Review of the Impact of Vehicle-to-Grid Technologies on Distribution Systems and Utility Interfaces

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***Abstract*—Plug-in vehicles can behave either as loads or as a distributed energy and power resource in a concept known as vehicle-to-grid (V2G) connection. This paper reviews the current status and implementation impact of V2G/grid-to-vehicle (G2V) technologies on distributed systems, requirements, benefits, challenges, and strategies for V2G interfaces of both individual vehicles and fleets. The V2G concept can improve the performance of the electricity grid in areas such as efficiency, stability, and reliability. A V2G-capable vehicle offers reactive power support, active power regulation, tracking of variable renewable energy sources, load balancing, and current harmonic filtering. These technologies can enable ancillary services, such as voltage and frequency control and spinning reserve. Costs of V2G include battery degradation, the need for intensive communication between the vehicles and the grid, effects on grid distribution equipment, infrastructure changes, and social, political, cultural, and technical obstacles. Although V2G operation can reduce the lifetime of vehicle batteries, it is projected to become economical for vehicle owners and grid operators. Components and unidirectional/bidirectional power flow technologies of V2G systems, individual and aggregated structures, and charging/recharging frequency and strategies (uncoordinated/coordinated smart) are addressed. Three elements are required for successful V2G operation: power connection to the grid, control and communication between vehicles and the grid operator, and on-board/off-board intelligent metering. Success of the V2G concept depends on standardization of requirements and infrastructure decisions, battery technology, and efficient and smart scheduling of limited fast-charge infrastructure. A charging/discharging infrastructure must be deployed. Economic benefits of V2G technologies depend on vehicle aggregation and charging/recharging frequency and strategies. The benefits will receive increased attention from grid operators and vehicle owners in the future.**

***Index Terms*—Battery degradation, charging infrastructure, distribution system, grid operator, grid-to-vehicle (G2V), plug-in electric vehicles (PEVs), regulation, smart charging, unidirectional/bidirectional power flow, utility interface, vehicle-to-grid (V2G).**

I. INTRODUCTION

WITH environmental and climate change issues and legislation, rising energy costs, concerns about energy security and fossil energy reserves, and growing consumer expectations, plug-in electric and hybrid vehicles (PEVs) are appearing worldwide [1]–[3]. Even though PEVs have not been widely adopted, in part because of technical limitations, social obstacles, and cost compared to conventional internal combustion engine (ICE) vehicles [4], based on moderate expectations, by 2020 up to 35% of the total vehicles in the U.S. will be PEVs according to the Electric Power Research Institute (EPRI) [5]. There is enough generation capacity in the U.S. to absorb one million or more PEVs without shortage [6]. Governments, the automotive sector, organizations such as IEEE, the Society of Automotive Engineers (SAE), and the EPRI are preparing standards and codes for system requirements at the utility/customer interface. PEVs have an advantage compared to self-contained hybrid electric vehicles (HEV) and ICE vehicles: a connection to the electric power grid. PEVs can serve in discharge mode as vehicle-to-grid (V2G) devices and in charge mode as grid-to-vehicle (G2V) devices [7]. The V2G concept has attracted attention from grid operators and vehicle owners. However, convenient recharging and available electricity supplies are necessary to realize the benefits of V2G capabilities.

This paper reviews V2G/G2V technology and requirements, economic costs, challenges, and strategies for V2G interfaces of both individual PEVs and vehicle fleets. V2G/G2V interfaces can reflect any possible charging rates; industry has defined three typical rates [8], as summarized in Table I. For purposes of the paper, "V2G" is used generically for both V2G and G2V energy flows. A range of proposed V2G concepts, services, benefits, components and power-flow technologies, individual and aggregated structures, and charging/recharging strategies are discussed. The context is PEVs—whether purely electric or hybrid. It will be shown that V2G concepts that allow benefits to be shared among grid operators and vehicle owners are likely to accelerate PEV deployment. Controls and usage patterns must be evaluated for short-term and long-term impacts on battery life and utility distribution networks.

PEVs can behave either as electric loads or as generators. The charging behavior of PEVs is affected by different factors,

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TABLE I
CHARGING POWER LEVELS

Power Level	Description	Power Level
Level 1	Opportunity charger (any available outlet)	1.4kW (12A) 1.9kW (20A)
Level 2	Primary dedicated charger	4kW (17A) 19.2kW (80A)
Level 3	Commercial fast charger	Up to 100kW

such as the type of connection (unidirectional or bidirectional), geographical location, the number of PEVs being charged in a given vicinity, their charging voltage and current levels, battery status and capacity, charging duration, etc. [9], [10]. First-generation mass-market PEVs, such as the Chevrolet Volt and Nissan Leaf [11], [12], connect to the grid for battery charging only—the most basic configuration. G2V includes conventional and fast battery charging systems. Fast charging can stress the grid distribution network because power is high: typical PEVs more than double an average household load [13]. Charging practices in different locations also have an effect on the amount of power taken from the electric grid by a fleet of PEVs. Charging at work in congested urban centers, for example, can lead to undesirable peak loads [14] and could require investments in expensive peaking generation. Injected harmonics and low power factor can be serious problems if the charger does not employ state-of-the-art conversion [15]. Previous studies [5], [16]–[19] show that nighttime charging has minimal impact on the power grid, provided suitable choices are made for intelligent controls.

Several studies about the impact of PEVs on the grid have been reported in the literature. When PEVs have adequate on-board power electronics, intelligent connections to the grid, and interactive charger hardware control, they can serve as stored energy resources and as a reserve against unexpected outages [16], [20]–[22]. Connection to the grid, control and communication between vehicles and grid operator, and on-board/off-board smart metering are required for beneficial V2G operation [23]. While the power flow can be either unidirectional and bidirectional, G2V is a logical first step because it limits hardware requirements, simplifies interconnection issues, and tends to reduce battery degradation. PEVs with unidirectional chargers can charge but not inject energy into the power grid. A bidirectional V2G system is required to support energy injection back to the grid [24]–[27].

Economic costs, emissions benefits, and distribution system impacts of PEVs depend on vehicle and battery characteristics as well as on charging and recharging frequency and strategies. When no smart charging or embedded controller is available, vehicles charge like any other load. Coordinated smart charging and discharging to optimize time and power demand appears to be the most beneficial and efficient strategy for both the grid operator and PEV owners [28]. Simple smart charging can help shift load and avoid peaks. Previous studies [5], [18], [19], [29] show that smart charging minimizes PEV impact on the power grid, provided suitable choices are made for intelligent controls. Direct coordination of charging and discharging can be done by means of smart metering, control, and communication. One strategy for achieving a higher return for grid operators is to offer real-time nonlinear electricity pricing for charging and discharging [30]. Each vehicle can be contracted individually or as part of an aggregation. Aggregators collect PEVs into a group to create a larger, more manageable load for the utility [31]. These groups can act as distributed energy resources to realize ancillary services and spinning reserves. Cooperation between the grid operator and vehicle owners or aggregators is important to realize the highest possible net return.

