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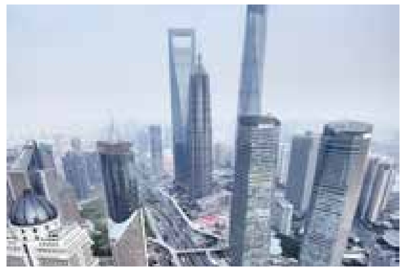

The Potential of Grid Integration of Electric Vehicles in Shanghai

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Table of Abbreviations

Abbreviation	Full Name
AC	Alternating Current
BEV	Battery Electric Vehicle
C&I	Commercial and Industrial
CD	Charge Depleting (Mode)
CS	Charge Sustaining (Mode)
DC	Direct Current
DR	Demand Response
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FYP	Five Year Plan
FR	Frequency Reductions
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ISO	Independent System Operator
NERC	North American Electric Reliability Corporation
NOx	Mono-Nitrogen Oxides
PCS	Power Conversion System
PHEV	Plug-in Hybrid Electric Vehicle
RMB	Renminbi (Yuan)
SDG&E	San Diego Gas and Electric
SOC	State of Charge
SHEIC	Shanghai Municipal Commission of Economic and Informatization
TOU	Time of Use
T&D	Transmission and Distribution
V	Volt
VA	Voltage Amps
V2G	Vehicle-to-Grid
W	Watt
Wh	Watt Hour
XLPE	Cross-Linked Polyethylene

1. EXECUTIVE SUMMARY

The development of electric vehicles is essential to improving energy efficiency and reducing emissions in China's transportation sector, as well as accelerating the structural transformation of China's industrial sectors. The government has recently enacted a series of policies supporting the development of the electric vehicle sector, focusing on increasing investment in related research and industry support, developing regulatory measures, and promoting the widespread adoption of electric vehicles. The government has also set a nationwide target of producing and selling five million electric vehicles and plug-in hybrid vehicles by 2020. These policies have promoted rapid growth in China's electric vehicle market. In 2015, more than 330,000 electric vehicles were sold in China, representing 1.34 percent of total annual vehicle sales in China and making China the world's largest market for electric vehicles.

The widespread adoption of electric vehicles will affect the electric power system in multiple ways. First, the growing number of electric vehicles will increase electricity demand. Peak power load, in particular, will be significantly increased as a large number of vehicles charge during peak hours. This will require improvements in the system capacity and stability of the power system. On the other hand, if power management and two-way technologies are promoted, electric vehicles can be viewed as both demand response resources and distributed energy resources. Therefore, large-scale electric vehicle integration can increase the efficiency of distribution infrastructure and also bring about additional benefits such as peak load shaving and the provision of ancillary services.

However, research in China on the potential applications of electric vehicles in the power system remains insufficient. Quantitative research on the economics and potential implications of electric vehicle load shifting is also lacking. To address this gap in research this study uses projected growth in electric vehicle ownership in Shanghai to evaluate the potential impacts of electric vehicle charging on the city's grid. Based on Shanghai's peak load and the current driving patterns of electric vehicle users, this study analyses the following:

CHARGING POWER DEMAND AND LOAD PROFILES

The following research on the development of the electric vehicle sector in Shanghai is based on two potential scenarios: a baseline growth scenario, where electric vehicle sales in 2030 account for 28 percent of the vehicle sales market with the number of electric vehicle users reaching 1.55 million; and a high-growth scenario, where electric vehicle sales in 2030 account for 43 percent of the vehicle sales market, with the number of electric vehicle users reaching 2.45 million. In terms of charging capacity, in the baseline growth scenario the annual charging demand for electric vehicles will reach 12.4TWh in the year 2030, comprising 7.4 percent of Shanghai's total electricity consumption; in the high-growth scenario, the charging demand will reach 19.6TWh, comprising 11.2% of total electricity consumption. In terms of charging load profiles, this study bases its findings on the projected growth in Shanghai's electric vehicle users, as well as on research on the driving patterns of electric vehicle users, in order to estimate the impact of charging on the load curve. The results demonstrate that unmanaged charging will significantly increase evening peak load and widen the difference between daytime peak load and off-peak load, thus putting pressure on the safety and stability of the power grid.

POTENTIAL OF MANAGED EV CHARGING ON LOAD SHIFTING

Compared to traditional demand side resources, electric vehicles have higher capacities to adjust their charge and discharge of electricity. In fact, when the integration of electric vehicles becomes more widespread, the impact of electric vehicles on load distribution may become one of the most important methods of load management in the power system. Therefore, appropriate management of the electric vehicle charging load is necessary for improving grid flexibility and for reducing the destabilizing impacts that large-scale electric vehicle integration may have on the grid. In order to evaluate the driving patterns of electric vehicle users in Shanghai, this study analyzes user behavior of electric buses, electric taxis, government electric vehicles, private electric vehicles, and electric vans. The study shows that, when considering private and government electric vehicles, managed charging leads to a reduction in the peak load and lessens the difference between daytime peak load and off-peak load. It also results in the charging load being mostly concentrated in low use periods, such as in the early morning.

ECONOMICS OF EV CHARGING MANAGEMENT

There is a big difference between electric vehicle charging and traditional demand response resources. For electric vehicles, as time spent driving is separate from time spent parked and charging, changes in charging duration would only minimally affect driving patterns, and in this aspect the cost of demand response for electric vehicles is comparatively lower than that of traditional demand response resources. This study made assumptions on demand elasticity of EV charging costs in Shanghai based on previous similar analysis. It found that under the premise of managed charging technologies, implementing time-of-use (TOU) pricing would have a significant effect on the charging behaviors of electric vehicle users in Shanghai. It predicts that under TOU pricing, more than 70 percent of private and government electric vehicles would charge off-peak. For power grid companies, increasing the difference between peak and valley prices would encourage charging load shift to off peak period, and hence lead to a reduction of summer peak load. In contrast, considering that the penetration of renewable energy will continue to increase, the economic value of EV load shifting will become more apparent. Currently, vehicle-to-grid (V2G)[1] services may not prove economically viable due to unfavorable market conditions and the absence of better battery technologies. In the long run, however, as the electric vehicle market develops, large-scale production will lead to decreased battery costs, and electric vehicle integration will not only bring about considerable economic benefits, but also achieve significant social and environmental benefits.

The above analysis shows that with the rising number of electric vehicles, managed charging would not only reduce the debilitating impacts that large numbers of electric vehicles may have on the grid, but also make electric vehicles an important demand side management resource. Realizing the full potential of the integration of electric vehicles in the power system relies on the following factors:

POWER MARKET ENVIRONMENT

China's electricity market currently lacks the mechanisms to incentivize EV owners to charge their vehicles during off-peak periods. First, the existing practice of planned power dispatch does not take advantage of the market value of flexible grid resources. While there is momentum for power sector reform, it will be necessary to establish an electricity spot market and simultaneously develop market mechanisms that reflect the value of flexible resources, including electric vehicles, in the power system. Spot markets should be established such that utility companies set prices at regular intervals. The value of flexible demand response resources can increased by lowering the market barriers for electric vehicles to enter the energy and ancillary services market. Facilitated by the formation of new electricity retailers, electricity prices in the competitive wholesale electricity market will change throughout the day. Electricity retailers and other demand response providers will then be able to optimize their costs and generate revenues based on fluctuating electricity prices by deploying high-quality, flexible resources capable of load shifting, such as electric vehicles.

MANAGED CHARGING TECHNOLOGIES

Operators of the existing EV charging infrastructure provide uneven support for managed charging. As a result, most electric vehicles still employ the 'plug and charge' method. Widespread use of electric vehicles in the future is expected to render them an important resource for distributed energy storage. Managed charging technologies and electric vehicle integration should focus on the energy storage potential in electric vehicles, stabilizing fluctuations in the peak load, and improving the power grid's capacity to access renewable energy and its overall operational efficiency. Therefore, power companies, as well as electric vehicle and charging infrastructure manufacturers, in conjunction with research in electric vehicle integration technology, could make the charging network a part of the larger energy distribution network and promote the managed development of charging infrastructure and grid planning and design.

COMMERCIAL OPERATION MODEL

Because electric vehicle charging infrastructure is often decentralized, and because the level of use can be unpredictable, it can be difficult to predict the charging load at any given time, diminishing the value of EVs to the power system. The introduction of charging service providers can, on one hand, improve the accuracy of load forecasting, and on the other hand, through vehicular networking technology, guide electric vehicle charging behavior and thus enhance the capacity of electric vehicles to serve as an effective means of balancing load in the power system. However, in practice, there are many challenges to the implementation of electric vehicle integration, and uncertainties remain. First, it is unclear which strategies and mechanisms should be adopted to attract enough electric vehicle users in order to ensure grid stability and allow for sufficient charging. Second uncertainty exists in how electric vehicle users are geographically distributed and how information on operation systems can be effectively monitored and controlled. Third, there needs to be a good system to track the state of charge (SOC) of each car's battery. Lastly, institutional mechanisms that can regulate the growing market for electric vehicle charging service providers need to be identified. Future research and testing is needed to address these areas of uncertainty.

CHARGING INFRASTRUCTURE AND RATES

Charging facilities act as the point of exchange between electric vehicles and the power grid and are a key means of determining electric vehicles' orderly access to the grid. Electric vehicle charging methods include slow charging, regular charging, fast charging, battery replacement, and wireless charging. The development of certain charging systems have faced financial constraints. For example, the construction of a large-scale fast charging infrastructure has been subject to grid capacity and cost restrictions, home charging infrastructure has been limited by restrictions on car parking spaces and public charging infrastructure has been constrained by limitations on parking time. Therefore, charging infrastructure cannot rely solely on one particular charging method alone; it is necessary to develop various charging methods for use in different contexts. This study found that from the perspective of increasing the flexibility of charging methods, priority should be placed on providing residential and office charging facilities, while simultaneously accelerating the development of fixed-time-charging and intelligent-charging software and construction of adequate hardware infrastructure, in order to make it more convenient for electric vehicle users to utilize charging facilities.

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[1] V2G is short for Vehicle-to-grid. V2G describes an interaction between EVs and the grid, whereby when EVs are not in use, excess electrical energy from batteries can be sold back to the grid, though if the car needs to charge, electricity can still flow into the battery from the grid. Currently, Delaware University, Pacific Gas and Electric Company (PG&E), Xcel Energy, National Renewable Energy Laboratory (NREL), the University of Warwick, and other research institutions are all continuing to advance research on V2G technology.

