

# Chapter 2

## Wireless Power Transfer for Electric Vehicles

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**Abstract** This chapter provides a basic description of OLEV and its enabling technology of SMFIR (Shaped Magnetic Field In Resonance). It then briefly compares OLEV/SMFIR with other vehicles that use IC engines and other electric vehicles in terms of environmental impact, performance, and cost, which are explored further in Part IV of the book. It also explains the potential benefits of electrifying ground transportation systems (EGTS) with a technology like OLEV and connecting these systems to smart electric grids. Finally, it describes efforts made to commercialize OLEV and lessons from these efforts.

### 2.1 Introduction to OLEV Technology

The key features of the On-Line Electric Vehicle (OLEV) are shown in Fig. 2.1. The OLEV wireless charging system consists of the following components:

- 1 A road-side *Power Inverter* to bring electricity from the electric grid system to the road embedded power tracks
- 2 A *Roadway Infrastructure* consisting of *Road-embedded Power Tracks* installed at selected locations of the bus route
- 3 A *Pick-Up and Regulator* kit for the wireless power transfer installed in or under the electric vehicle.

The OLEV road-embedded power tracks can be deployed in variable lengths on the route to meet the vehicle operating needs for recharging the battery to maintain

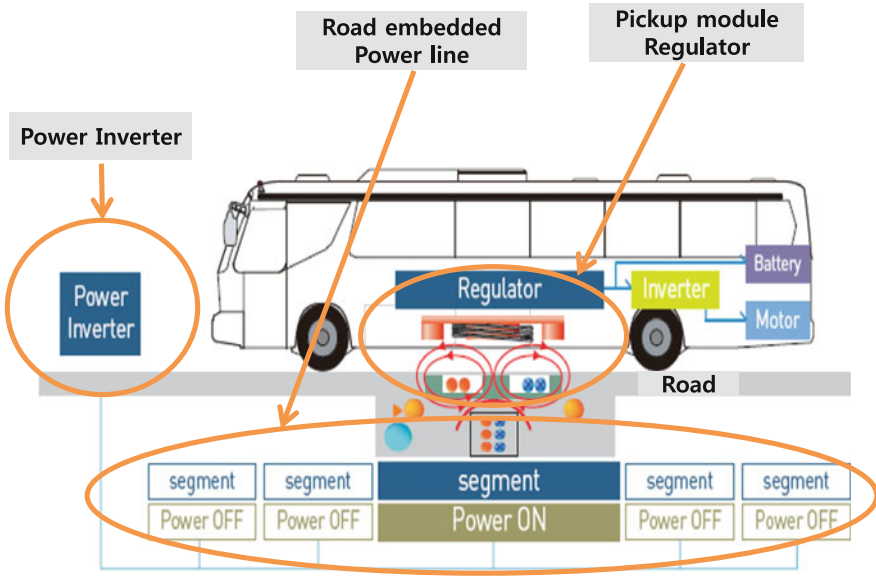
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**Fig. 2.1** Schematic diagram of an OLEV system

the energy balance level or providing sufficient power for its operation. The OLEV road-embedded power tracks are deployed in multiple segments so that only the segment over which the vehicle is moving above is turned on. The underground power supply system generates a two-dimensional magnetic field (perpendicular to the vehicle moving direction), which is picked up by the moving vehicle. It satisfies all international regulations, including safety.

The On-Line Electric Vehicle (OLEV) avoids the problems of conventional, battery-powered EVs—not just the weight but also the volatility of lithium-ion batteries, and the need to recharge the battery—by receiving its electric power dynamically (i.e., while in motion) and wirelessly via roads equipped with an underground power supply system. It is virtually, though not entirely, battery-less, for to provide autonomous mobility on roads not equipped with the underground power supply, OLEV carries a small battery on board. The externally supplied electric power both propels the OLEV and recharges the battery. The OLEV bus system is designed so that the electric charge in the battery returns to its original charge state when the vehicle makes a complete round trip. This charging occurs automatically when the vehicle is moving on roads with the underground power supply, without any input from the vehicle’s operator. The battery size for an OLEV bus is 5–20% the size needed for an all-battery-powered EV bus. (In the case of private vehicles that use plug-in charging, the battery must be large enough to supply electric energy until the vehicle can be plugged-in at home or at a charging station. OLEV batteries are typically charged to about 50% of capacity, which allows for the storage of excess energy and helps preserve battery life.) The length

of the underground power supply system, meanwhile, is optimized to minimize the overall cost of the OLEV system—which includes the cost of installing the underground power supply, the cost of the battery, and the cost of the vehicles themselves—while maximizing the speed of the vehicle and the range of autonomous mobility.

The new wireless electric power transfer technology is named as the shaped magnetic field in resonance (SMFIR).<sup>1</sup> SMFIR transfers heavy electric power—

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<sup>1</sup>Attempts to use wireless technology to charge electric vehicles have a long history. In 1894, Nikola Tesla, who spent many years experimenting with the wireless transmission of electricity, received a U.S. patent for his invention of an electric railway system using inductive coupling, although his idea was never put to use. In the 1990 s, General Motors and Toyota experimented with inductive charging in their first electric vehicles, and in 2002 a system of inductive charging (manufactured by the German firm Conductix-Wampfler) was implemented on city buses in Turin and Genoa, Italy. The Italian buses, however, use stationary charging, meaning that the vehicles can be charged only when stopped over induction coils installed in the road. See Markkus Rovito, “OLEV Technologies’ dynamic wireless inductive system charges vehicles while in motion,” *Charged*, 5/1/14, <https://chargedevs.com/features/olev-technologies-dynamic-wireless-inductive-system-charges-vehicles-while-in-motion/> (originally in *Charged* Issue 12–FEB 2014).

