AUBURN UNIVERSITY

Smart Grids

Chapter 3. Smart Energy Resources – Supply and Demand
3.5 Electric Vehicles

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Sources:

1. Smart Grids – Advanced Technologies and Solutions, Second Edition, Edited by Stuart Borlase, CRC Press, Taylor & Francis Group, 2018
2. www.nrel.gov/publications.html

3.5 ELECTRIC VEHICLES
3.5.1 REGULATORY AND MARKET FORCES

- With the implementation of smart grid technologies and the associated improvements in the reliability, sustainability, security, and economics of the electric grid comes the opportunity *to include vehicles as an active participant in the smart grid.*
- Although electrification of segments of the transportation energy sector does not require any technological or systemic advancements of the electric grid over what is presently available, the large scale of the transportation energy sector will provide long-term challenges to the legacy systems of the electric grid along with considerable opportunities for improved *power, energy, and economic* management in a smart grid system.

3.5.1 REGULATORY AND MARKET FORCES

- Electric transit (including electric trains and catenary trolleybuses) has a long history of integration with the electric grid. Electric transit has traditionally always operated at large, centralized scales, “tethered” to the grid (AKA Light Rail).
- These technologies require a more-or-less continuous provision of electricity during operation of the vehicle.
- The introduction of high-density energy storage has introduced a watershed change in electric transportation in the form of distributed, small vehicles operating in an untethered mode.
- The ongoing and large-scale introduction of Plug-in Electric Vehicles (PEVs) to the world automotive fleet is one of the most important changes to the transportation energy sector in history, and the capabilities of the smart grid will play a large role in determining whether the electricity sector can realize benefits from this integration.

3.5.1 REGULATORY AND MARKET FORCES

Cincinnati streetcars in April 1951, a week before streetcars service was ended. Streetcars in Cincinnati were replaced by trolleybuses (seen behind the streetcars).

Pacific Electric Railway streetcars stacked at a junkyard on Terminal Island, March 1956

Opened in 2001, the Portland Streetcar was the first streetcar system to be established in the United States in over 50 years.

"tethered" to the grid

3.5.1 REGULATORY AND MARKET FORCES

- Relative to a conventional internal combustion engine (ICE) vehicle or conventional HEV baseline, there are numerous potential benefits that come with the electrification of transportation energy through PEVs:
  - Reduced petroleum (fossil fuel) consumption
  - Lower life-cycle greenhouse gas and pollutant emissions (depending on the mix of electricity generation type)
  - Typically lower fueling costs
  - Lower life-cycle cost of ownership (depending on vehicle comparison)
- The investment in infrastructure will include public and in-home electric charger installations, which will incorporate passive or active forms of communication to facilitate the integration of large fleets of PEVs onto the electric grid.

3.5.1 REGULATORY AND MARKET FORCES

Comparison of tailpipe and upstream CO_2 emissions[(1)] estimated by EPA for the MY 2014 plug-in hybrids available in the U.S. market as of September 2014[171]

Vehicle	EPA rating combined EV/hybrid (mpg-e)	Utility factor[(2)] (share EV miles)	Tailpipe CO_2 (g/mi)	Tailpipe + Total Upstream CO2		
				Low (g/mi)	Avg (g/mi)	High (g/mi)
BMW i3 REx[(3)]	88	0.83	40	134	207	288
Chevrolet Volt	62	0.66	81	180	249	326
Cadillac ELR	54	0.65	91	206	286	377
Ford C-Max Energi	51	0.45	129	219	269	326
Ford Fusion Energi	51	0.45	129	219	269	326
Honda Accord Plug-in Hybrid	57	0.33	130	196	225	257
Toyota Prius Plug-in Hybrid	58	0.29	133	195	221	249
BMW i8	37	0.37	198	303	351	404
Porsche Panamera S E-Hybrid	31	0.39	206	328	389	457
McLaren P1	17	0.43	463	617	650	687
Average gasoline car	**24.2**	**0**	**367**	**400**	**400**	**400**

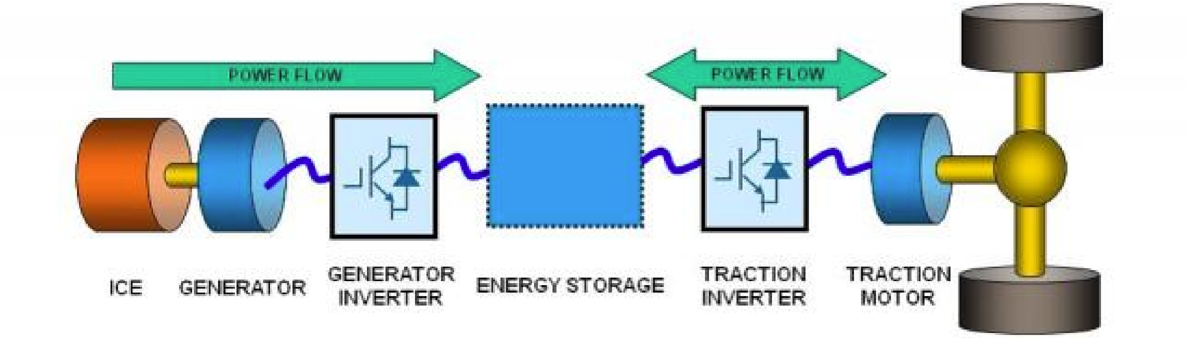
Notes: (1) Based on 45% highway and 55% city driving. (2) The utility factor represents, on average, the percentage of miles that will be driven using electricity (in electric only and blended modes) by an average driver. (3) The EPA classifies the i3 REx as a series plug-in hybrid[171][173]