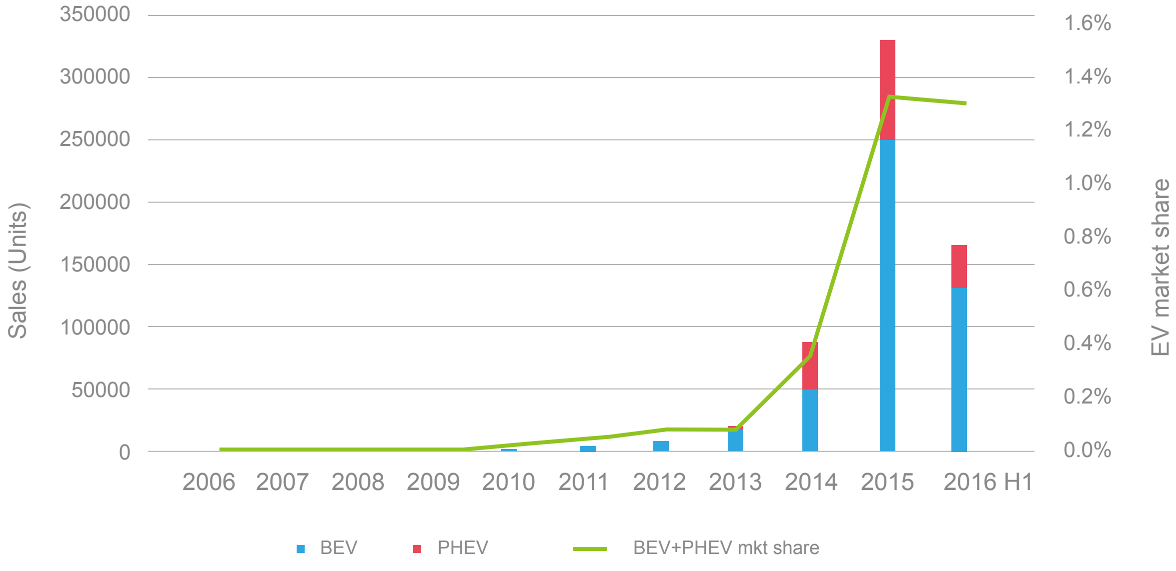
Currently, the pricing mechanism for electric vehicle charging in Shanghai is inconsistent in terms of the electricity price and service fees. For example, although the government has requested that electric vehicle charging prices should reflect the stipulated TOU price at specific charging facilities, in actuality, residential, office and public car park charging facilities often charge users based on fixed prices, leading to a lack of incentive for users to charge during off-peak hours, preventing potential peak shifting. Secondly, current electric vehicle charging waives the electricity capacity fee and it is difficult for one-off time-of-use pricing to accurately reflect the capacity cost of the user. In particular, residential and office building charging facilities have a lower load than other charging facilities, and thus, electric vehicles take up less capacity cost and do not contribute as much to grid stability. In terms of electricity costs, overall electric vehicle integration can be improved if residential charging facilities have time-of-use pricing. Even so, this may lead to a new peak load, and the pre-set residential TOU pricing may not sufficiently take advantage of the flexibility of real-time adjustment pricing. In terms of charging service fees, current charges have a price cap, but because there is currently a huge gap between the cost of AC and DC charging infrastructure, the single price mechanism has created little incentive for the development and mass production of fast charging facilities and other emerging technologies like wireless charging. When considering the pricing for electric vehicle charging in terms of capacity pricing, electricity pricing and service charges, ultimately the final price should reflect the true competitiveness of electric vehicle charging prices in comparison to fuel costs, and should provide return on the initial investment in charging infrastructure. In addition, price signals should guide grid-friendly charging behavior, so as to effectively encourage electric vehicle users to participate in the integrated charging system and maximize the potential of electric vehicle applications in the power system.

2. BACKGROUND ON THE DEVELOPMENT OF ELECTRIC VEHICLES

2.1 The Development of Electric Vehicles and the Impact on the Power System

As a result of fast-paced economic development and urbanization, China has entered an era of mobility, where vehicle ownership is increasing significantly. In 2015, national car sales reached 24.6 million, and the total number of vehicles in China exceeded 170 million.[1] The rapid growth of the vehicle industry has led to the heavy consumption of oil resources and the release of large amounts of pollutants, creating the need to develop a new generation of low carbon, electrically-powered intelligent vehicles.

Electric vehicles are the future of transportation. In terms of energy conservation and reducing dependence on traditional fossil fuels, electric cars have unparalleled advantages over conventional vehicles. The Chinese government has named electric vehicles one of the seven strategic emerging industries in China, and has focused significant efforts on the development of electric vehicles. The report by the State Council in 2012, “Energy saving and new energy automotive industry development plan” (2012-2020)” [2] stipulated that by 2015, battery electric vehicles and plug-in hybrid vehicles total sales would reach 500,000. It further stated that in the year 2020, the production capacity of battery electric vehicles and plug-in hybrid vehicles would reach two million, and the cumulative total number of vehicles would be more than five million. Subsequently, the National Development and Reform Commission, Ministry of Finance, Ministry of Industry and several local governments have introduced new subsidies for new-energy vehicles[3], which are exempt from purchase tax and limited access traffic lanes[4][5], and can receive free license plates[6][7]. In addition, these bodies have formulated strategic plans for policies regarding charging infrastructure and pricing mechanisms, industry management, tax incentives, technological innovation and an infrastructure policy support system[8][9], all of which will lead to the rapid growth and popularization of China’s electric vehicle industry. In 2015, national electric car sales reached 331,000, nearly four times the sales figure in 2014, accounting for 1.34 percent of total car sales. The total number of clean energy vehicles in China reached 583,000 that year, of which battery electric vehicles comprised 332,000, a 317 percent increase from 2014. In 2016, from January to June, 126,000 electric vehicles were sold, along with 44,000 plug-in hybrid vehicles, an increase of 127 percent and 162 percent, respectively.[10]



BEV: Battery Electric Vehicles

PHEV: Plug-in Hybrid Electric Vehicles

Figure 2-1 2006-2016 China Electric Car Sales and Market Share

As one of the cities promoting new-energy vehicles in China, Shanghai has had a rapid increase in the number of electric vehicles in recent years. According to statistics published in 2015 by the Shanghai New-Energy Vehicles Public Data Acquisition and Monitoring Research Center, there were 46,507 new-energy vehicles in use; 10,574 or 22.7 percent were battery electric vehicles, and 35,933 or 77.3 percent were plug-in hybrids. From 2011 to 2015, the city has promoted 57,970 new-energy vehicles (national top1), where 13,794 or 23.8 percent were battery electric vehicles, and 44,176 or 76.2 percent were plug-in hybrids. [11]

The popularization of electric vehicles will necessitate careful consideration of their implications on the power system. Firstly, electric vehicles will increase the grid load, and large numbers of vehicles charging during peak load will put significant pressure on the power system, potentially having a negative impact on grid stability and efficiency. Secondly, the unpredictable charging behavior and geographical distribution of electric vehicle users will pose challenges for regulating the grid and load shifting. Thirdly, because electric vehicle charging is considered a non-linear load and will generate harmonics, problems in power quality may result [12]. Electric vehicle charging may also influence the voltage of different distribution networks and cause phase imbalances. Lastly, increasing the number of charging facilities will change the structure of the power distribution network, thereby making traditional distribution network system protocols and planning unfit for large-scale electric vehicle use.

On the other hand, taking into account the length of time for electric vehicle parking, and the distributed energy storage capacity of electric car batteries, electric vehicle users can take advantageof increasingly sophisticated distribution network technology, and according to load levels, energy output, electricity pricing and other sources information, adjust their electric vehicle charging load power and minimize the negative impact of large-scale electric vehicle use on the grid. Electric vehicle integration will result in load shifting and the creation of ancillary services, transitioning away from the traditional model of power system operations where ‘supply follows the load’, and toward a model of ‘cooperation between supply and load’.

2.2 Electric Vehicle Technologies

Currently available electric vehicle technology includes four categories:1) hybrid vehicles (HEV), which have a small battery capacity and are mainly used to improve engine efficiency and brake energy regeneration, 2) plug-in hybrid vehicles (PHEV), whose battery can be charged directly from the grid, 3) battery electric vehicles (BEV), which do not have an engine and run completely from battery power, and 4) fuel cell vehicles (FCV), which generate electricity to power the vehicle via hydrogen fuel cells. Because traditional hybrid cars do not charge from the grid, and fuel cell vehicles are costly to produce, they are promoted on a smaller scale. Therefore, the following study mainly focuses on the expansion of plug-in hybrids and battery electric vehicles.

Plug-in Hybrids

The majority of electric vehicles being sold in Shanghai are plug-in hybrid models. In 2015, they accounted for 77.3 percent of total new-energy vehicles sold. Plug-in hybrid electric vehicles (PHEV) can be charged from an external power grid, and can also rely on battery alone for short trips (such as 50km/trip). When the battery power runs out, the vehicle can still operate like a traditional hybrid vehicle (or a traditional internal combustion vehicle, more generally), using the internal combustion engine to keep running.

The main advantages of the plug-in hybrid include: longer traveling distances and better suitability for users’ daily travel needs, such as for commuting, when compared to EVs. For long distance travel, PHEV’s internal combustion engine is used to provide energy, similarly to traditional gasoline and diesel-powered vehicles. PHEV and battery electric cars can similarly take advantage of low power consumption during evening hours to charge their batteries, leading to less reliance on the combustion engine and improved fuel efficiency, as well as environmental benefits such as saving fuel, reducing reliance on fossil fuels and oil imports, and reducing greenhouse gas emissions. The operation of plug-in hybrid vehicles is generally divided into two different modes:

(1) Charge Depleting Mode, CD

If the battery is fully charged (SOC = 100%), the vehicle relies entirely on battery power, until the battery SOC decreases and eventually reaches the preset value (such as SOC = 50%).

2) Charge Sustaining Mode, CS

After the battery reaches a certain state of charge level (e.g. 50%), the vehicle enters hybrid mode, where the engine and generator work together, and the SOC remains at a stable level.

When the market for electric vehicles was first developing, insufficient charging infrastructure made charging inconvenient for battery electric cars, thus limiting the distances they could travel. Plug-in hybrid vehicles use internal combustion engines to make up for limitations of battery life and deficiencies in the charging infrastructure network, and are thus more practical and feasible options for the transition to new-energy vehicles. Plug-in hybrids are already technologically akin to battery EVs, but because the mileage requirement of battery electric vehicles is highly dependent on the battery capacity only, PHEVs have significant cost advantages for longer driving ranges.

	Motor power（kW）	Engine power（kW）	Battery capacity（kWh）	Battery BEV range（km）	Energy Intensity（kWh/100km)
BMWi 3 Plug-in	125	28	20	150	13.3
BMW 530Le plug-in hybrid	70	177	11.4	58	19.7
BYD Qin	110	113	13	70	18.6
BYD Tang	110	151	18.4	80	23.0
Prius Plug-in	60	73	4.4	23	19.1
SAIC Roewe Plugin550	67	80	11.8	58	20.3

Table 2-1 Key Parameters for Domestic Plug-in Hybrid Vehicles

Battery Electric Vehicles

Battery electric vehicles rely on onboard energy storage devices (car battery, super capacitor, flywheel battery) to drive the vehicle. Battery electric vehicles can be divided in low speed electric vehicles (less than 40km/h), medium-high speed electric vehicles (40-70km/h), high-speed electric vehicles (70-100km/h), and ultra-high-speed electric vehicles (above 100km/h). Depending on their application, battery electric vehicles can be divided into cars, buses, vans, and special purpose vehicles (such as vehicles used for postal, sanitation, logistics and construction services, golf carts, tour buses, etc.)