Many researchers have investigated potential benefits and costs issues of V2G concepts [29]–[48].V2G-capable vehicles offer a possible backup for renewable power sources including wind and solar power, supporting efficient integration of intermittent power production [7], [32]–[34]. V2G systems can provide additional opportunities for grid operators, such as reactive power support [29], active power regulation, load balancing by valley filling [13], [35], [36], peak load shaving [37], [38], and current harmonic filtering. These systems can enable such ancillary services as frequency control and spinning reserves [23], [31], [39]–[42] and can improve grid efficiency, stability, reliability [43], and generation dispatch [44]. They reduce utility operating costs and even potentially generate revenue [30]. PEV owners benefit when electricity is cheaper than fuel for equivalent distances. Researchers estimate that potential net returns from V2G methods range between \$90 and \$4000 per year per vehicle based on power capacity of electrical connections, market value, PEV penetration, and PEV battery energy capacity [20], [23], [45]–[48]. Emissions are reduced [19], [49], [50], and it has been reported that V2G strategies have the potential to displace 6.5 million barrels of oil-equivalent per day in the U.S. in addition to the intrinsic benefits of EVs [37]. Peterson *et al.* estimate annual grid net social welfare benefits of \$300–400 [51]. There is also a "vehicle-to-building" concept that brings additional benefits including backup power, high power quality for buildings, and peak shaving to buildings when grid powered [52], [53].

Impediments and barriers to V2G strategies include battery degradation in bidirectional applications [46], [54], requirements for intensive communications and monetization of any extra energy losses [55], resistance from automotive and oil sectors [5], necessary infrastructure changes, and social, political, cultural, and technical obstacles [45]. Frequent charging and discharging of V2G devices may reduce battery cycle life and storage capability. These impediments can be resolved by using cheaper and more efficient batteries with extended life, acceptable infrastructure and standards for manufacturers and grid operators, as well as cooperation between the grid operator and vehicle owners or aggregators.

The current status and implementation impact of V2G technologies on distributed systems are reviewed in this paper, beginning with an overview of V2G system requirements and unidirectional and bidirectional power flows. This is followed by an overview and evaluation of charging and recharging frequency and strategies for V2G interfaces of both individual vehicles and fleets. PEV aggregation as a source of stored energy, challenges, and benefits of the V2G concept for grid operators and vehicle owners are presented and evaluated.

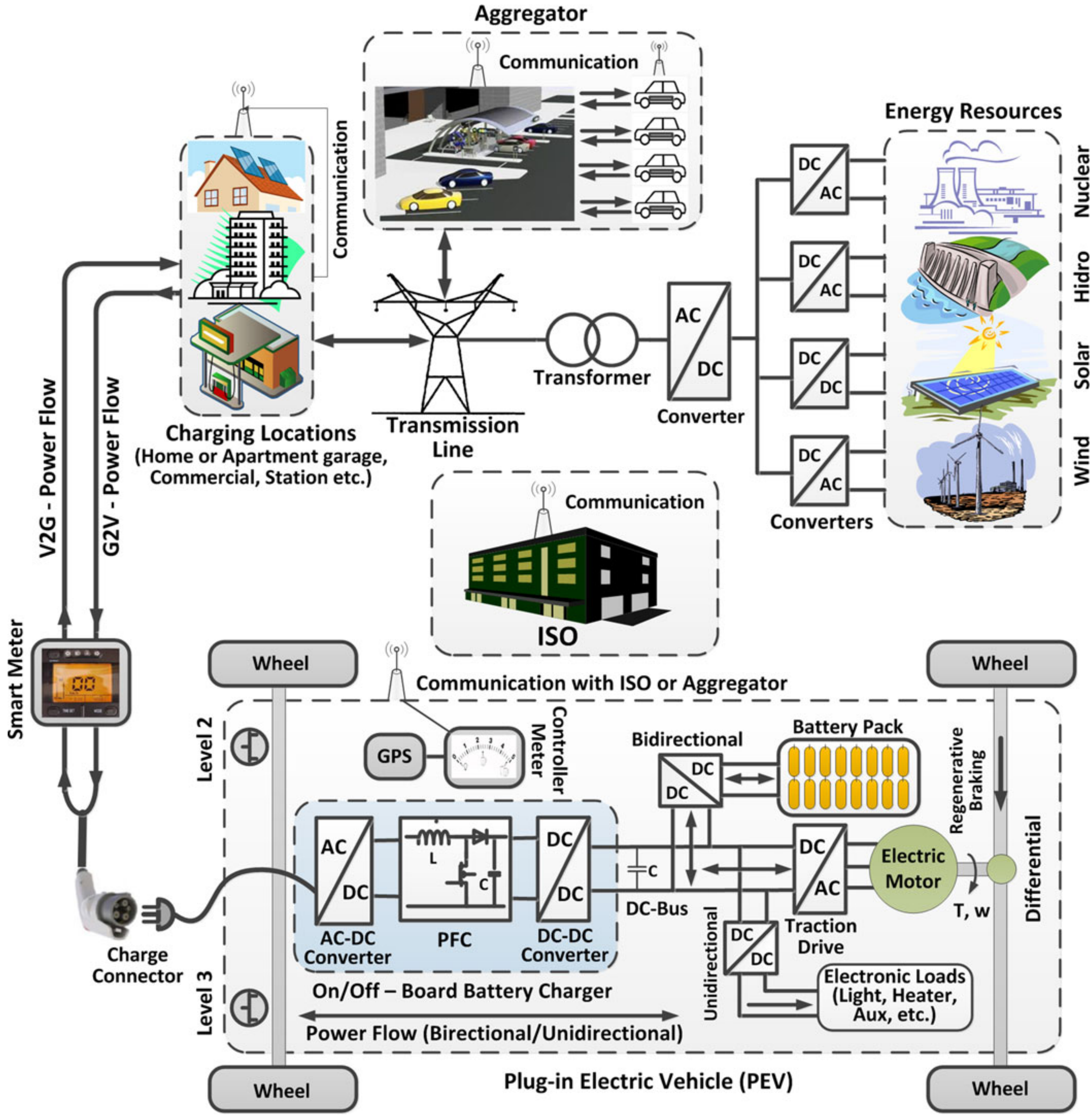

Fig. 1. Components and power flow of a V2G system.

II. V2G SYSTEM REQUIREMENTS AND POWER FLOW

The components and power flow of a V2G system are represented in Fig. 1. The system consists of six major subsystems: 1) energy resources and an electric utility; 2) an independent system operator and aggregator; 3) charging infrastructure and locations; 4) two-way electrical energy flow and communication between each PEV and ISO or aggregator; 5) on-board and off-board intelligent metering and control; and 6) the PEV itself with its battery charger and management. In general, PEVs with V2G interfaces can charge or inject energy into the grid when parked and connected [56]. The concept requires three elements: a power connection to the grid, a communication connection with the grid operator, and suitable metering; an efficient power transaction requires substantial information exchange [53]. In general, communications must be bidirectional to report battery status and receive commands [57], [58]. Intelligent metering and information control that is aware of battery capacity and state of charge (SOC) is challenging [23], [59]–[61]. Both on-board and off-board smart meters have been proposed

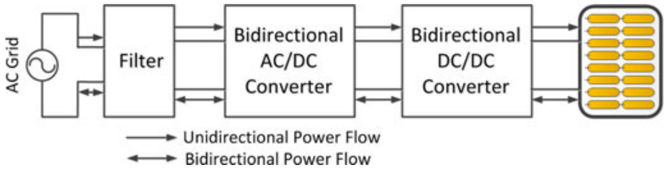

Fig. 2. General unidirectional and bidirectional power flow topology.

to support V2G methods [13], [29], [62]. Smart metering can make PEVs controllable loads and help combine PEVs and renewable energy [63]. GPS locators and on-board meters are useful [43], [62]. Sensors and smart meters on charging stations can monitor and exchange information with the control center through a field area network [53].