There are many ways of sending electric power over a large distance. One of oldest technologies for this is the electromagnetic radio signal transmitted by TV or radio antennas. The signal is propagated over a long distance, but because it is weak it must be picked up and amplified by supplying external electric power to the TV or radio. The technologies for wireless power transfer to EVs that have been tried may be classified into the following three types:

### 1. Magnetic induction

AC current flowing through a circular ring will generate three-dimensional magnetic waves. This field is picked up by a pickup unit mounted on a vehicle. This inductive technology has a basic limitation for EVs: the three-dimensional shaped magnetic field it generates cannot be picked up by another coil (on top of it) unless the two coils are in close proximity. Therefore, in some wireless power transfer technologies that use this technology, the top pickup unit is lowered to bring it into the requisite proximity to the bottom coil align precisely to obtain acceptable efficiency. This technology cannot be applied to moving vehicles.

### 2. Magnetic resonance

WiTricity Corp. has developed a technology based on an invention by Professor Marin Soljačić of MIT. In this technology, the coils generate electromagnetic waves that are picked up by a resonator at a large distance. This technology cannot be used to transmit the high power needed for transportation, however.

### 3. Shaped Magnetic Field in Resonance (SMFIR)

This technology, pioneered by OLEV, is different from the above technologies in several important ways:

- (a) It uses ferrite cores to shape the two-dimensional magnetic field in order to create a “magnetic field path” from the bottom ferrite core to the core attached to a moving vehicle. The high-intensity field is confined in a relatively well-defined space between the ground and the vehicle. This is equivalent to creating a loop from the poles of the underground ferrite core (think of the top two ends of the letter U as the two poles) through the poles of the top ferrite core (an inverse-shaped U) of the pickup unit attached to the vehicle. As the magnetic field oscillates through these ferrite “loops,” we pick up the energy associated with the magnetic

more than 100 kW—and overcomes the limitations of conventional EVs that have to recharge its batteries. (EVs need about 500–1250 kWh of electric energy, or 100–250 kW of electric power for about five hours of operation). The gap between the ground surface and the pickup unit attached to an OLEV bus is typically about 20–25 cm. The maximum efficiency of power transfer achieved to date is 85%, which depends on the size of the gap and the vehicle’s alignment with the magnetic field. (See Fig. 2.2) As the gap decreases—e.g., when vehicles are moving on rails—the efficiency increases significantly. In current installations, the underground power supply system is connected to a conventional electric grid, which will eventually be replaced by smart electric grids to better optimize the power distribution, generation, and storage. The resonance and the high quality factor (i.e.,  $Q$  factor) are the key requirements of SMFIR.

The input power to the underground system is 200 A at 440 V and 20 kHz. The magnetic field above the ground is shaped to reach the vehicle. To maximize the power pickup, the pickup unit mounted on the vehicle is tuned to the frequency of the magnetic field. The power picked up is supplied at 60 Hz in AC to the electric motor that drives the wheels of the OLEV, and to the battery in DC to recharge it. Two kinds of electromagnetic field (EMF) shielding are deployed to protect people from EMF radiation emitted by the SMFIR system: one embedded underground, and a passive cancellation system mounted on the vehicle. (Sometimes an active shielding system is mounted on the vehicle.) The EMF radiation from OLEV is well below the internationally specified level of 62.5 mG at 20 kHz. The power supply is segmented so that only the segment directly below the vehicle is activated.

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(Footnote 1 continued)

field using the resonance effect. In order to pick up the magnetic field, the top pickup unit must be in resonance with the field frequency of the lower unit imbedded in the ground, which creates a “continuous loop” of magnetic field. This is why we call our technology “Shaped Magnetic Field in Resonance” (SMFIR), which is a patented technology.

- (b) We control the height of the heavy magnetic power transfer by changing the width of the two ends of U-shaped ferrite cores; the farther apart they are, the greater is the height the field can reach.
- (c) Unlike magnetic induction, which generates a three-dimensional magnetic field, OLEV generates a two-dimensional magnetic field along the direction of the vehicle motion by having a series of U-shaped ferrite structure of the lower unit imbedded in the ground, which creates a “continuous loop” of magnetic field. This is why we call our technology “Shaped Magnetic Field in Resonance” (SMFIR), which is a patented technology.

Additional technical detail about SMFIR is provided in later chapters of this book. The technology for shaped magnetic field in resonance (SMFIR) system, a critical part of the development of OLEV, was designed and implemented by researchers at KAIST under the leadership of Professor D.H. Cho, using the theoretical design framework of axiomatic design. There are a large number of patents covering these technologies. For further discussion of wireless technology and its various uses, and of future applications for SMFIR, see Chap. 19.

		1G(Bus)	2G(Bus)	3G(Bus)	4G(Bus)
Date		July 14, 2009	Jan. 31, 2010.	Oct. 25, 2012.	Dec. 25, 2013.
Vehicle					
System Spec.	air-gap	17cm	23cm	23cm	23cm
	Efficiency	72%	81%	85%	85%
EMF		Less than 51mG	Less than 50mG	Less than 62.5mG	Less than 62.5mG
Power Rail (width)					
					
	1400mm		800mm	800mm	800mm
Pick-up	Pict ure				
	Power	12kW(pickup unit) 60kW(pickup total)	15kW(pickup unit) 75kW(pickup total)	33.33kW(pickup unit) 100kW(pickup total)	20kW(pickup unit) 100kW(pickup total)
	Weight	160kg(pickup unit) 800kg(pickup total)	110kg(pickup unit) 550kg(pickup total)	150kg(pickup unit) 450kg(pickup total)	90kg(pickup unit) 450kg(pickup total)
	Size (unit)	1600(W)×600(L)×110(H) mm <sup>3</sup>	1250(W)×740(L)×177(H) mm <sup>3</sup>	1250(W)×710(L)×165(H) mm <sup>3</sup>	1250(W)×740(L)×165(H) mm <sup>3</sup>