Because battery electric vehicles are driven entirely by electric power, they are a vital resource that can help achieve diversified energy, reduce or even eliminate dependence on oil, and furthermore, operate without releasing any greenhouse gas emissions at the tailpipe. In addition, high capacity battery power system can be used as distributed energy storage resources, which can improve low carbon and energy efficiency within the power system and promote the growth of smart grids. However, battery electric vehicles also pose some technical issues. Firstly, the battery specific energy capacity is relatively low, resulting in a single charge only being able to sustain shorter driving ranges. Secondly, the requirement of long time charging will reduce the mobility of the vehicle. Thirdly, the high cost of batteries has resulted in a bottleneck preventing more large-scale promotion of electric vehicle technology. [13]

	Mileage（km）	Motor Power（kW）	Battery Capacity（kWh）	Efficiency（kWh/100km)
BAICEV200	200	53	30.4	15.2
Nissan	175	80	24	13.7
Denza	300	86	47.5	15.8
JAC iEV5	170	50	23.3	13.7
ZOTYE	152	18	15	9.9
Roewe e50	170	52	22	12.9
BYD e6	400	90	82	20.5

Table 2-2 Key Parameters for Domestic Battery Electric Vehicles

2.3 Electric Vehicles and Demand Response

The development of electric vehicles will play an important role in electricity demand response. Firstly, the electric vehicle market represents a new source demand for power consumption; large-scale access to electric vehicles has brought with it a large potential demand for electricity, and promoted the electrification and informatization of end-use energy consumption. Secondly, the electric vehicle charging and discharging process includes fast charging, battery replacement, and infrastructure construction and maintenance; it is therefore poised to become a focal point for retail power competition. Thirdly, charging data monitoring and measuring devices are already integrated into electric vehicles, and users can use the onboard computer and telematics system to monitor and adjust the charging and discharging of the vehicle battery, reducing the need for demand response communication and investment in advanced metering infrastructure. Fourth, with the rise of the concept of low-carbon transportation, nascent business models such as car rental and car sharing are emerging, and electric vehicle integration has become a competitive player in the electricity market. Fifth, electric vehicle integration and standardization in the market will help unify different stakeholders in the market, such as end users, electricity retailers, the distribution network, etc., and help to simplify the profit distribution between these stakeholders. Sixth, electric vehicle users are generally willing to accept current charging costs because upper limit charging prices are comparable with fuel costs, allowing for a level of pricing flexibility that will encourage demand response. In summary, innovative EV operational business models could become the leading source of demand response and will further promote the development of the energy Internet.

3. THE IMPACT OF ELECTRIC VEHICLE CHARGING LOAD ON SHANGHAI'S ELECTRICAL GRID

The spread of electric vehicles will impact the operations of power systems in several ways. First, as a new way of using electricity, an increased number of EVs will undoubtedly raise electricity demand. Large numbers of vehicles charging simultaneously during peak hours would add substantially to the peak load, thereby requiring not only greater generation and transmission capacities but also more rigorous efforts at maintaining the grid's operating safety and stability. On the other hand, if two-way communication technologies are implemented, EVs can be viewed as a demand response resource or even as a form of distributed energy storage. As such, large-scale EV charging on the grid can not only reduce investments in new electricity infrastructure, but also shift load from peak hours to off-peak hours, and even be used to provide ancillary services to the grid. Currently, plug-in hybrid electric vehicles (PHEV) and EVs both possess the capacity to interact with the grid. In the past few years, domestic and international research has opened up a range of studies on the impact of connected electric vehicle networks on power systems:

- **Impact of Electric Vehicle Charging Load on Electricity Grids.** The load from EV charging is dependent on a range of factors, including driving and parking behaviors and the times and modes of charging. As EV development is still in the nascent stage, data on EV usage is relatively limited, so existing analyses of EV charging capacity and load profiles have generally depended on modeling and simulation work. Furthermore current research analyzing how EV charging will impact electrical loads, economic grid dispatch, electrical quality, and distribution infrastructure, etc., has mainly relied on EV growth forecasts, assumed EV users' driving behaviors and expected grid functioning. [14][15][16][17]

- Application of EV Energy Storage in Power Systems. It is a given that EVs will increase the electrical load on grids. However, by means of managed charging, EVs can be used to shave peak loads, increase the efficiency of electrical system operations, lower the costs of further system investments, and improve the flexibility of power system operations.[18][19][20][21] In addition, EV batteries can serve as distributed energy storage and feed electricity back to the grid or to other customers, thus presenting yet another source of value that EVs can provide to electrical grids.[22][23][24] Current research is mainly focused on managed charging and vehicle to grid (V2G) interactions, also known as unidirectional V1G and bi-directional V2G.

- **Cost-benefit Analysis of Electric Vehicle Charging and Discharging.** The viability of managed EV charging and EV as distributed energy resources depends on the costs of battery charging and discharging, the profits earned through providing system services for the EV owner, and the net benefits to the grid-system operator. Currently, research on this subject has been focused on the economics of ancillary services and demand response. [25][26][27][28][29]

This study is based on relevant experience, both in China and abroad. With Shanghai as the subject of research, it is divided into three sections regarding the value of EVs to power systems: the impact of electric vehicle charging load, potential and economics of EV demand response, market mechanisms and business models.

3.1 The Scale Of Shanghai Electric Vehicle Stock

The upper-limit of the growth in the number of EVs depends upon both local vehicle sales volumes and aggregate demand for vehicles. Shanghai is the first city in China to use license plate quotas as a means to control motor vehicle sales. In the past few years, the number of passenger vehicles in Shanghai has increased by roughly 350,000 annually, and by the end of 2015, the total number of motor vehicles reached 3,340,000, 2,910,000 of which were automobiles[2], representing a net increase of 295,300 year-on-year. Passenger vehicles in Shanghai now total 2,474,200, 83.2% of which are privately owned. There are 52 private vehicles to every 100 households.[30] Currently there are 33 manufacturing firms selling EVs in Shanghai, including over 64 EV models, indicating a full-fledged growth in the diversity of offerings. Promoted through free Shanghai license plate incentives and other policies, Shanghai's electric vehicle sales have rapidly increased. In 2015, the electric vehicle stock grew by 46,507, a more than three-fold increase from the previous year. Of Shanghai's 42,227 new passenger EVs, 29,085 of them are private vehicles, 4,194 are rental vehicles, and 8,292 are government vehicles. Particularly, in December 2015, following the strengthening of the end-of-the-year sales push, the expiration of district- and county-level subsidies, and other related factors, EV

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[2] Excluding two or three wheelers.

sales exploded. During this month, of the 14,000 new cars issued license plates, 13,000 were electric passenger vehicles. As for service providers, 131 EV maintenance outlets have been established in the city, 80 of which serve private vehicles, and the remaining 51 cater to commercial or specialized vehicles. By the end of 2015, total cumulative sales of all types of EVs reached 57,666, which included 51,754 private electric vehicles.

According to Shanghai's "Special Planning for Electric Vehicle Charging Infrastructure Projects (2016 – 2020) [31]," the total number of EVs will reach 131,000 by 2017, among which 85,000 will be private EVs with 25,000 government-owned EVs and 4,700 electric buses; in 2020, the total number of EVs is expected to reach 263,000, with 172,000 private EVs, 49,000 government-owned EVs and 8,000 electric buses. Shanghai's EV development plan is shown in figure 3-1.

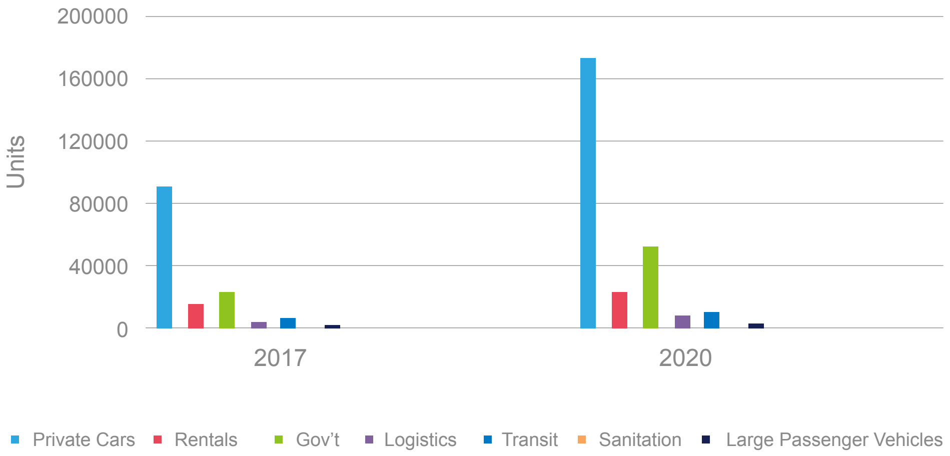

Figure 3-1 Planned Growth of Shanghai's Electric Vehicles

3.2 Charging Infrastructure

The main modes of EV charging include slow charging, regular charging, fast charging, battery swapping, and wireless charging. In 2011, the National Energy Administration released four EV charging ports and communication protocols [32], which were implemented on March 1st, 2012. According to the Electric Vehicle Conductive Charging Port standards, China's charging modes are divided into slow charging (Level 1), regular charging (Level 2), and fast charging (Level 3), as described in Table 3-1. Slow charging has a rated output of 3.5 kilowatts, while standard charging has a rated output of 7 kilowatts. Fast charging can reach rates of over 100 kilowatts.

Charging Mode	Rated Voltage （V）	Rated Current （A）	Charging Capacity （kW）	Suitable For:
L1	Single Phase AC 220	16	3.5	Residences
L2-1	Single Phase AC 220	32	7	Residences, Offices, Public Parking, Bus Stations
L2-2	Three Phase AC 380	32	12.2	
L2-3	Three Phase AC 80	64	24.3	
L3	DC 600	300	180	Highway Service Areas

Table 3-1 EV Charging Modes

Each mode of charging has its own areas of application. For example, slow and regular charging are more suitable for use in residential communities and commercial district parking lots, while fast charging fits better in highway service areas. The development of each mode of charging also faces a corresponding set of resource limitations. The large scale construction of fast charging stations must deal with infrastructure costs and electric grid capacity constraints; household charging stations are constrained by the fixed number of parking spaces; and public parking charging stations face charging time constraints. The future of EV charging, therefore, cannot depend on any single charging mode. Instead, modes complementing each other can cover the different needs and constraints of different localities.

As of 2015, a total of 21,170 charging stations of various kinds have been built in Shanghai, with over 16,500 private residential charging stations, 3,200 specialized, commercial, and governmental charging stations, 800 public transportation and logistics charging stations, and 1,200 public charging stations. Meanwhile, the expansion of charging stations is currently held back by parking space constraints. It has been projected that in downtown Shanghai, nighttime residential parking space demand outstrips supply by 52%, and the scarcity situation is even worse in legacy residential areas. Additionally, while charger operators in Shanghai have all developed their own independent service platforms and payment mechanisms, there is no unified information service platform for public charging facilities in the greater Shanghai metropolitan area, and this lack of unity has prevented the development of a convenient, identifiable, and open payment platform.

According to Shanghai's "Special Planning for Electric Vehicle Charging Infrastructure Projects (2016 – 2020)," Shanghai is planning to build a citywide charging infrastructure network as well as charging facility corridors, to satisfy in all types of localities the basic needs of electric vehicle development and usage. By 2020, the number of electric vehicle charging stations in Shanghai is expected to exceed 211,000. Future charging facility development will mainly focus on private/dedicated chargers, supplemented by public use stations, with a combination of slow and fast charging modes. A network of charging stations will gradually form throughout metropolitan residential and office areas, containing mainly private and dedicated stations, but also other public charging facilities. Intercity highways will serve as additional locations for public charging facilities. Private stations will mainly use slow charging modes, dedicated chargers will adopt a combination of slow and fast charging modes, and public charging stations will mainly use the fast charging mode. In order to provide capital for the development of EV charging stations, Shanghai plans to invest in and give subsidies to private and public charging facilities. [3]

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[3] 30% tax subsidy; Public transportation, sanitation operation were give 0.1 RMB per kilowatt hour, setting the subsidy ceiling.

3.3 Shanghai's Electricity Sector

Electricity Generation and Consumption Mix

Shanghai's citywide electric load has consistently ranked as one of the highest among cities across China [33]. As of the last few years, construction of Shanghai's electricity grid is approaching saturation, and the grid load has remained stable. Looking at Shanghai's typical load curves, one can clearly observe two main features within the city's load profiles. First, the average daily peak-valley difference is relatively large. Second, Shanghai's electrical load remains relatively stable year-round; the difference between summer and winter loads is relatively small. This indicates that the proportion of residential and tertiary sector loads is large and that people activities correlate very strongly with Shanghai's daily load. Of Shanghai's summer peak loads and winter peak loads, the summer loads pose more threat to Shanghai's grid reliability. Shanghai's electricity consumption and loads on weekdays do not vary too significantly from those during the weekends[4] .

