“Wireless charger”. “Electric vehicles”. Two concepts that are much talked about. Putting them together in a single sentence, as in “let me hook up my electric vehicle to my wireless charger?” Not so much.

Almost all EVs today use conductive charging, but there are lingering concerns. Safety is a potential issue, especially in wet conditions. Home-based 110V or 220V systems take up to 10 hours to fully recharge an EV. Public fast-charging stations have more power available and can charge EVs in much less time, but they take up large amounts of space, and the equipment can be stolen. Also, fast chargers can degrade battery life.

Wireless charging has been around for years in low-power consumer applications - wireless shavers are widely available, and electric toothbrushes have used it since the early 1990s. Even the medical field is using wireless charging for subcutaneous implants.

In automotive, wireless charging was a feature of the GM EV1, the first mass-produced EV from a major manufacturer. The EV1, as well as a few hundred first-generation Toyota RAV4 EVs and Chevrolet S10 EVs, charged via induction using a paddle conforming to the J1773 standard.
There were three charging levels. The vehicle itself included a 1.2kW level 1 charger, which ran off a standard 120V outlet. It could provide a full charge, but took as long as 14 hours; it was primarily intended to provide a quick charge to get the vehicle home or to a commercial charging station.

For home installation, a level 2 charger provided 6.6kW but required a 208-240vac supply. Recharging the EV1 to full capacity took as long as eight hours, although it could achieve 80% charge in one to three hours.

Unfortunately for J1773, in 2001 the California Air Resources Board (CARB) decided on J1772, a conductive (wired) charging interface, as the standard for California EVs, causing its demise.

After that, progress in wireless charging has been glacial, even though electric vehicles have been a part of the mainstream automotive landscape since the introduction of the Toyota Prius in 1997.

Now, though, the future is looking brighter. In its research report, “Wireless Charging Systems for Electric Vehicles”, Navigant Research forecasts that worldwide sales of wireless EV charging equipment for light-duty vehicles will grow by a compound annual growth rate (CAGR) of 108% from 2013 to 2022, achieving annual sales of slightly less than 302,000 units in 2022.

Let’s not get too excited, though. To reach the quoted sales in 2022 with a CAGR of more than 100%, the forecast needs to begin from a minuscule starting point of 400 units in 2013, a year that saw
Despite its slow progress in the market, wireless charging has several desirable features:

- The charging process is simple, automatic and doesn't require driver input
- Compared to a wired system, it’s resistant to vandalism and can even be installed underneath the garage surface
- No contact is required, and there are no exposed electric connections
- The impact on the vehicle is low – the installed equipment is small and light
- New designs have high efficiency, comparable to that of wired charging

**Principles of wireless charging**

Wireless charging for EVs uses near-field charging (NFC): a transmitting coil produces a magnetic field that transfers energy via induction to a nearby receiving coil. The fraction of the magnetic flux generated by the transmitter coil that penetrates the receiver coil and contributes to the power transfer is a function of the distance between the two coils. The transfer efficiency depends on the coupling (k) between the coils and their quality factor (Q).

![WPT system block diagram](source: Witricity)

A tightly-coupled system gives the most efficient transfer of power but at the cost of high sensitivity.
to coil misalignment. Such systems are popular for consumer applications such as cell phones where the transmitter and receiver are within a few millimeters. EV wireless charging demands more flexibility in coil alignment and a longer range, so it uses a system with a resonant receiver-transmitter combination. This allows for looser coupling but is less efficient.

Figure 1 shows the block diagram of a resonant charging system. If two high-Q resonators are placed in close proximity such that there is coupling between them, the resonators can exchange energy.

![Figure 1: Block diagram of a resonant charging system](image)

The equivalent circuit for such a coupled resonator is shown in Figure 2. The generator outputs a sinusoidal voltage with amplitude $V_g$ and frequency $\omega$ with output resistance $R_g$. The source (transmitter) and device (receiver) resonator coils are represented by the inductors $L_s$ and $L_d$, coupled through their mutual inductance $M$, where $M = k \sqrt{L_sL_d}$.

![Figure 2: Equivalent circuit for a coupled resonator system (source: Witricity)](image)

A resonator is formed by a coil and a capacitor in series. $R_s$ and $R_d$ are the parasitic resistances of the coil and resonant capacitor for the respective resonators. The load is represented by an equivalent AC resistance $R_L$.

The maximum power transfer efficiency (PTE) occurs at the resonant frequency and is a function of the electromagnetic coupling of the two coils. The power transfer (PT) between them occurs when the source and device impedances are matched. If the two coils are strongly coupled, PT varies with frequency, with twin peaks above and below the resonant frequency.

Both PTE and PT cannot be optimized simultaneously; EV charger designs normally focus on improving the PTE first, then use techniques such as adaptive impedance matching to boost the PT.
Coil design

The design and shape of the transmitter and receiver resonator coils have a key effect on system performance. For stationary charging, the transmitter coil is in the form of a flat pad containing the coil to generate the field and a ferrite layer to guide it, plus an aluminum layer for shielding.