Fig. 2.2 Four generations of OLEV

OLEV’s first test of its SMFIR system in 2009 was the first successful demonstration of a wireless power system for electric vehicles in motion. The OLEV system has so far been deployed at four sites in Korea. The OLEV tram system originally installed in Seoul’s Grand Park as a pilot project in late 2009–early 2010 has been running as a commercial service since 2011, replacing a noisy and smelly diesel system. It travels on a 2.2 km circular path around the park, powered by an underground power supply system totaling 372.5 m in four segments (Fig. 2.3). In 2012, OLEV buses serviced the international exhibition Expo 2012 in Yeosu. Since 2012, two OLEV buses have been transporting students, staff, and faculty around the KAIST campus in Daejeon. In August 2013, OLEV was also installed in Gumi, an important industrial city in Korea with a population of 350,000. The thirty-five kilometer route is serviced by six buses and powered by six charging pads under the road (Fig. 2.4). Gumi added two more OLEV buses to its system in May 2016. The latest to install an OLEV system is Sejong, a newly developed city that houses many central government offices.



**Fig. 2.3** OLEV tram installed in Seoul's Grand Park



**Fig. 2.4** OLEV bus in Gumi. The *blue lines* indicate the location of the underground power supply cables

One exciting prospect arising from this technology is high-speed trains equipped with SMFIR. Europe has had high-speed electric trains for three decades, Japan for only somewhat less. Korea also has a high-speed electric train that is the primary mode of transport between major cities; the electricity cost of transporting a passenger on these high-speed trains from Seoul to Busan (about 200 miles) is extremely low. China has been building high-speed train-systems throughout the country, which may be a good investment in the long term. (Although the United States, for political reasons, has not yet been able to build high-speed railways, sooner or later it will end up building them—albeit at greater cost than necessary owing to the delay.) In Korea, KAIST and the Korea Railroad Research Institute

(KRRI) developed the proof of concept system for high-speed trains that can travel at 450–600 km/h using SMFIR transmitting one megawatt of electric power. These trains operate without the cumbersome overhead infrastructure (including sliding mechanical contacts for electric power transfer) that limits the speed of current high-speed train systems,<sup>2</sup> and thus require smaller (by 30%) tunnels than do current systems. Subways could also be built more cheaply with SMFIR since the overhead superstructure would not be needed. In existing subway tunnels, double-decker trains could be used at minimal additional cost. The KAIST team has also applied the SMFIR technology to a tram that runs on rails in cooperation with KRRI (Fig. 2.5).<sup>3</sup> Recently, in cooperation with many industries, KRRI and KAIST are developing the light rail transit with wireless charging, which will be commercialized in 2019.

In Korea, the one country in the world in which OLEV has so far been successfully commercialized, two studies have demonstrated the benefits, in terms of cost (including, in one case, the “CO<sub>2</sub> cost”), of OLEV technology versus more conventional technologies for city buses. It is estimated that, over a ten-year period, the cost of implementing and operating a new OLEV six-bus system (like the one currently operating in Gumi City) in another location in Korea would be about half of the cost of implementing and operating a similar route with CNG (compressed natural gas) buses [2].<sup>4</sup> In another study, the total cost of four different bus systems, i.e., diesel, CNG, OLEV, and plugin electric vehicles (PEVs), are compared as shown in Fig. 2.6 [2]. The total cost of the OLEV bus system is the lowest, despite a greater initial bus cost for the OLEV bus than for the diesel or CNG buses.

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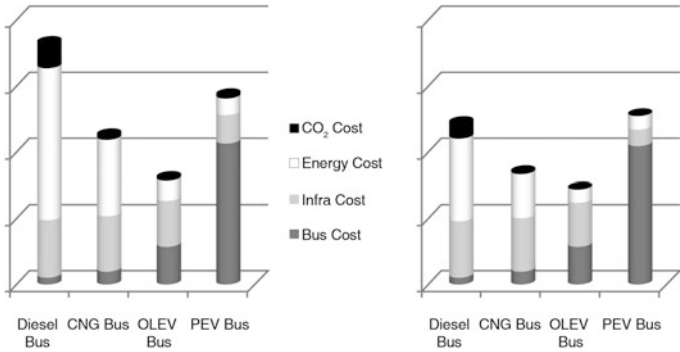
<sup>2</sup>Typical high-speed trains in Korea run at about 300 km/h. What limits their speed is the mechanical sliding contact between catenary electric wires and the pantograph on top of the train for transmission of electricity. Since the OLEV train runs on rails, its efficiency is expected to be up to 90% higher than that of the OLEV bus, because the pickup unit can be closer to the emitting unit. For additional discussion of wireless power transfer technology for trains, see Chap. 17.

<sup>3</sup>One interesting application area is the use of SMFIR to transmit electric power wirelessly to ships. Since the magnetic field is not affected by water, the SMFIR system can be deployed in water. A ship can charge its battery while in dock or while in motion in shallow waters.