Overall, Shanghai's fairly stable grid use is a clear indicator of the structure and growth patterns of Shanghai's economic structure and growth characteristics. With its stable population, large tertiary industry[5] and growing financial services sector, Shanghai has been able to keep its electricity consumption growth relatively flat.

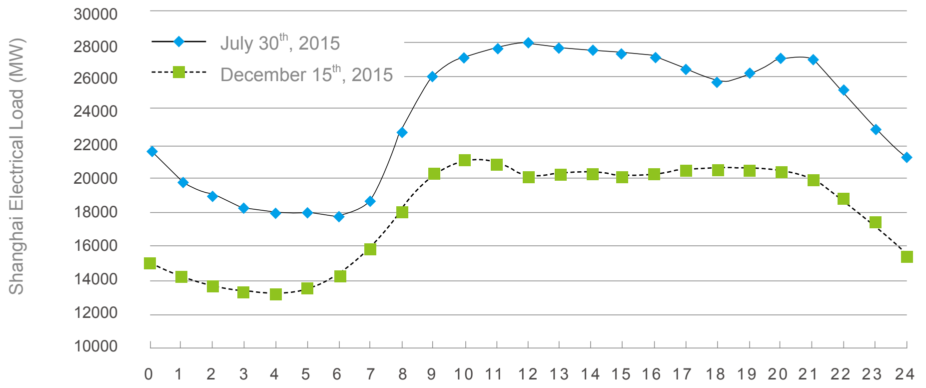

Figure 3-2 Typical Daily Load Curves in Shanghai in Winter and Summer in 2015

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[4] Total electricity consumption in Shanghai on Saturday, July 26, 2014 was 452 GWh, and 508 GWh on Wednesday, July 30, 2014.

[5] Primary industry: agriculture; secondary industry: manufacture, building, etc; tertiary industry: service.

Shanghai's power generation mix is dominated by fossil fuels: mainly coal, petroleum and natural gas. Figure 3-3 shows Shanghai's sources of power generation in 2015, with 65% electricity generation from coal, 26% from natural gas, and 3.6% from petroleum. In addition, Shanghai also relies on combined thermal power generation, which is fueled by urban waste incineration, gas generation from organic landfills, and other energy sources [34].

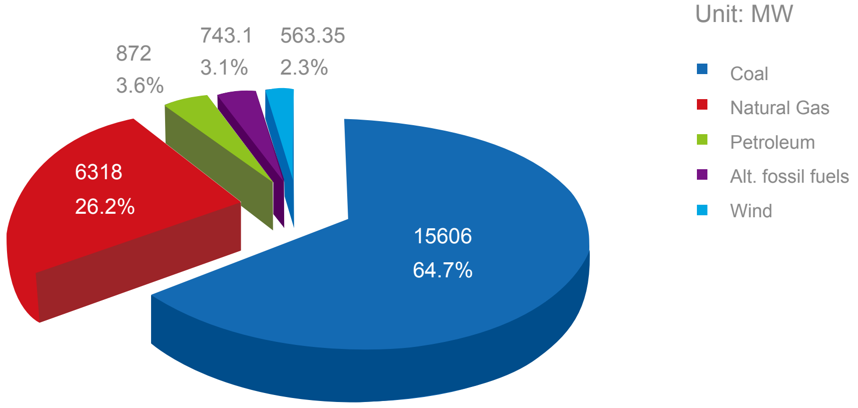

Figure 3-3 Shanghai Power Generation Mix in 2015

"Actively bringing in clean energy, reducing local emissions" – has been the core strategy of Shanghai's power sector development in the last few years, and one that has also brought unprecedented challenges to the city's grid dispatch and operations. In recent years, the volume of hydroelectricity imported from southwest China to Shanghai has risen steadily, reaching 12 million kilowatts. At times, imported clean electricity constitutes as much as 70% of the total power supply in Shanghai. With such large volumes of clean electricity feeding into Shanghai's grid, on top of Shanghai's large peak-valley differences, which is typical of megacities, the pressure for local generators to adjust power output to maintain grid balance has increased substantially. In summary, a situation is emerging where large-scale power fed to the Shanghai grid [35] is moderated with weak grid-balancing generation capacities. It is thus imperative for Shanghai to invest in flexible demand side resources that can aid in grid balancing.

Forecasting Electricity Demand

In the past few years, the growth of Shanghai's electricity demand has gradually slowed down. The electricity planning in Shanghai's 12th Five Year Plan estimated that, in 2015, Shanghai's peak load could reach 37,000 MW and total electricity consumption could reach 171.5 billion kilowatt hours. However, Shanghai's actual peak load in 2015 was 29,820 MW and it expended 140.5 billion kilowatt hours of electricity[36], representing a relatively large difference from the expected consumption levels. Shanghai's historical electrical consumption curve can be drawn using statistics from the China Economic Information Network, and its electrical consumption in 2020 and 2030 can be estimated according to historical data (Figure 3-4).

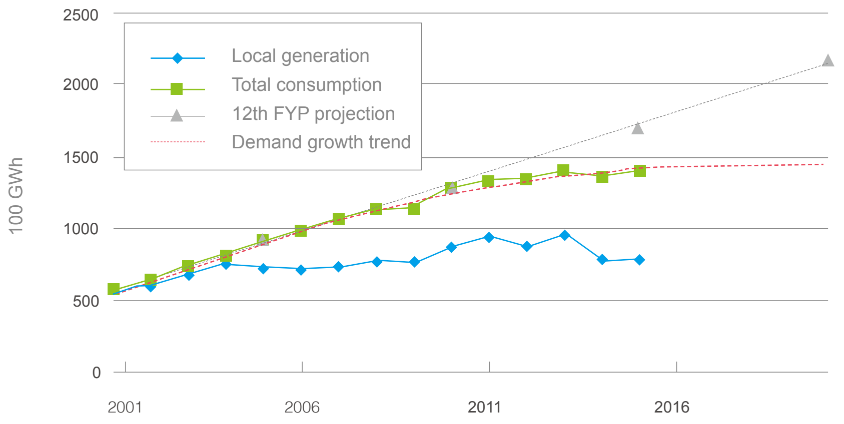

Figure 3-4 2020 Projections of Shanghai's Total Electrical Consumption

It is evident that Shanghai's total electricity demand is trending towards saturation. Furthermore, electricity consumption in Shanghai's secondary industry in 2015 showed a decline of 1.4% from the previous year, the first time consumption has declined in 40 years. For future projections, therefore, it is reasonable to assume that Shanghai's electrical consumption is plateauing. Predictions from a quadratic-fit model show that Shanghai's total electrical consumption will not exceed a growth rate of 1.6% in 2016, with the growth rate decreasing in subsequent years. According to this forecast, total electricity consumption in Shanghai in 2020 is predicted to be around 145.8 billion kilowatt hours. According to estimates based on the previous experiences, the average annual growth rate of Shanghai's electricity consumption until 2020 is expected to be around 0.7%. Predicted annual electricity consumption in Shanghai is forecasted to be around 156 billion kilowatt hours.

The peak load forecasts closely resemble the trends of electricity consumption. Mirroring China's economic transition, Shanghai's peak load experienced slower growth in the 12th FYP period, after a period of fast growth during the 11th FYP. It can therefore be expected that during the next five years leading up to 2020, growth of the maximum load of Shanghai's electricity grid will continue to slow, leading to a point of saturation (Figure 3-5).

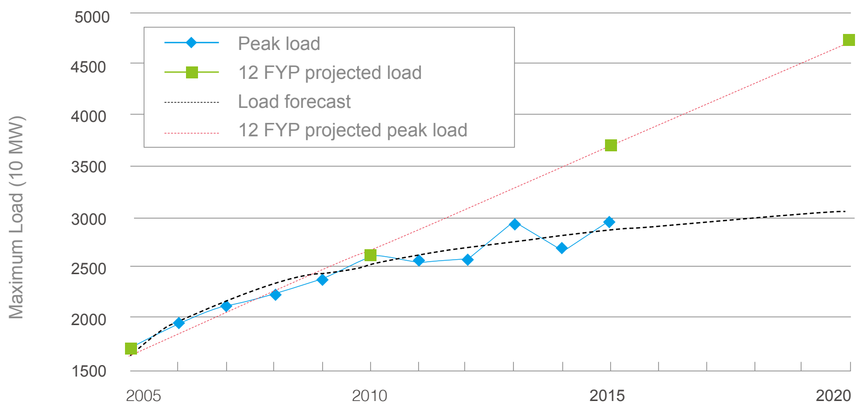

Figure 3-5 2020 Estimates of Shanghai's Electricity Grid's Maximum Load

According to data published by the Shanghai Statistics Bureau[37], although Shanghai's peak load reached historical levels in 2015, the levels since 2011 have exhibited an overall trend of flatter growth, deviating from the maximum load growth forecasted by Shanghai's "12th Five-Year" electrical plan. If Shanghai's maximum load grows according to the exponential law, it is forecasted to reach 30,400 MW in 2020 and 32,900 MW in 2030. Given the slowing growth of electricity demand and the growing importation of electricity from south-west regions, an increasing conflict between imported hydropower and local thermal power generation can be observed. Exploring marginal flexibility resources in Shanghai, therefore, will be important to addressing the shortage of regulation capacity. [6, 7]

3.4 Electric Vehicle Charging Demand

The impact that electric vehicle charging will have on peak load depends upon factors including consumer behavior, charging modes, and charging capacity. This study uses the Bass Diffusion model to predict the growth of EVs in metropolitan Shanghai. The Bass model assumes that when a new product enters a market, its popularity is affected by messages communicated by mass media (like advertisements) as well as by feedback that current users give to future users. Using China's electric vehicle market as an example (see below), the function "n (t)" represents the number of newly added electric vehicles at time "t," where "a" represents an "innovative" coefficient (an external factor), and "b" represents an "imitative" coefficient (an internal factor).

$$n(t) = a[m - N(t)] + \frac{b}{m} N(t)[m - N(t)]$$

Where:

n(t)—— the number of electric vehicles added at time t；

N(t)——the cumulative number of electric vehicles up to time t；

m—— the largest market potential (market carrying capacity)；

a，b—— external（innovation）coefficient、internal（imitation）coefficient

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6 Hydropower from Sichuan province to Shanghai reach 939 GWh, China Electricity Countil, http://www.cec.org.cn/zdlhuiyuandongtai/dianwang/2015-07-08/140266.html

7 Compensation for ancillary services provided by hydropower from Xiangjiaba to Shanghai, Eastern China Energy Administration, http://news.bjx.com.cn/html/20141205/570801.shtml

Under current policies, purchasers of EVs in Shanghai receive free license plates and cash-back subsidies. Considering that the price of a vehicle license plate in Shanghai can currently reach tens of thousands of RMB, such policies will undoubtedly help the growth of the EV market[38]. However, given the uncertainty of the future of motor vehicle restrictions and tax subsidies, this study used two different EV growth scenarios: baseline and high-growth. The baseline growth scenario is based on historical data from 2010-2015 regarding internal combustion engine (ICE) vehicle and EV sales and the projected sales for 2020. Based on the EV development target set by the local government, this study calculates the innovation coefficient and imitation coefficient for a reference scenario by fitting EV growth trend to 2020. This scenario uses an innovation coefficient and imitation coefficient of a = 0.01 and b = 0.08, respectively. However, given the recent fast growth of EV market in China and the large cost reduction of battery, we also made a fast-paced growth scenario where the innovation coefficient remains unchanged, but the imitation coefficient is raised to 0.15. According to the recursive sales growth from the model, under the conventional growth scenario, EV sales would reach 28% of the entire vehicle market sales volume by 2030, with 1.55 million total EVs, 1.44 million of which would be small passenger vehicles. Under the fast-paced growth model, EV sales would reach 43% of the total motor vehicle market sales volume by 2030, with 2.45 million total EVs, 2.28 million of which would be small passenger vehicles. In both scenarios, the plug-in hybrid vehicle to battery electric vehicle ratio would remain the same; 76% to 24%, respectively.