Control and communication are essential for services such as dynamic adjustments that track intermittent resources and alter charge rates to track power prices, frequency or power regulation, and spinning reserves [7], [64]–[67]. A variety of communication protocols have been discussed for this purpose, including ZigBee, Bluetooth, Z-Wave, and HomePlug [68]–[72]. In the U.S., IEEE and SAE provide requirements and specifications on the necessary communications [73]–[75]. The National Electric Infrastructure Working Council is also working to define a communications standard, enabling PEVs to communicate with chargers [76], [77].

PEV chargers without state-of-the-art power electronics can produce deleterious harmonic effects on the distribution system [78]. IEEE-519 [79], IEEE-1547 [80], SAE-2894 [81], and International Electrotechnical Commission-IEC-1000–3-6 [79], [82] standards limit allowable harmonic and dc current injection into the grid, and PEV chargers are usually designed to comply. Sophisticated active power converter technology has been developed to reduce harmonic currents and provide high power factor [25], [83]–[86].

Shock hazard risk reduction for PEV charging is addressed in the standard for personnel protection systems for PEV supply circuits [87]. Isolation is beneficial for PEV functions, including the high-voltage battery, dc–dc converter, traction inverter, and charger. Galvanic isolation in electric vehicle supply equipment can be provided either with a line transformer or in the dc–dc converter stage with a high-frequency transformer. High-frequency transformer isolation supports voltage adjustment for better control, safety for load equipment, compactness, and suitability for varying applications. Although galvanic isolation is a favorable option in the charger circuits for safety reasons, isolated on-board chargers are usually avoided owing to extra cost. There is a possibility of avoiding these problems by using the traction motor and inverter for the charger circuit, thus providing an integrated drive system and charger. To overcome the isolation problem, various possibilities have been investigated with emphasis on special electric machine configurations that have an extra set of windings.

A. Unidirectional Power Flow

Power flow is bidirectional in general, as shown in Fig. 2. Unidirectional V2G, the basic battery charge process, can provide services based on reactive power and dynamic adjustment of charge rates even without reversal. It requires no hardware other than an outlet and avoids extra EV battery degradation from cycling. Implementation of this system can be done at almost no additional cost [88]. Basic control can be managed with time-sensitive energy pricing. A typical circuit is realized using a diode bridge in conjunction with filtering and dc–dc conversion. Today, these converters are implemented in a single stage to limit cost, weight, volume, and losses [25]. High-frequency isolation transformers can be employed when isolation is desired [24]. Control complexities outlined in grid interface standards such as IEEE-1547 are avoided since utility backfeed is not possible [80]. Properly designed unidirectional chargers can supply or absorb reactive power by means of current phase-angle control.

In many regions, additional transmission investments would not be required for unidirectional charging. According to [89], for example, approximately 500 000 PEVs can be charged from the grid in Ontario, Canada, without any additional transmission or generation investments. Control simplicity makes it relatively easy for a utility to manage heavily loaded feeders due to multiple PEVs [90]. Research on unidirectional charging has developed optimal charging strategies that maximize benefits to the vehicle owner, aggregator, and utility, and explores the impact on distribution networks [38], [90], [91]. With unidirectional charging, however, PEVs are likely to be connected for relatively short intervals since owners may not need to connect a fully charged vehicle. Some services can only be supported while batteries are charging, so this trades off utility benefits against owner practices. Even so, with a higher penetration of PEVs and active control of charging current, a unidirectional charger can meet most utility objectives while avoiding cost, performance, and safety concerns associated with bidirectional chargers [90], [92]. Sortomme and El-Sharkawi [88] simulated the potential benefits and impacts by combining bids associated with regulation and reserves with unidirectional V2G in the Houston area. Comparisons with bidirectional V2G algorithms showed that the unidirectional algorithms provide lower benefits. Nevertheless, unidirectional V2G has significantly less risk because of the extra capital costs of bidirectional V2G and owner concerns about energy extraction. In the simulations, system ancillary services prices decreased by approximately 3% with 10 000 PEVs and 70% for 300 000 PEVs. There is opportunity for market-based financial incentives for early adopters of PEVs with unidirectional V2G [88].

B. Bidirectional Power Flow

A typical bidirectional charger has two stages: an active grid-connected bidirectional ac–dc converter that enforces active power factor correction, and a bidirectional dc–dc converter to regulate the battery charge or discharge current. When operating in charge mode, the charger should draw a sinusoidal current with a defined phase angle to control power and reactive power. In discharge mode, the charger should return current in a similar sinusoidal form [85], [93]–[96]. While most studies have focused on bidirectional power flow for V2G, there are serious

TABLE II
UNIDIRECTIONAL AND BIDIRECTIONAL POWER FLOW COMPARISONS

	Situation	**Power Flow and Switches**	**Power Level**	**Control**	**Cost**	**Battery Effect**	**Distribution system**	**Requirements and Challenges**	**Benefits**
Unidirectional Power Flow	Available	One-way electrical energy flow, basic battery charge (G2V) Diode Bridge + Unidirectional converter	Levels 1, 2 and 3	Simple. Active control of charging current. Basic control can be managed with time-sensitive energy-pricing.	Low price, no additional cost	No discharging degradation	No update or investment. With high penetration of PEVs: meets most utility objectives	Power connection to the grid	-Simplifies interconnection issues -Simple control and easy management - Provides services based on reactive power and dynamic adjustment of charge rates, even without reversal -Supplies or absorbs reactive power, without having to discharge a battery, by means of current phase-angle control -Voltage and frequency control
Bidirectional Power Flow	Not available	Two-way electrical energy flow and communication, charge/discharge (V2G) MOSFET (low power) IGBT (Medium power) GTO (High power level)	Expected only for Level 2	Complex. Extra drive control circuits. Extensive measures.	High price	Extra degradation due to frequent cycling	Necessary updates and investment costs	-Two-way power connection and communication -Suitable smart metering/sensors -Substantial information exchange -Extra investment and cost -Energy losses -Device stress	-Ancillary services -Active power regulation and stabilization Voltage regulation Frequency regulation (down-up) -Spinning reserves -Reactive power support -Peak shaving -Valley filling -Load following -Energy balance -Current harmonic filtering -Tracking the output of renewable energy sources

challenges for adoption [62]. These include battery degradation caused by frequent charge and discharge cycling for regulation. There are extra costs for bidirectional converters, metering issues, and interface concerns. Anti-islanding protection and other interconnection issues must also be addressed. Bidirectional V2G is not currently available with existing PEVs [88], but customers are likely to require an energy guarantee to ensure that vehicle SOC is predictable (and high) when they wish to drive [51]. A successful bidirectional charger will require extensive safety measures [97], [98]. Table II summarizes unidirectional/bidirectional power flow comparisons that include requirements, challenges, benefits, cost, battery and distribution system effect, safety, control, and power level. Benefits, costs and challenges of bidirectional V2G systems will be discussed in detail in subsequent sections.

