).

(c) Regulations and standards that support high-efficiency transportation solutions and reduce petroleum consumption (e.g. fuel-economy standards, zero-emission-vehicle mandates, and low-carbon-fuel standards). These regulations are being supported by technology-push measures, consisting primarily of economic instruments (e.g. grants and research funds) that aim to stimulate technological progress (especially batteries), and market-pull measures (e.g. public-procurement programs) that aim to support the deployment of clean-mobility technologies and enable cost reductions due to technology learning, scale, and risk mitigation.

Transport electrification also has started a virtuous self-reinforcing circle. Battery-technology developments and cost reductions triggered by EV adoption provide significant economic-development opportunities for the companies and countries intercepting the battery and EV value chains. Adoption of alternative vehicles both is enabled and constrained by powerful positive feedback arising from scale and learning by doing, research and development, consumer experience and familiarity with technologies (e.g. neighborhood effect), and complementary resources, such as fueling infrastructure (Struben and Sterman 2008). In this context, more diversity in make and model market offerings is supporting vehicle adoption. As of April 2020, there are 50 EV models available commercially in U.S. markets (AFDC 2020), and ∼130 are anticipated by 2023 (Moore and Bullard 2020).

Measures that support transport electrification have been, and increasingly shall be, accompanied by policies that control for the unwanted consequences. Thus, the measures need to be framed in the broader energy and industry contexts.

When looking at the future, EV-adoption forecasts remain highly uncertain. Technology-adoption projections are used by a number of stakeholders to guide investments, inform policy design and requirements (Kavalec *et al* 2018), assess benefits of previous and ongoing efforts (Stephens *et al* 2016), and develop long-term multi-sectoral assessments (Popp *et al* 2010, Kriegler *et al* 2014). However, projecting the future, including technology adoption, is a daunting task. Past projections often have turned out to be inaccurate. Still, progress has been made to address projection uncertainty (Morgan and Keith 2008, Reed *et al* 2019) and contextualize scenarios to explore alternative futures in a useful way. Scenario analysis is used largely in the energy-environment community to explore the possible implications of different judgments and assumptions by considering a series of 'what if' experiments (BP 2019).

Adoption of advanced technologies historically has been underestimated in modeling and analysis results (e.g. Creutzig *et al* 2017), which fail to capture the rapid technological progress and its impact on sales. Historical experiences suggest that technology diffusion, while notoriously difficult to predict, can occur rapidly and with an extensive reach (Mai *et al* 2018). Projecting personally owned LDV sales is particularly challenging because decisions are made by billions of independent (not necessarily rational) decision-makers valuing different vehicle attributes based on incomplete information (e.g. misinformation and skepticism toward new technologies) and limited financial flexibility.

Many studies make projections for future EV sales (see figure 1 for a comparison of different projections). Some organizations (e.g. Energy Information Administration [EIA]) historically have been conservative in projecting EV success, mostly due to scenario constraints and assumptions. Still, U.S. EV-sales projections from EIA in recent years are much higher than in the past. Others (e.g. BloombergNEF and Electric Power Research Institute [EPRI]) consistently have been more optimistic in terms of EV sales and continue to adjust sales projections upward. Policy ambition for EV adoption is also optimistic. For example, in September 2020, California passed new legislation that requires that by 2035 all new car and passenger-truck sales be zero-emission vehicles (and that all medium- and heavy-duty vehicles be zero-emission by 2045) (California, 2020). Projected EV sales and outcomes from major energy companies vary widely, ranging from somewhat limited EV adoption (e.g. ExxonMobil) to full market success (e.g. Shell). A survey from Columbia University (Kah 2019) considers 17 studies and shows that 'EV share of the global passenger vehicle fleet is not projected to be substantial before 2030 given the long lead time in turning over the global automobile fleet' and that 'the range of EVs in the 2040 fleet is 10% to 70%'. The studies compared in figure 1 show an even greater variability for 2050 projections, ranging from 13% to 100% of U.S. EV adoption for LDVs.

The future remains uncertain, but there is a clear trend in projections of light-duty EV sales toward more widespread adoption as the technology improves, consumers become more familiar with the technology, automakers expand their offerings, and policies continue to support the market.

A number of studies analyze the drivers of EV adoption (Vassileva and Campillo 2017, Priessner *et al* 2018) and highlight several barriers for EVs to achieve widespread success, including consumer skepticism for new technologies (Egbue and Long 2012); uncertainty around environmental benefits (consumers wonder whether EVs actually are green; see section 7 for more clarity on the environmental benefits of EVs) and continued policy support; unclear battery aging/resale value; high costs (Haddadian *et al* 2015, Rezvani *et al* 2015, She *et al* 2017); lack of charging infrastructure (Melaina *et al* *2017*, Narassimhan and Johnson

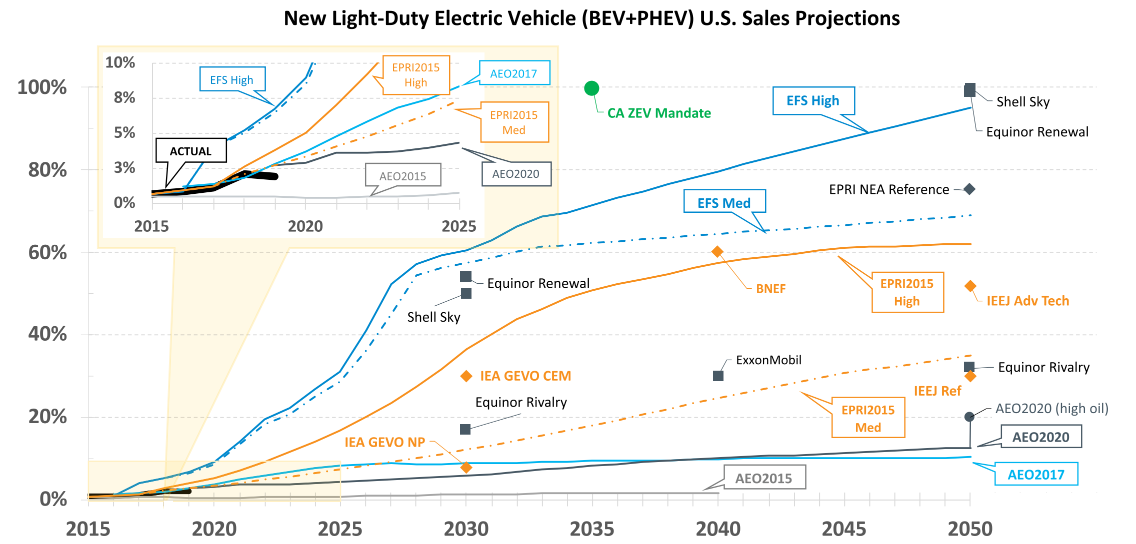

Figure 1. Electric LDV (BEV and PHEV) new sales projections from numerous international sources. Unless otherwise noted, data refer to new U.S. sales. AEO2015 = EIA Annual Energy Outlook 2015, Reference Scenario. AEO2017 = EIA Annual Energy Outlook 2017, Reference Scenario. AEO2020 = EIA Annual Energy Outlook 2020, Reference Scenario. AEO2020HO = EIA Annual Energy Outlook 2020, High Oil Scenario. EFS Med = National Renewable Energy Laboratory (NREL) Electrification Futures Study, Medium Scenario. EFS High = NREL Electrification Futures Study, High Scenario. EPRI Med = EPRI Plug-in Electric Vehicle Projections: Scenarios and Impacts, Medium Scenario. EPRI High = EPRI Plug-in Electric Vehicle Projections: Scenarios and Impacts, High Scenario. EPRI NEA = EPRI National Electrification Assessment, Reference Scenario. GEVO NP = IEA Global EV Outlook 2019, New Policies Scenario. GEVO CEM = IEA Global EV Outlook 2019, Clean Energy Ministerial 30@30 Campaign Scenario. BNEF = BloombergNEF EV Outlook 2020. Equinor Riv = Equinor 2019 Energy Perspectives, Rivalry Scenario. Equinor Ren = Equinor 2019 Energy Perspectives, Renewal Scenario. Shell Sky = Shell Sky Scenario. ExxonMobil = 2019 ExxonMobil Outlook for Energy. IEEJ Ref = The Institute of Energy Economics, Japan. 2019 Outlook, Reference Scenario (global sales). IEEJ Adv = The Institute of Energy Economics, Japan. 2019 Outlook, Advanced Technologies Scenario (global sales). CA ZEV Mandate = California zero-emission vehicle (ZEV) Executive Order N-79-20 (September 2020).

2018); range anxiety (the fear of being unable to complete a trip) associated with shorter-range EVs; longer refueling times compared to conventional vehicles (Franke and Krems 2013, Neubauer and Wood 2014; Melaina *et al* 2017); dismissive and deceptive car dealerships (De Rubens *et al* 2018); and other EV-supply considerations, such as limited model availability and limited supply chains.

A recent review of 239 articles published in top-tier journals focusing on EV adoption draws attention to 'relatively neglected topics such as dealership experience, charging infrastructure resilience, and marketing strategies as well as identifies much-studied topics such as charging infrastructure development, TCO, and purchase-based incentive policies' (Kumar and Alok 2019). Similar reviews published recently focus on different considerations, such as market heterogeneity (Lee *et al* 2019a), incentives and policies (Hardman 2019, Tal *et al* 2020), and TCO (Hamza *et al* 2020). Other than some limited discussions on business models and TCO, the literature is focused on one side of the story, namely demand. However, the availability (makes and models) of EVs is extremely limited compared to ICEVs (AFDC 2020). This is justified, in part, by new technologies requiring time to be introduced, and, in part, by the higher manufacturer revenues associated with selling and providing maintenance for ICEVs. Moreover, slow turnover in legacy industry (Morris 2020) and other supply constraints can be a major barrier to widespread EV uptake (Wolinetz and Axsen 2017, De Rubens *et al* 2018). Kurani (2020) argues that in most cases, 'Results of large sample surveys and small sample workshops mutually reinforce the argument that continued growth of PEV markets faces a barrier in the form of the inattention to plug-in electric vehicles (PEVs) of the vast majority of car-owning and new-car-buying households even in a place widely regarded as a leader. Most car-owning households are not paying attention to PEVs or the idea of a transition to electric-drive.'

3. EVs beyond light-duty applications

While much of the recent focus on vehicle electrification is with LDVs and small two- or three-wheelers (primarily in China), major progress also is being made with the electrification of medium- and heavy-duty vehicles. This includes heavy-duty trucks of various types, urban transit buses, school buses, and medium-duty vocational vehicles. As of the end of 2019, there were about 700 000 medium- and heavy-duty commercial EVs in use around the world (EV Volumes 2020, IEA 2020).

