I Charge, Therefore I Drive: Current State of Electric Vehicle Charging Systems

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I charge, therefore I drive: Is this the new paradigm? The ambitious goals set by governments worldwide to phase out gasoline-powered cars are the driving force behind the upgrade of electric vehicle charging infrastructures. The EV industry and roadways departments may be asked to invest more in wireless charging, that is, without the need for any cable. Transmitter pads that can charge the EV in the garage, or even briefly at traffic lights, may convey the stationary wireless charge, whereas coils embedded into roadways may power electric vehicles as they drive overhead. The standardized wireless charge appears to be the optimum solution to placate the anxiety of drivers.

The transition to electric mobility is the natural choice to increase the overall efficiency of the public and private transport sector in relation to the ever-increasing use of energy from renewable sources. It is also worth noting the growing interest in autonomous driving technologies, which lend themselves to the smooth integration with electric vehicles, an ulterior push toward electric mobility. In addition, global zero-emission vehicle mandates and internal combustion engine bans also create additional push for EVs. For example, California announced a plan to ban the sale of new gasoline-powered vehicles starting in 2035. This ban will require that all new cars sold in the state by 2035 be free of greenhouse gas emissions.

May the near future have in store a scenario in which the streets of our cities will be noiseless apart from the quiet rustle of the electric motors?

Introduction

Vehicles need energy, of any form, to be driven. In terms of specific energy, 1 kg of gasoline contains approximately 12 kWh of energy, whereas 1 kg of Lithium-Ion battery may store an energy of 0.15 kWh; there is a ratio of 80 between the two energy sources, which is in favor of the gasoline. An internal combustion engine vehicle discharges approximately 160 gCO_2/km into the environment, whereas an electric vehicle (EV) discharges 45 gCO_2/km, due to CO_2 emissions from electricity generation. As electricity generation shifts more towards renewable sources like solar and wind, the upstream emissions for EVs will decrease even further. The tank-to-wheel efficiencies vary widely in range: 14 and 33% for vehicles that use gasoline, between 28 and 42% for diesel vehicles, between 14 and 26% for natural gas vehicles, and between 64.4 - 86% for EVs.

Though the higher efficiency of EVs and their reduced carbon footprint compensate for the lower energy density, one element seems to be the major concern: battery capacity. Based on manufacturers' datasheets, the authors have created the chart in Fig. 1, which shows the declared ranges (in km) of popular electric cars versus the battery energy available for that vehicle (in kWh).