<sup>4</sup>Implementing such a system, this study found, would cost approximately \$900,000 per bus for purchase of the vehicles plus installation of the OLEV infrastructure. This compares with a cost of approximately \$600,000 per bus for the purchase of six CNG buses (factoring in the government subsidy of \$300,000 for each OLEV bus and \$100,000 for each CNG bus; typical heavy-duty diesel buses cost from \$200,000 to \$600,000 [3]). However, the initial cost for the OLEV system would be offset by fuel savings over a ten-year period (during which the fuel costs for CNG buses would significantly surpass the fuel costs for OLEV buses). To make one round trip, a CNG bus uses \$20.58 worth of fuel, but the OLEV bus uses just \$3.92 worth of electricity. Over ten years, this adds up to \$4,500,000 of fuel for the six CNG buses, and just \$860,000 of electricity for the six OLEV buses. Adding in the carbon tax of \$401,000 for the use of natural gas, the total operating and capital cost of the CNG buses is about \$5,510,000 over ten years, while the OLEV buses cost \$2,659,000—about 50% less than the CNG bus system. Even without the government subsidy for the buses, the OLEV bus system still costs about \$1.5 million less. This study also estimates that over a ten-year period, the overall cost of an OLEV system is 40–60% that of an equivalent diesel bus system, because of fuel savings.



**Fig. 2.5** SMFIR-based tram tested in Korea (90 kHz power supply)



**Fig. 2.6** Cost comparison of diesel, CNG, OLEV and PEV bus systems. The figure on the *left* is for one dispatch every four minutes, and the figure on the *right* is for every ten minutes. The vertical axis is millions of US dollars [2]

The PEV bus is the most expensive of the four systems because of the higher initial cost for a bus. The operating costs of diesel and CNG are higher because of the fuel cost.<sup>5</sup>

<sup>5</sup>This analysis was based on a proposal submitted to the government by a city in Korea for a bus rapid transit (BRT) system. It assumed a 20 km bus line traveled by fifteen buses running at four-minute or ten-minute intervals (except for the PEV system, which would require an additional seven buses due to the thirty-minute battery charging time). The analysis also assumed an amortization period of nine years. The total operating cost was calculated based on the costs of the buses, the infrastructure, the fuel, and the CO<sub>2</sub>. The CO<sub>2</sub> cost was calculated under the assumption that 50% of the electricity was generated by nuclear power plants, via a formula advanced by a national environmental research institute in Korea.

How much would it cost to transition from a ground transportation system built mainly around vehicles with IC engines to EGTS using the SMFIR technology? To answer this question, we have to assess two major costs in addition to those for owning and operating OLEVs: the cost of generating more electric power for electrified ground transportation and the cost of laying the underground power supply system on roadways. To electrify ground transportation, additional electric power plants would obviously need to be built, although utilities and financial markets would support this because the costs would be recovered through increased electricity sales. (Although reductions of CO<sub>2</sub> and other GHGs achieved through EGTS would have to be balanced against increases in emissions from electricity generated from fossil fuels, capturing and sequestering emissions at power plants is more efficient than capturing it at the tailpipes of individual IC vehicles. Moreover, as we shall see, a system of wirelessly powered electric vehicles connected to the grid would facilitate the use of clean, renewable energy sources for electricity generation.)

The cost of electrifying roadways depends, of course, on what fraction of the roadway must have the underground power supply system installed in it. The three OLEV bus systems currently operating in Korea run with between 2 and 15% of their roadways electrified. Continuous, nonstop operations require longer roadway installations than those in which a bus waits at a station before the next run (since stations are equipped with infrastructure that charges the batteries automatically when the buses are stopped there). In major cities like Seoul, a maximum of only about 30% of streets might need to have the underground power supply system if all cars, buses, and trucks were OLEVs equipped with a small battery that could propel them for about ten miles between charges. Highways, where vehicles move at higher speeds, might need the underground power supply system installed in more than 50% of the roadway.<sup>6</sup> At any rate, as the number of OLEVs on the road increased, the cost of the infrastructure would be spread over this increased number and the cost per vehicle would decline, as the same infrastructure can be used by any number of OLEVs. This is in contrast to BEVs using stationary charging, for which additional infrastructure (charging stations or pads) must be installed as the number of vehicles on the road increases.

In Korea, which imports all of its energy, as well as in other energy-dependent countries, a commercial bus system like the one now operating in Gumi City could be cost-effectively implemented throughout the country. Korea consumes about 2.5 million barrels of oil per day, and in 2013 about 68%<sup>7</sup> of that oil was used for ground transportation. With the price of oil at \$100 per barrel,<sup>8</sup> Korea's annual expenditure for fuel used in ground transportation is roughly \$62 billion. If

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<sup>6</sup>Regardless of the speed of the OLEV vehicle, the time required to recharge the battery for use on roads without the underground power supply system remains the same. Therefore, as the average speed of OLEV increases, the length of the underground power supply system must be longer to maintain the same charging time.

<sup>7</sup>Energy Data Handbook 2013.

<sup>8</sup>The cost of petroleum fluctuates. In 2015, it came down to about \$50 a barrel.

adoption of EGTS reduced oil imports for ground transportation by 30%,<sup>9</sup> Korea could save about \$18 billion annually on fuel, which it could use to install the underground power supply system on about 9000 miles of roadways per year, assuming a cost of \$2 million per mile.<sup>10</sup> Electrification of all of Korea's 56,000 miles of paved roadways would take about six years, if all of the savings on oil imports were used for electrification (These are estimates that obviously depend on many factors including the price of oil, cost reductions via economies of scale, and the profit margins of vendors.).

All this being said, a more realistic scenario for the introduction of EGTS in most countries in the world would be not an immediate transition from IC vehicles to EGTS but, rather, a slower shift during which IC vehicles are gradually replaced (not without enormous resistance from those heavily invested in IC technology, primarily the oil industry and the old-line automobile manufacturers) with electric vehicles employing a variety of power and charging technologies that would then compete among themselves for dominance. The question we then need to answer is: Why OLEV rather than primarily battery-powered alternatives for EVs?