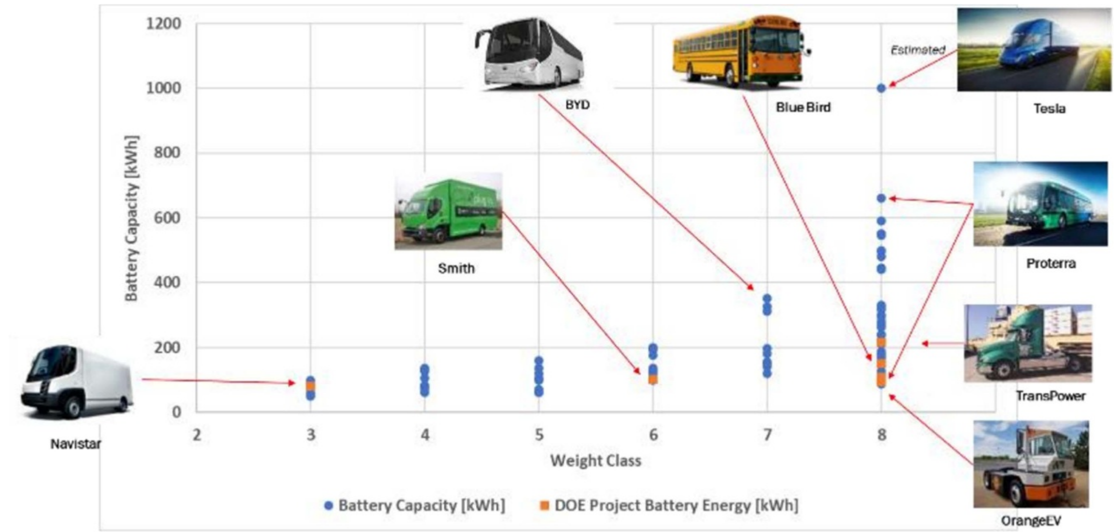

Figure 2. Battery capacity requirements vs. weight class for medium- and heavy-duty vehicles (Smith *et al* 2019).

A major challenge facing both manufacturers and end-users of medium- and heavy-duty vehicles is the diverse set of operational requirements and duty cycles that the vehicles encounter in real-world operation. When designing powertrain configurations and on-board energy-storage needs for new technologies, it is of critical importance to represent vehicle behavior accurately for different operations, including possible changes triggered by electrification (Delgado-Neira 2012). Medium- and heavy-duty vehicles can require a large number of powertrain and battery configurations, control strategies, and charging solutions. These needs depend on vehicle type (covering the full U.S. gross vehicle weight ratings [GVWR] spectrum from class 3 to class 8, 10 001–80 000 lb [4536–36 287 kg]), commercial operational situations and activities, and diverse drive cycles and charging opportunities (e.g. depot-based operations vs. long-haul). An example of this potential variability and its effect on the required battery capacity across multiple vehicle vocations is shown in figure 2 (Smith *et al* 2019).

Another example of the highly variable use cases for medium- and heavy-duty EVs shows energy efficiencies range between 0.8 kWh mile^{-1} and 3.2 kWh mile^{-1} (0.5–2.5 kWh km^{-1}) (Gao *et al* 2018). If the on-board energy-storage needs for these vehicles are considered, assuming a daily operational range of between 50 miles and 200 miles (80–322 km), this results in battery-size requirements between 40 kWh and 640 kWh (assuming that the vehicle is recharged once daily). If additional charging strategies are considered (with their variability in expected charge times and associated power ratings), the range of vehicle-hardware and charging-infrastructure possibilities increases further. When adding variability across use cases with respect to temperature effects, battery-capacity degradation, payload, and road grade, it becomes clear that medium- and heavy-duty truck manufacturers face a significant challenge in designing, developing, and manufacturing systems that are able to meet the diverse operational requirements.

There are potential synergies between components of light-duty and medium- and heavy-duty electric vehicles. However, the requirements of medium- and heavy-duty vehicles place much greater burdens on powertrain components. The power and energy needs in heavy-duty applications are much larger than in light-duty applications. Heavy-duty vehicles could demand twice the peak power, four times the torque, and can consume more than five times the energy per mile (or km) driven compared to LDVs. In addition to using more energy per mile (or km) driven, typically, commercial vehicles drive many more miles (or km) per day, requiring much larger batteries and possibly much higher-power charging. Moreover, heavy-duty-vehicle users expect their vehicles to last more than a million miles, pointing to significantly higher durability requirements for heavy-duty-vehicle components (Smith *et al* 2019). Overall, these requirements, in combination with the needs for very high durability and very high-power drivelines and charging, may cause battery chemistries of heavy-duty vehicle batteries to diverge from those that are used in LDVs, hindering economies of scale. Demands for high efficiency, high power, and lower weight will put pressure on commercial vehicles to work at higher voltages than LDVs do. While LDVs are designed typically with powertrains that operate at a few hundred volts, it may be desirable to design large EVs with kilovolt powertrains. This will have a particularly significant impact on power electronics and could drive the development of wide-bandgap power electronics.

Historically, EVs have not been considered capable alternatives to heavy-duty diesel trucks (above 33 000 lb [14 969 kg] GVWR) due to high capital costs, high energy and power requirements, and weight and range-related battery constraints. International Council on Clean Transportation (ICCT), for example, suggests that while conventional EV-charging methods may be sufficient for small urban commercial vehicles, overhead catenary or in-road charging are required for heavier vehicles (Moultak *et al* 2017). Recent studies dispute this, anticipating a much greater opportunity for EVs to replace diesel trucks in the short-term, even for long-haul applications (Mai *et al* 2018, McCall and Phadke 2019, Borlaug *et al* Forthcoming), but the potential for battery-electric models to work well in long-haul applications has yet to be established (NACFE 2018). Studies show that a significant amount of payload capacity will be consumed by batteries, potentially up to 7 tons or 28% of capacity in a truck with a 500 mile (805 km) range with 1100 kWh battery capacity (Burke and Fulton 2019). Thus, batteries would reduce significantly the amount of cargo that can be carried. Other studies suggest this could be much less—on the order of 4% of lost payload capacity for 500 mile range (805 km) trucks and with overall lower TCO than diesel trucks (Phadke *et al* 2019). For short-haul applications, such as port drayage and regional or local deliveries, EVs appear well suited and battery weight may not affect the cargo or payload capacity adversely. Several heavy-duty battery-electric trucks for short- and medium-haul applications have been developed and tested in recent years by Balqon, Daimler Trucks NA, Peterbilt, TransPower, Tesla, US Hybrid, Volvo, and others (AFDC 2020).

Urban buses are also a major emerging market for electrification. In California, Innovative Clean Transit rules require transit agencies to transition completely to zero-emission technologies (batteries or fuel cells), with all new bus purchases being zero-emission by 2029 (CARB 2018). Eight of the ten largest transit agencies in California already are adopting zero-emission technologies into their fleets (CARB 2018). In a comparative study of urban buses running on diesel, compressed natural gas, diesel hybrid, fuel cells, and batteries, the battery buses are estimated to have the lowest CO_2 emissions in both California and Finland bus duty cycles at the time of the study (Lajunen and Lipman 2016). This study also shows that battery buses have only slightly higher overall costs per mile (or km) than fossil-fuel-based alternatives. Future projections out to 2030 show that electric buses have the lowest overall life-cycle costs, especially when CO_2 costs are included (Lajunen and Lipman 2016).

Medium-duty delivery vehicles (typically 10 000–33 000 lb [4536–14 969 kg] GVWR) are another attractive emerging area for electrification. The goods-delivery market is growing at approximately 9% per year in recent years, with a projected $343 billion global industry value in 2020 (Accenture 2015). The 'last mile' delivery vehicles that are needed for this market are undergoing changes and present good opportunities for electrification. Amazon, for example, has announced plans to purchase 100 000 custom-designed Rivian electric delivery vans by 2030, with 10 000 of the vehicles delivered by late 2022 (Davies 2019).

A significant challenge with electrifying these heavy- and medium-duty vehicles revolves around the installation of the required charging infrastructure (either at depots or along highways). While LDVs typically charge at power levels of 3 kW–10 kW, and potentially 50 kW–250 kW with DC fast chargers (DCFCs), a heavy-duty vehicle may require higher-power charging, depending on its duty cycle. Fleets of these vehicles charging in one location, such as a truck depot or travel center, may require several megawatts of power. This requires expensive charging infrastructure, potentially including costly and time-consuming distribution-grid upgrades, to provide the higher voltage and current levels that are needed. For example, a single 350 kW DCFC that may be suitable for heavy-duty applications costs almost $150 000 today (Nelder and Rogers 2019, Nicholas 2019). These costs would, in turn, impact the business case for vehicle electrification. Potential costs of grid upgrades to support these new electrical loads would be additional expenses that may or may not be supported by the local utility, depending on the circumstances. To enable reliable, low-cost charging, which is crucial when considering the TCO for a fleet owner, the installation and operational costs of the charging infrastructure must be optimized, requiring engagement with power-supply stakeholders.

4. Batteries, power electronics, and electric machines

Electrification is a key aspect of modern life, and electric motors and machines are prevalent in manufacturing, consumer electronics, robotics, and EVs (Zhu and Howe 2007). One reason for the recent success and rise in adoption of EVs is the use of advanced lithium-ion batteries with improved performance, life, and lower cost. Improved energy and power performance, increased cycle and calendar life, and lower costs are leading to EVs with longer electric range and better acceleration at lower cost premia that are attracting consumers. This section summarizes the state-of-the-art for batteries and for power electronics, electric machines, and electric traction drives in terms of cost, performance, power and energy density, and reliability, and highlights some research challenges, pathways, and targets for the future.

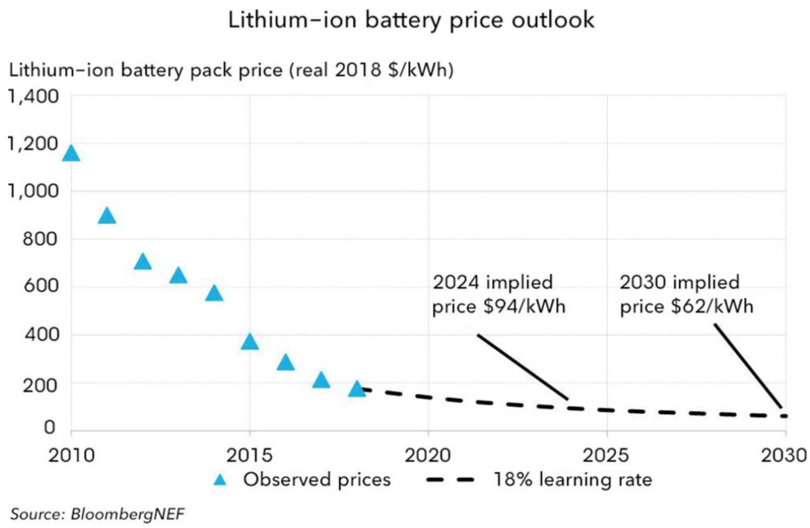

Figure 3. Evolution of battery prices over the last 10 years and future projections (Goldie-Scot 2019). BloombergNEF 2019.