III. CHARGING/RECHARGING FREQUENCY AND STRATEGIES

Battery size and capacity are important factors in determining the initial price for a PEV. Reduction in battery weight also increases overall vehicle efficiency. Operating costs and emissions are reduced low-capacity PEVs. When battery size rises from a PEV7 (a hypothetical vehicle with nominal 7-mi electric-only range) to a much more battery-intensive PEV60, there will be about a 10% increase in average energy needs (in terms of Wh/km), and an 8% increase in effective fuel consumption [99]. Lower energy can be an advantage for utilities wanting to limit on-peak PEV impact to minimize costs. High power charging was found to increase peak power demand by about 50% (home-work) to 62% (anywhere) [100]. Each plug-in hybrid electric vehicle (PHEV) could add 560–910 W at peak times to the system load depending on the size of the charger and the charging scheme. It was reported that in a U.S. simulation study [100], the availability of charging stations at workplaces increases the daily electric energy use of PHEVs by 24% to 29%.

The economic costs, emissions, and distribution system impacts of the V2G concept depend on PEV penetration and charging/discharging strategies. Large-scale unregulated deployment can have a detrimental and destabilizing effect on the electric grid. The impact of large-scale deployment of PEVs on the California grid [101] is summarized in Fig. 3. As penetration increases, so does the total annual electrical energy demand [see Fig. 3(a)]. And, PEV peak power demand significantly increases the total peak requirements [see Fig. 3(b)]. Thus, a high level of PEV penetration could disrupt distribution systems, depending on the charging power and schedule.

A. *Uncoordinated Charging/Discharging*

Uncoordinated charging indicates that PEV batteries either start charging immediately when plugged in or start after a

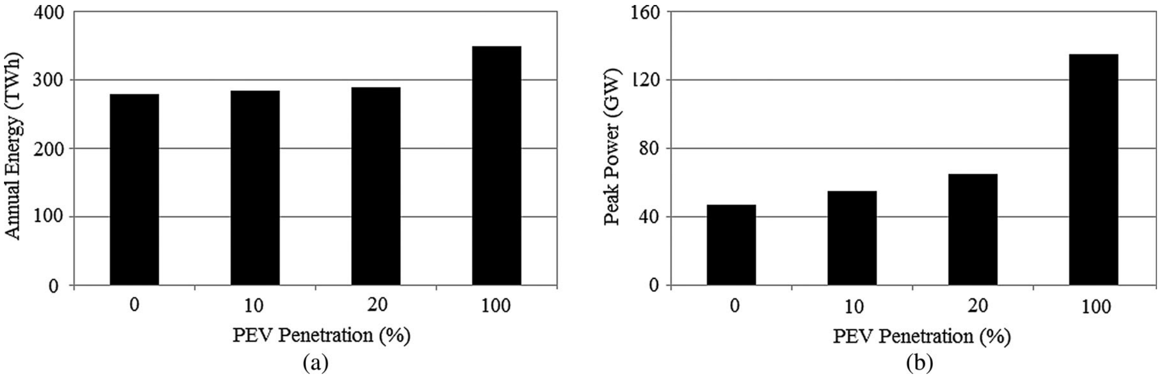

Fig. 3. Impact on California's (a) annual electrical energy demand and (b) peak power demand for varying levels of PEV penetration from the state's 30 million light duty vehicles [101].

user-adjustable fixed delay, and continue charging until they are fully charged or disconnected [102], [103]. This charging system is most likely at Level 1. Uncoordinated charging operations tend to increase the load at peak hours and can cause local distribution grid problems such as extra power losses and voltage deviations that affect power quality. They may lead to overloads in distribution transformers and cables, increased power losses, and reduction in grid reliability and cost [104].

A simulation study into impacts of random uncoordinated PEV charging on the performance of transformers was investigated in the Western Australia 1200-node test system [105]. The results showed significant transformer load surging and voltage deviations even under low PEV penetrations. Load growth on transformers for PEV penetrations from 17% to 31% showed a significant rise in transformer currents (e.g., from 37% to 74%). Voltage deviations close to 10% were reported for a 30% PEV penetration during evening peaks in a test grid in Belgium [45]. A model study in the Netherlands showed that uncoordinated charging would increase the national peak load by 7% at 30% penetration, and household peak load by 54%, which may exceed the capacity of existing distribution infrastructure [102]. In the U.K. [28], a 10% penetration of PEVs is shown to result in an increase in daily peak demand by up to 17.9%, while a 20% PEV penetration would lead to a 35.8% increase in peak load for uncontrolled charging in the distribution system. If load exceeds peak capacity, the utility operator must increase peak power generation. These costs are passed on to vehicle owners. Wu *et al.* [106] used a 2009 survey of American drivers to create virtual PHEVs based on random battery size. Annual average charging profiles for weekdays and weekends were created under uncontrolled home charging and uncontrolled "anywhere charging" scenarios which showed a peak of approximately 200–600 W per PHEV, depending on the scenario. Halbleib *et al.* [107] showed that uncontrolled charging can cause an increase in the monthly electric bill of up to 22% due to demand charges, even at only 10% PEV penetration. A simulation study on impacts of uncoordinated PEV charging on the daily peak power and base consumption was carried out in the Danish island of Bornholm, based on 2200 vehicles [108]. The aggregated load in the simulated system is shown in Fig. 4, and peaks increase substantially.

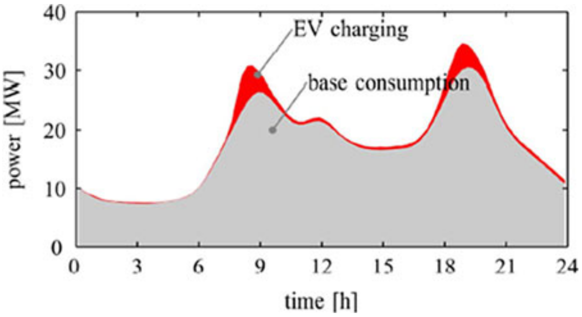

Fig. 4. System base load and total aggregated PEV (2200) charging using uncoordinated direct charging of all the PEVs [108].

Some utility companies offer a dual tariff (cheap night rates) to PEV owners as a way to reduce peak load [109]–[111]. When the user agrees to an adjustable fixed delay, owners can wait for cheap off-peak prices. Off-peak charging takes place during the night when the electricity demand is low and generation is mostly base load [37], [112]. Van Vliet *et al.* showed that off-peak charging would result in a 20% higher, more stable base load and no additional peak load based on the Netherlands national grid. Thus, no additional generation capacity would be required [102]. In the U.K. case study [28], off-peak charging was shown to increase electricity consumption throughout the night with no impact on the daily peak load. In fact, when PEV nightly charging is added, the load factor improves as some portions of the off-peak valley are filled. Table III summarizes the results of simulation and case studies for uncoordinated charging.