## 2.2 OLEV Versus Other EV Technologies

As noted in Chap. 1, there are several problems with using batteries as the primary source of power for EVs. The need to charge the battery periodically and the attendant limitations on vehicle range (particularly at the present stage of battery technology) create one major drawback for BEVs. The danger of electric shock posed by plug-in battery charging is another, while a lithium-ion battery—the type currently favored in BEVs—carries a flammable electrolyte that makes it essentially an explosive, as evidenced by the major fire and explosion of a Tesla car in 2013 when the lithium battery was punctured after the battery pack was hit by a “large metallic object.”<sup>11</sup> Finally, the disposal of used lithium-based batteries is going to be a major environmental issue when more than a billion vehicles use batteries, which is already

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<sup>9</sup>This is lower than Rao's estimate of 60%.

<sup>10</sup>The system installed in Gumi City cost \$1.4 million for 35 km (~22 miles), or \$64,000 per mile. It incorporated six charging stations, each costing about \$230,000. A new installation in the same city is budgeted to cost \$150,000 per charging section. The number of charging stations required increases with average vehicle speed, so highways require more of them than city streets. Two million dollars per mile is a generous allowance to cover costs such as installing electric power supply lines in Korea. In America the cost of the power supply infrastructure will be higher than \$2 million per mile, and in China it will be lower, due to differences in the cost of power components and equipment in the two countries.

<sup>11</sup>Per Liljas, “America's Safest Car Ablaze After Fire Starts in Battery Pack,” *Time*, October 3, 2013 (<http://business.time.com/2013/10/03/americas-safest-car-ablaze-after-fire-starts-in-battery-pack/>, accessed December 5, 2015.) In January 2016, a 2014 T Model S was destroyed after bursting into flames while charging at one of Tesla's “Supercharger” stations in Norway; see Clifford Atiyeh, “Tesla Model S Catches Fire at Supercharger Station in Norway,” *Car and Driver*, January 4, 2016

the most recycled consumer product [1]. Although we do not have experience with lithium-based batteries, the recent articles on lead batteries highlight future potential problems associated with using a massive number of lithium-based batteries.<sup>12</sup>

The weight of electrochemical batteries also decreases a vehicle's efficiency. In urban driving, with its frequent stops and starts, pure battery-powered EVs require more energy than an OLEV due to the weight of batteries. Since OLEVs are expected to be lighter than all-battery-powered EVs by 25% or more, the energy consumption of OLEV per unit of distance driven is expected to be less than those of BPEVs by roughly 10–20%. Moreover, if the same size engine is used in an EV as in an OLEV, the OLEV is going to have much higher acceleration, since acceleration is inversely proportional to the mass of the vehicle.

Finally, electrochemical batteries store electric energy (when charged) as chemical energy, then convert chemical energy to electric energy again, with a loss of energy and efficiency with every phase change. Simply put, carrying a vehicle's energy supply on the vehicle itself is an inherently inefficient system—particularly in contrast to wireless transmission for EVs, which is weightless. This is a compelling reason for hastening the transition to wirelessly powered EVs rather than continuing to rely on battery power.<sup>13</sup>

While few studies are available at this point for comparing OLEVs and more conventional EVs in terms of cost, effects on emissions, and the merits and demerits of carrying a large number of Li-ion batteries on board, this book presents research on the energy efficiency of OLEV buses versus plug-in hybrid and pure battery-powered ones (further details in Chap. 21), and on the systemic impacts of both OLEV and more conventional EV concepts on the transportation-electricity nexus in relation to which the performance of any EV must ultimately be evaluated (further discussed Chap. 20). Such research should help quantify the effect on GHG emissions of implementing BEV versus wireless dynamic technology. Future research will need to examine the long-term implications for safety, cost, sustainability, and geopolitics of using an astronomical number of lithium-ion batteries with increases in the number of EVs on the road. For example, just as the need for oil for automobiles has altered and even distorted geopolitics, the need to access lithium supply could have a similar effect, especially in the regions around the lithium-rich countries.

This is all separate, of course, from the issue of the potential impact of the two technologies on how electricity is generated and electricity usage managed as EVs

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(Footnote 11 continued)

(<http://blog.caranddriver.com/tesla-model-s-catches-fire-at-supercharger-station-in-norway/>, accessed January 5, 2016).

<sup>12</sup>Joshua Parlow and Joby Warrick, “A Dangerous Export—America's car-battery wastage is making Mexican communities sick”, Washington Post, February 26, 2016 (<http://www.washingtonpost.com/sf/national/2016/02/26/a-dangerous-export-americas-car-battery-waste-is-making-mexican-communities-sick/>).

<sup>13</sup>As battery technology continues to evolve in the direction of greater efficiency and safety, OLEV will benefit, as it uses small batteries for free autonomous mobility on roads without the underground power supply system.

began to supplant vehicles powered by IC engines. In 2014, the United States, the world's second-largest consumer of electric power (after China), generated roughly 37% of its CO<sub>2</sub> emissions from electric power plants fueled by coal and natural gas,<sup>14</sup> while 28% of its CO<sub>2</sub> emissions came from vehicles burning fossil fuels.<sup>15</sup> Thus the transition from internal combustion vehicles to EVs, which will increase demand for electric power, will only heighten the urgency of replacing fossil fuels with nuclear power and renewable energy sources to meet future electricity needs. One advantage of using OLEV technology for EGTS, compared with relying on battery power and stationary charging, is the way in which OLEV and EGTS could be used both to manage electricity demand and to facilitate the transition to renewable sources of energy for electricity generation.