4.1. Batteries

Over the last 10 years, the price of a lithium-ion battery pack has dropped by almost 90% from over $1000 kWh^{-1} in 2010 to $156 kWh^{-1} at the end of 2019 (BloombergNEF 2020). Meanwhile, the specific energy of a lithium-ion battery cell has almost doubled from 140 Wh kg^{-1} to 240 Wh kg^{-1} during that same window of time (BloombergNEF 2020). The improvement in performance and cost comes mainly from engineering improvements, use of materials with higher capacities and voltages, and development of methods to increase stability for longer life and improved safety. Improvements in cell, module, and pack design also help to improve performance and lower costs. Increases in manufacturing volume due to EV sales contribute significantly to cost reductions (Nykvist and Nilsson 2015, Nykvist *et al* 2019). However, further reductions in battery costs, along with a reduction in the cost of electric machines and power electronics, are needed for EVs to achieve purchase-price parity with ICEVs. This parity is estimated by U.S. Department of Energy (DOE) to be achieved at battery costs of ~$100 kWh^{-1} (preferably less than $80 kWh^{-1}) (VTO, 2020). At that point, EVs should have both a purchase- and a lifetime-operating-cost benefit over ICEVs. Such cost benefits are likely to trigger drastic increases in EV sales. Figure 3 shows the observed price of lithium-ion battery packs from 2010 to 2018, as well as estimated prices through 2030. BloombergNEF projects that by 2024 the price for original equipment manufacturers (OEMs) to acquire battery packs will go below $100 kWh^{-1} and reach ~$60 kWh^{-1} by 2030 if high levels of investments continue in the future (BloombergNEF 2020).

The typical anode material that is used in most lithium-ion EV batteries is graphite (Ahmed *et al* 2017). Research is underway to utilize silicon, in addition to graphite, due to its higher specific-energy capacity. For cathodes, there is more variety (Lee *et al* 2019, Manthiram 2020). Consumer electronics such as mobile phones and computers almost exclusively have used lithium cobalt oxide, $LiCoO_2$, due to its high specific-energy density (Keyser *et al* 2017). Most EV manufacturers (except Tesla) have avoided using $LiCoO_2$ in EVs due to its high cost and safety concerns. Lithium iron phosphate also has been used for electric cars and buses because of its long life and better safety and power capabilities. However, due to its low specific-energy density (110 Wh kg^{-1}) when paired with a graphite anode, lithium iron phosphate is not used commonly for light-duty EVs in U.S. In recent years, battery makers and vehicle OEMs have moved to lithium nickel manganese cobalt oxides (NMC) with varying ratios of the three transition metals. Initially, OEMs used NMC111 (the numbers represent the molar fractions of nickel, manganese, and cobalt, which are equal in this case), but they have transitioned to NMC532 and utilize NMC622 now while working to stabilize the NMC811 cathode structure. The goal is eventually to reduce the amount of cobalt in the cathode to less than 5% and perhaps even eliminate the use of cobalt. The use of these cathodes with higher specific-energy density and less cobalt leads to lower battery cost per unit energy ($ kWh^{-1}). Table 1 shows the specific energy and estimated (bottom-up) cost from Argonne National Laboratory's BatPaC Battery Performance and Cost model (Ahmed *et al* 2016) based on large-volume material processing, cell manufacturing, and pack manufacturing.

The cost of batteries is expected to decline in the future due to improved capacity of materials (such as Si anodes), increased percentage of active material components, use of lower-cost elements (no cobalt),

Table 1. Calculated specific energy and cost of advanced lithium-ion batteries with different cathode/anode chemistries. Numbers are from BatPaC (Ahmed *et al* 2016) and are intended for relative comparison only. Final values can change depending on the components used and production volume, and costs reported do not reflect what a negotiated price could be between a battery and EV maker.

	Type of chemistry (cathode/anode)	Specific energy (cells) Wh kg^{-1}	Specific energy (pack) Wh kg^{-1}	Estimated cost (pack) \$ kWh^{-1}
Current	LCO/Gr	224.1	181.8	250
	NMC111/Gr	204.9	167.6	145
	NMC622/G	224.1	181.7	135
	NMC811/Gr	241.3	194.2	120
	NCA/Gr	230.4	186.4	130
Future	High Voltage NMC622/Gr	231.4	186.5	125
	High Voltage NMC622/Si	294.8	235.3	110
	High Voltage NMC/Li Metal	332.4	259.3	120
	Lithium–Sulfur	346.2	257.3	95

improved packaging, and continued automation to increase yield while leading to a longer electric range. However, price increases for certain metals such as Ni and Li could prevent achieving those lower-battery-cost projections. Moreover, different battery chemistries can lead to very different costs and specific energies. For example, table 1 shows results obtained from bottom-up calculations with Argonne National Laboratory's BatPaC Battery Performance and Cost Model (Ahmed *et al* 2016), for a 100 kWh battery pack showing great variability in battery cost and performance for different chemistries.

Opportunities to improve performance and reduce costs further are being pursued in a number of major research areas. The battery community is investigating a number of materials, with the aim of reducing the cost and increasing the energy density of battery systems (Deign and Pyper 2018). Future work will involve utilizing silicon (Salah *et al* 2019) or lithium metal (Zhang *et al* 2020) as the anode while utilizing high-energy cathodes, such as NMC811 or lithium sulfur (Zhu *et al* 2019). Reducing the amount of critical material in lithium-ion batteries, especially cobalt, is an opportunity to lower the cost of batteries and improve supply-chain resilience. The private and public sectors are working toward developing new cathode materials along these lines (Li *et al* 2009, 2017b). Research and development (R&D) projects are underway to develop infrastructure and recycling technologies to collect batteries and recover the key battery materials economically and environmentally (Harper *et al* 2019). Reuse of end-of-life batteries from EVs would delay the need for additional battery materials, which should have positive environmental benefits (Neubauer *et al* 2012). Different battery technologies also are being explored. To increase energy density, reduce cost, and improve safety, the battery community is pursuing development of solid-state batteries with solid-state electrolytes (Randau *et al* 2020) that have ionic conductivities approaching those of today's liquid electrolyte systems. Solid-state lithium batteries enable the use of metallic lithium anodes, together with solid electrolytes and high-energy cathodes (such as high-nickel NMC or sulfur). Lithium-metal batteries based on solid electrolytes can, in principle, alleviate the safety concerns with current lithium-ion batteries with a flammable organic electrolyte. The main challenges facing lithium-metal anodes are dendritic growth, especially at low temperatures and higher current rates. Dendritic growth could lead to short circuit and thermal runaway and low Coulombic efficiency leading to poor cycle life (Xia *et al* 2019). Slow ion transport through the solid-state electrolyte leading to low power densities and manufacturing challenges, including poor mechanical integrity, pose additional challenges. Significant R&D activities are focused on developing solid-state electrolytes that prevent dendrite growth, have high ionic conductivity, good voltage-stability windows, and low impedance at the electrode–electrolyte interface. Recent cathode formulations in Li-S cells overcome the polysulfide problem, which could lead to lower efficiency and cycle life. Nevertheless, the deployment of cells with lower electrolyte-to-sulfur ratios for scale-up to large sizes is a remaining challenge. It may take another 5 to 10 years to mass-produce solid-state lithium batteries for EV applications.

As is discussed in section 5, a network of fast chargers and batteries that can handle high charging-power rates is needed to address any potential barriers to widespread EV adoption. Research is focusing on developing batteries that can be charged very quickly (e.g. 80% of capacity in less than 15 min). A number of challenges to high-power charging, such as lithium plating, thermal management, and poor cycle life, need to be addressed (Ahmed *et al* 2017; DOE 2017, Michelbacher *et al* 2017). Significant efforts also have focused on developing electrochemical and thermal modeling of batteries for EV applications (Kim *et al* 2011, Chen *et al* 2016, Keyser *et al* 2017, Zhang *et al* 2017) to improve battery lifetime and efficiency in real-world applications. These efforts include lifetime-estimation and degradation modeling under different real-world climate and driving conditions (Hoke *et al* 2014, Neubauer and Wood 2014, Liu *et al* 2017b, Harlow *et al* 2019, Li *et al* 2019); simplified models for control and diagnostics (e.g. state-of-charge estimation) (Muratori

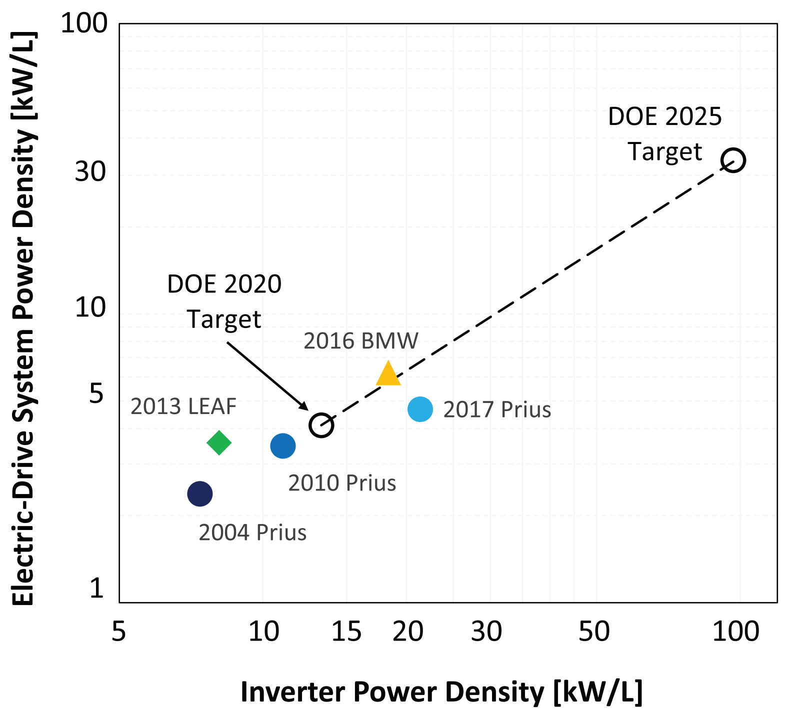

Figure 4. Integrated electric-drive system and inverter power density for several commercial light-duty vehicles and DOE targets (data from U.S. DRIVE 2017, Chowdhury *et al* 2019).

et al 2010, Fan *et al* 2013, Cordoba-Arenas *et al* 2015, Bartlett *et al* 2016); and developing effective thermal management and control strategies (Pesaran 2001, Serrao *et al* 2011).