3.5.2.2 Plug-in Hybrid (PHEV)

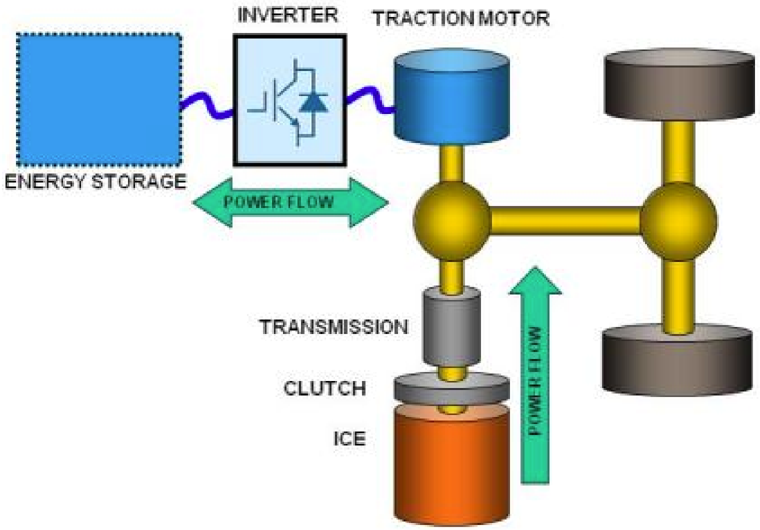
- A PHEV is a type of EV that has an ICE and an electric motor (like an HEV) and a high-capacity battery pack that can be recharged by plugging-in the car to the electric power grid (like a BEV). There are two basic PHEV configurations:
  - Series PHEVs or Extended Range Electric Vehicles (EREVs) are Plug-in Electric Vehicles (PEVs) where only the electric motor and drivetrain provide tractive power to the wheels and the ICE is only used to generate electricity.
  - Parallel or blended PHEVs are PEVs where both the engine and electric motor are mechanically connected to the wheels, and both propel the vehicle under most driving conditions. Electric-only operation usually occurs only at low speeds.
- The main advantage of PHEVs with respect to BEV is that PHEVs have longer driving range and shorter recharge time. Relative to conventional internal combustion engine vehicles, PHEVs are characterized by lower operation cost and lower environmental impact.

3.5.2.2 Plug-in Hybrid (PHEV)

- **Series hybrid systems** - use two power sources linked together, with only one source directly connected to the vehicle's transmission. A small ICE is used to power a generator that converts the energy to provide electric power to the vehicle's wheels and auxiliary devices as well as to a battery system and/or capacitor(s).



- **Parallel hybrid systems** - provide a dual power supply that is physically connected to the vehicle's driving wheels. Either the ICE or the electric motor – or both – can power the vehicle's wheels.



3.5.2.2 Plug-in Hybrid (PHEV)

Cost comparison between a PHEV-10 and a PHEV-40[148][150] (prices for 2010)

Plug-in type by EV range	Similar production model	Type of drivetrain	Manufacturer additional cost compared to conventional non-hybrid mid-size	Estimated cost of battery pack	Cost of electric system upgrade at home	Expected gasoline savings compared to a HEV	Annual gasoline savings compared to a HEV(2)
PHEV-10	Prius Plug-in(1)	Parallel	US$6,300	US$3,300	More than US$1,000	20%	70 gallons
PHEV-40	Chevy Volt	Series	US$18,100	US$14,000	More than US$1,000	55%	200 gallons

Notes: (1) Considers the HEV technology used in the Toyota Prius with a larger battery pack. The Prius Plug-in estimated all-electric range is 14.5 mi (23 km)[151]
(2) Assuming 15,000 miles per year.

3.5.2.3 Battery (BEV)

- A battery electric vehicle (BEV) is a type of EV that uses rechargeable battery packs to store electrical energy and an electric motor for propulsion.
- Intrinsically it is a PEV since the battery packs are charged via the electric vehicle supply equipment (EVSE), that is, by "plugging-in" the BEV.
- Society of Automotive Engineers (SAE) standard SAE J1772 for the EV Charging:

	Voltage	Max. Continuous Current
Ac Level 1	120 V (input ac)	12/16 A (input ac)
Ac Level 2	240 V (input ac)	<80 A (input ac)
Dc Level 1	50–500V (output dc)	80 A (output dc)
Dc Level 2	50–500V (output dc)	200 A(output dc)

3.5.2.3 Battery (BEV)

- At present, a variety of lithium-ion chemistries has demonstrated the ability to meet these requirements in the automotive application.
- Since BEVs do not have ICE, their operation fully depends on charging from the electric grid. Therefore, uncontrolled charging cycles of BEVs under scenarios of high market penetration may cause increased loads on power distribution systems.
- If BEVs are charged upon their return to “home,” their loads may be coincident with the afternoon/evening residential demand peak, leading to higher costs to generate, transmit, and distribute electricity to vehicles
- In the US, BEVs are, as of 2016, the highest selling EVs in the market.
- US PHEV and BEV sales for the 2010–2016 period exceeded 450,000 units, as shown in Figure 3.7.