### 2.3 OLEVs, Smart Grids, and Renewable Energy Sources

One of the well-known issues with renewables such as solar is that electricity generation from these intermittent sources fluctuates in ways that cannot be controlled, greatly adding to the inherent complexity of managing supply and demand on an electric grid. Although the simplest system is one in which total power generation and total power consumption match exactly at all times, this rarely occurs. Some systems have time-varying power demand, which must be matched by the power input. Conversely, the power input may vary as a function of time, such as when power is generated by windmills or solar cells.

When the input to the system cannot be controlled, the output (i.e., demand) side must be modulated to consume all the power coming into the system from the input ends. This modulation is performed by a “buffer” in the system. When the input power to the system is greater than demand, the excess energy is stored in the buffer (unless the demand for power can be increased artificially). When the demand for power is greater than the supply, the grid can use energy stored in the buffer (or increase the power input at the supply side by using standby electric power generators—e.g., gas turbines). In theory, with a large number of “smart” OLEVs connected to the grid and equipped with the requisite sensing and communications devices operating in real time, their batteries could act as buffers for the grid. Their limitation for this purpose would be the smallness of the battery or battery pack on an OLEV, although precise information on the time-varying fluctuation of demand, or of the power input, should allow a “smart” grid to function with a smaller buffer than otherwise.<sup>16</sup>

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<sup>14</sup>U.S. Energy Information Administration. <http://www.eia.gov/tools/faqs/faq.cfm?id=77&t=11>.

<sup>15</sup>U.S. Energy Information Administration. <http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=10>.

<sup>16</sup>To manage the dynamic nature of an electric grid with many diverse energy sources, sinks, and storage sites (and where some individual nodes can act as either a source, sink, or storage unit at various times), information must be measured and transmitted among all the elements on the grid including central power generation plants, distributed generation and storage systems, transmission

Meanwhile, the fact that OLEVs draw power from the grid and charge their batteries in real time (when most appropriate from the standpoint of system optimization), while battery-powered EVs have to be charged at fixed intervals, points to a way in which OLEVs could lend themselves much better than conventional EVs to deployment with renewable sources of electricity. The complexities of managing supply and demand on a typical electric grid are exacerbated by the fact that the value of electricity depends on the time of the day at which it is consumed: at night, when demand is lower, electricity is more plentiful and thus cheaper than during the day. For owners of battery-powered EVs, this is currently creating an incentive to charge vehicles overnight after they have discharged their batteries during the day. According to a recent report, however, from the U.S. National Renewable Energy Laboratory that examines new technologies and systems with the potential for achieving “transformative reduction” of GHG emissions from transportation, “analysis of the electrical energy demand of electrified roadways highlights that the demand time period may coincide with renewable generation and thus lead to expanded capability to accommodate renewables in the electrical grid and reduction of the GHG impacts of transportation.” In other words, a system like OLEV that draws its power in real time from electrified roadways could actually help advance the integration of renewables into electrical power supply systems—thereby increasing the impact it would already have on reducing GHG emissions because of its greater efficiency compared with vehicles that carry their power source on board.<sup>17</sup>

Finally, smart OLEVs connected in real time to the grid in an electrified ground transportation system could also provide accurate and dynamic data on vehicles in use for: (1) communication among vehicles for purposes including minimizing traffic congestion, collision avoidance, driverless steering, and even remote control of EV operating speeds; and (2) systems for charging drivers for electricity use, which could facilitate uses including congestion pricing and vehicle sharing.

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(Footnote 16 continued)

nodes and plants, and consumers (stationary or mobile). This is the reason for making the electricity grid “smart.”

<sup>17</sup>As this report notes in another place, “In high renewable penetration scenarios, curtailment of renewable generation occurs seasonally when load is low and renewable generation is high. Electrified roadway scenarios move some of the load that would have occurred in the evening to the daytime periods and thus offers new load that can utilize the excess renewable generation.” Laura Vimmerstedt et al., *Transformative Reduction of Transportation Greenhouse Gas Emissions: Opportunities for Change in Technologies and Systems* (Golden, CO: National Renewable Energy Laboratory, April 2015), pp. 45, 47. The author is grateful to one of the report’s co-authors, Tony Markel of NREL, for answering questions about its findings.

## 2.4 Paving the Way for OLEV

OLEV offers considerable advantages as a technology for the ground transportation of the future, and in many ways seems far and away the most logical one so far invented and actually demonstrated. Yet its introduction and adoption on a large scale are, of course, by no means inevitable and will not happen without difficulty. Some of the major challenges are suggested by the attempts to date to commercialize the technology outside of its home country of Korea.

The commercial implementation of OLEV in Korea to date has been carried out by a company, Dongwon OLEV, that was founded in 2011 and granted an exclusive license to commercialize the technology in Asia. The Dongwon Group is a Korean conglomerate involved in marine products and logistics, food processing and distribution, industrial materials, construction, information and communication technology, IT services, and—with the establishment of Dongwon OLEV—green transportation. Dongwon OLEV installed the OLEV systems now operating in Gumi City, KAIST campus and Seoul Grand Park and will do the installations in Sejong. The central government and regional government in Korea jointly provided funding for these projects. These OLEVs operate at 20 kHz and are designed to receive 100 kW of power. The high-speed train developed by KAIST and KRRI operates at 60 kHz and transmits 1000 kW wirelessly. Meanwhile, a company called OLEV Technologies, headquartered in Boston, was also founded in 2011 with an exclusive license to commercialize OLEV in the Americas and co-exclusive rights (with Dongwon OLEV) for Europe and Africa. Two old friends in the United States who were on the President's Advisory Council at KAIST and who wanted to help KAIST realize its goal of commercializing OLEV<sup>18</sup> put personal funds into a venture company in the United States to launch the company.