Besides EV applications, batteries can offer energy-storage solutions for hybrid- or distributed-energy systems. These solutions include the use of batteries in integrated configurations with wind or solar photovoltaic (PV) systems or with EV fast-charging stations (Bernal-Agustín and Dufo-Lopez 2009, Badwawi *et al* 2015, Muratori *et al* 2019a). Batteries also can provide stabilization and flexibility and can improve resilience and efficiency for power systems in general, especially for critical services or when a high share of variable power generation (e.g. from solar or wind) is expected (Divya and Østergaard 2009, Denholm *et al* 2013; De Sisternes *et al* 2016). Lithium-ion batteries that have been developed for EV applications have found their way into stationary applications (Pellow *et al* 2020) because of their lower cost and modularity compared to other energy-storage technologies (Chen *et al* 2020). Moreover, EV batteries can be reused or repurposed at the end of their 'vehicle life' (usually considered when energy storage capacity drops below 70%–80% of the original nominal value, (Podias *et al* 2018)) for stationary applications, improving their economic and environmental performance (Assuncao *et al* 2016, Ahmadi *et al* 2017, Martinez-Laserna *et al* 2018, Olsson *et al* 2018, Kamath *et al* 2020).

4.2. Power electronics, electric machines, and electric-traction-drive systems

While batteries are playing a key role in the rise of EVs, power electronics and electric motors and machines are also key components of an EV powertrain. Traditionally, the motor and power electronics drive were separate components in an EV. However, recent trends toward integration promise to deliver benefits in terms of increased power density, lower losses, and lower costs compared with separate motor and motor-drive solutions (Reimers *et al* 2019). Figure 4 shows the 2020 power density for power electronics, electric machines, and electric-traction-drive system from some example commercial vehicles as well as the 2025 DOE and U.S. DRIVE Partnership targets for near-term improvements (U.S. DRIVE 2017, Chowdhury *et al* 2019). Commercially available vehicles exceed the 2020 power-density target. However, the 2025 target is at least a factor of six to eight higher than current commercial baselines. U.S. DRIVE Partnership also proposes electric-traction-drive-cost targets for 2020 and 2025: \$8 kW^{-1} and \$6 kW^{-1}, respectively, both of which are challenging targets (U.S. DRIVE 2017, Chowdhury *et al* 2019). The authors are not aware of commercial systems meeting the 2020 target, and the 2025 target represents a further 33% reduction.

Improvements in compact power electronics and electric machines are applicable to novel emerging wheel-integrated solutions as well (Iizuka and Akatsu 2017, Fukuda and Akatsu 2019). The development of advanced electric traction drive with improved efficiency is a strategy for increasing the range of electric-drive vehicles. In addition to this, chassis light-weighting is another strategy that is being pursued by the industry and the research community for increasing EV driving ranges. There are several technical challenges in meeting the DOE power-density targets (shown in figure 4). Challenges in meeting related DOE cost targets remain as well. A range of integration approaches are proposed in the literature, including surface mounting the power electronics on the motor housing (Nakada, Ishikawa, and Oki 2014), mounting on the motor stator iron (Wheeler *et al* 2005), and piecewise integration. Piecewise integration involves modularizing both power modules and machine stators into smaller units (Brown *et al* 2007). In all cases, the close physical positioning of the power electronics relative to the machine and the associated harsh thermal environment necessitate new concepts related to the active cooling of both components. A first strategy may be to isolate the power electronics from the machine thermally using parallel cooling mechanisms (Wheeler *et al* 2005). Another approach may be to use a fully integrated, series-connected, active-cooling loop (Tenconi *et al* 2008, Gurpinar *et al* 2018). In either case, cost benefits may be realized through the possible elimination or combination of cooling loops. Significant research also has been focused on reducing rare-earth and heavy-rare-earth materials within the electric machines because that is an additional important pathway to reduce costs (U.S. DRIVE 2017).

Higher levels of integration go hand-in-hand with the utilization of wide-bandgap (WBG) semiconductor devices, which may be used at higher operational temperatures (e.g. >200 °C versus 150 °C for silicon) with reduced switching loss (Millán *et al* 2014). However, the adoption of WBG devices requires new packaging technologies to support the end goals of high temperature, high frequency, higher voltages, and more compact footprints. High-performance electrical interconnects (Cheng *et al* 2013), die-attach (Liu *et al* 2020), encapsulation (Cao *et al* 2010), and power-module-substrate technologies (Stockmeier *et al* 2011), along with thermal management and reliability of these technologies (Moreno *et al* 2014, Paret *et al* 2016, 2019), are critical aspects to consider. The new materials, devices, and components must be cost-effective and high-temperature-capable to be compatible with WBG devices. The downsizing of passive electrical components is another added benefit of adopting WBG devices and a further necessity for integrated machine-drive packaging solutions. Fortunately, the higher switching frequencies that are supported by WBG devices enable the downsizing of both the inductors and capacitors found in a traditional power-control unit (Hamada *et al* 2015). The development of economically viable and high-temperature-capable passives, capacitors in particular (Caliari *et al* 2013), is an area of great interest.

Besides EV applications, power electronics and electric machines with low cost, high performance, and high reliability are important for numerous energy-efficiency and renewable-energy applications, such as solar inverters, generators and electric drives for wind, grid-tied medium-voltage power electronics, and sensors and electronics for high-temperature geothermal applications (PowerAmerica 2020).

5. Charging infrastructure

Infrastructure planning and deploying an ecosystem of cost-effective and convenient public and private chargers is central to supporting EV adoption (CEM 2020). The lack of a sufficient refueling infrastructure has hampered many past efforts to promote alternatives to petroleum fuels (McNutt and Rodgers 2004). Extensive research is being done to address the diverse challenges that are posed by a transition from fossil-fuelled ICEVs to EVs and the special role of charging infrastructure in this transition (Muratori *et al* 2020b).

At the end of 2019, there were an estimated 7.3 million EV chargers (or plugs) worldwide, of which almost 0.9 million were public, including approximately 264 000 public DCFCs (81% in China) (IEA 2020). Significant government support and private investments are helping to expand the network of public charging stations worldwide. With about 7.2 million light-duty BEVs on the road, there is about one public charger per 10 light-duty BEVs, and most vehicles have access to a residential charger. However, the number of public chargers per BEV varies widely among the 10 countries with the most BEVs (figure 5) because of different strategies for deploying fast versus slow public chargers. In addition to these LDV chargers, IEA estimated there are 184 000 fast chargers dedicated to electric buses (95% in China).

Studies show consistently that today's EVs do the majority (50%–80%) of their charging at home, followed by at work (15%–25% when workers use their vehicles to commute), and using public chargers (only about 5% of charging) (Hardman *et al* 2018). PHEVs conduct more charging at home than BEVs do, and they rely more on level-1 charging (Tal *et al* 2019). While single-household detached residences readily can accommodate level-1 or -2 charging, multi-unit dwellings require curbside public charging or installations in shared parking facilities (Hall and Lutsey 2017). Historical data on the charging behavior of California BEV owners reveals that 11% of their charging sessions were at level 1, 72% were at level 2, and 17% used DCFCs (Tal *et al* 2019). Use of DCFCs is lowest for BEVs with less than 100 miles (161 km) of range, highest for medium-range BEVs, and lower again for BEVs with ranges of 300 miles (483 km) or more.

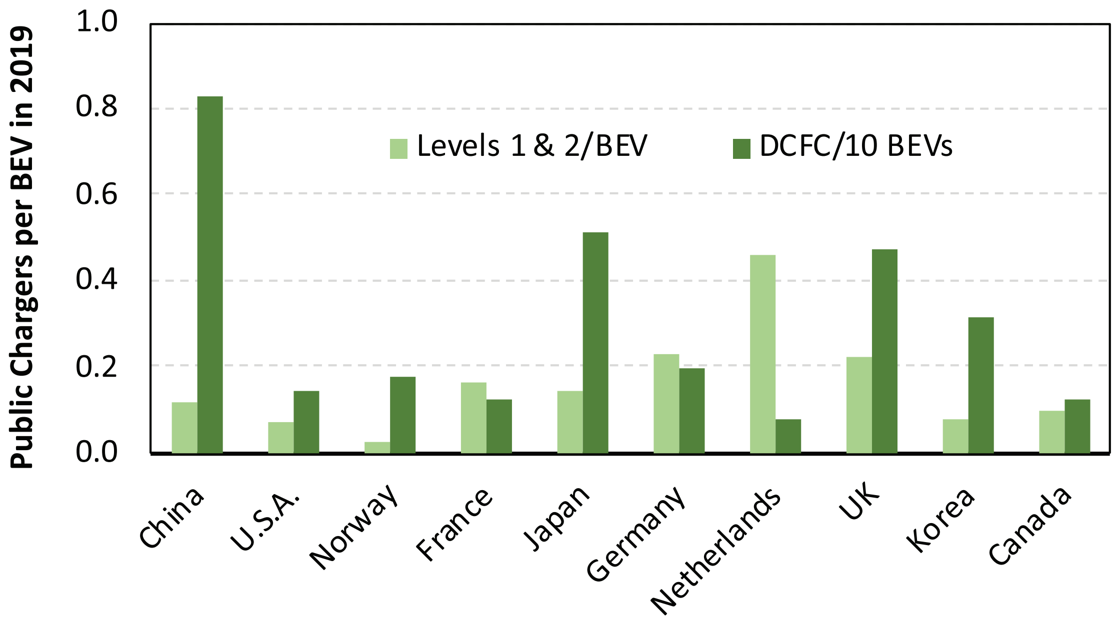

Figure 5. Public charging availability by country in 2019, measured as Level-1 and Level-2 chargers per BEV and DCFC per 10 BEVs (Data from IEA 2020).

5.1. Charging-siting modeling

Public charging infrastructure is clearly important to EV purchasers and supports EV sales by adding value (Narassimhan and Johnson 2018, Greene *et al* 2020). However, how best to deploy charging infrastructure, in terms of numbers, types, locations, and timing remains an active area for research (Ko *et al* 2017, Funke *et al* 2019 provide reviews). The literature includes many examples of geographically and temporally detailed models to optimize the location, number, and types of charging stations (e.g. Wood *et al* 2017, Wu and Sioshansi 2017, Zhao *et al* 2019). Geographically and temporally detailed data recording the movements of PEVs and their charging behavior are scarce. With few exceptions (e.g. Gnann *et al* 2018), simulation analyses rely on conventional ICEV databases (e.g. Dong *et al* 2014, Wood *et al* 2015, 2018), which do not reflect the changes PEV owners will make to maximize the utility of PEVs.