B. Coordinated Smart Charging/Discharging

Coordinated smart charging and discharging can optimize time and power demand [28] and reduce daily electricity costs, voltage deviations, line currents, and transformer load surges [104], [113]–[116]. It can also flatten the voltage profile of a distribution node [117], [118]. Incremental investments and high energy losses can be avoided, and wasting renewable energy and network congestion prevented. Fernández *et al.* [55] showed that it is possible to avoid up to 60–70% of the required incremental

TABLE III
RESULTS OF SIMULATION AND CASE STUDIES FOR UNCOORDINATED CHARGING

Uncoordinated Charging				
		Reference Number	Penetration Level of PEVs	Peak Load Increase (%)
Simulation and Case Studies	United Kingdom	[28]	10 %	17.9
			20 %	35.8
	Belgium	[45]	30 %	56
	Los Angeles	[67]	5 %	3.03
			20 %	12.47
	California	[99]	10 %	17
			20 %	43
	Netherlands	[100]	30 %	7 (national)
			30 %	54 (household)
	Western Australia	[103]	17 %	37
			31 %	74
	Danish Island of Bornholm	[106]	2,200 vehicles	20
	Belgium	[149]	10 %	22
			30 %	64
	New York	[151]	50 %	10
	Portugal	[113]	11 %	14

investment with smart charging; smart charging allows attaining the highest PEV penetration level without violating the network technical limits [119]. Coordinated charging system is more suitable for high power level (Levels 2 and 3). Optimization of charging time and energy flows reduces daily electricity cost with little effect on peak capacity needs. Cao *et al.* [120] proposed an intelligent method to control PEV charging loads in response to time-of-use price in a regulated market. A heuristic method was implemented to minimize the charging cost by considering the relation between the acceptable charging power of PEV battery and the SOC. Results showed that the optimized charging pattern is beneficial in reducing cost and flatting the load curve. According to their calculations, optimized patterns can reduce charging cost by about 51% for a single isolated PEV, and almost 40% for multiple coordinated vehicles when penetration is higher.

Coordinated charging management concepts can be divided into centralized and decentralized approaches. The decentralized approaches let the PEV optimize its charging behavior based on a price signal broadcast. The drawback of this approach is that the PEV needs to collect and store the trip history. The centralized approaches focus on a centralized unit that directly controls PEV charging [108].

The grid in the U.S. is not used to full capacity at night and PEV power demand could be shifted by smart charging to prevent a 50% peak load increase at a 10% fleet penetration of EVs [121]. Smart charging has a great potential for increasing value to EV owners and to the grid [122]. Rotering and Ilic [123] showed that smart charge timing reduces daily electricity costs for driving from \$0.43 to \$0.20 per day in California. The voltage deviations for a 30% penetration in a residential distribution grid are reported to be below 10% [45]. Power losses and power quality quantities for coordinated and uncoordinated charging strategies in a Belgian test grid are shown in Table IV.

TABLE IV
POWER LOSSES AND POWER QUALITY FOR BELGIUM TEST GRID [45]

	Without PEVs (Average Household Load)	Uncoordinated Charging	Coordinated Charging
Peak Load (kVA)	23	36	25
Line Current (A)	105	163	112
Node Voltage (V)	220	217	220
Power Losses (%) (Totals in the grid)	1.4	2.4	2.1

Masoum *et al.* [104] investigated the role of charging coordination in improving distribution transformer performance in Western Australia. While a coordinated approach is beneficial in overall system load leveling and peak shaving, high PEV penetrations (e.g., 63%) may still result in significant increases in individual transformer loads that may exceed their ratings.

Smart V2G charging and discharging, in which PEVs are charged from renewable resources and discharged to the grid at peak load, is reported to offer the best potential for maximum utilization of renewable sources to reduce cost and emissions [59], [124], [125]. A smart metering and control system must be implemented to combine PEVs and renewable energy. In a Danish study [29], PEVs with night charging and intelligent V2G were projected to enhance electric power system efficiency, reduce CO_2 emissions and improve the ability to integrate wind power [29]. The effects of a PEV fleet on the grid in Ohio are analyzed for both controlled and uncontrolled charging scenarios in [126]. The analysis shows that PEV use could reduce gasoline consumption by about 70% compared to ICE vehicles under both charging scenarios. Schuller *et al.* [124]

TABLE V
SMART CHARGING METHODS AND UNCOORDINATED/COORDINATED SMART CHARGING/DISCHARGING COMPARISONS [28]–[30], [37], [45], [51], [55], [59], [64], [66], [67], [88], [101]–[126], [155], [193]–[200]

	Power Level	**Charging/ Discharging Time**	**Methods, Algorithms and Approaches**	**Requirements and Costs**	**Impact on Power Distribution System**
Uncoordinated Charging/Discharging	Most likely at Level 1	-Continuous (PEV can charge whenever possible) -Fully charged or disconnected any time	-Immediately when plugged (decision to charge PEV is independent of price and peak hours) [45] -Start after user-adjustable fixed delay [66] -Off-peak uncoordinated (during the night when the overall electricity demand is low and generation is mostly base load) [28] -Single tariff [66] -Dual tariff [197]	-No specific requirements, coordination and aggregation -Charging PEV is cheap	-Reduces the reliability and cost effectiveness -Increase the load at peak hours -Voltage deviations -Extra power losses -Low load factor -Overload distribution transformers and cables -Increase in the monthly electric bill
Coordinated Smart Charging/Discharging	Most likely at Level 2 and 3	Charging during low demand (off-peak hours, overnight) Discharging daily peaks	-Formulated objective functions to peak demand minimize losses, voltage deviations, load variance, charging cost and maximize load factor, profits for the vehicle owners [28, 45, 66, 120, 130] -Quadratic programming (QP, *optimize a quadratic function of several variables in order to determine the optimal continuous charging profile*), Dynamic programming (DP, *discrete charge profile, slower than quadratic*) and Linear programming (LP) *to find optimal solution* [45, 200] -Load shifting, interruptions or adjusting the charging rate [51] -Multi-agent (MAS) distributed solution (demand side management and hierarchical methodology) [113, 196] -Computational intelligence-based optimization algorithms. -Valley-filling algorithm (utility-centric assumptions) [146] -Particle swarm optimization (PSO) distributed method (*solve the unit commitment*-UC) [30] -Real-time nonlinear electricity pricing algorithm (Each vehicle can be contracted individually or as part of an aggregator) [28, 59] -Forecast of future electricity prices [123] -Customer usage model, power management and financial model [118] -Centralized approach (directly controls the charging/ discharging; obtain global optimum); the final decision to begin or end the charging process is made by a central control entity [45, 64, 196] -Decentralized approach (price signal broadcast, collect and store the trip history; obtain global optimum) [55, 116] -Time-of-use (TOU) price with heuristic method (retail time-of-use rates, dual-use program, time-differentiated tariffs) [66, 120, 198] -Incentive-based charging (time-varying price) [195] -Real-time smart load management (RT-SLM) control [193] -Price-signal-based, load-signal-based, renewable energy based charging (preferred operating point (POP) algorithms) [88, 199] -Market based multi-agent approach [194, 196] -Local energy control strategies (determine the charging times and rates based on the predicted local base load) and global energy control strategy (determine a charging schedule based on global load information) [155]	-Sensors and on-board/off-board intelligent meters (real-time monitoring and substantial exchange information, price, battery capacity and SOC) -Communication connection and control (it must be bidirectional to report battery status and receive commands) -Energy management (Measurement/ Billing) -Software (real-time monitoring, management and control) -Identification -Energy efficiency (PFC, filtering and quality analyzer) -Charging/ discharging infrastructure	-Optimizes power demand and time -Little effect on peak capacity, shift load and avoid peaks, maximizes the grid load factor. -Reduces voltage deviations, daily electricity costs, line currents and transformer load surges -Balances the daily load pattern and voltage profile -Avoids incremental grid investments and high energy losses -No significant impact to transformer -Maximizes utilization of renewable sources and makes efficient use of available generation capacity -Maximizes consumer convenience through use of available infrastructure -Increased operating efficiency

show that the coordinated charging strategies can increase the relative wind power utilization up to 14.7% for employees and 15.6% for retired EV customers as compared to the average share for 2007 of 8% in the German power system.