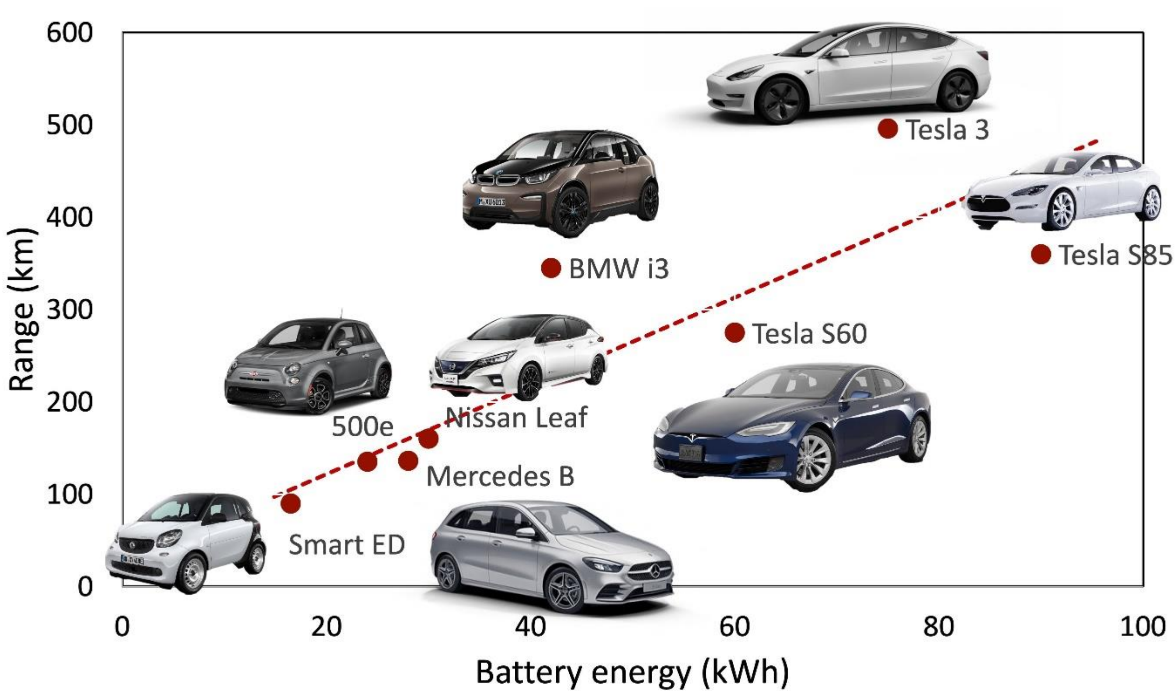

Fig. 1 Range vs. battery energy of EVs

As expected, the greater the battery capacity, the longer the range. Electric vehicles that deviate from the linear trend shown in the chart may feature different aerodynamics or have a different body mass.

Charging Infrastructures

Contrary to common assumptions, the challenges associated with recharging electric vehicles trace back even further than one might imagine, taking us back to the dawning days of the 20th century. During that era, the automotive arena featured a triad of electric, gasoline, and steam-powered vehicles. Electric cars, due to their limited range, excelled in short urban hops. Notably, the hummingbird moniker, a nod to their gentle motor hum resonating along London's avenues, graced electric taxis in bustling cities like Paris and London. However, the tide turned. The discovery of abundant oil reserves offered cost-efficient fuel, while expanding road networks and combustion engine innovations, such as the electric starter and the exhaust silencer to muffle the noise of the blasts inside the engine, which dealt a blow to both steam and electric rivals. And yet, EVs did not, and do not, require the replacement of various components such as oil, air filters, belts, caskets, spark plugs, and brake pads, etc., which makes them cheaper to maintain than fuel-powered automobiles. EV batteries are estimated to last 8-10 years or 100,000 - 200,000 miles before needing replacement. Gasoline engines may need major repairs like transmission rebuild or cylinder head gasket replacement around 100,000 miles. Improvements in battery chemistries and thermal management are extending EV battery life expectancy. Gasoline engines have matured technologically so major advancements are unlikely. A 2022 Consumer Reports study found the average battery replacement cost to be $6,000 for popular EVs like the Nissan Leaf and Chevy Bolt. CarMD estimates the average cost of an engine rebuild to be $3,861. While low-end EV battery replacements may be comparable to major engine repairs, the high end of battery replacement is still more expensive, currently. However, costs are expected to come down with better battery chemistries.

Today's charging infrastructure for electric vehicles (EV) leaves much to be desired. It takes at least 30 minutes to recharge a car and, more often, requires an hour of valuable time. This is not a problem when cars are parked at home overnight but when people are out and about, they would rather spend their time someplace other than a charging station. Compare this experience to a quick stop at a gas station, and you will see why electric vehicle owners may feel frustrated by the state of charging today.

The EV industry and local roadways departments may be asked to invest more in wireless charging - that is, without any cable, and may be stationary or dynamic. The stationary wireless charge calls for transmitter pads that can charge the EV when it is parked at home or even briefly at traffic lights. In some cases, this application is also referred to as stationary wireless charging. The dynamic wireless charge involves embedding coils into roadways that power electric vehicles as they drive overhead. The wireless charge may be the optimum solution to charging electric vehicles in the long run. This is especially true when considering the possible phasing out of gasoline-powered cars, as in the case of California and the European Union (EU); each has the objective to reduce emissions by 2035 and to ensure that by 2050 the transport sector can become carbon-neutral. EVs, therefore, might soon become the new normal, and the charging session at the pedestal may become longer due to the increased charging demand.