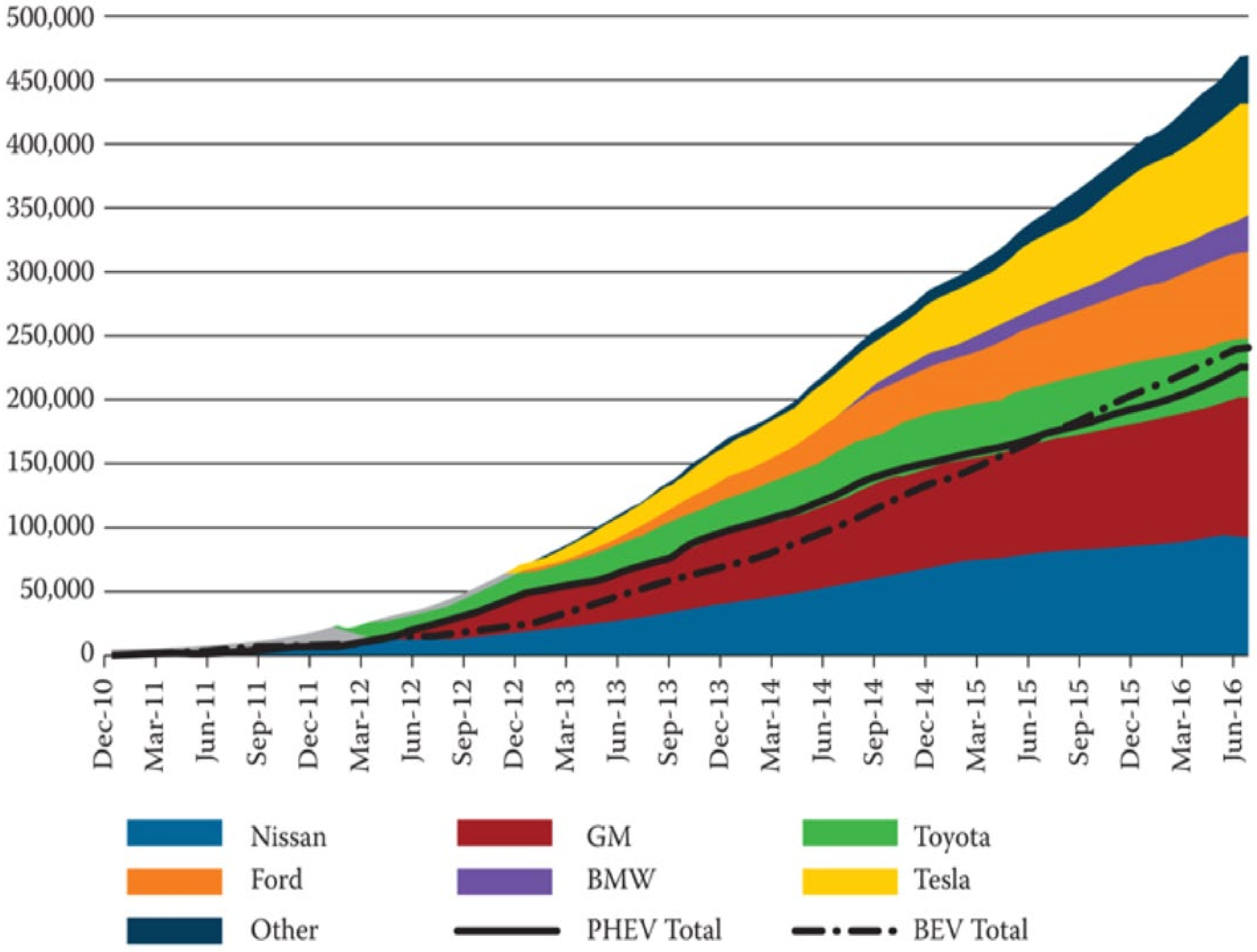
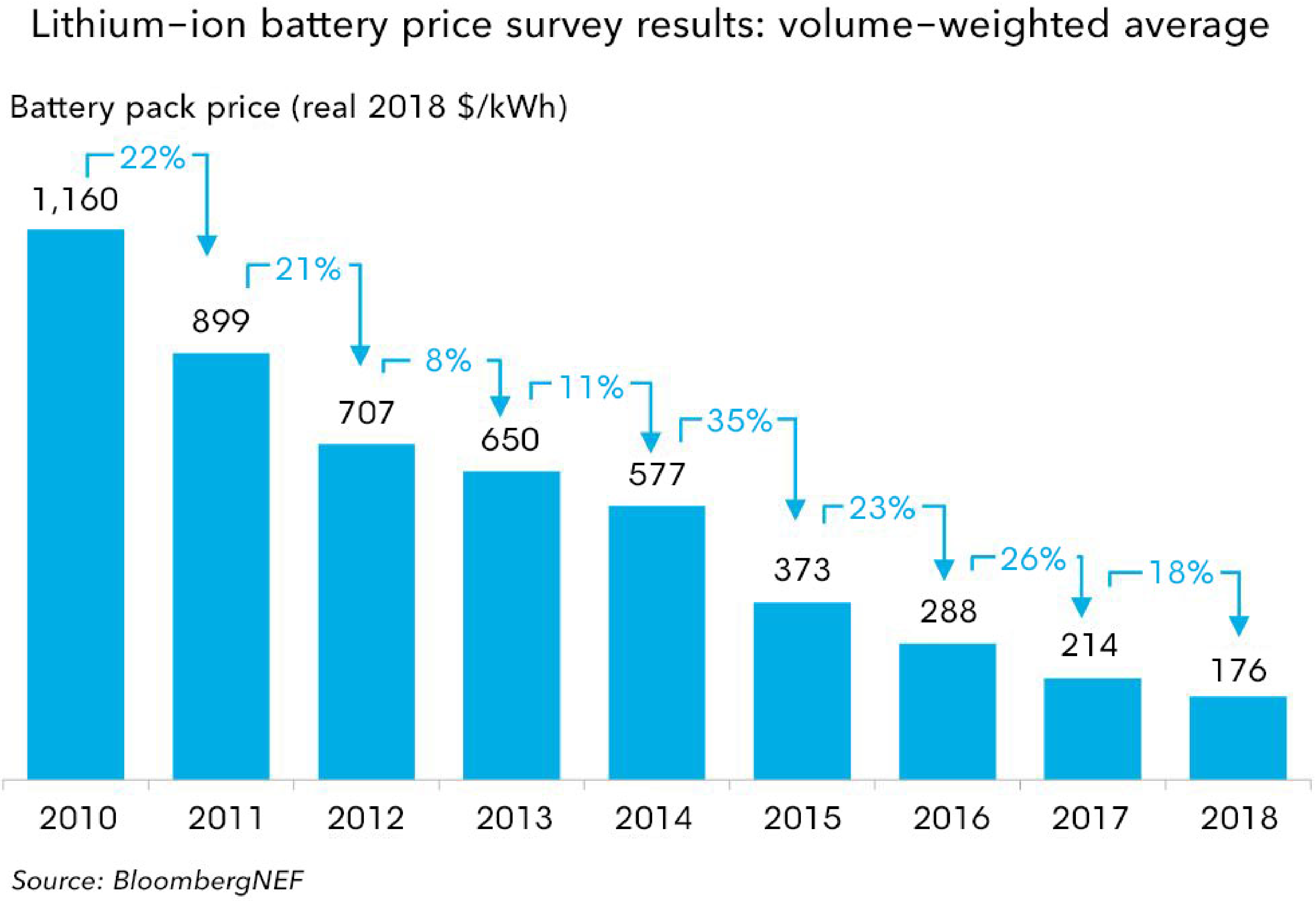