Given the importance of home charging, access to chargers for on-street parking in residential areas comprising attached or multi-unit dwellings is likely to be essential for PEVs to be adopted at large scale. Grote *et al* (2019) employ heuristic methods with geographical-information systems to locate curbside chargers in urban areas using a combination of census and parking data. The works of Nie and Ghamami (2013), Ghamami *et al* (2016), and Wang *et al* (2019) are examples of the variety of optimization methods that are applied to design DCFC networks to support intercity travel. Despite these examples, applied research is hindered by the scarcity of data on long-distance vehicle travel by PEVs (Eisenmann and Plötz 2019). Jochem *et al* (2019) estimate that 314 DCFC stations could provide minimum coverage of EU intercity routes with approximately 0.7 charging points per 1000 BEVs. Using a database of simulated U.S. intercity travel, He *et al* (2019) employ a mixed-integer model to optimize the location and number of DCFCs. They conclude that 250 stations could serve 98% of the long-distance miles of BEVs with ranges of 150 miles (241 km) or greater but only 73% of the long-distance miles of 100 mile range (161 km range) BEVs. Similarly, Wood *et al* (2017) estimate that 400 DCFC stations are required to cover the U.S. interstate-highway network with a 40 mile (64 km) spacing between stations. Others consider the optimal location of dynamic, wireless charging in combination with stationary charging (Liu and Wang 2017).

Optimization models for locating chargers to support commercial PEV fleets also appear in the literature (Jung *et al* 2014, Shahraki *et al* 2015). In the future, if vehicle sharing becomes much more common, the downtime for charging could be an important disadvantage for PEVs. Using an integer model to optimize station allocation and PEV assignment, Roni *et al* (2019) find that charging time represents 72%–75% of vehicle downtime but that charging time could be reduced by almost 50% by optimal deployment of charging stations.

5.2. Beyond LDV charging

The electrification of medium- and heavy-duty commercial trucks and buses introduces unique charging and infrastructure requirements compared to those of LDVs. These requirements stem from the significantly higher battery capacities required on-board the vehicles, potentially shorter charging-dwell times (due to the in-service time requirements of the vehicles), and the potential of large facility charging loads (due to multiple trucks or buses charging in one location). One challenge is to understand the costs associated with the multitude of charging scenarios for commercial vehicles for current operations as well as future operations. It is expected that on-road freight vehicle miles (or km) traveled will increase by 75% from 2012 to 2045 (McCall and Phadke 2019). This increase may bring about new business models and potentially new charging-infrastructure approaches to meet this demand with electrified trucks. California's Innovative Clean Transit regulation, which will require California transit agencies to adopt zero-emission buses by 2040, is likely to drive large charging-infrastructure investments for buses (CARB 2018).

Today's commercial diesel-powered trucks in small fleets typically are fueled at publicly available on-road fueling stations, while nearly half of trucks in fleets of 10+ vehicles use company-owned facilities (Davis and Boundy 2020). Likewise, commercial EVs are charged primarily in fleet-owned facilities as their daily schedule allows (most often overnight). This depot-charging approach, which enables seamless integration of EVs into fleet logistics, might limit the electrification of some vehicle segments in the long term due to the battery capacity that is needed to satisfy their daily-range requirements (the need to complete their full-day function) and return to the facility to recharge fully[14]. Some studies suggest that long-haul battery-electric trucks are technically feasible and economically compelling (Phadke *et al* 2019) while others are more skeptical (Held *et al* 2018). Publicly available, high-power charging or en-route charging infrastructure for commercial vehicles could enable electrification for longer-distance vehicles (by enabling smaller on-board battery-capacity needs), but this scenario has cost challenges. En-route, high-power charging of over 1 MW might be needed to enable 500 miles (805 km) or more of daily driving. Installation of a 20 MW truck-charging station in California (capable of multiple 1.5 MW charge events for heavy-duty freight vehicles) is estimated to cost as much as 15 million USD. McCall and Phadke (2019) estimate that as many as 750 of these stations are needed to electrify the fleet of California Class-8 combination trucks. Charging commercial vehicles at depots requires additional infrastructure costs to install lower-power EV-supply equipment networks (e.g. 50 kW–100 kW) capable of charging multiple vehicles at these lower rates. These depot charging systems also will challenge existing facility electrical systems by adding a significant load that was not planned previously at the facility (Borlaug *et al* Forthcoming).

5.3. Economics of public charging

PEV-charging economics vary with location and station configuration and depend critically on equipment and installation costs and retail electricity prices, which are dependent on utilization (Muratori *et al* 2019b, Borlaug *et al* 2020). In the early stages of market development, when there are relatively few vehicles, future demand is uncertain, and most charging is done at an EV's home base (Nigro and Frades 2015, Madina *et al* 2016). Public charging stations tend to be lightly used during these initial stages (e.g. INL 2015), which poses a difficult challenge for private investment. Understanding and quantifying the value of public charging is hindered by lack of experience with PEVs on the part of consumers (Ito *et al* 2013, Greene *et al* 2020, Miele *et al* 2020) and the complexity of network effects in the evolution of alternative-fuel-vehicle markets (Li *et al* 2017a). Nevertheless, it is likely that DCFCs will be profitable with sufficient demand. Considering vehicle ranges of between 100 km and 300 km and charging-power levels of between 50 kW and 150 kW, Gnann *et al* (2018) conclude that charger-usage fees could be between 0.05 € kWh^{-1} and 0.15 € kWh^{-1} in addition to the cost of electricity. The estimates were based on simulations with average daily occupancy of charging points of 10%–25% and peak-hour utilization of 20%–70%. In their simulations, utilization rates increase with increasing charger power and decrease with increased EV range. For intercity travel along European Union highways, Jochem *et al* (2019) estimate that a surcharge of 0.05 € kWh^{-1} of DCFC would make a minimal coverage of 314 stations (with 20 charge plugs each) profitable, even for station capital costs of one million EUR. He *et al* (2019) optimize DCFC locations along U.S. intercity routes and conclude that providing an adequate nationwide charging network for long-distance travel by 100 mile (161 km) range BEVs is more economical than increasing vehicle range and reducing the number of charging stations. Muratori *et al* (2019a) consider a set of charging scenarios from real-world data and thousands of U.S. electricity retail rates. They conclude that batteries can be highly effective at mitigating electricity costs associated with demand charges and low station utilization, thereby reducing overall DCFC costs.

Early estimates show that the cost of public DCFC in U.S. can vary widely based on the station characteristics and level of use (Muratori *et al* 2019a). Numerous new technology options are being explored to provide lower-cost electricity for light-duty passenger and medium- and heavy-duty commercial BEVs.

[14] 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).

Increasing the range of EVs through higher-power public charging stations as well as accommodating new potential BEV business models, such as transportation-network companies or automated vehicles, are driving new charging-technology solutions. Managed charging solutions that are available today can provide increased value to the BEV owner (lower electricity costs), charging station owner (lower operating costs), or grid operator (lower infrastructure-investment costs). For example, a managed-charging solution has been adopted and is currently in operation at a Santa Clara Valley Transportation Authority depot to charge a fleet of Proterra electric buses optimally to ensure minimal stress on the grid (Ross 2018).

5.4. Emerging charging technologies

Wireless charging, specifically high-power wireless charging (beyond level-2 power levels), could play a key role in providing an automated charging solution for tomorrow's automated vehicles (Lukic and Pantic 2013, Qiu *et al* 2013, Miller *et al* 2015, Feng *et al* 2020). Wireless charging also can enable significant electric range for BEVs by providing en-route opportunity charging (static or dynamic charging opportunities). If a network of wireless charging options is available to provide convenient and fast en-route charging, it could help reduce the amount of battery that is needed on-board a vehicle and reduce the cost of ownership for a BEV owner. Wireless charging is being developed for power levels of up to 300 kW for LDVs, 500 kW for medium-duty vehicles, and 1000 kW for heavy-duty vehicles. Bidirectional functionality, improved efficiency, interoperability of different systems, improved cybersecurity, and increased human-safety factors continue to be developed (Ozpineci *et al* 2019).

Connectivity and communication advances will enable new BEV-charging infrastructure and managed charging solutions. However, emerging cybersecurity threats also are being identified and should be addressed. There are concerns associated with data exchange, communications network, infrastructure, and firmware/software elements of the EV infrastructure (Chaudhry and Bohn 2012), and new charging-system security requirements and protocols are being developed to address these concerns (ElaadNL 2017). New emulation and simulation platforms also are being developed to address these threats and help understand the consequences and value of mitigating cyberattacks that could affect BEVs, electric-vehicle-supply equipment, or the electric grid (Sanghvi *et al* 2020).

6. Vehicle-grid integration (VGI)

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), 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, Eid *et al* 2016, Knezovic *et al* 2017, Borne *et al* 2018, Hoarau and Perez 2019, Gomes *et al* 2020, Muratori and Mai 2020, Thompson and Perez 2020).

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, U.S. DRIVE 2019, Doluweera *et al* 2020). 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, Weiller and Sioshansi 2014, IRENA 2019, Zhang *et al* 2019). 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.

6.1. Impact of EV loads on distribution systems

At the local level, EV charging can increase and change electricity loads significantly, having possible negative impacts on distribution networks (e.g. cables and distribution transformers) and power quality or reliability (Khalid *et al* 2019). Residential EV charging represents a significant increase in household electricity consumption that can require upgrades of the household electrical system which, unless managed properly, may exceed the maximum power that can be supported by distribution systems, especially for legacy infrastructure and during times of high electricity utilization (e.g. peak hours and extreme days) (IEA 2018b). The impact of EVs on distribution systems also is influenced by the simultaneous adoption of other distributed energy resources, e.g. rooftop PV panels. While this interdependency complicates assessing the impact of EV charging, Fachrizal *et al* (2020) show that the two technologies support one other. Similarly, Vopava *et al* (2020) show that line overloads caused by rooftop PV panels can be reduced (but not avoided) by increasing EV adoption and vice versa.

The impact of EV charging on distribution systems is particularly critical for high-power charging and in cases in which many EVs are concentrated in specific locations, such as clusters of residential LDV charging and possibly fleet depots for commercial vehicles (Saarenpää *et al* 2013, Liu *et al* 2017a, Muratori 2018). Smart charging, by which EV charging is timed based on signals from the grid and electricity prices that vary over time, or other forms of control, can help to minimize the impact of EV charging on distribution networks. However, smart charging requires both appropriate business models and signals (with related communication and distributed-control challenges). The market for distribution-system operators to provide such services is not mature yet (Everoze 2018, Crozier, Morstyn, and McCulloch 2020). Time-varying pricing schemes, which are effective at influencing the timing of EV charging (PG&E 2017), typically do not include any distribution-level considerations. Thus, while consumers are responsive to such signals, the business models to include distribution-level metrics still are lacking. Moreover, price signals are offered usually to a large consumer base with the intent of reshaping the overall system load. At the local level, however, multiple consumers responding to the same signal might cause 'rebound peaks' (Li *et al* 2012, Muratori and Rizzoni 2016) that can overstress distribution systems, calling for coordination among consumers connected to the same distribution network (e.g. direct EV-charging control from an intermediate aggregator).