Significant experiments have already confirmed the usability of dynamic wireless systems for both light- and heavy-duty vehicles from the point of view of electrical infrastructure. However, the impact of the coils below the topmost layer of the road surface and the implementation of the billing mechanism still need to be assessed.

To address some of these issues, Siemens has proposed a conductive charging solution targeted at heavy transport called the eHighway, which is inspired by trolleybuses and their use of the pantograph. Despite the successful testing of this solution, the required infrastructure introduces significant installation and maintenance problems, especially in the presence of tunnels and viaducts. Some automakers, on the other hand, are focusing on the standardization of battery packs and their in-vehicle housing to perform the so-called battery swapping: The stop is no longer required to recharge but to replace the depleted battery pack with a charged one. Clearly, even this solution introduces significant logistical and operational problems related to battery ownership and interchangeability.

At present, even the most well-established wired charging of EVs is far from perfect. The rise of competing technical standards and proprietary solutions may have unnecessarily complicated things for EV owners. Knowing there are so many different wired charging technologies and plugs may discourage drivers from investing in an EV. People may worry they may not be able to charge their vehicle at a public charging station, just because their plug may not fit in the socket.

Worldwide Technical Standards

The major worldwide technical standards for wired charging include the IEC 62196; the CHAdeMO standards, proposed by five major Japanese automakers; the Tesla proprietary plugs; the Combined Charging System (CCS) standards; the SAE J1772; and the Chinese recommended standards GB/T 20234.

If you take a drive in Los Angeles with a zero-emission vehicle, hopefully you're in an EV that is not equipped with a GB/T 20234 plug, as you may not be able to find the right socket in the entire city to replenish the battery. In some cases, EV owners can buy adapters to charge EVs from different systems. For example, one can charge a Tesla from a CHAdeMO system, if they purchase an adapter for several hundred dollars but clearly this is not ideal.

In the US, the technical standard SAE J1772 Electric Vehicle Conductive Charge Coupler spells out the requirements for the wired (i.e., conductive) charging system and coupler with the power grid. The standard defines four levels of charging and the electrical ratings associated with each level.

To fully charge a FIAT 500e, which has a 24-kWh battery, with an AC Level 1 charge (i.e., the standard wall receptacle in a U.S. dwelling), it would take roughly 17 hours. To charge a Tesla S85, which has a 90-kWh battery, with a DC Level 2 charger (i.e., a standard recharge pedestal), it would take 1 hour. Charging it with a Tesla supercharger would take about 30 minutes.

Wireless Charging

There are other issues with wired charging besides its inconvenience and incompatibility. Disability advocates have raised concerns about the charging procedure, which they allege to be challenging to individuals with disabilities; this is due to difficulties accessing the plug hanging at the pedestal and the socket on the EV. In addition, there have been cases where charging stations have been vandalized and rendered unusable.

A further worry of EV drivers and vehicle occupants is range anxiety. On the global stage, Norway claims the title of the electric vehicle capital of the world. A telling testament to the prominence of this issue, the Norwegian Language Council, in 2013, assigned the second place on its "words of the year" list to the Norwegian equivalent of "range anxiety," known as "rekkeviddeangst".

The fear that the electric vehicle has insufficient capacity to reach its destination has been considered one of the major barriers to the large-scale adoption of all-electric cars. In 2016, a study suggested that range anxiety may not be justified by facts. Researchers stated that the analysis of people's driving habits across the country points out that current EVs have batteries with enough capacity for 87% of the total car trips.