FIGURE 3.7 U.S. PHEV and BEV sales from 2010 to 2016. (Willard, S., *Energy Storage Trends and Challenges*. Electric Power Research Institute, Palo Alto, CA, 2016. Copyright Electric Power Research Institute. With permission.)

3.5.2.3 Battery (BEV)

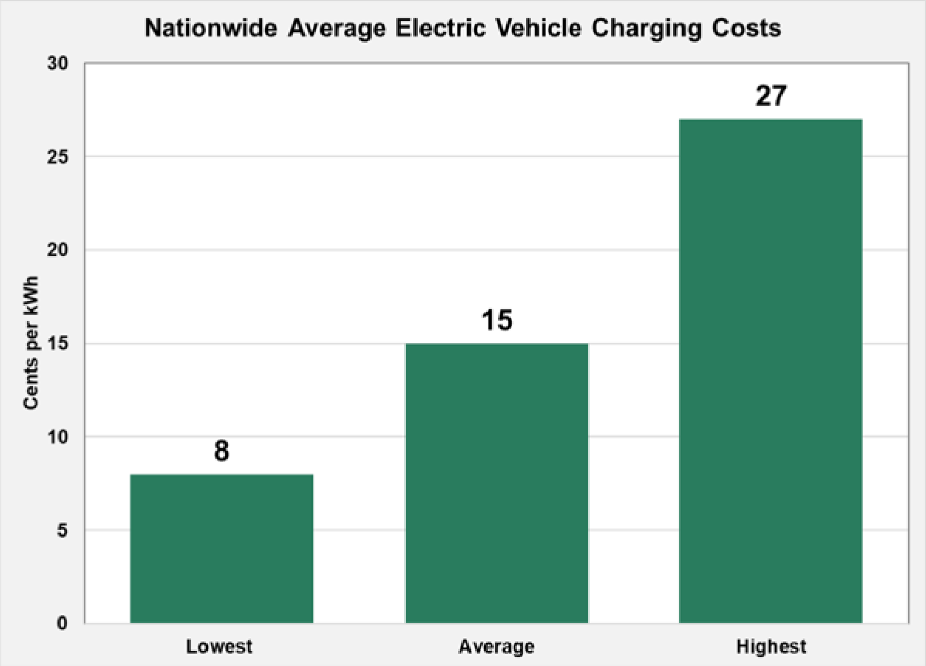


3.5.2.3 Battery (BEV)

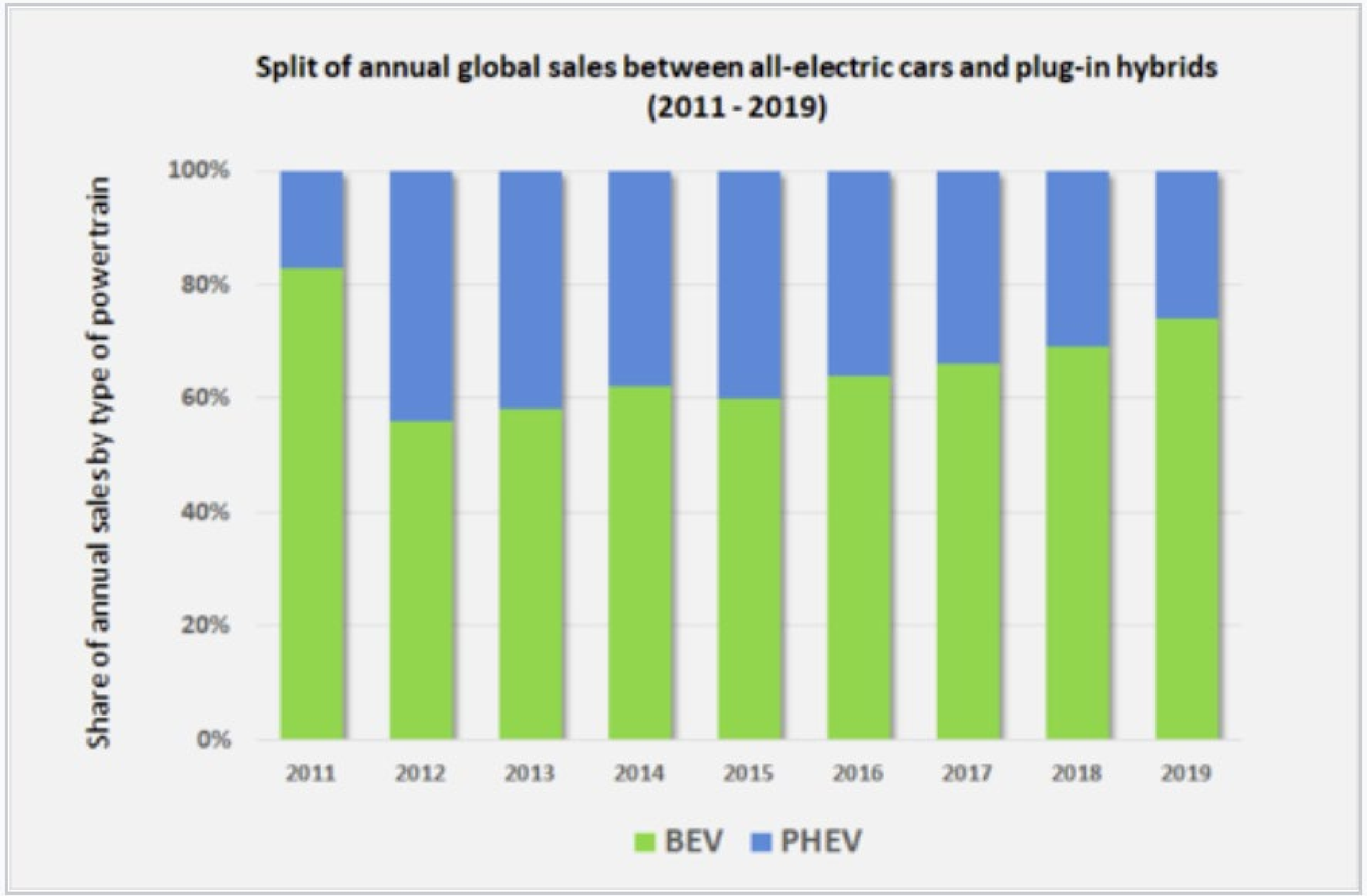
August 31, 2020

The Cost of Charging an Electric Vehicle in the United States Averages 15 Cents per Kilowatt-Hour

The cost of charging electric vehicles varies depending on multiple factors, including electricity price, charging equipment type, installation cost, and number of miles driven. The National Renewable Energy Laboratory and Idaho National Laboratory studied data on all-electric vehicle (EV) use and charging to determine a weighted average cost of charging an EV. They found that the national average EV charging cost ranges from eight cents per kilowatt-hour (kWh) to 27 cents per kWh, with an average of 15 cents per kWh. Based on current charging behavior patterns, the average assumes that 81% of charging was at home, 14% at the workplace or public station, and 5% with a DC fast charger. This translates to an average vehicle lifetime fuel cost savings of $3,000 to $10,500, offsetting or exceeding the higher upfront cost of EVs.



Source: National Renewable Energy Laboratory, "News Release: Research Determines Financial Benefit from Driving Electric Vehicles," June 22, 2020.



Evolution of the ratio between global sales of BEVs and PHEVs between 2011 and 2019.[178][182][183]