Table V summarizes smart charging methods and uncoordinated and coordinated smart charging/discharging comparisons. These methods make certain assumptions regarding the charging infrastructure, rates and duration, battery status, energy capacity, size and technology, PEV type, and mathematical approaches.

An alternative battery charging strategy is to swap depleted batteries with a fresh pack. If this can be automated, exchanges can be compared to duration of conventional vehicle refueling. This method reduces the impact on distribution systems since more flexible charge timing becomes possible [127]–[129].

IV. PEV AGGREGATION AS A SOURCE OF STORED ENERGY

The energy stored in an individual PEV is negligible relative to the grid. The aggregation concept has been proposed to provide viable storage and add to the smart grid for better coordination and reliability [23], [31], [122]. The aggregator is introduced as the controller of V2G. This entity plays an important role between PEV owners, the electricity market, and distribution and transmission system operators [58], [130], [131]. To maintain grid stability, two-way energy flow and communication needs to be controlled between the aggregated vehicles and the grid [117]. An aggregator in a V2G system is shown in Fig. 1. It collects individual PEV data, detects and records the SOC of each PEV, and provides an interface to the independent system operator [91]. When the power grid requests power, the power grid operator sends signals to the aggregator to manage PEV discharging [132]. This minimizes charging and discharging costs subject to a number of technical and contractual constraints [133]. Each PEV can be contracted individually or an aggregator can negotiate a contract for a fleet to implement ancillary services [43], [134]. In the aggregative structure, the aggregator receives ancillary service requests from the grid operator and issues individual power and reactive power commands to contracted vehicles. The aggregator can bid to perform ancillary services, while individual vehicles can engage and disengage [64]. Aggregation can improve compatibility of V2G with existing ancillary services markets by improving the reliability of V2G ancillary services, distributing vehicles, and establishing minimum and maximum contract limits. Wu *et al.* [135] proposed a vehicle-to-aggregator interaction game, where vehicles are independent players making charging or discharging decisions and the aggregator serves as a coordinator. They simulated a smart pricing policy and designed a mechanism to achieve optimal frequency regulation performance. Han *et al.* [136] designed an optimal V2G aggregator control strategy for frequency regulation. Pillai and Bak-Jensen [137] modeled aggregated PEVs for the use in a long-term dynamic power system simulation in the western Danish power system.

While it is difficult to determine whether a particular vehicle will be parked or on the road at a particular time, aggregation is likely to be more predictable, perhaps even supporting a unit commitment approach [30]. The charging of aggregated PEVs at night helps reduce off-peak regulation-down requirements. PEV aggregations can also provide spinning reserves. These reserves are normally provided by additional generating capacity that is synchronized to the system. They must respond immediately. PEV aggregations can easily start generating within a ten-minute requirement [39]. Bessa *et al.* [130] presented an optimization approach to support the aggregation agent participating in the day-ahead and secondary reserve in Iberia. Communication and control between the aggregator and PEVs are likely to be more manageable than an individual structure [67], and the aggregated entity can make purchases more economically than individual PEV owners [31]. The aggregation concept has been implemented in some projects such as Portugal, the industrial network MOBIE [138], and Better Place [139]. In these models, the aggregator buys electrical energy in the market for clients but has no direct control over EV charging rates.

V. BENEFITS OF V2G SYSTEMS

Average personal vehicles in the U.S. travel on the road only 4–5% of the time, sitting in home garages or parking lots the rest of the day [23], [62], [65]. In many cases, these vehicles can support V2G capabilities. Studies have shown that PEVs could provide ancillary services such as voltage and frequency regulation (primary, secondary, and tertiary control) [23], [31], [39], [40], spinning reserves, reactive power support, peak shaving, valley filling (charging at night when demand is low), load following, and energy balance [13], [29], [37]. V2G systems can reduce overall costs of service and prices to customers, and selling energy to the grid could improve load factors and reduce emissions [5]. They could also replace large-scale energy storage systems.

A. Environmental Advantages on the Grid

A number of existing studies have shown that PEVs have emissions benefits over HEVs and conventional vehicles, even accounting for generation emissions. Studies by NREL and the Northwest Power and Conservation Council [140] determined that CO_2 emissions would fall significantly if PEVs replace conventional ICE vehicles. When the V2G concept is added, PEVs could offer further environmental benefits and directly reduce greenhouse gas (GHG) emissions [18], [30]. On a per-vehicle basis, CO_2 emissions are projected to drop from about 6.2 tons per year to fewer than 4 tons [33], [57]. GHG emissions linked to driving depend on the electricity generation fuel type. If electricity is produced from polluting sources, the environmental advantages of PEVs are more limited: GHG emissions range between 0 g/km for renewables and 155 g/km for lower coal-based plants [102], [141]. If PEVs charge their batteries from low quality coal-fired sources, their emissions may be 7–21% lower than HEVs [19], [142]. Even when powered entirely by coal-fired electricity, PEVs still produce around 25% fewer GHG emissions than ICE vehicles [143]. Estimated reductions for PEVs range from 15% to 65% in another U.S.-based study that examined low-carbon electricity sources [5], [19].

The V2G concept is analyzed in 12 regions of the U.S. in [37]. The analyses project GHG emissions reduction of 27% and nitrogen oxides (NO_x) emissions reduction of 31%. Stephen and Sullivan [17] present case studies in the U.S. in which PEVs, compared to hybrid vehicles, reduce CO_2 emissions by 25% in the short term and as much as 50% in the long term by using a mix of generating plants. PEVs with shorter charge-depleting ranges may reduce more GHG emissions than PEVs with longer ranges [19]. PEVs cut emissions by more than one-third in current California energy scenarios and by one-quarter in future scenarios compared to ICE vehicles. These California emissions scenarios show that long-term GHG reductions depend on reducing the carbon intensity of the grid [144], [145]. Another study in California presented a resource dispatch and emissions model [146]. A 40% PEV penetration in the U.S. western grid would increase grid GHG and CO emissions intensity. Only NO_x emissions intensity would be reduced with the addition of PEVs. Ohio, with a high penetration of coal in its power system, showed a 24% reduction from ICE vehicles in net GHG emissions [126]. However, CO_2 and NO_x emissions would increase.

Automotive and oil companies allege that EVs would have a net negative effect on the environment because of lead discharges from battery manufacturing facilities and battery disposal [4], [147], but this conflicts with results from the existing lead-acid battery market, which dwarfs that of vehicles, and moves to other battery chemistries.

B. Ancillary Services

Ancillary services are necessary in the power system for maintaining grid reliability, balancing supply and demand, and supporting the transmission of power from seller to purchaser. A bidirectional V2G concept can provide higher quality ancillary services than are currently available: quick frequency and voltage regulation, load leveling and peak power management, and effective spinning reserves. Aggregators are expected to collect PEVs into a group to create a larger, more desirable load for the utility [31], [148].

1) Voltage and Frequency Regulation: Regulation services are a likely first step for V2G because of high market value and minimal stress on the vehicle power storage system [62], [149]. Frequency regulation is used to balance supply and demand for active power [132]. Currently, frequency regulation is achieved mainly by cycling large generators [135], which is costly. Fast charging and discharging rates of PEV batteries makes V2G a promising alternative for frequency regulation [23]. Voltage regulation is used to balance supply and demand for reactive power. PEVs can respond quickly to regulation signals [39]. This regulation can be controlled independently by each PEV. A voltage control can be embedded in the battery charger. A charger can compensate inductive or capacitive reactive power by properly selecting the current phase angle [150]. When the grid voltage becomes too low, vehicle charging can stop. When the voltage becomes high, charging can start [66]. Connection of a large number of PEVs might cause transformer or line-overloading and voltage stability problems, especially at lower voltage levels [151]. Local regulation based on reactive power is also possible [45].