Charging of larger commercial vehicles and highway fast-charging stations typically involves higher power levels: DCFC is typically at 50 kW/plug today, but power levels are increasing rapidly. Commercial charging locations with multiple plugs co-located at a specific location may lead to possible MW-level loads, which is roughly equivalent to the peak load of a large hotel. Commercial DCFC may require costly upgrades to distribution systems that can impact the cost-effectiveness of public fast charging heavily, especially if stations experience low utilization (Garrett and Nelder 2016, Muratori *et al* 2019b). While charging timing and speed at commercial stations is less flexible (consumers want to charge and leave or commercial fleets must meet business requirements), business models are often already in place to incentivize curbing maximum peak power from commercial installations. For example, demand charges (a fixed monthly payment that is proportional to the peak power that is drawn during a given month) are fairly common in U.S. retail tariffs and provide a reason to limit peak power. Furthermore, Muratori *et al* (2019a) show that distributed batteries can be effective at mitigating the cost associated with demand charges by up to 50%, especially for 'peaky' or low-utilization EV-charging loads. Batteries also can facilitate coupling EV-charging stations with local solar electricity production or can provide grid services (Megel, Mathieu, and Andersson 2015), generating additional revenue.

6.2. Value of managed ('smart') EV charging for power systems

The integration of EVs into power systems presents several opportunities for synergistic improvement of the efficiency and economics of electromobility and electric power systems. These synergies stem from two inherent characteristics of EVs and power systems. Demand response and other forms of demand-side flexibility can be of value for power-system planning and operations (Albadi and El-Saadany 2007, 2008, Su and Kirschen 2009, Muratori *et al* 2014). Contemporaneously, most personal-vehicle driving patterns entail vehicle-use for mobility purposes a relatively small proportion of the time (Kempton and Letendre 1997). If EVs are grid-connected for extended periods of time, they can provide demand-side flexibility in the form of smart charging or V2G services. Such use of an EV can improve its economics by leveraging cheaper electricity at little incremental cost (e.g. the costs of monitoring, communication, and control equipment that are needed to manage smart charging). EVs can support grid planning and operations in a number of ways. Figure 6 summarizes the key support services that EVs can provide. These services include reducing peak load and generation-, transmission-, and distribution-capacity requirements, deferring system upgrades, providing load response, supporting power-system dispatch (including VRE integration and real-time energy and operating reserves), providing energy arbitrage, and supporting power quality and end retail consumers.

Habib *et al* (2015) and Thompson and Perez (2020) provide detailed surveys of different potential uses of EVs for smart charging and V2G services. This includes active- and reactive-power services, load balancing, power-quality-related services (e.g. managing flicker and harmonics), retail-bill management, resource

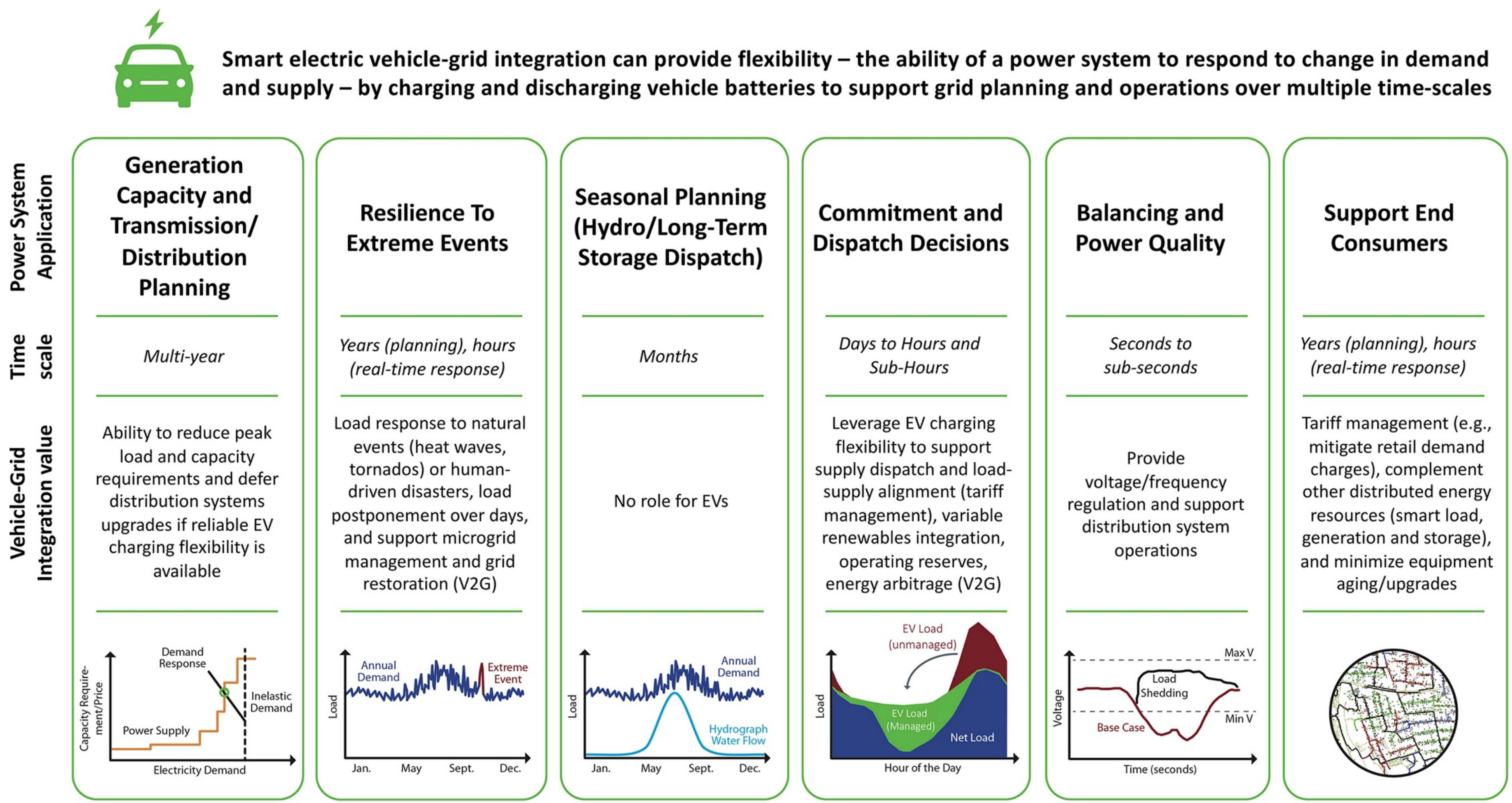

Figure 6. Summary of opportunities for EVs to provide demand-side flexibility to support power system planning and operations across multiple timescales.

adequacy, and network deferral. In addition, Habib *et al* (2015) discuss different standards and technology needs relating to V2G services.

Kempton and Letendre (1997) provide the first description of the concept of EVs providing grid services, either in the form of smart charging or bidirectional V2G services (which can involve discharging EV batteries). Denholm and Short (2006) study the benefits of controlled overnight charging of PHEVs for valley-filling purposes. They demonstrate that with proper control of vehicle charging, up to 50% of the vehicle fleet could be electrified without needing new generation capacity to be built and at substantial savings compared to using liquid fuels for transportation. They show also that under conservative utility-planning practices, PHEVs could replace a significant portion of low-capacity-factor generating capacity by providing peaking V2G services. Tomić and Kempton (2007) examine the economics of using EVs for the provision of frequency reserves and demonstrate that such services can yield substantive revenues to vehicle owners in a variety of wholesale markets. Thompson and Perez (2020) conduct a meta-analysis of V2G services and value streams and find that power-focused services are of greater value than energy-focused services. They distinguish the two types of services based on the extent to which EV batteries must be discharged and degraded. Sioshansi and Denholm (2010) come to a similar conclusion in comparing the value of using PHEV batteries for energy arbitrage and operating reserves.

Another important synergy between EVs and power systems is using the flexibility of EV charging to manage the integration of VRE into power systems (Mwasilu *et al* 2014, Weiller and Sioshansi 2014). Hoarau and Perez (2018) develop a framework for examining the synergies between EV charging and the integration of photovoltaic-solar resources into power systems. They find that the spatial footprint across which solar resources and EVs are deployed and the regulatory, policy, and market barriers to cooperation between solar resources and EVs are critical to realizing these synergies. Szinai *et al* (2020) find that controlled EV charging in California under its 2025 renewable-portfolio standards can reduce operational costs and renewable curtailment compared to unmanaged charging. They find that properly designed time-of-use retail tariffs can achieve some, but not all, of the benefits of controlled EV charging. They show also that these two approaches to managing EV charging (controlling EV charging directly and time-of-use tariffs) reduce the cost of infrastructure that is necessary to accommodate EV charging relative to a case of uncontrolled EV charging. Chandrashekar *et al* (2017) conduct an analysis of the Texas power system and find similar benefits of controlled EV charging in reducing wind-integration costs. Coignard *et al* (2018) show that under California's 2020 renewable-portfolio standards, controlled EV charging can deliver the same renewable-integration benefits that California's energy-storage mandate does but at substantially lower costs. They show that bidirectional V2G services deliver up to triple the value of controlled EV charging. Kempton and Tomić (2005) show that high penetrations of wind energy in U.S. could be accommodated at relatively low costs if 3% of the vehicle fleet provides frequency reserves and 8%–38% of the fleet provides operating reserves and energy-storage services to avoid wind curtailment. Loisel *et al* (2014) and Zhang *et al* (2019) conduct more forward-looking analyses of the synergies between EVs and renewables. The former examines German systems, and the latter examines California systems under potential renewable-deployment scenarios in the year 2030.

An important assumption underlying these works is that EV owners (or aggregations of EVs) are exposed to prices that signal the value of these services and that there are regulatory and business models that allow such services to be exploited (i.e. consumer are willing to engage in these programs and are compensated properly for providing flexible charging). Several pilot studies suggest that EV owners have interest in participating in utility-run controlled-charging programs and that a set of different compensation strategies beyond time-varying electricity pricing might maximize engagement (Geske and Schumann 2018, Hanvey 2019, Küfeoğlu *et al* 2019, Delmonte *et al* 2020).