3.5.3 ELECTRIC VEHICLES IN THE SMART GRID

- The adoption of electric vehicles reduces gasoline consumption and tailpipe emissions and improves the urban area air quality.
- As BEV deployment increases, distribution system problems, such as transformer overloading and feeder congestion, may become more prevalent. At a larger scale, the bulk system may lack the necessary supply capacity to meet the added demand.
- Therefore, generation, transmission, and distribution systems are expected to require costly upgrades to support the demand of many more electric vehicles.
- However, the difference between the total time required to fully charge an electric vehicle and the total time that the vehicle is plugged in allows for charging flexibility that can potentially be used to charge vehicles in a more grid-friendly way.

3.5.3 ELECTRIC VEHICLES IN THE SMART GRID

- The environmental benefits of fuel switching from gasoline to electricity is not going to be fully achieved if primarily fossil resources are used to supply the energy requirement of electric vehicles.
- The main obstacle to non-fossil resources (excluding nuclear that has its own challenges) is the intermittency of renewable generation, which limits the amount that can be integrated and compels system operators to schedule/dispatch expensive reserve units.
- Implementation of charge controlling strategies eases the operation of bulk power systems and beneficial from both economic and environmental perspectives.
- The role of electric vehicle demand response is to facilitate both economic and environmental benefits.