Great progress in high-frequency switching converter technology has been made in the last few years, which has made wireless charging feasible at a reasonable price. Numerous standards on wireless charging have been published. [JM1]Notably:

- ✓ IEC 61980-1:2020 Electric vehicle wireless power transfer (WPT) systems - Part 1: General requirements;
- ✓ IEC 61980-2:2023 Electric vehicle wireless power transfer (WPT) systems - Part 2: Specific requirements for MF-WPT system communication and activities;
- ✓ IEC 61980-3:2022 Electric vehicle wireless power transfer (WPT) systems - Part 3: Specific requirements for magnetic field wireless power transfer systems;
- ✓ SAE J2954 202208 Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology;
- ✓ SAE J2954/2_202212 Wireless Power Transfer for Heavy-Duty Electric Vehicles;
- ✓ EN ISO 19363:2021 Electrically propelled road vehicles - Magnetic field wireless power transfer - Safety and interoperability requirements;
- ✓ GB/T 38775 Electric vehicle wireless power transfer standard;
- ✓ GB/T 38775.1-2020 Part 1: General requirements; GB/T 38775.2-2020 Part 2: Communication protocols between on-board charger and wireless power transfer device;
- ✓ GB/T 38775.3-2020 Part 3: Specific requirements;
- ✓ GB/T 38775.4-2020 Part 4: Limits and test methods of electromagnetic environment;
- ✓ GB/T 38775.5-2021 Part 5: Electromagnetic compatibility requirements and test methods;
- ✓ GB/T 38775.6-2021 Part 6: Interoperability requirements and testing-Ground side; and,
- ✓ GB/T 38775.7-2021 Part 7: Interoperability requirements and testing-Vehicle side.

Wireless power transmission has been studied for centuries. Nikola Tesla (1856-1943), for instance, conducted experiments on wireless electric energy transmission at long distance and presented a contactless system at the World Exposition of Chicago in 1893. Today, WPT covers several technologies in a wide range of applications, power, and distances; the resonant inductive power transmission (IPT) seems to be the most effective for EV charging. With this technology, a charging magnetic field is generated around a charging pad and is activated when an EV with a corresponding receiver, is present above it. In the case of dynamic WPT, consecutive charging pads can form a charging lane to allow the EV user to charge as they drive.

Different static applications have passed the prototype phase and may become the application of choice for automotive applications. Other systems have been tested for dynamic applications and include the Polito CWD system, developed by the team of the Politecnico di Torino (Italy), and whose structure is shown in Fig. 2. Another comparable system was tested at the Vedecom Institute in France. Both systems were developed and tested within the European Project "FeAsiBility analysis and development of on-Road chargIng solutions for future electric vehiCles" (FABRIC). Systems based on similar architectures are already being tested in real environments such as the Smartroad project in Gotland (Sweden) or the Arena del Futuro project in Italy. In the latter cases, the systems are applied to heavy vehicles oriented to public transport.