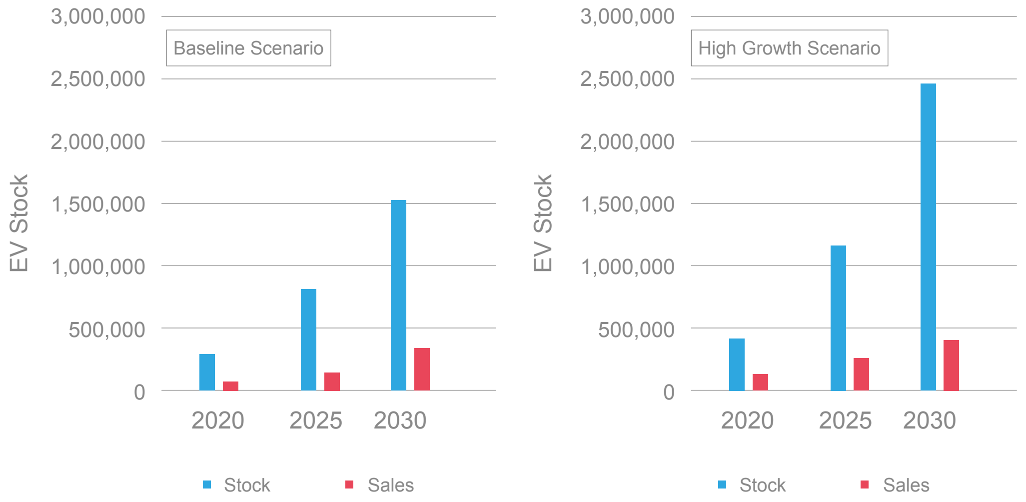

Figure 3-6 Sales Volume and Total EVs in Shanghai 2020-2030: Two Scenarios

Currently, EVs in Shanghai require 10 to 20 kilowatt hours of electricity to travel 100 kilometers, and can be charged at a rate of 3.3 to 7 kilowatts. This study assumes that EVs in Shanghai in 2030 will require 15 kilowatt hours to travel 100 kilometers and will be able to be charged at a rate of 7 kilowatts. In 2015, BYD Qin and Roewe E50 users drove a daily average distance of 31 kilometers and 26 kilometers, respectively. Considering that transportation mobility will be further improved in Shanghai, this study assumes that in 2030, passenger electric vehicles will travel an increased daily average of 50 kilometers with an annual increase rate of 3%. Similarly, this study assumes that in 2030, large electric buses will require 100 kilowatt hours of electricity per 100 kilometers, the average daily distance travelled by electric buses will be 300 kilometers, and that electric buses will charge at a rate of 100 kilowatts. Furthermore, this study assumes that electric passenger vehicles and buses will be able to be charged at an efficiency of 90%. Under the baseline EV growth model, total EV charging demand in Shanghai in 2030 will reach 12.4 terawatt hours, accounting for 7.4% of the city's total electrical consumption. Under the high-growth scenario, the charging demand is expected to reach 19.6 terawatt hours, representing 11.2% of the city's total electricity consumption[8].

3.5 Electric Vehicle Charging Load Profiles

Analysis of EV charging dynamics and potential for load shifting assumes the random nature of EV charging. EV charging load profiles are mainly determined by charging behaviors, and are also impacted by factors including driving and parking behaviors, the time of charging, and charging modes (slow, regular, fast). Data showing the probability distribution of BYD Qin users' traveling time suggests that EV users travel mostly during peak morning and evening hours (7:00-9:00 AM, 5:00-7:00 PM), accounting for 8.8% and 10.2%, respectively, of the total number of trips taken daily.[39] Other than during these periods, driving behavior remains fairly stable, with small peaks around noon. The lowest number of trips occur during the early morning (1:00-5:00 AM), accounting for not even 0.7% of daily driving. Average single trips from BYD Qin users lasted 35 minutes, with trips shorter than 25 minutes accounting for 51% of all trips.

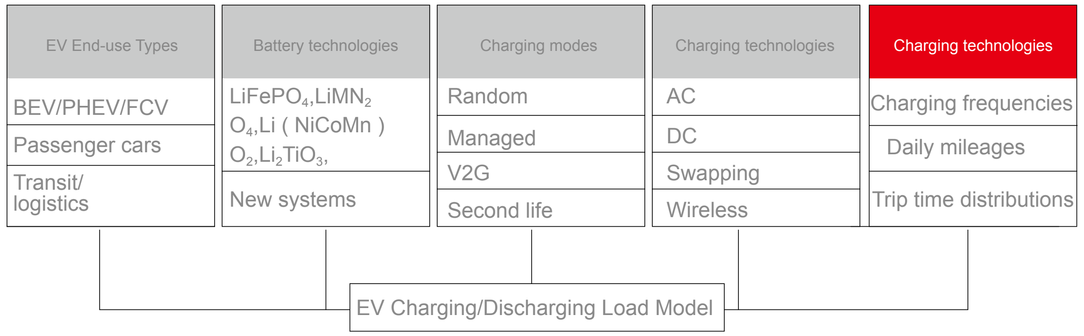

Figure 3-7 Factors Influencing Electric Vehicle Charging Load

In order to study the characteristics of different EV charging methods in Shanghai, this study investigated the parking and charging behavior of 73 electric vehicles, representing five different types of electric vehicles.[9] Figure 3-8 shows the probability distribution of parking times of four types of electric vehicles over 24 hours. Taking private EVs as an example, most users preferred to charge their vehicles using their chargers installed in parking lots in their own residential communities. Peak charging time for privately owned vehicles occurred at 7:00 PM in the evening and the daily minimum charging time occurred at around 8:00 AM in the morning. Conversely, peak parking time for electric taxis was usually concentrated at around 10:00 PM in the evening to the next day morning.

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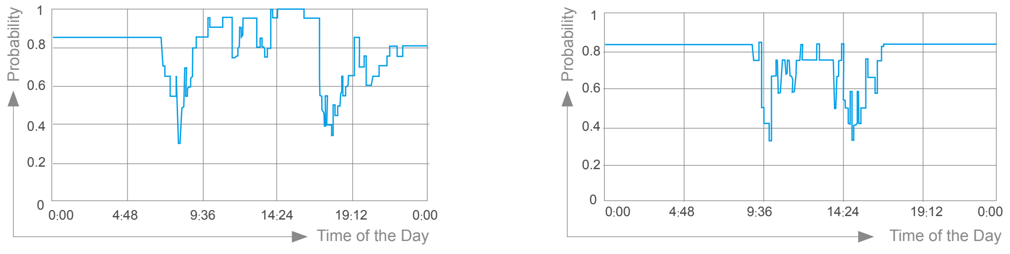
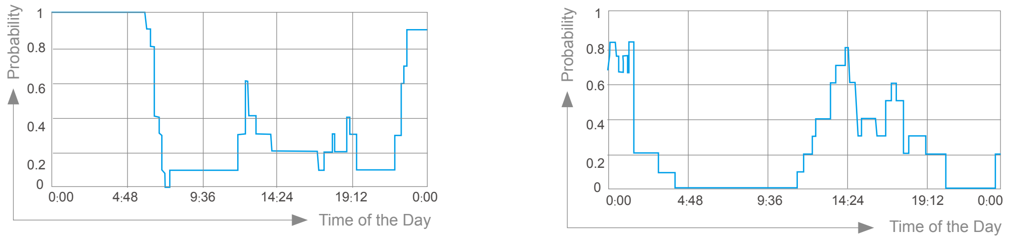
8 A detailed analysis of this is in Appendix 1.

9 This included 10 EV buses, 10 electric taxis, 10 electric logistic vehicles, 16 government-owned EVs, and 27 private passenger EVs.



Private EVs

Government owned EVs



Electric Taxis

Electric Buses

Figure 3-8 Probabilistic Distribution of Charging Time among Different EV Types in Shanghai

The charging load curve of a single electric vehicle depends on the charging time and duration. The charging load curve for a fleet of EVs can be established by superimposing multiple single EV charging load curves. For example, if an EV that uses 20kWh/100km travels 50 kilometers a day and charges with 90% efficiency, its daily charging demand will be 11 kilowatt hours. If it charges at 7 kilowatts, the charging peak of a fleet of this type will usually lag behind the grid's peak demand time by about 1.57 hours. This study used research on the growth of Shanghai's electric vehicles and user data to estimate an EV charging load curve.[10] The results show that under the high-growth scenario, peak EV charging load will reach 6.33 gigawatts, occurring at approximately 7:00 PM. Minimum EV charging load will be as low as 15 megawatts, occurring roughly at 4:00 AM. Superimposing the EV charging load curve onto the grid's electric load curve reveals that peak grid load will be 37.93 gigawatts, occurring approximately at 8:00 PM in the evening. Minimum grid load will be as low as 21.07 gigawatts, occurring approximately at 6:00 AM in the morning. The difference in grid peak and valley loads increase from 11.90 gigawatts to 16.86 gigawatts. On the whole, under random charging, the charging load of EVs will significantly increase evening peak load and the peak-valley difference, thus further burdening the operations of Shanghai's electrical grid.

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[10] For a detailed analysis of these calculations, see Appendix 2.

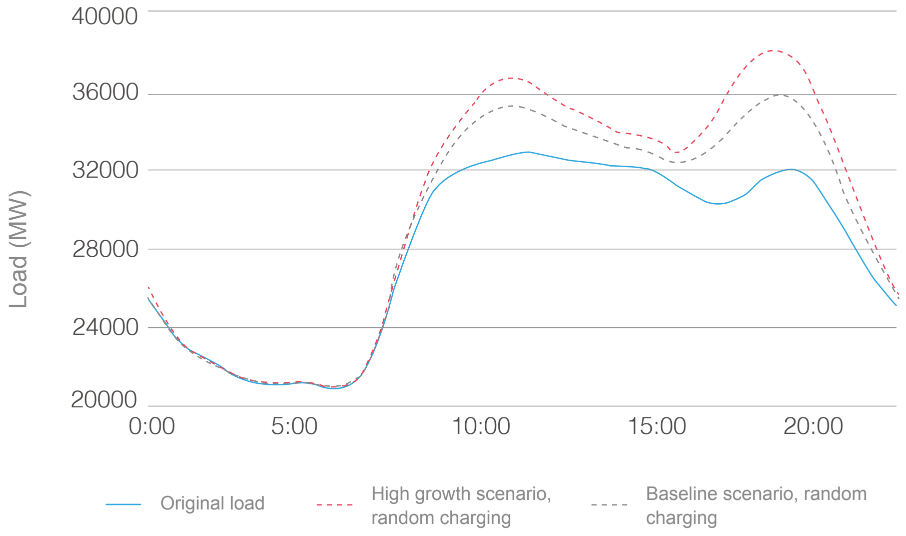

Figure 3-9 2030 Summer EV Charging Load in Shanghai Under Two Scenarios

3.6 The Impact of EV Charging on the Transmission and Distribution (T&D) Networks

EV charging on a wide scale has clear impacts on the power grid. According to a Navigant projection[40], EV sales in the United States in 2030 will exceed 514,000 vehicles. If charging remains unmanaged, future additional investments in power generation and T&D infrastructure will be inevitable. Hadely and Tsvekova projected that by 2030, 10 out of the 13 North American Electric Reliability Corporation (NERC) territories would require additional T&D capacity to meet the EV charging needs[41]. Annual growth of electricity consumption in the Southeast Reliability Corporation territory would reach up to 34 TWh, and the state of California would need to expand its existing capacity by up to 5.5%. Notwithstanding, research by the Pacific Northwest National Laboratory shows that the existing T&D capacity in the United States can satisfy the charging needs of an EV fleet 73% the size of the existing U.S. light-duty internal combustion engine vehicle fleet. With regards to distribution networks, EV charging can accelerate the deterioration of voltage transformers, incur more severe line losses, cause congestion to the distribution networks, as well as affect the quality of electricity transmitted. All of these would take a toll on system reliability and call for system upgrades.