Niesten and Alkemade (2016) survey the literature on these topics and numerous European and U.S. pilot programs in terms of value generation for V2G services. They find that the ability of an aggregator to scale is related to its ability to develop a financially viable business model for V2G services. Another important consideration is the availability of control and communication technologies to manage EV charging based on power-system conditions. Key considerations in the design of control strategies are robustness in the face of uncertainty (e.g. renewable availability, EV-arrival times and charge levels upon arrivals, and EV-departure times), data privacy, and robustness to communication or other failures. Le Floch *et al* (2015a), Le Floch *et al* (2015b), (2016), develop a variety of distributed and partial-differential-equation-based algorithms for controlling EV charging. Rotering and Ilic (2011) develop a dynamic-optimization-based approach to control EV charging and bidirectional V2G services (with a focus on the provision of ancillary services). Donadee and Ilic (2014) develop a Markov decision process to optimize the offering behavior of EVs that participate in wholesale electricity markets to provide frequency reserves.

6.3. Remaining challenges for effective vehicle-grid integration at scale

There are still many challenges to tackle before smart charging and V2G can be deployed effectively at large scale. These challenges are linked to the technical aspects of VGI technology but also to societal, economic, security, resilience, and regulatory questions (Noel *et al* 2019a). With regard to the technical challenges of VGI, existing barriers notably include battery degradation, charger availability and efficiency, communication standards, cybersecurity, and aggregation issues (Eiza and Ni 2017, Sovacool *et al* 2017, Noel *et al* 2019a).

While the technical aspects of VGI are studied widely, this is much less the case for its key societal aspects. Societal issues include the environmental performance of VGI, its impact on natural resources, consumer acceptance and awareness, financing and business models, and social justice and equity (Sovacool *et al* 2018). There are also various regulatory and political challenges linked to clarifying the regulatory frameworks applicable to VGI as well as market-design issues, such as the proper valuation of VGI services and double taxation (Noel *et al* 2019a) and the trade-offs between bulk power and distribution-system needs. Regulatory changes may be required to enable distribution-network operators and EV owners (or aggregators) to take a more active role in electricity markets. The Parker project, an experimental project on balancing services from an EV fleet, underlines some of the barriers to providing ancillary services, such as metering requirements (Andersen *et al* 2019). It is argued that insufficient regulatory action might keep us from attaining the full economic and environmental benefits of V2G (Thompson and Perez 2020) and that regulations are lagging behind technological developments (Freitas Gomes *et al* 2020). The lack of defined business models is seen by many experts as a key impediment (Noel *et al* 2019b).

Major challenges that are linked to data-related aspects of VGI, including who has the right to access data from EVs (e.g. the state of EV batteries and charging) and how these data can be exploited, remain. Privacy concerns are one of the major obstacles to user acceptance (as is fear of loss of control over charging) (Bailey and Axsen 2015). In addition, there are also questions linked to cybersecurity (Noel *et al* 2019a).

Nevertheless, VGI offers many opportunities that justify the efforts required to overcome these challenges. In addition to its services to the power system, VGI offers interesting perspectives for the full exploitation of synergies between EVs and renewable energy sources as both technologies promise large-scale deployment in the future (Kempton and Tomić 2005, Lund and Kempton 2008). Exploiting EV batteries for VGI also is appealing from a life-cycle perspective, as the manufacturing of EV batteries has a non-trivial environmental footprint (Hall and Lutsey 2018). However, there are a few future developments that might compromise the potential of VGI, most notably cheaper batteries (including second-life EV batteries) that might compete with EVs for many potential services (Noel *et al* 2019b). In addition, the impacts of new mobility business models, such as the rise of vehicle- and ride-sharing, on grid services remain unclear. Although smart charging will come first in the path toward grid integration, V2G services have the potential to provide additional value (Thingvad *et al* 2016).

7. 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). WTW emissions are expressed typically on a per-mile or per-kilometer basis over a vehicle’s assumed lifetime.

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

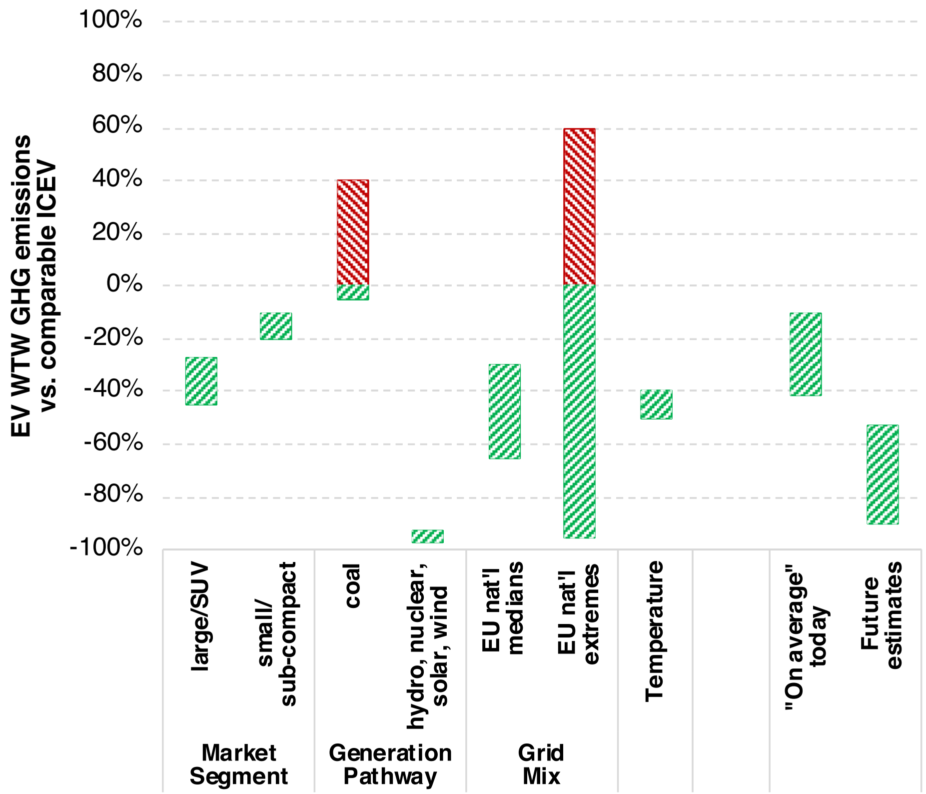

Figure 7. WTW GHG emissions for EVs versus comparable ICEVs on average and with illustrative variability by market segment, electricity generation pathway, grid mix, and ambient temperature.

(Samaras and Meisterling 2008, Ambrose and Kendall 2016, Elgowainy *et al* 2016, Hall and Lutsey 2018, Ricardo 2020). 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).

Even including upstream emissions, EVs are championed as a critical technology for decarbonizing transportation (in line with anticipated widespread grid decarbonization). National Research Council (2013) identifies EVs as one of several technologies that could put U.S. on a path to reducing transportation-sector GHG emissions to 80% below 2005 levels in 2050. Furthermore, National Research Council (2013) estimates that BEVs would reduce emissions by 53%–72% compared to ICEVs in 2030. IEA (2019) contends, similarly, that EVs can reduce WTW GHG emissions by half versus equivalent ICEVs in 2030. Recently published literature also agrees, even on a C2G basis, estimating that future EV pathways offer 70%–90% lower GHG emissions compared to today's ICEVs (Elgowainy *et al* 2018). As such, the broad view across national, international, and academic-research perspectives is that EVs offer the potential to reduce transportation-related GHG emissions by 53% to 90% in the future.

Several studies find that EVs already reduce WTW GHG emissions today by as little as 10% or as much as 41% on average versus comparable ICEVs based on current electricity-production mixes. Samaras and Meisterling (2008), who are among the first to relate a range of potential electricity carbon intensities to associated EV-lifecycle emissions explicitly, estimate a 38%–41% GHG emissions benefit for EVs powered by the average 2008 U.S. grid. Hawkins *et al* (2012a), informed by a meta-study of 51 previous LCAs, highlight great variations based on different electricity generation assumptions and vehicle lifetime. Hawkins *et al* (2012b) estimate a decline of 10%–24% global warming potential (a measure proportional to GHG emissions) for EVs powered by the average 2012 European electricity mix. Elgowainy *et al* 2016, 2018) estimate that EVs emit 20%–35% fewer GHG emissions when operating on the average 2014 U.S. grid mix.

Many factors contribute to variability in EV WTW emissions and estimated reduction opportunities compared to ICEVs—electricity-carbon intensity, charging patterns, vehicle characteristics, and even local climate (Noshadravan *et al* 2015, Requia *et al* 2018). To illustrate these variabilities, figure 7 compares WTW GHG emissions of EVs versus comparable ICEVs. Relative emissions reductions are generally larger for larger vehicles. Woo *et al* (2017) find that electrifying SUVs reduces emissions more than electrifying sub-compact vehicles on a WTW basis versus comparable ICEVs (30%–45% and 10%–20%, respectively, assuming median national grid mixes). Ellingsen *et al* (2016) find that large EVs emit proportionally less than small EVs compared to comparable ICEVs on a C2G basis (27% and 19%, respectively).

Low-carbon electricity can lead to greater reductions in EV emissions. Electricity that is produced from coal, which has a high carbon intensity, can increase EV emissions by as much as 40% or decrease EV emissions by as much as 5% compared to an ICEV (depending on other assumptions). Conversely, electricity from hydropower, nuclear, solar, or wind, all of which offer near-zero carbon intensities, can decrease EV emissions by more than 95% compared to an ICEV (Woo *et al* 2017). Such variability in electricity-generation pathways affects the relative benefits of real-world grid mixes. For example, while EVs offer 30%–65% lower emissions versus comparable ICEVs on average in Europe (Woo *et al* 2017, Moro and Lonza 2018), in individual countries relative emissions can range from as much as 95% lower to 60% higher (Orsi *et al* 2016, Moro and Lonza 2018). Typically, U.S. EVs provide emissions reductions, but in some regions EV emissions are higher compared to an efficient ICEV (Reichmuth 2020). Changes in regional climate and daily weather add further variability: EV emissions can vary between 40% and 50% lower than a comparable ICEV even when charged from the same grid mix (Yuksel *et al* 2016). While outside the scope of a typical WTW comparison, the additional consideration of refueling infrastructure (i.e. gasoline stations for ICEVs and recharging equipment for EVs) is estimated to increase EV emissions by 4%–8% compared to a more modest 0.3%–0.7% increase for ICEV emissions (Lucas *et al* 2012).

When assessing EV emissions, average or marginal grid-emission factors are considered (Anair and Mahmassani 2012, Traut *et al* 2013, EPRI 2015, Nealer and Hendrickson 2015, Nealer *et al* 2015, Elgowainy *et al* 2018), leading to significantly different results. Average emissions factors consider all electricity loads as equivalent, while marginal emission factors consider EVs as an additional load on top of existing electricity demands and estimate the associated incremental generation emissions. Marginal emissions could be higher or lower than average, depending on the relative emissions of marginal plants compared to the average in different regions. Different questions lead to using average or marginal metrics. Proper assessment of indirect EV emissions associated with electricity generation is complicated by numerous factors, including timescale (short or long term, aggregate or temporally explicit), system boundaries, impact of EV loads on power-system-expansion and -operation decisions, and non-trivial supply-demand synergies and allocation complexities. Yang (2013) reviews different grid-emissions-allocation methods concluding that there is no ideal approach to the allocation of emissions to specific end-use and stressing how different assumptions make it difficult to determine EV emissions and compare them to other alternatives and across studies. Nealer and Hendrickson (2015) discuss whether it is more appropriate to use marginal or average grid-emission factors to estimate EV emissions, concluding that 'average emissions may be the most accessible for long-term comparisons given the assumptions that must be made about the future of the electricity grid.'