Figure 3: Resonator coil arrangement (Source: Vahle/coilwindingexpo.com)

Each design has different characteristics: for example sensitivity to coil rotation, or flux pattern. Figure 3 shows a transmitter coil in a “double-D” (DD) shaped configuration with a bipolar field where the flux in each coil flows in opposite directions. This design has high sensitivity to receiver coil orientation (rotation) but does not require underbody shielding.

Standardization: SAE J2954

Standardization: SAE J2954

Although J1773 is dead, efforts are reaching fruition to develop an inductive charging standard for EVs, now renamed Wireless Power Transfer (WPT). The SAE has been working since 2012 on J2954, the standard that will govern wireless power transfer (WPT) for electric vehicles.

Participants include automotive OEMs such as GM, BMW, Ford, Nissan & Toyota, Tier 1 suppliers Delphi, Panasonic and Magna, WPT suppliers such as Qualcomm and LG, and a collection of other organizations such as the Argonne National Laboratory, the EPA, the DOT, UL and the University of Tennessee.
The goal is at least 90% efficiency for static charging in residential locations or parking lots. J2954 also plans for future on-road dynamic charging with embedded systems. The standard defines three levels of charging for both light-duty and heavy-duty applications, WPT1 (residential: 3.7kW), WPT2 (private/public parking: 3.7kW) and WPT3 (fast charge: 22kW).

For light-duty vehicle use, the SAE team has settled on a charging frequency of 85 kHz, which lies within an internationally available frequency band. The team hopes to finalize the J2954 standard by 2017 with recommendations to be released by the end of 2016.

Aftermarket systems and OEM activity

A number of suppliers are developing aftermarket inductive charging systems that can be added to EVs without voiding the warranty. Typically these make use of ground-based charging pads installed in a garage, parking facility or on the roadway.

Qualcomm's Halo WEVC technology uses such an approach. Tests have shown that a distance of 150mm (6 inches) provides the best efficiency, but a maximum height of 250mm (10 inches) is possible, allowing SUVs to use the wireless charging pads; operation at greater height will be needed to install pads under driveways or road surfaces in the future.

Evatran offers their Plugless L2 3.3kW static charging system for sale or lease direct to consumers. The system runs on 208 – 240 VAC residential power and includes an interlock to prevent simultaneous inductive and conductive charging. Initially, versions are available for the Chevrolet Volt, the Nissan Leaf, and Cadillac's ELR.
Witricity, working with resonant coupling IP developed at MIT, has announced the WiT-3300 development kit to help users evaluate their WPT technology. The company claims a power transfer of up to 3.3kW and coil-to-coil efficiency of up to 97% over a distance of up to 15 cm. Available options include testing software, a resonator test bench, and other evaluation items.

What of the OEMs themselves? They're waiting for inductive charging standards to be finalized before taking the plunge, although Infiniti did include WPT in their LE concept vehicle that they exhibited at the New York Auto Show in 2012.

Other OEMs are conducting feasibility studies and trials. In 2014, for example, Toyota announced that it was conducting verification testing of its 2kW wireless charging system. To help the driver park in an optimum charging position, the test vehicles include a parking assist function that indicates the position of the transmitting coil in the parking space.

In motorsports, although Formula E, the open-wheel racing series for electric vehicles, doesn't yet use wireless charging for race cars, its modified BMW i8 and i3 course cars stay charged with the Qualcomm Halo system; one car is located at each end of the pit lane to sprint to on-track incidents when needed.
Safety concerns

There are two main safety concerns with wireless systems: foreign objects between the coils, and the effects of EMI.

A metallic object between the transmitter and receiver coils can be heated by the magnetic field. Above a certain size, the heat generated poses a safety risk. One way to detect its presence is by the disturbance in the magnetic field caused by induced eddy currents, which can be detected by a sensor array. The WiTricity Wit-3300 system uses just such an approach; if it detects a potentially hazardous object, it shuts down the WiTricity power source via the CAN serial bus. Metallic objects less than 2.5 cm² do not pose a risk and are not detected.

The other concern is EMI. Careful coil design minimizes the amount of EM radiation that emanates outside the vehicle envelope, so even lying on the ground up against the vehicle does not heat tissue or pose an increased risk of cancer. In equipment, there is concern that wireless charging might interfere with the operation of other wireless equipment such as remote keyless entry (RKE) systems.

Looking to the future

Static WPT systems will slowly make their appearance over the next few years as aftermarket systems become more widely available. The pace will accelerate once J2954 is finalized, and OEMs begin incorporating WPT as a standard feature. Longer term, the charging infrastructure will slowly expand, with both standalone installations and as additions to gas stations.

One method being investigated is dynamic charging, where an EV recharges in quick bursts from distributed chargers during its daily travels. A partially dynamic charging system has undergone trials in buses; the bus picks up energy from when it pauses for thirty seconds or so each stop. Adding WPT allows the bus to have smaller batteries, reducing size, weight and cost.

Looking forward a decade or two, the really big change will be the implementation of fully dynamic charging, where EVs pick up power as they pass over coils embedded at intervals under the road surface.