In general, wide scale EV charging could have the following impacts on the distribution networks:

Overloading Distribution Transformers and Power Lines

Overloading of distribution transformers could be a key obstacle to the future scaling of electric vehicles. In addition, the impact of EV charging load on the grid could increase grid volatility, thus overloading local distribution transformers. The overload would result in higher internal temperatures, which would degrade transformer oil and other insulators in the transformers. Potential damages to transformers can explain why overloading could constrain future EV penetration. Before EVs connect to the grid on a wider scale, the impacts of EV charging on transformers and power lines must be analyzed. The State Grid Corporation conducted a study[42] on 27 residential communities and 21 office buildings in Beijing, Zhejiang, Jiangsu, Anhui and Ningxia, and found that if EV ownership remained below 20% and the mode of charging used was AC slow charging, no upgrades would be required for the 10 kV distribution networks in most locations studied. The study also found that if EV ownership exceeded 20% and DC fast charging was used, the distribution power infrastructure of 21 residential communities would have to rebuilt, and one of the residential communities would also have to upgrade its 10kV distribution lines. In addition, it found that 12 office buildings would need to rebuild their distribution transformers, and five of these buildings would also need to rebuild their 10 kV power lines.

Harmonic Pollution

The rectifiers in EV chargers cause harmonic pollution to the grid. In their comprehensive analysis on harmonic pollution and solutions, Huang and colleagues indicate that as slow chargers have low charging capacities, the harmonic pollution they could cause to the distribution grid is limited. [43][44][45] Conversely, large charging stations have larger charging loads, and thus the harmonic pollution that they produce should not be ignored. Single-phase chargers produce harmonic numbers of 3,5,7,9, etc.; three-phase chargers (higher charging capacity) produce harmonic numbers 5,7,11,13, etc. Vast amounts of harmonics cause more severe line losses, drag down power factors, lower the dependability of protective relaying, and interfere with the stability of control systems. Harmonics patterns are related to the topology structure of EV chargers. For large EV charging stations, harmonics can be managed with active power filters and other filtering devices.

To help evaluate the costs of distribution network upgrades needed for electric vehicle integration, this study uses a Shanghai 10 kV industry and commerce related distribution network upgrade project. This project consists of capacity upgrades to both transformers and power lines. Specific components include the installation, design and administrative costs of a new 400 kVA transformer, power lines, in-building cabling and a lighting arrester. The total project cost is about RMB 385,000, or RMB 962 /kVA. The project also requires the laying of 25 meters of cross-linked polyethylene (XLPE) cable of type ZA-YJV-10/8.7-3×70mm2 with a capacity of 3500 kVA. 14 meters of concrete road surface also needs to be restored. The power line installation costs RMB 44,800, or RMB 13 per kVA of line capacity.

Another task that must be undertaken in the integration of EVs is the rebuilding of electric cables. The overall cost of line capacity upgrade projects is generally 1.5 times the cost of the needed materials. The expansion of the EV fleet will also require upgrades in transformer capacities. A 400 kVA transformer costs approximately 50,000 RMB, or 60,000 RMB if including fuses and connectors, which would account for 15.8% of the total cost of this commercial and industrial (C&I) project. Materials would account for 183,000 RMB or 47.5 % of the total project cost. Therefore the major cost category in this C&I project is the materials, such that the total project cost is roughly two times the cost of materials. In summary, the cost of equipment needed for this C&I project is about RMB 150/kVA; but project construction poses additional costs. The total investment cost also depends on additional factors like the density of the planned charging infrastructure. Therefore, the total cost for the distribution grid update is about 1200 RMB/kVA, where the cost of materials account for the 40% and transformers account for 15%.

4. THE POTENTIAL AND ECONOMICS OF EV DEMAND RESPONSE IN SHANGHAI

As introduced in Chapter 2, electric vehicles can become a valuable resource for the electric grid by providing demand response (DR) by adjusting their charging times and capacities. This chapter will analyze the potential and the economics of EV charging load adjustments.

4.1 Demand Response in Shanghai

Demand response (DR) is an important way to add flexibility to electricity grid operations. Shanghai's summer peak loads have been continuously increasing in the recent years, resulting in increasing peak-valley differences. The city has also been integrating a growing proportion of imported hydroelectricity into its electricity supply mix. All the above-mentioned factors and the lack of flexible grid resources at the city's disposal pose considerable challenges to the security of the operation of Shanghai's power grid. [11]

In early 2014, the National Development and Reform Commission and State Grid Corporation of China directed the Shanghai Municipal Commission of Economic and Informatization (SHEIC) to establish a DR pilot, wherein participating industrial and large commercial building customers reduce power demand on hot summer days with temperatures exceeding 35 degrees Celsius (~90 F) or when the grid experiences power supply shortages. Participating customers in turn would be compensated based on their actual load reduction volumes, which is supported by peak load curtailment compensation policies in Shanghai. Shanghai Electric Power Company and NARI Communications and Power Inc., organized by SHEIC, established the pilot platform with their own funding. Shanghai has recruited a number of customers with DR capacity and also established a mechanism where participating customers can follow the protocols when providing DR services: 45 office buildings with 54 MW of curtailable load as well as 31 industrial customers with 100 MW of curtailable load have signed up as regular DR providers. However, compared with the estimated high peak power level of more than 30 GW in 2030, this current size of DR capacity can hardly meet the formidable need for load shifting. Therefore, securing more DR resources is imperative to improve flexibility of the power grid in Shanghai.

Optimal charging strategies for EVs would not only help minimize burdens to the power grid when EV deployment takes off at a large scale, but could even provide valuable regulation services to the power grid.[46][47] Moreover, using EV batteries as energy storage devices can also provide a form of DR.[48][49] In the United States, a number of electricity market and DR mechanisms are incenting EV owners to provide DR as well as ancillary services to help lower the operating costs of the grid, defer transmission/distribution infrastructure upgrades, and mitigate grid congestion.[50][51][52][53][54]

4.2 The Potential of Electric Vehicles as a Demand Response Resource

Compared with conventional DR resources, electric vehicles are potentially better able to adjust charging and discharging times due to their relative long parking time. When EVs are deployed at a large scale, EVs could become one of the most important resources to balance the grid. Currently, incentives to avoid charging during the peak are limited to peak-valley and time-of-use tariffs in China. To further incentivize EVs to provide system services, EVs have been included in DR programs in a number of jurisdictions abroad. Proper policy instruments, technology support and market mechanisms must be in place to design strategies to utilize managed charging of EVs through DR programs. Several factors can affect the potential impact of managed charging of EVs as a DR resource:

Driving patterns directly impact the location and time distribution of EV charging. Specifically, lifestyles and driving patterns of EV owners determine the start time as well as the duration of charging. Average daily driving mileage, frequency of charging and the times at which an EV is plugged into the grid are all important factors which should be taken into consideration when evaluating the potential of EVs as a DR resource.

Charging profiles include current and voltage fluctuations during charging events, as determined by various technologies, battery capacities and the charging capacity ranges of different battery types. Different options for charging – DC slow charging, AC fast charging, battery swapping and wireless charging, etc. – can all impact the DR potential of EVs.

EV fleet composition affects the DR potential of EVs. EVs, depending on their purposes, demonstrate

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[11] Due to the big peak-valley difference, the domestic generation capacity in Shanghai operates at a low efficiency rate, which increases energy consumption and corresponding emissions. In 2015, the peak load in Shanghai reached 298 GW. The number of hours with the electricity load 250 GW or above only amounted to 300 hours out of 8760 hours, only 4%, throughout the year. If peaker plants are coal-fired, like the Gaoqiao Plant in Shanghai, 5GW generation capacity with other related costs will require more than 50 trillion RMB. Itwill be hard to recover the investment costs considering the short duration of operating hours.

various extents of DR potential. For instance, private EVs have greater potential to participate in DR, as they sit idle for long hours. In contrast, EVs for public transport uses have limited DR capability because they are driven for fixed, long and intensive service hours. The charging hours are, therefore, both short and hard to move around. There is little room for them to adjust charging loads and times.

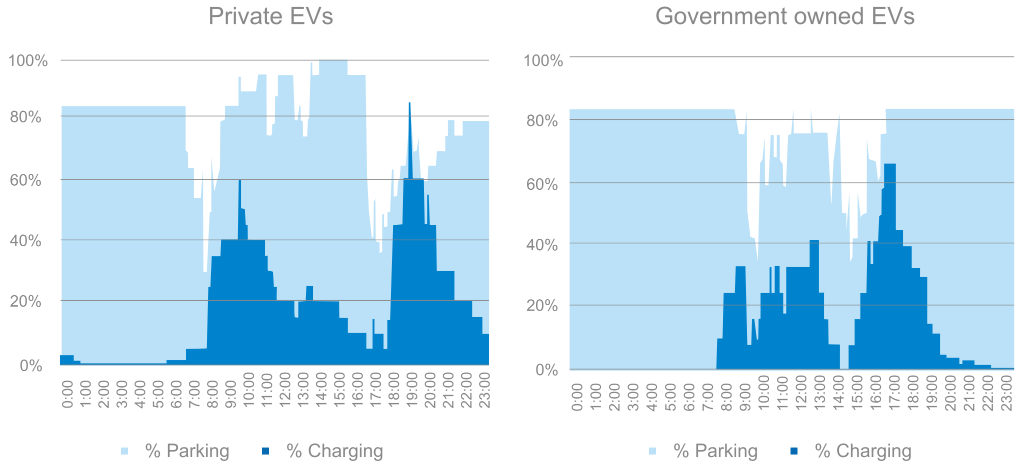

Figure 4-1 Probability Distribution of Charging and Parking Hours of Private and Government-Owned EVs

EVs for public transport purposes in Shanghai have limited room for further optimizing of current charging patterns due to their long driving hours and huge charging demand, which leave only a few idle hours. In contrast, as both private and government-owned EVs in Shanghai are parked and not charging during the peak hours (noon and 5-6 AM) (Figure 4-1), they possess high DR potential. Average private EVs drive for 2-4 hours per day and are available to participate in DR programs for the remaining 20 hours. Similarly, government-owned EVs only drive limited and particular hours during the day.