To keep frequency stable in the distribution system, three types of control are defined by the Union for the Coordination of Transmission of Electricity: primary, secondary, and tertiary frequency control [103], [152]. A PEV could provide *regulation down* by charging its battery. If there is a need for *regulation up*, the battery could be discharged into the grid. If the PEV is charging at this moment, charging can be stopped [62] rather than transitioning to discharge. For secondary and tertiary frequency control, activation is based on bids. When demand for regulation up arises, the lowest bid is activated first. Because delivering regulation down means charging at a lower price, this can be profitable for PEVs [46]. In [23] and [153], primary control is expected to have the highest value for V2G.

Business models and potential profit based on V2G support compared to existing grid regulation have been analyzed by Kempton and Tomić in [23], [62]. PEVs show a wide range of profit based on market value, power capacity of electrical connections, and energy capacity of the PEV battery. Values ranging from \$3777 to \$4000 per year were found for a vehicle providing regulating power of 10–15 kW. Tomić and Kempton [62] have also found net profit in four different U.S. ancillary service markets in the range of \$90–2400 per year, with each vehicle providing 2.9–6.2 kW of regulation down. Brooks showed the annual value between \$3038 and \$5038 for V2G application in California [154].

Vehicle fleets are of special interest. The annual net profit for a 100 Th!nk City fleet discussed in [62] ranges from \$7000 to \$70 000 providing regulation down with Level 2 charging. For a 252 Toyota RAV4 fleet discussed in [62], the annual net profit ranges from \$24 000 to \$260 000 providing regulation down and up in two U.S. regional regulation markets (Texas and PJM—Pennsylvania, New Jersey, and Maryland). De Los Ríos *et al.* [149] simulated a 250-vehicle fleet in the New England regulation services market. According to their calculations, an EV/PHEV can earn \$700–900 per year per vehicle by performing regulation down services, resulting in a 5–7% lifetime ownership costs reduction. Further, an EV/PHEV can earn \$1250–1400 per year per vehicle by providing regulation up and down services, resulting in a 9–11% reduction in ownership costs. A PEV fleet can also generate substantive cost savings for a power system. A simulation study in Texas showed that the power system saved more than \$200 annually per vehicle for a fleet with 15% penetration level of PEVs [48].

Studies of frequency regulation in Europe show a profit range from 0 to 9600 €/year per vehicle. In [20], profits based on secondary and tertiary control in Denmark were found to be in the range of 72–1920 €/year per vehicle. A Portuguese study gives a net revenue of 240 €/year based on a vehicle providing 3.5 kW of regulation services [47]. Andersson *et al.* [46] investigate PEVs as providers of primary, secondary and tertiary frequency control in Germany and Sweden. The maximum average profits generated in Germany were in the range of 360–9600 € /year per vehicle. No profit was found in Swedish regulating markets. Dallinger *et al.* [41] established a new approach to analyzing the economic impacts of V2G regulation reserves by simulating restrictions arising from unpredictable mobility in the German market. It was shown that negative secondary control is economically the most beneficial for EVs because it offers the highest potential for charging with low-priced energy from negative regulation reserves.

2) Load Leveling and Peak Power (Load Shifting): V2G can level the energy load by discharging during daily peaks and charging during low demand (overnight, off-peak hours). Mets *et al.* [155] described local and global smart charging control strategies. They showed that smart charging can reduce peak load and level the load curve. Takagi *et al.* [36] proposed an electricity pricing algorithm for load leveling. They identified an electricity price curve that can realize an ideal bottom charge while PEV owners minimize their electric bill. In terms of load leveling for the grid, PEVs should be charged late at night. A study which considers the integration into the California grid of 4 million PEVs showed that the charging load could be accommodated by the current power system without requiring new sources [156]. Chakraborty *et al.* [157] observed that for New York City (100 000 vehicles were simulated with using Level 2 charging), up to 10% of peaking capacity can be safely contributed by vehicles at PEV penetration levels around 50%, representing an economic benefit of \$110 million per year. PEV charging safety is not found to be an issue for up to about 87.5% penetration. Load shifting may significantly reduce the impact of a PEV fleet on the grid. This can be achieved by coordination of charging PEVs. The development of a controlled battery charger aims to reduce peak load and to shift energy demand [35], [158]. This also gives opportunities for smart charging. A study in 13 U.S. regions without smart charging but estimating high penetration of PEVs showed that 160 new power plants will be required if every PEV is charged in the early evening [159]. Some other studies show that there is little financial incentive with increased PEV penetration when V2G is used for peak load reduction [51], [148]. According to [160], peak power control could be the most economical solution in Japan.

C. Renewable Energy Supporting and Balancing

PEVs can be combined with renewable energy to buffer and store energy generated by intermittent wind and solar plants [7], [33], [34], [137], [161]. For example, peak solar radiation occurs a few hours before peak energy draw in many markets [66]. Wind power is more complex, and unpredictable variations in wind speed make it strongly intermittent, leading to imbalances [33], [125], [162]. Kempton and Tomić [7] investigate whether V2G could handle the fluctuating in-feed of wind power. Guille and Gross [31] proposed a model predictive control framework and estimated the positive effect of PEV on wind power operations. Ota *et al.* [163] proposed an autonomous distributed V2G control scheme providing a distributed spinning reserve for the unexpected intermittency of the renewable sources. Goransson *et al.* [164] elicit different strategies for integrating EVs into a wind-thermal power system. A combination of demand response and wind power integration has been provided by Wang *et al.* [165]. If the energy injected to the grid from renewable resources is too high, centralized power plants must decrease their production to restore balance or the distributed generator units must be curtailed. Vehicles can help match consumption and generation by discharging and charging so the utility does not need to decrease the power output. PEVs also can store excess renewable energy. This stored energy can be used for driving needs or to provide power to the grid at a later time [66]. V2G thus increases the flexibility for the grid to better utilize intermittent renewable sources. A simulation study of an independent system operator of a ten-unit system with 50 000 registered PEVs, which are charged from renewable sources as loads and discharged to the grid as sources, was carried out in [59]. This study showed that the smart grid model with renewable sources can reduce emissions and save the electricity and transportation industries at least $3.58 per vehicle per day.

VI. CHALLENGES TO V2G CONCEPT

Although there are many benefits of V2G systems, increasing the number of PEVs may impact power distribution system dynamics and performance through overloading of transformers, cables, and feeders. This reduces efficiency, may require additional generator starts, and produces voltage deviations and harmonics [166], [167]. There are also some impediments and barriers to the V2G transition: battery degradation, investment cost, energy losses, resistance of automotive and oil sectors, and customer acceptance. The biggest challenges are battery technology and the high initial costs compared to ICE vehicles. The limitations to using the PEV for V2G will likely be related to the challenge of implementing assured and secure communications particularly between the aggregator and the large number of PEVs [58]. A reliable two-way communication infrastructure network is needed to enable V2G technology [53]. In [168], the U.S. Department of Energy reported specific challenges and opportunities in terms of communication needs. Security issues are another challenge, and important in the communication network at public charging facilities [169]. An additional issue is that the distribution grid has not been designed for bidirectional energy flow, and this tends to limit the service capabilities of V2G devices.