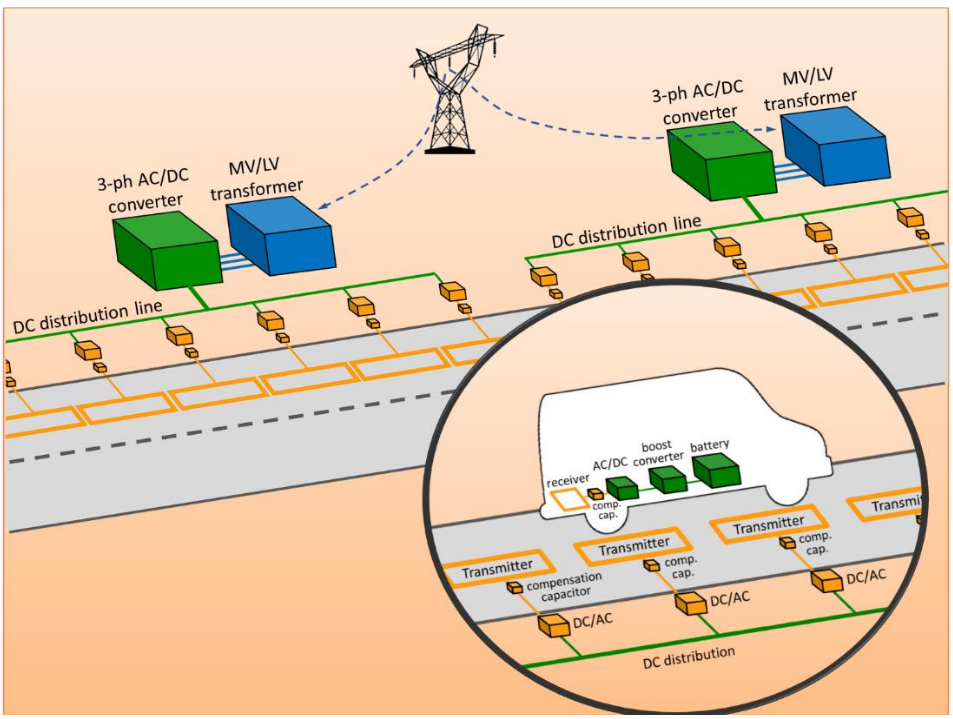

Fig. 2 Electrical system for the dynamic IPT proposed by the team of the Politecnico di Torino (Italy).

The transmitter pads can be embedded into the ground and supplied by the power grid via a power conversion chain. The contactless charge makes the system more reliable and noninvasive in urban areas. The future implementation of electrified road infrastructures (Fig. 3) would extend the range of EVs, placate the perceived range anxiety, and improve market penetration of EVs.

Following the description of the tested dynamic IPT systems, many wonder what effect such systems might have on the size (e.g., the capacity) of the battery installed in the vehicle. The answer, not immediately intuitive, is none. The same answer would apply to the conductive-type charging systems described earlier.

This misunderstanding stems from the misuse of the term charging which, in recent decades, has been associated with experimentation with IPT technology. In fact, in nearly all scientific works, dynamic IPT is intended as a substitute for conductive-type systems, such as those for railway or trolleybus traction. The main function of such systems is not recharging but powering. The ultimate goal is to maintain the level of the vehicle's battery charge throughout an entire long-distance journey, from that achieved when leaving the urban area. In this way, once exiting powering highway sections, the available energy will still be sufficient to reach the ultimate destination of the trip or a charging station in the urban area.

Clearly, the satisfaction of this balance depends on three factors: the average power absorbed by the vehicles during the journey, the rated power of the charging system, and the arrangement of the road sections equipped with the transmitter section components.

Fig. 3 Possible look of a future charging highway lane. *(from: https://www.bloomberg.com/news/articles/2015-08-13/the-u-k-is-testing-high-tech-roads-that-charge-your-electric-vehicle-as-you-drive)*

It is important to stress that existing lithium-ion battery packs used in most modern EVs today are compatible with wireless charging and do not require any modifications or special chemistry. The wireless power transfer works independently of the battery technology.

Solutions to Practical Issues

Solutions to practical issues for the deployment of the dynamic IPT are still to be standardized. The charging pad, for example, has been proposed in very different designs. For dynamic applications, the geometries on the transmitting side can be macroscopically divided into long track coils (i.e., order of 100 m) and lumped pads.

Clearly, this power level with this spatial displacement would require adequate electrical infrastructure at medium voltage levels.

The dynamic IPT standardization process has not fully started, yet the contactless charging system looks viable in its development, as confirmed by the interest of private and public investors. It is a fact that the present transportation system is a massive greenhouse gas contributor since almost 95% of its energy originates from petroleum-based fuels. Smart freeways and EVs, supported by the dynamic IPT technology, may be the sustainable transportation alternative, which will only be possible if supported by the political choices of governments, and with the interest of private and public institutions.

For static systems, standards have already established a minimum efficiency value under different alignment and power rating conditions. All experimentally validated prototypes in the literature present efficiency values not less than 90%, considering the entire conversion chain from the grid connection point to the battery terminals.