	Charging modes	Peak load (MW)		Minimum load (MW)		Peak-valley difference (MW)
		Time	Load	Time	Load	
Baseline Scenario	Random	20:00	35757	6:00	21045	14712
	Managed	12:00	34906	2:00	23184	11722
High growth scenario	Random	20:00	37931	6:00	21069	16862
	Managed	12:00	35987	3:00	24018	11969

Table 4-1 Projections of Shanghai's Load Profiles in 2030 With and Without Managed Charging

This section discusses a simulation of the charging loads of private and government-owned EVs using the charging load model discussed in Chapter 3, while factoring in parking hours and battery capacity constraints. Table 4-1 compares Shanghai's load profiles under the random and managed charging scenarios. Figure 4-2 shows the load curves of random and managed charging under the two EV ownership growth scenarios (baseline and high-growth). It can be seen that managed charging lowers overall system peak loads, reduces peak-valley differences and moves most of the charging loads to the off-peak hours during early mornings.

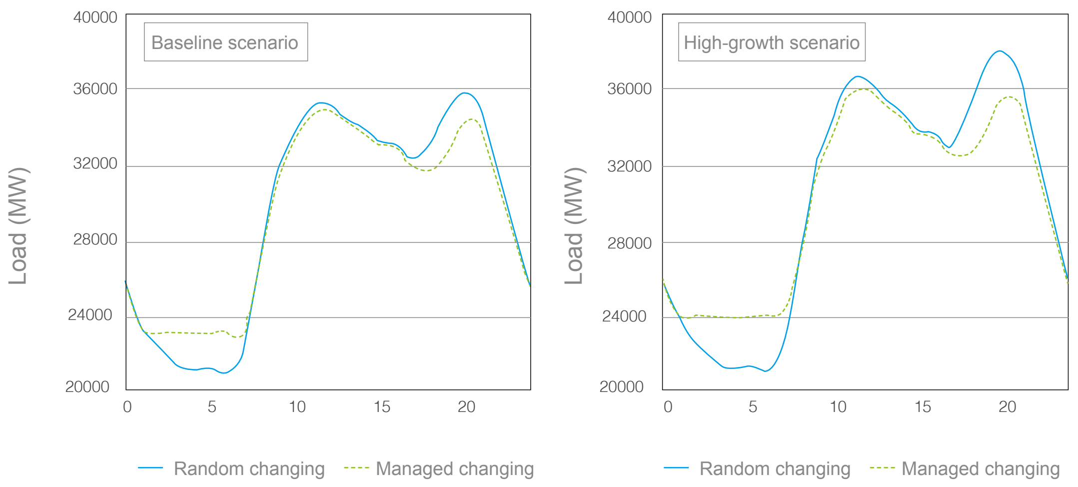

Figure 4-2 Grid impacts of managed EV charging in two growth scenarios

Figure 4-3 illustrates the EV load curves of random and managed charging by private and government-owned EVs under the high-growth scenario. It is observable that, with the introduction of demand response, much of the afternoon and evening charging loads are shifted to early mornings.

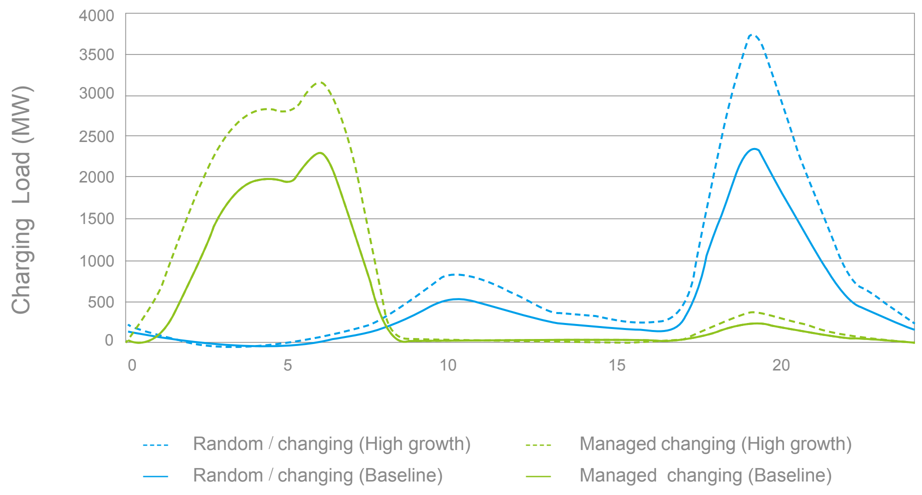

Figure 4-3 Charging Loads of Private and Government EVs under Two Scenarios

4.3 The Economics of EV as a Demand Response Resource

The economics of EV participation in DR programs can be assessed by studying the costs and benefits. The costs of managed charging include the costs of enabling soft/hardware and the incentive payments to participant EVs. The benefits are improved peak-load shaving and valley-filling through load management and corresponding environmental benefits. (Figure 4-4).

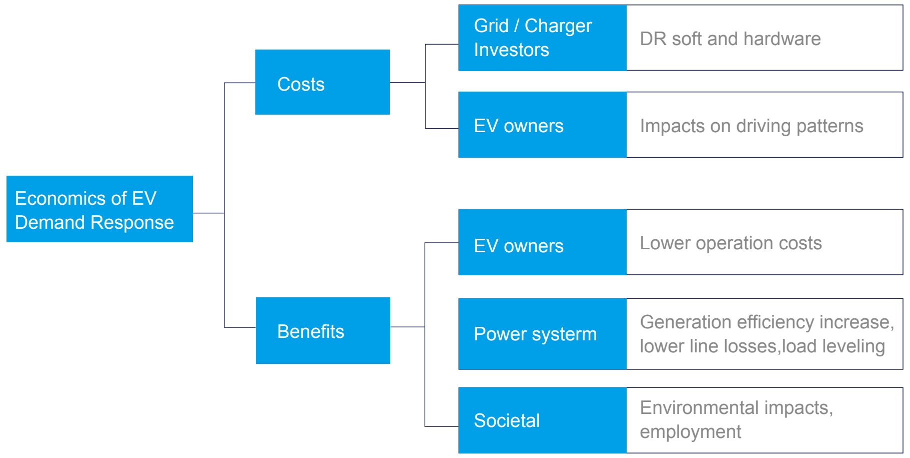

Figure 4-4 Costs and Benefits of EV Providing Demand Response

Private and government-owned EVs are generally charged at home or at office-based locations through AC charging. AC chargers cost between RMB 2,000-5,000 in the Chinese market, and some of those chargers are equipped with DR capabilities such as shifting charging times though programming, which makes such chargers more expensive than traditional AC chargers without DR capabilities, though they are in a similar price range. As technologies for smart use of electricity advance, the cost disparity between DR-equipped chargers and non-DR equipped ones will diminish. It is expected that DR capabilities of EV chargers are to be included in the equipment standards by 2030.

There are notable differences between electric vehicles and conventional demand response resources (e.g. air conditioning and lighting), which requires customers to adjust electricity consumption behaviors, representing a constraint on consumer freedom. In contrast, as EV charging and driving do not occur simultaneously, adjusting EV charging times while the vehicle is parked would not typically affect EV owners' daily patterns. Therefore, the cost to the EV owners of providing demand response could be lower than the case with conventional DR resources. (Figure 4-5).

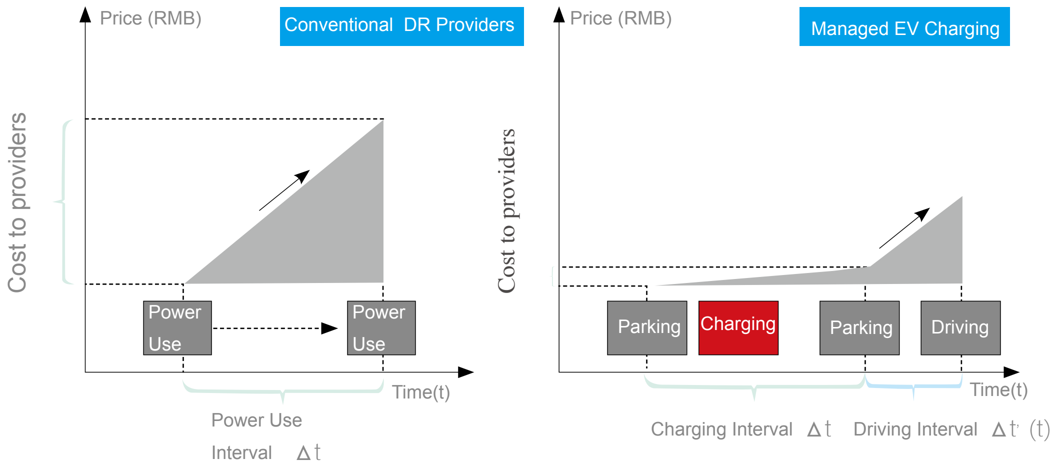

Figure 4-5 Conventional DR Resources and Managed EV Charging Cost Comparisons

The EV Project initiated by the U.S. Department of Energy conducted a study on the price elasticity of EVs as a DR resource. The study shows that price signals have significant impact on EV owners charging behaviors. In the San Diego Gas and Electric (SDG&E) service territory, 70% of EV owners would shift charging to the cheaper, off-peak hours at night when the peak/off-peak rate ratio reaches 2:1, with the dollar differential at $0.13/kWh (approx. RMB 0.85). When the rate ratio reaches 6:1, constituting a $0.3/kWh (approx. RMB 2) difference, 90% of EV owners will adopt off-peak charging. Although, when the ratio exceeds 6:1, the incremental number of EV owners who shift their charging time to off-peak starts to drop, suggesting that the behavior of approximately 10% of the EV customers is inelastic to changes in charging prices.

The current time-of-use (TOU) residential electricity rates in Shanghai are illustrated in Table 4-2. The rate is RMB 0.677/kWh during peak hours (6:00-22:00), and RMB 0.337/kWh during off-peak hours (22:00-6:00), making the peak/off-peak ratio 2:1. Provided that Shanghai EV owners are as likely to respond to the rate incentives as those in the SDG&E territory, then 75% of EVs in Shanghai would charge off-peak at 2:1 peak/off-peak rate ratio, and 90% at 6:1. Based on these assumptions, we project the load leveling effects of off-peak EV charging in Shanghai in Figure 4-2.

		Fixed prices	Existing TOU	Charging TOU (Hypothetical)
Peak	6:00-22:00	0.667	0.677	0.975
Off-peak	22:00-6:00	0.667	0.337	0.155
Benefits	Peak shifted per year (billion kWh)	-	4.22	5.06
	Peak-valley difference eliminated (GW)	-	3.7	4.4

Table 4-2 Benefits to theGrid of Off-Peak Charging under Three Rate Scenarios (RMB/kWh)

At the 2:1 peak/off-peak rate ratio, most EVs will charge off-peak, cutting the peak-valley difference by 3.7 GW (from 16.9 GW to 13.2 GW); the annual electricity consumption shifted from peak hours could reach 4.22 billion kWh. On average, each EV would shift 1.8kW of load and 2050 kWh of electricity every year. At a rate ratio of 6:1, the peak-valley difference will be further decreased by 0.7 GW with 5.06 billion kWh shifted away from the peak hours. An average EV would contribute to 2.1 kW of peak load shift, amounting to 2,460 kWh of electricity annually.

Under the single rate scenario, an average EV's electricity demand is 8.33 kWh/day, and the annual charging cost is RMB 2,028, which would be cut by 65% to RMB 709 under the above-mentioned TOU rate scheme with the peak/off-peak price ratio of 2:1. Deeper cuts could be realized under a 6:1 structure. At a charging expense of RMB 392 every year, this is a mere 19% of the original cost.