3.5.3 ELECTRIC VEHICLES IN THE SMART GRID

EV demand response will increase the diversity of the flexible load fleet, and potentially its performance capabilities:

(1) EV loads can be delayed for relatively more time than thermostatically controlled loads;

(2) EVs can potentially feed electricity into the grid (V2G);

(3) EV chargers are physically located where other flexible loads may not exist;

(4) Charging stations are equipped with controls that can provide system operators with voltage response resources even when no EV is plugged to it;

(5) The power factor of the EV charger load differs from other flexible electric loads, which is valuable from the operation point of view.

3.5.3.1 Grid Support

- Studies have shown that vehicles sit unused, on average, for >90% of the day.
- Using this fact, researchers have conducted studies on the ability of PEVs to provide grid support services (V2G) to provide a source of revenue for the vehicle owner, it could increase the incentive for consumers to purchase PEVs.
- The primary means for monetizing the capabilities of PEVs is proposed participation in a deregulated ancillary services market.
- Studies to date have determined that frequency regulation is the component of the ancillary services market most compatible with plug-in vehicle capabilities and will provide the largest financial incentive to vehicle owners.

3.5.3.1 Grid Support

- There are two primary types of power interactions between the vehicle and grid.
  - Grid-to-vehicle charging (G2V) consists of the electric grid providing energy to the plug-in vehicle through its charging connector.
  - A vehicle-to-grid (V2G) capable vehicle has the additional ability to provide energy back to the electric grid. V2G provides the potential for the grid system operator to call on the vehicle as a distributed energy and power resource.
- For PEVs to achieve widespread near-term penetration in the ancillary service market, the two primary stakeholders in the plug-in vehicle ancillary service transaction must be satisfied: grid system operators and vehicle owners.
- The grid system operators demand *industry standard* availability and reliability for regulation services.
- The vehicle owners demand a robust return on their investment in the additional hardware required to perform the service and minimal impact on the performance and lifetime of the vehicle's battery.

3.5.3.1 Grid Support

- Since PEVs are not stationary but instead have stochastic driving patterns, these resources possess unique availability and reliability profiles in comparison to conventional ancillary services generation system.
- In addition to this, the power rating of an individual plug-in vehicle is significantly less than the power capacity of conventional generation systems that utilities normally contract for ancillary services.
- These key aspects of PEVs create unique challenges for their integration and acceptance into conventional power regulation markets to provide ancillary services.
- The connection between the grid system operators and the PEVs to provide grid support services can be classified as one of two types that have been proposed to date: a direct, deterministic architecture and an aggregative architecture.
- The direct, deterministic architecture, shown conceptually in Figure 3.8, assumes that there exists a direct line of communication between the grid system operator and the plug-in vehicle so that each vehicle can be treated as a deterministic resource to be commanded by the grid system operator.