In dynamic systems, the evaluation of efficiency presents much more significant critical issues. The inevitable change in position during driving causes a continuous variation of the system's operating and measurement conditions. Thus, the efficiency evaluation is facilitated if performed in integral terms, such as comparing energies referring to a passage along a charging lane. The technical and technological complexity of such measurement brought forth the European project “Metrology for inductive charging of electric vehicles” (MICEV), in order to accurately measure the efficiency of inductive power transfer by analyzing several prototypes of static and dynamic IPT systems.

It is difficult, therefore, to identify a reference value for the efficiency expected from dynamic IPT systems. Based on the data accessible from the scientific literature, it seems reasonable to expect values of around 80%.

Safety Considerations

Because the EV occupants do not leave the vehicle during the dynamic wireless inductive charge, attention must also be paid to the possible adverse effects of the electromagnetic field on the driver and the passengers. Studies indicate that the magnitude of electromagnetic fields to which EV occupants, or pedestrians, may be subjected are below the basic restriction established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), as well as the IEEE, under all realistic operating conditions.

On the other hand, wired charging stations would be installed at locations such as shopping centers, parking lots, etc. Thus, the public interacting with EVs during charge must be protected against the risk of electric shock under both normal operating conditions and in the case of electrical failure of the charger and/or the vehicle. The electrical safety of the charging installation depends on the features of the charger itself. An effective solution consists of Class II chargers that feature double, or reinforced, insulation; this may be equipped with isolation transformers, galvanically separating the EV from the power grid. In this case, the probability of the failure of the double or reinforced insulation is deemed very low, and so is the chance that the public might come in contact with energized parts during the charge of the EV.

Amid discussions surrounding wireless charge adoption, a pivotal aspect often overlooked is its utilization by individuals with disabilities. By eliminating the need for complex cables, plugs, or charging stations, the act of charging is transformed into a mere parking maneuver.

Notably, this innovation extends its reach to protected cultural zones like historical city centers. Here, the wireless charging process seamlessly integrates without marring the aesthetic fabric, thus preserving the charm of these heritage-rich locales.

Furthermore, security remains at the forefront. The discreet nature of the wireless charging approach minimizes vulnerability to vandalism, thus ensuring a resilient and reliable charging experience.

Redundancy and fail-safes will be important in the infrastructure design to maintain uptime. Multiple power sources and segmented coil sections could provide N-1 or N-2 redundancy, similar to the power grid. The roads could allow both wireless and plug-in charging as a backup. Vehicles may have enough reserve charge to reach the next wired station in case of wireless outage. The infrastructure could be designed with resiliency against localized failures. Disabling one section of roadway coils should not cascade into widespread outage. Monitoring systems and physical security measures will help detect and prevent cyber attacks. Encryption of communication signals may also be implemented.

In essence, this transformative EV charging method transcends boundaries and caters to the needs of all, while harmonizing with the tapestry of both modern urbanity and historical heritage.

Conclusions

The transition towards electric mobility is critical to reducing greenhouse gas emissions and mitigating climate change. As outlined in this paper, advancements in battery technology and charging infrastructure will be instrumental in facilitating widespread adoption of electric vehicles.

While batteries with greater energy density will alleviate range anxiety, the development of ubiquitous and fast charging systems will also play a pivotal role. In particular, wireless and induction charging technology has emerged as a promising solution to enhance convenience and accessibility. By eliminating cables and standardizing connections, wireless charging can make “refueling” an electric vehicle as simple as parking.

Additionally, the integration of wireless charging coils into roadways could further extend range and reduce range anxiety. But work remains to optimize roadway infrastructure and address potential inefficiencies in energy transfer. Safety and accessibility for all users will also be paramount considerations going forward.

In summary, realizing the full potential of electric vehicles will require continued innovation across batteries, charging technology, and infrastructure. Key areas for additional research include increasing battery capacity and density, improving charging speeds, standardizing connections, and developing efficient on-road charging systems. As wireless and inductive charging matures, range anxiety will subside, and electric vehicles will become the sustainable and convenient option for green mobility.

For Further Reading

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