A. Battery Degradation

Battery degradation depends on the amount and rate of energy withdrawn and is a function of discharge depth discharge and cycling frequency. Bidirectional V2G for ancillary services is likely to reduce battery life. The cost of battery degradation is difficult to estimate, because technologies are still developing. The equivalent series resistance (ESR) is one parameter that helps predict battery cycle life. For many types of batteries, deeper discharge increases the cell deterioration rate, resulting in a faster ESR increase [170]. The internal resistance tends to increase at low temperatures and at both ends of SOC. Using the battery in the middle SOC range is a good way to slow the degradation [171]. Quinn *et al.* [172] proposed a novel battery SOC control model and simulated the effects of SOC limitations on V2G economics and reliability. Intelligent control and optimization of charging time and energy flows can assure that the additional degradation rate is minimized [31]. Ongoing battery research seeks to improve battery cycle life [173]. When the number of cycles is increased by the battery technology improvement, the investment price per stored energy will be lower.

Battery cycle life greatly varies depending on chemical structure and manufacturing process. Li-ion batteries are the best present candidate for V2G, because of their long cycle life, reasonable deep cycling capability, relatively high energy density, and high efficiency. An Li-ion battery lasts for 2000–4000 deep cycles, and estimated future Li-ion battery investment for mass production lies in the range of $200–500 per kWh [54]. A battery investment cost of $300 per kWh and a lifetime of 3000 cycles at a depth of discharge of 80% suggest battery degradation cost of $130 per MWh [46]. In [51] and [174], economic losses associated with battery degradation were calculated based on data collected from A123 Systems lithium cells for a 16-kWh battery pack. If the measured battery degradation is included, the maximum net annual benefit for V2G services is only $10–120.

Beer *et al.* [175] analyzed the possibility of extending the lifecycle of PEV batteries in a secondary, stationary application in three case studies. Battery usage can be optimized by installing used battery packs in buildings microgrids. This storage is managed by an aggregator, with a contract for frequency regulation and for selling or buying the required energy on the ISO energy market. Results showed that used PEV batteries retain significant monetary value if subsequently used for stationary applications.

B. Effects on Distribution Equipment

PEV charging is likely to have a considerable impact on distribution equipment [176], [177]. Depending on the PEV penetration scenarios, Level 2 and 3 battery chargers [178]–[180] can quickly overload local distribution equipment. They increase distribution transformer losses, voltage deviations, harmonic distortion, and peak demand [181]–[183]. This calls for additional investments in larger underground cables and overhead lines, and more transformer capacity [9]. The cost could significantly impact the reliability, security, efficiency, and economy of newly developing smart grids due to possible loss of transformer life [184], [185]. Degradation in life of a typical distribution transformer can be reduced considerably by using a controlled charging scheme [86]. Different penetrations of PEVs were studied based on transformer insulation life using a thermal model in [186]. The results showed that a large penetration of PEVs can have great impact on the power grid—particularly with poor coordination of charging times. At a PEV penetration of 50%, transformer life is reduced by 200–300% relative to the base case with uncontrolled charging; controlled charging increases life 100–200% with respect to uncontrolled charging [187]. The aging rate of low-voltage transformers with high PEV penetration is modeled and simulated in France [188]. It is shown that aging of a transformer is quadratic in presence of PEVs. Clement-Nyns *et al.* [45] have shown that if a 30% PEV penetration is introduced in the Belgium test grid, the power demand in the grid increases about 10%. This is beyond the range of transformer and conductor capacity. Farmer *et al.* [189] presented a PEV distribution circuit impact model to estimate the impact of an increasing number of PEVs on transformers and underground cables. In order to minimize the impact of charging PEVs on a distribution circuit, a demand response strategy is proposed in the context of a smart distribution network in [190]. Voltage drop problems can be tackled by employing a capacitor bank or a load-tap changing transformer [45], or by using reactive power services of PEV chargers.

C. Investment Costs and Energy Losses

Oak Ridge National Laboratory [191] performed a thorough analysis of PEV penetration into regional power grids, and reported that all regions would need additional generation investments to serve the extra PEV demand. Fernández *et al.* [55] presented impacts of different levels of PEV penetration on distribution network investments and incremental energy losses. Depending on the charging strategies, up to 15% of the total actual distribution network costs would need to be invested, and energy losses could increase up to 40% in off-peak hours when 60% of the total vehicles are PEVs. In [45], an optimal PEV fleet charging profile is proposed for minimizing the distribution system power losses. According to [192], if PEVs are to become the preferred vehicles within the U.K., a significant investment in electrical networks will be required.

VII. CONCLUSION

The impact of V2G technologies on distributed systems, and requirements, benefits, challenges, and strategies for V2G interfaces of both individual PEVs and vehicle fleets were reviewed in this paper. Components and unidirectional/bidirectional power flow technologies of these systems, individual and aggregated structures, and charging/recharging frequency and strategies were addressed. PEVs can serve as stored energy resources and act as a reserve against unexpected outages when they have adequate on-board power electronics, power connection to the grid, communication and control between grid operator, and smart on-board metering systems. Unidirectional V2G is a traditional and logical first step because it limits hardware requirements, simplifies interconnection issues, and tends to reduce battery degradation. A bidirectional V2G system supports charge from the grid, battery energy injection back to the grid, and power stabilization. Economic costs, emissions benefits, and distribution system impacts of V2G-capable PEVs depend on vehicle aggregation, charging and recharging frequency, and strategies. Coordinated smart charging and discharging to optimize time and power demand appears to be the most beneficial and efficient strategy for both the grid operator and PEV owners. Cooperation between the grid operator and vehicle owners or aggregators is important to realize the highest possible net return.

The V2G concept can improve the technical performance of the grid in areas such as efficiency, stability, reliability, and generation dispatch. V2G-capable vehicles offer reactive power support, active power regulation, sources, current harmonic filtering, peak shaving, and load balancing by valley filling. They also offer possible backup for renewable power sources such as wind and solar power, supporting efficient integration of intermittent power production. These systems can enable ancillary services including voltage and frequency control, and spinning reserves. They reduce utility operating costs and even potentially generate revenue. V2G approaches also save money for the vehicle owners. Researchers estimate the potential net returns from V2G methods range between $90 and $4000 per year per vehicle based on power capacity of the electrical connections, market value, penetration number of PEVs, and PEV battery energy capacity. Costs and impediments of V2G include battery degradation in bidirectional applications, the need for intensive communication between the vehicles and the grid, effects distribution equipment, infrastructure changes, and social, political, cultural, and technical obstacles.

A range of proposed V2G concepts, services, requirements, costs, and benefits were discussed. It will be shown that although V2G can reduce the lifetime of PEVs, it is more economical for the vehicle owners and the grid operator. It benefits the environment and will accelerate PEV deployment. Success of the V2G concept depends on standardization of requirements and infrastructure decisions, efficient and smart charging/recharging strategies, and PEV aggregations as a source of stored energy. An interface with the smart grid needs to be provided for better integration of PEVs into the grid. PEV batteries also must have an extended cycle life, use lower cost and lightweight materials, and be more efficient in order to better support the V2G concept. Communication, controls and usage patterns also must be evaluated for short-term and long-term impacts on battery life and utility distribution networks.

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