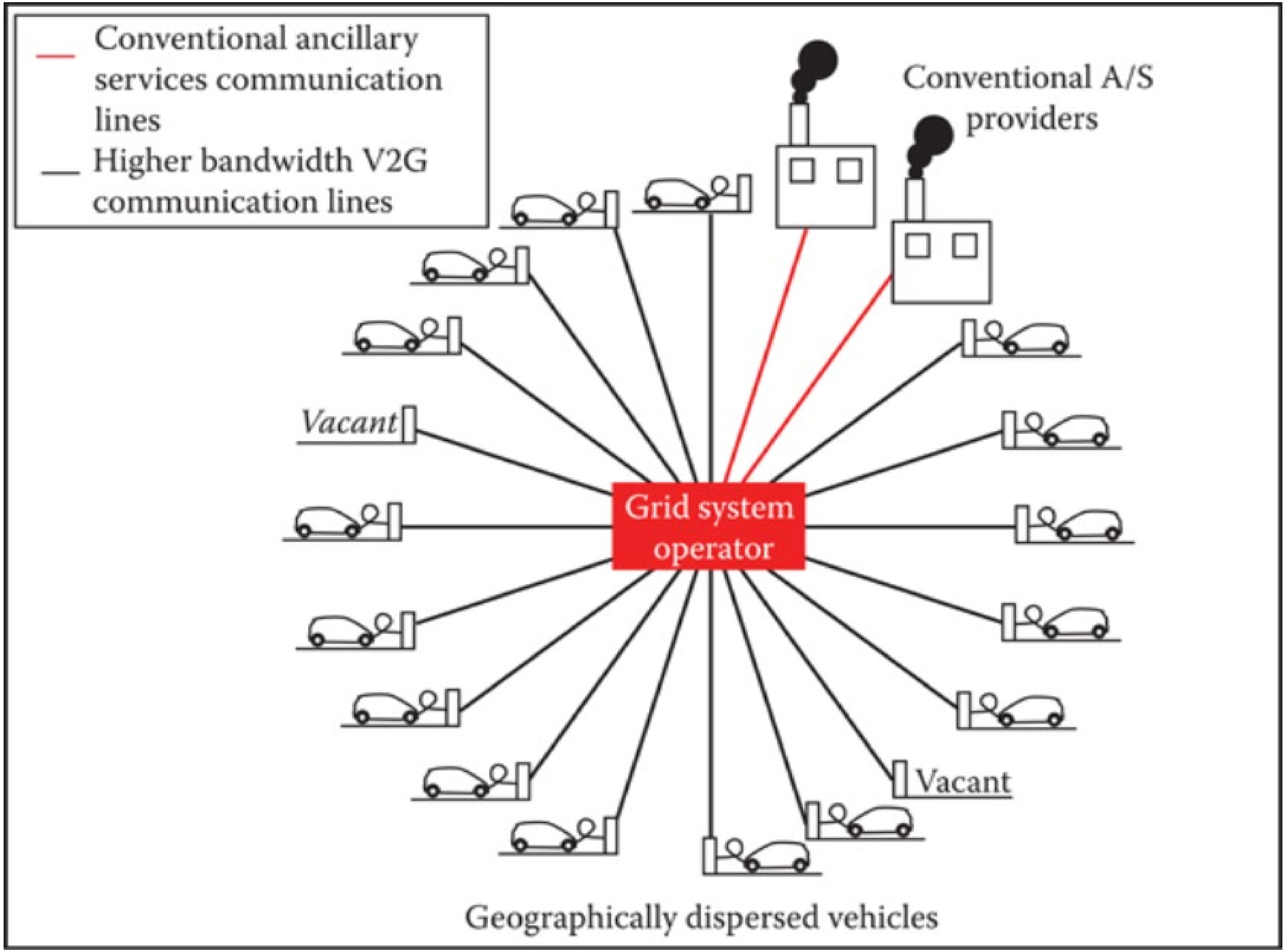


FIGURE 3.8 Example V2G network showing geographically dispersed communications connections under the direct, deterministic architecture. (From Quinn, C. et al., *Journal of Power Sources*, 195(5), 1500, 2010. With permission.)

3.5.3.1 Grid Support

- In the longer-term, the grid system operator might be required to centrally monitor and control all the PEVs subscribed in the power control region—a potentially overwhelming communications and control task.
- As these millions of vehicles engage and disengage from the grid, the grid system operator would need to constantly update the contract status, connection status, available power, vehicle state of charge, and driver requirements to quantify the power that the system operator can deterministically command.
- The aggregative architecture is shown conceptually in Figure 3.9. In the aggregative architecture, an intermediary is inserted between the vehicles performing ancillary services and the grid system operator.
- This aggregator receives ancillary service requests from the grid system operator and issues power commands to contracted vehicles that are both available and willing to perform the required services.
- Under the aggregative architecture, the aggregator can bid to perform ancillary services at any time, while the individual vehicles can engage and disengage from the aggregator as they arrive at and leave from charging stations.
- This allows the aggregator to bid into the ancillary service market using existing contract mechanisms and compensate the vehicles under its control for the time that they are available to perform ancillary services.