Just as EVs offer typically a WTW-emissions reduction compared to ICEVs while shifting those emissions from the tailpipe to upstream, EVs shift costs as well. Operational (fuel and maintenance) costs of EVs are typically lower than those of ICEVs, largely because EVs are more efficient than ICEVs and have fewer moving parts. While data are still scarce, a recent Consumer Reports study estimates that maintenance and repair costs for EVs are about half over the life of the vehicle and that a typical EV owner who does most fueling at home can expect to save an average of \$800 to \$1000 a year on fuel costs over an equivalent ICEV (Harto 2020). Insideevs (2018) estimates a saving of 23% in servicing costs over the first 3 years and 60 000 miles (96 561 km). Borlaug *et al* (2020) estimate fuel savings between \$3000 and \$10 500 compared with gasoline vehicles (over a 15 year time horizon). However, vehicle capital costs for EVs are higher (principally due to the relatively high cost of EV batteries). In general, studies use a TCO metric to combine and compare initial capital costs with operational costs over a vehicle's lifetime. While some studies find that EVs are typically cost-competitive with ICEVs (Weldon *et al* 2018), others find that EVs are still more costly, even on a TCO basis (Breetz and Salon 2018, Elgowainy *et al* 2018), or that the relative cost depends on other contextual factors, such as vehicle lifetime and use, economic assumptions, and projected fuel prices. Longer travel distance and smaller vehicle sizes favor relatively lower EV TCO (Wu *et al* 2015), as do lower relative electricity-versus-gasoline price differentials (Lévay *et al* 2017). Despite these differences regarding TCO conclusions across studies, there is general agreement that future EV costs will decline (Dumortier *et al* 2015, Wu *et al* 2015, Elgowainy *et al* 2018).

The existing literature suggests future EV emissions will decline, in large part due to expectations for continued grid decarbonization (Elgowainy *et al* 2016, 2018, Woo *et al* 2017, Cox *et al* 2018). For example, Ambrose *et al* (2020) anticipate that evolution in vehicle types and designs could accelerate future decreases for EV GHG emissions. Several studies also posit repurposing used EV batteries for stationary applications could accrue additional GHG benefits (Ahmadi *et al* 2014, 2017, Olsson *et al* 2018, Kamath *et al* 2020). Cox *et al* (2018) suggest future connectivity and automation technologies will enable energy-optimized EV-recharging behavior and associated lower carbon emissions. Similarly, future EV costs also are expected to decline as battery costs continue to decline (cf section 4), and new mobility modes such as ride-hailing lead to higher vehicle use that favors the business case for highly efficient EVs compared to ICEVs.

8. 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) 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, Aghaei *et al* 2020). Yamaguchi *et al* (2020) 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, Zarif *et al* 2019, Tuncer and Brown 2020). 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). 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, Clewlow and Mishra 2017, Movmi 2018, Walmsley 2018, Henao and Marshall 2019, Arevalo 2020). 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). 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). 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). 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). 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). 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).

Automation trends are also poised to have the potential to disrupt transportation as we know it. The combination of electric and connected automated vehicles (CAVs) is hypothesized to offer natural synergies, including easier integration with CAV sensors and a greater affinity for cheaper fuels aligning with greater travel (Sperling 2018). The chief counterargument relates to high power requirements for a heavily instrumented CAV, which would deplete EV batteries quickly and may be accommodated better with PHEV powertrains. Wireless EV charging, both stationary and dynamic, increases the potential synergies enabling autonomous recharging. Also, CAVs may be required to maximize the efficiency of dynamic wireless charging. In fact, without the alignment accuracy enabled by CAVs, in-road dynamic charging may have limited efficacy. The literature on these synergies is relatively sparse, though some studies are beginning to investigate the implications of combining EV and CAV technologies.

Even though the technology is not widely available commercially, several studies are beginning to examine how consumer preferences may be influenced by the combination of connected, automated, and electric vehicles[15]. Thiel *et al* (2020), for example, highlight how full EV success may emerge as automated shared vehicles become predominant in a world where the border between public and private transport will cease to exist. Tsouros and Polydoropoulou (2020) develop a survey combining traditional attributes (e.g. car

[15] 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'.

type and vehicle style) alongside future technology attributes (e.g. fuel type and degree of automation) and estimate preferences using a latent-class structural-regression approach. They find a specific class of consumers, described as technology-savvy, who have a high proclivity for both alternative-fuel vehicle technologies and higher degrees of automation. While the proportion of the population that can be classified as technology-savvy is unclear, Tsouros and Polydoropoulou (2020) provide early compelling evidence that consumers see explicit value in the combination of EVs and automation. Hardman *et al* (2019) provide a complementary perspective of early adopters of automated vehicles based on a survey of existing U.S. EV owners. Similar to the work of Tsouros and Polydoropoulou (2020), Hardman *et al* (2019) find that the type of consumers who would pursue automated vehicles have similar lifestyles, attitudes, and socio-demographic profiles as EV adopters. These include high-income consumers, with high levels of knowledge about technology features, who have positive perceptions of CAV attributes and technology in general, provided that safety concerns are resolved.

Another benefit of the combined technologies is the potential to integrate charging events better with the needs of the electricity grid. Several studies assess the combination of these technologies with new mobility services such as car-sharing systems to optimize VGI. Iacobucci *et al* (2018) consider a case study in Tokyo of the ability of connected, automated EVs to be dispatched to respond to both transportation demand and charging to meet demands and constraints of the electricity system. The authors observe the vehicles can take advantage of a variety of different time-of-day pricing structures—leading to a tradeoff between wait times and cost benefits from lower fuel prices. They find that the vehicles in Tokyo can supply on the order of 3.5 MW of charging flexibility per 1000 vehicles, even during times of high mobility demand. Miao *et al* (2019) conduct a similar study in a generic region. The authors develop an algorithm that simulates operational behavior of the connected, automated EV technology that includes trip demand and vehicle usage, vehicle relocation, and vehicle charging. Their results indicate that charging behavior is highly sensitive to different levels of charging due to the length of charging—which can affect service provision of trip demand.

The final topic of study considering synergistic opportunities between connected, automated vehicles and EVs focused on emissions benefits. Taiebat *et al* 2018 explore the environmental impacts of automated vehicles showing net positive environmental impacts at the local vehicle-urban levels due to improved efficiency, but acknowledge that greater vehicle utilization and shifts in travel patterns might to offset some of these benefits. Of course, EVs provide the significant benefit of eliminating tailpipe criteria-pollutant emissions, yielding significant human-health benefits. Regarding GHG emissions, two of the earliest studies on this topic examine the net effect of automation on reducing transport GHG emissions (Brown *et al* 2014, Wadud *et al* 2016). Greenblatt and Saxena (2015) conduct a case-study application of connected and automated vehicles in taxi fleets and find large emissions benefits associated with electrification. They find a decrease of GHG emissions intensities ranging from 87% to 94% below comparable ICEVs in 2014 and 63% to 82% below hybrid electric vehicles (HEVs) in 2030. The total emissions benefit is augmented relative to privately owned vehicles due to the higher travel intensity of taxi vehicles. Following these earlier works, additional case studies examine the hypothetical application of automated and electric fleets. These include two studies in Austin, Texas. Loeb and Kockelman (2019) examine a variety of scenarios to simulate the operation of different vehicle fleets replacing current-day transportation network companies and taxis. The primary goal of their work is to estimate costs associated with operation. They find that automated EVs are the most profitable and provide the best service among the vehicle-technology options that they examine. Gawron *et al* (2019) also perform a case study in Austin, Texas, but focus on the emissions benefits of electrifying an automated taxi fleet. They find that nearly 60% of emissions and energy in a base case CAV fleet can be reduced by electrifying powertrains. These improvements can be pushed up to 87% when coupled with grid decarbonization, dynamic ride-sharing, and various system- and technology-efficiency improvements. These results are consistent with a more generalized study by Stogios *et al* (2019), who, in a similar approach simulating fleet behavior, find that emissions from CAVs are most dramatically improved via electrification.

While EVs are a relatively new technology and automated vehicles are not widely available commercially, the implications and potential synergies of electrification and automation operating in conjunction are significant. The studies mentioned in this section are investigating a broad set of impacts when CAVs are coupled with EVs. Future research is necessary to generalize and refine many of these results. However, the potential for transformative changes to transportation emissions is clear.

8.1. Expectations for the future

EVs hold great promise to replace ICEVs for a number of on-road applications. EVs can provide a number of benefits, including addressing reliance on petroleum, improving local air quality, reducing GHG emissions, and improving driving experience. Vehicle electrification aligns with broader electrification and decarbonization trends and integrates synergistically with mobility changes, including urban micro-mobility, automation, and mobility-as-a-service solutions. The effective integration of EVs into power systems presents numerous opportunities for synergistic improvement of the efficiency and economics of electromobility and electric power systems, with EVs capable of supporting power-system planning and operations in several ways. Full exploitation of the synergies between EVs and VRE sources offers a path toward affordable and clean energy and mobility for all, as both technologies promise large-scale deployment in the future. To enable such a future continued technology progress, investments in charging infrastructure (and related building codes), consumer education, effective and secure VGI programs, and regulatory and business models supporting all aspects of vehicle electrification are all critical elements.

The coronavirus pandemic is impacting LDV sales in most countries negatively, and 2020 EV sales are expected to be lower than 2019, marking the first decline in a decade (BloombergNEF 2020). However, sales of ICEVs are set to drop even faster and, despite the crisis, EV sales could reach a record share of the overall LDV market in 2020 (Gul *et al* 2020). Despite these short-term setbacks, long-term prospects for EVs remain undiminished (BloombergNEF 2020).

Several studies project major roles for EVs in the future, which is reflected in massive investment in vehicle development and commercialization, charging infrastructure, and further technology improvement, especially in batteries and their supply chains. Consumer adoption and acceptance and technology progress form a virtuous self-reinforcing circle of technology-component improvements and cost reductions that can enable widespread adoption. Forecasting the future, including technology adoption, remains a daunting task. Nevertheless, this detailed review paints a positive picture for the future of EVs for on-road transport. The authors remain hopeful that technology, regulatory, societal, behavioral, and business-model barriers can be addressed over time to support a transition toward cleaner, more efficient, and affordable mobility solutions for all.

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