The primary challenge OLEV Technologies has faced to date is that EVs of the kind for which OLEV, in its current state of development, is well suited have not yet penetrated the market in sufficient numbers.<sup>19</sup> There are currently less than 100

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<sup>18</sup>These two angel investors were Dr. A. Neil Pappalardo, the founder and CEO of MEDITECH, Inc., and Dr. "BJ" Park, the founder and former CEO of MTL, Inc.

<sup>19</sup>The first president of OLEV Technologies, Dr. Hikyu Lee, attempted to sell the patented and proprietary OLEV system for use with buses in the United States. As each OLEV 20 kW power unit weighs 400 lbs., the technology is currently too heavy for smaller vehicles but still lighter than the battery packs carried on battery-powered electric buses. A regional port authority showed interest in purchasing the system for airport buses but balked at the idea of OLEV Technologies, a for-profit company, making a profit from the sale.

In 2013, with OLEV Technologies having gone through its first round of funding, the board wanted new leadership to pursue opportunities for sales to the private sector. We brought in Bryan S. Wilson, who had spent the previous twelve years developing infrastructure for the wireless communications industry. The company's two angel investors put in a second round of funding and Wilson began to looking to sell the OLEV technology to concerns including shuttle operators, ports (where electric vehicles are an attractive option for transferring cargo from ships to trucks and trains and vice versa), and mining companies. A major multinational corporation with mining interests showed interest in OLEV for electric mining vehicles that operate underground (making battery

electric buses in operation in the United States. These vehicles are either battery-powered and being recharged with plug-in systems overnight, or are powered by overhead conductive systems. Both options are much less than optimal, but this is the way the vehicles are currently being built by the OEMs. For OLEV Technologies to have an adequate customer base, there will have to be a sufficient number of EVs in the marketplace, or being readied for the marketplace, so that OLEV systems could either replace existing systems or become a component of new vehicles. (The latter would require partnering with OEMs who are currently not selling enough of their own vehicles using plug-in technology or battery-swapping to be seeing any demand for online vehicles, at the cost of an OLEV system, at present.) Even at its current cost, OLEV (as one of the studies cited above makes clear) makes good economic sense in terms of total cost of ownership for bus operators using diesel buses, although this has not yet created enough demand for such a system. It also seems worth noting that two major companies selling inductive power transfer systems for electric vehicles (IPT Technology in Germany and the Canadian multinational Bombardier<sup>20</sup>) have installed numerous systems for electric buses in Europe, but all of these systems currently use wireless power only for stationary charging. If a deep-pocketed company like Bombardier—which has its own technology for wireless dynamic power transfer—saw a market, at present, for a wirelessly powered vehicle, it would certainly have the means to commercialize it, but so far it has not.

Given the reality, however, that the IC engine needs to be replaced by electric ones in order to reduce GHG emissions from vehicles to the necessary levels, wireless dynamic power transfer for vehicle operation (not just for charging a battery-powered vehicle) is the best technology available over the long run because of the inherent inefficiency of a vehicle carrying its own energy supply on board. In some countries, government will step in, embrace the idea of EGTS as part of its long-term energy policy, and give the technology a boost by

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(Footnote 19 continued)

charging and swapping challenging), but wanted to have a product to try out; not being in the business of producing vehicles, or having relationships with OEMs that could produce vehicles equipped with OLEV pickup units, OLEV Technologies was unable to supply a product. A company that makes vehicles for airport baggage transfer expressed interest in having its vehicles equipped with OLEV technology, but the technology costs more, at present, than the vehicles it would have been installed for. A heavy equipment manufacturer making electric vehicles for which OLEV would be a good fit appeared to be another prospect, but was still trying to develop its own customer base for its products. As these sales efforts came up short, OLEV Technologies began seeking grant money from government agencies interested in trying out its system, only to have these initiatives founder on the complexities of doing business with government.

<sup>20</sup>For a description of Bombardier's PRIMOVE wireless power transfer system for trams, see Chap. 17.

underwriting road electrification just as it constructed today's highway systems.<sup>21</sup> The cost-benefit analysis for installing the infrastructure for a system like OLEV will, of course, vary from place to place and is subject to many variables including future improvements in battery technology for BEVs, in capacitors (which could replace the batteries in OLEVs if there were enough underground charging infrastructure installed), and in OLEV technology itself (e.g., reduction of the weight and size of the pickup unit).<sup>22</sup> China and India may prove to be the real proving grounds for wirelessly powered vehicles. China will eventually have the largest market for automobiles in the world, followed by India. These two