3.5.3.1 Grid Support

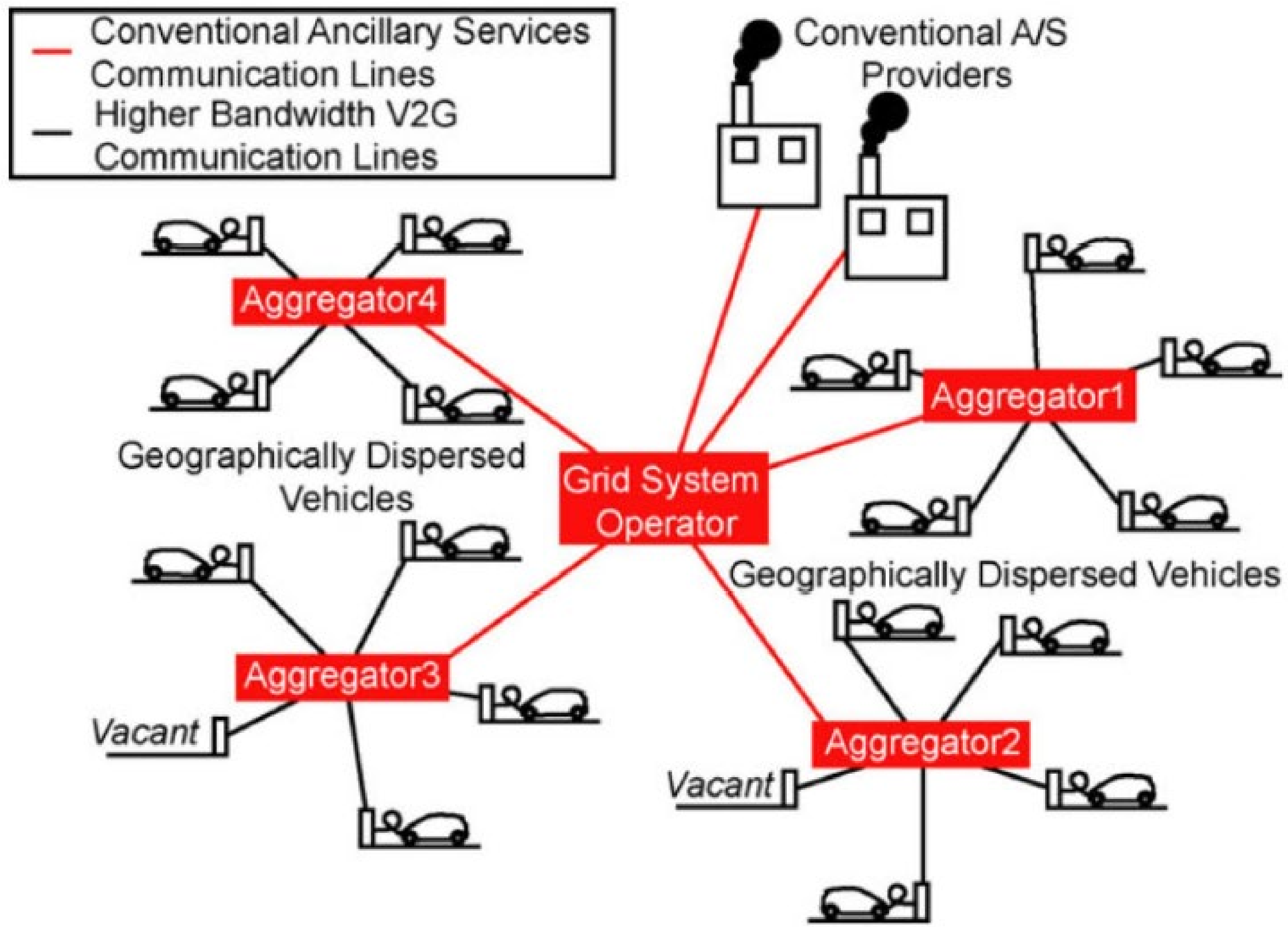


Fig. 2. Example plug-in vehicle-to-grid network showing geographically dispersed communications connections under the aggregative architecture.

FIGURE 3.9 Example V2G network showing geographically dispersed communications connections under the aggregative architecture. (From Quinn, C. et al., *Journal of Power Sources*, 195(5), 1500, 2010. With permission.)

3.5.3.1 Grid Support

- Since many distribution utilities are installing "advanced metering" systems, allowing two-way communication with individual consumers, these utilities could potentially enter the ancillary service market by providing such aggregation services using their metering communications networks.
- From the perspective of the grid system operator, the aggregative architecture represents a more feasible and extensible architecture for implementing PEVs as ancillary service providers.
- For the system operator, the aggregative architecture is an improvement relative to the direct, deterministic architecture because it allows PEVs to make use of the current market-based, command and control architectures for ancillary services.
- Aggregators can control their reliability and contractible power to meet industry standards by controlling the size of their aggregated plug-in vehicle fleet, thereby providing the grid system operator with a buffer against the stochastic availability of individual vehicles.
- This allows the aggregator to maintain reliability equivalent to conventional ancillary service providers including conventional power plants.

3.5.3.2 Energy Buffering

- There exists a daily load cycle for the U.S. electric grid. In general, the grid is relatively unloaded during the night and reaches peak loading during the afternoon hours in most U.S. climates.
- Balancing authorities dispatch power plants to match the power generation to the time-varying load. Types of generation resource are dispatched differently to meet different portions of the load.
- Nuclear and large thermal (coal) plants are typically dedicated to “base-load” power.
- Power plants with fast response rates (e.g., gas turbines), hydropower, and energy storage can be dispatched to meet predicted and actual load fluctuations.
- By combining generation types, the control authority meets the time-varying load with a time-varying power generation, while meeting constraints imposed by environmental requirements, emission caps, transmission limitations, power markets, generator maintenance, unplanned outages, and more.

3.5.3.2 Energy Buffering

- Even at relatively low market penetrations, plug-in vehicles will represent a large new load for the electric grid, requiring the generation of more electrical energy. NREL researchers found that a 50% plug-in market penetration corresponded to a 4.6% increase in grid load during peak hours of the day.
- When vehicle charging and discharging can be controlled, other studies have found that as many as 84% of all U.S. cars, trucks, and SUVs (198 million vehicles) could be serviced using the present generation and transmission capacity of the U.S. grid.
- Controlling the electrical demand of PEVs will determine the infrastructure, environmental and economic impacts of these vehicles.
- Smart grid technologies can provide the control, incentives, and information to enable the successful transition to PEVs
- These SG technologies must reconcile the requirements of the electricity infrastructure with the expectations, and economic requirements of the vehicle owner.

3.5.3.2 Energy Buffering

- Smart grid technologies enable the control of the energy consumption of plug-in vehicles is by providing incentives for off-peak charging through a time-of-use (TOU) rate.
- A TOU rate is an electricity rate structure where the cost of electricity varies with time.
- Smart grid technologies, such as advanced metering and consumer information feedback, are necessary conditions for implementation of TOU tariffs.
- TOU rates are designed to incentivize the conservation of electricity during the day (peak load reduction).
- Special TOU rate structures have been designed for EV use to encourage EV owners to charge their vehicles at night, thereby conserving electricity during hours of peak of peak demand.
- In theory, TOU rates should be able to be designed to provide an economic incentive for plug-in vehicle owners to charge their vehicles at night.
- In practice, the TOU rate can provide robust economic incentives for EV owners to charge their vehicle during off-peak periods because electricity is the only fuel cost for EVs.

3.5.3.2 Energy Buffering

- When TOU rates are applied to “low range” PHEVs, they can only provide partial compensation by delaying charging until off-peak periods.
- For “high range” PHEVs, TOU rates are very effective at incentivizing off-peak charging of PHEVs.
- Smart grid must be used to engage the consumers in understanding how they can improve the sustainability and economy of the vehicle/grid systems.
- Consumer education and real-time information exchange between the utility and consumers will be a critical component of controlling the energy consumption rate and timing of plug-in vehicles.