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<sup>21</sup>Sweden and the U.K. are two countries where the government has been funding, or has pledged to fund, research on the feasibility of electrified roads for vehicles using wireless dynamic power transfer. In Sweden, a project launched in 2010, managed by Volvo Group Trucks Technology, and partly financed by the Swedish Energy Agency studied and proposed means of transmitting electrical energy from highways to vehicles via both conductive and inductive (i.e., wireless) technology. Scania AB, the Swedish commercial vehicle manufacturer, and Bombardier developed the project's "inductive energy transfer solution" based on Bombardier's PRIMOVE. In 2014, two organizations involved in this study, the Swedish Transport Administration and the research institute Viktoria Swedish ICT, partnered with the independent Swedish National Road and Transport Research Institute to test electrified roads employing both conductive and inductive technology in a "driving simulator." In 2015, the U.K.'s Transport Minister, Andrew Jones MP, announced that the government was allocating £500 million (\$781 million) over five years to finance off-road trials for road electrification using dynamic wireless power transfer technology. Both countries have also begun implementing wirelessly charged city buses. See Viktoria Swedish ICT on behalf of Volvo GTT and Scania CV, "Slide-in Electric Road System, *Inductive project report*" (Scania CV, October 18, 2013), pdf available at [https://www.viktoria.se/sites/default/files/pub/www.viktoria.se/upload/publications/slide-in\\_inductive\\_project\\_report\\_draft\\_phase\\_1\\_2013-10-18.pdf](https://www.viktoria.se/sites/default/files/pub/www.viktoria.se/upload/publications/slide-in_inductive_project_report_draft_phase_1_2013-10-18.pdf) (accessed January 6, 2016); VTI (Swedish National Road and Transport Research Institute), "Electric roads: a solution for the future," press release January 16, 2015 (<http://www.vti.se/en/news/electric-roads-a-solution-for-the-future/>, accessed January 6, 2016); Highways England and Andrew Jones MP, "Off road trials for 'electric highways technology,'" press release August 11, 2015 (<https://www.gov.uk/government/news/off-road-trials-for-electric-highways-technology>, accessed January 6, 2016); Federico Guerrini, "The UK Will Be Trialling Roads That Wirelessly Recharge Your Electric Vehicle While You Drive," *Forbes*, August 13, 2015 (<http://www.forbes.com/sites/federicoguerrini/2015/08/13/the-uk-will-be-trialling-roads-that-wirelessly-recharge-your-electric-car-while-you-drive/>, accessed January 6, 2016); Scania Group, "Scania to test wirelessly charged city bus for the first time in Sweden," press release December 17, 2014 (<http://www.scania.com/media/pressreleases/N14050EN.aspx>, accessed January 6, 2016); and Neil Bowdler, "Wirelessly charged electric buses set for Milton Keynes," BBC News, January 9, 2014 (<http://www.bbc.com/news/technology-25621426>, accessed January 6, 2016).

<sup>22</sup>The size and weight of the pickup unit mounted on an OLEV vehicle should be able to be reduced so that the weight drops from 400 lb to about 100—perhaps by laminating thin layers of ferrite to get rid of eddy current fields and skin effects. (This is pure speculation at this point, not based on firm physics.) Meanwhile, we can do a rough lower-bound estimate of the cost of EVs and EGTS. We will assume that there are six billion people on earth and one billion cars on the road. If we assume that cars are used for ten years, we will have to replace 100 million cars a year. If we further assume that the cost of the battery in each EV is \$1000, we will be spending \$100 billion a year on batteries. If we assume that the infrastructure for EGTS lasts six years, each year we could invest \$600 billion for infrastructure rather than in batteries. The need for additional cost-benefit analysis for OLEV is discussed in Chap. 16.

nations must expand their transportation systems since both are still in the process of catching up in terms of automobiles per capita. What they ultimately do for the electrification of ground transport systems will have a big impact on OLEV and other EV technologies, and the fact that their systems are in nascent state could enable them to leapfrog at least some road construction for IC vehicles and BEVs and go straight to electrified roads. If they embrace EGTS, they will become a formidable force pushing the global automotive market in this direction, stimulating innovation and demand for OLEV-type systems and helping to drive down costs for both vehicles and infrastructure including inverters, ferrite and other magnetic materials, special electric cables, capacitors, and special construction equipment.<sup>23</sup>

In the United States, which lags other advanced countries in public spending for transportation infrastructure, the adoption of OLEV or another OLEV-like technology is most likely to be accomplished through a gradual commercialization process that will resemble the spread of cellular phone technology, expanding outward from a small core of users as the technology is proven and gains in popularity while network effects increase its economic value. Such a process may begin with buses traveling on fixed routes in urban settings—school buses and transit buses, for example—with public-sector vehicle operators paying for cost of the infrastructure. As inverters and underground coils are installed, systems could then be extended for public uses like garbage pickup, or private ones like corporate shuttles, and expand outward from there. This process will begin in urban cores, where services such Uber and ZipCar will also benefit from it, and move outward from there. Inter-city and long-distance road electrification even in such a large country as the United States might also not prove as daunting as one might think. The National Renewable Energy Laboratory, for example, has already estimated that “[e]lectrifying 1% of U.S. Interstate Highways would cover 17% of traveling road vehicles ... [e]lectrifying 5% of U.S. Interstate Highways would cover 40% of traveling road vehicles ... [and] [e]lectrifying 25% of U.S. Interstate Highways would cover 80% of traveling road vehicles.”<sup>24</sup>

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<sup>23</sup>The production cost of airplanes decreases by 10% each time the production volume doubles. Assuming a similar pattern in bus production, if Korea were to produce 1000 OLEV buses a year, the cost of the buses would be reduced by 65%. The U.S. market for buses in 2012 was around 74,000 [3]. Using the same mass production algorithm, we would expect a similar reduction in manufacturing cost. Mass production of key components of the ground transportation system, including buses, inverters, and ferrite cores, could reduce the cost per component by two-thirds (Willcox 2004). Overall, I believe that the cost of the components that go into OLEV and EGTS will decrease by 50% or more if demand increases sufficiently. The price for the ferrite core, for example, should come down through redesign and more R&D when demand for the product increases.

<sup>24</sup>Vimmerstedt et al. “Transformative Reduction of Transportation Greenhouse Gas Emissions: Opportunities for Change in Technologies and Systems,” National Renewable Energy Laboratory/U.S. Department of Transportation (NREL/TP-5400-62943 April 2015), p. 72. For an analysis of how EV penetration will be affected by choices made about plug-in versus online infrastructure, see Chap. 22.

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