"Basic charges", or capacity charges in China are usually measured based on the transformer capacity (kVA) or customer's maximum demand (kW), which are irrelevant to actual electricity consumption. Customers are free to choose either of the two measures; however, basic charges determined by the maximum demand are generally higher than that determined by the transformer capacity. The current summer capacity charge of Shanghai's TOU rate is RMB 40.5/kW/month, or RMB 486/kW per year. As mentioned above, 2.1 kW load can be shifted by an average EV. The annual value of avoided basic charges per vehicle is thus about RMB 1,000 in Shanghai.

The environmental benefits of peak load shifting by off-peak charging mainly result from absorbing renewable energy during the off-peak hours. The Shanghai municipal grid currently absorbs large amounts of hydroelectricity produced in the southwestern part of China. In particular, the Xiangjiaba-Shanghai ultrahigh voltage DC transmission line will transmit up to 32 billion kWh of renewable electricity to Shanghai annually. At the maximum transmission rate, this imported renewable electricity will be equivalent to about one-third of Shanghai's peak load. Such magnitude of hydroelectricity supply makes grid balancing even more difficult in Shanghai [56]. To compensate for the ancillary services provided by generators in Shanghai, East China Energy Regulatory Bureau directed a pilot in 2014 where Shanghai local generators were compensated for the ancillary services they provided for the Shanghai grid to better incorporate hydroelectricity from the Xiangjiaba Hydroelectric Power Station.[57] EV charging shifted to off-peak hours, especially at night when Shanghai imports abundant hydroelectricity, will lighten the burden of grid balancing and increase the city's capacity to consume more imported renewable energy. Assuming that the entire 5.06 billion kWh of off-peak charging from 2.06 million EVs (Table 4-2) is utilized to consume the imported hydroelectricity annually, managed charging would help reduce 2.3 million tons of coal consumption, as well as avoid the emissions of carbon dioxide by 4.5 million tons, sulfur dioxide by 11,000 tons, NOx by 12,000 tons, and soot by 2,000 tons.

In addition, off-peak EV charging could lower transmission line losses and mitigate grid congestion, thus increasing the reliability of the power grid system. As managed charging for EVs becomes an available resource, related industries, such as smart charging infrastructure and smart distribution networks, will develop their businesses, ultimately increasing investment and economic output in the region.

4.4 V2G

With the development of EV-grid bidirectional communications protocols and standards as well as relevant technology advancement, EVs could play a role as distributed energy storage to provide services to the power grid system operation. Currently, some EVs in the Chinese market are already equipped with discharging functions, which enables bidirectional power transmissions between EVs and the grid, EVs and other electronic devices, and between two EVs.[58]

The advantages of V2G include:

- Fast response. EVs can switch to supply power back to the grid within milliseconds, much faster than conventional peaker generators;

- Higher energy efficiency. With a discharging rate of 85%-95%, EV batteries perform better than average pump-hydro power plants, which operate at an average of 75% efficiency;

- Lower line losses. The travel range of EVs are mostly within the city, where electricity demand is high and often concentrated in particular areas. The nature of convenient mobility of EVs helps to supply power back to the distribution level of the grid, which also minimizes line losses, compared to traditional peaker plants whose power must be transmitted long distances resulting in significant line losses.

- Lower upfront costs. Large amounts of idle vehicles serving as energy storage lowers the investment required to realize V2G at scale.

Other countries in Europe and the United States started relevant research on V2G relatively early on.[59] In 1997, Dr. Willett Kempton from University of Delaware was the first to put forward the V2G concept. He also conducted a series of studies on the feasibility[60] and potential benefits[61][62] of V2G. Kempton's research showed that, compared to traditional power sources, EVs as distributed storages feature high capacity, fast response yet low energy content and high unit electricity cost, making EVs as a good ancillary service resource in markets that have high generation capacity costs and require fast response and short durations of ancillary services.

A number of studies have been devoted to analyzing the costs and benefits of ancillary services provided by different types of EVs, with a variety of results. [63][64][65][66][67][68] Kempton analyzes the costs and benefits of providing frequency regulation (FR) and capacity reserves by BEV, HEV and fuel-cell vehicles, indicating that the greatest revenue is earned from frequency regulation. [69] Some studies looked at the profits of FR by BEVs in NYISO, CAISO, ERCOT and PJM, finding that the maximum net return is realized from providing only regulation down, mainly because it would otherwise require additional investment in V2G-equipped chargers and meters to provide regulating up, or to ramp down EV charging capacity.[70]

Those advantages notwithstanding, there are a number of barriers to the commercialization of V2G. Beyond the high cost discussed in the previous section, V2G would profoundly reshape the way that the power systems operate today. Though the introduction of V2G will add to the pool of distributed energy resources, it will require grid companies directly with the end users in bidirectional power purchases which, consequently, will involve two-way financial flows. Furthermore, grid companies will need to appropriately price the V2G services in order to incentivize and aggregate sufficient numbers of electric vehicles to provide reliable system services with the reliability at scale on par with large and centralized power generators (and other resources).

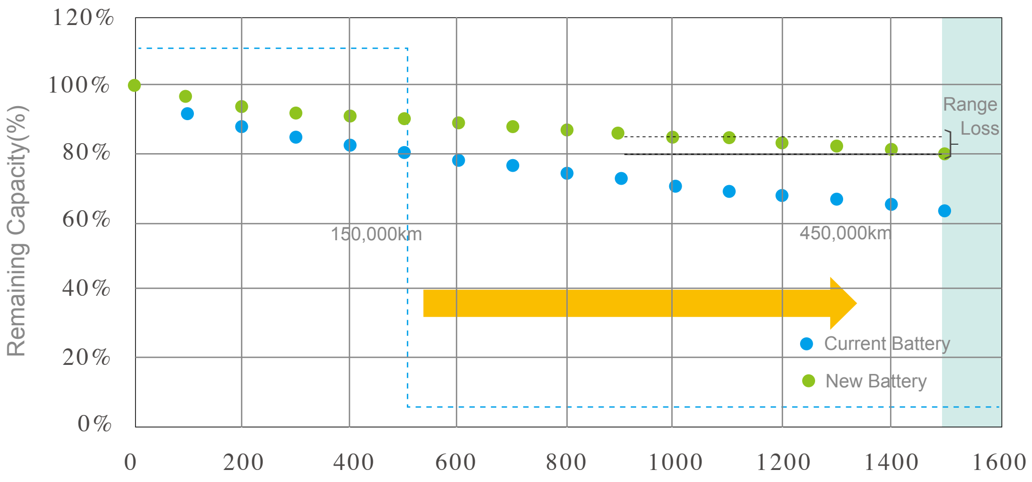

Figure 4-6 Cost Reduction Potential of V2G

The economics of V2G hinges considerably on EV battery cycle life. Current EV batteries usually could reach a cumulative mileage of 150,000 km (93,000 miles) over 500 charging cycles on a battery before the remaining capacity degrades to 80% (Figure 4-6). At this mileage, only basic travel needs will be met, leaving little spare battery capacity to provide sustained V2G. However, the availability of EV batteries for V2G will increase as battery capacities improve. If the lifetime mileage of EV batteries greatly exceeds owners' travel needs, then EVs would be able to provide V2G services virtually cost-free, thus greatly increasing the overall economic value of EV batteries.

The current V2G market has not yet reached its technical and economic maturation. In the long term, however, higher EV penetration could drive down battery costs, and technology advancement will also improve battery performance. When V2G application takes off at scale, enormous societal and environmental benefits as well as economic benefits will follow.

4.5 Case study: An EV Battery Storage Grid Integration Project by BMW ConnectedDrive Lab in Shanghai

This chapter discusses a Chinese energy storage pilot project using EV battery. The project was conducted by BMW Group's ConnectedDrive Lab, on Gaolan Road in Shanghai.

The lab purchased seven batteries, with the storage capacity of 313 kWh, typically used for plug-in electric vehicles under the brand of BMW Brilliance's ZINORO. They purchased just the batteries to test their ability to power the buildings of the lab. In the lab, electrical loads primarily come from the server rooms, air conditioners, elevators, four EV charging piles, and other ordinary electrical appliances inside the four-floor buildings. The server rooms and air conditioning system (in summers) represent the highest contributing loads. Since the buildings are connected to the grid, batteries can store energy by charging during off-peak periods at night (between 10 p.m. and 7 a.m. the next day) when the price is low, and can supply power to the buildings by discharging during peak hours in the day. After the discharging mode has met the threshold, usually around 3 p.m., the building then switches its power supplier from the battery to the grid. During discharging hours, the energy supply of a building relies on the battery alone. The rated charging power of a PCS battery is 130kW, while its rated discharging power is 100kW. Additionally, the lab installed five photovoltaic panels (they have planned to install more but are held up in the approval process) to power the battery, which can maximally contribute 5 kW in summer in total, with an average 1-2 kW per panel.

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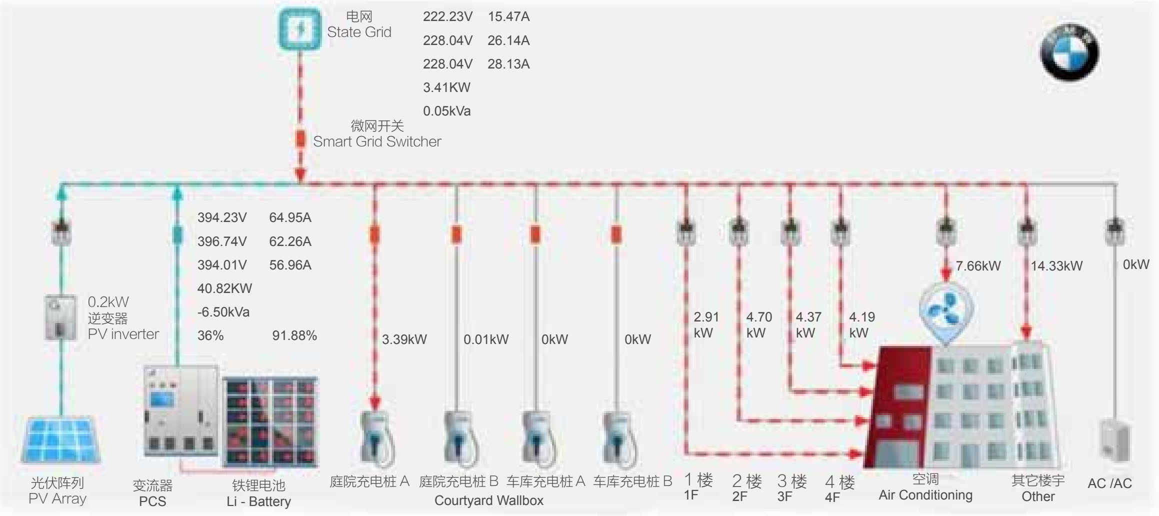

Figure 4-7 Framework for BMW ConnectedDrive Lab's EV and Energy Storage Project in Shanghai

As shown in the above figures, during a typical summer day (e.g. Tuesday, August 25th, 2015), the maximal discharging power of the battery was 62kW, and its maximal charging power was 50kW. The maximum discharging power of the grid is 80kW. The total capacity of 313kWh is divided into five cabinets (in parallel circuits), each of which contains 24 battery packs (in series circuits). Each pack consists of 10 individual batteries (in series circuits). In total, there are 240 batteries in each cabinet, thus there are 1,200 batteries in all five cabinets. The capacity of each battery is 0.26kWh. During a three-year period of operation, the total capacity of the batteries was reduced from 313 kWh at the beginning of the project to 260 kWh by April 18th, 2016. Specifically, in August 2013, the battery capacity was around 310 kWh. The capacity of the battery degrades to 83% of its original capacity after performing a charging-discharging routine once per day for 3 years (around 1,000 times). This shows that batteries can provide a very valuable service with acceptable level of degradation.

Beyond the Shanghai BMW project, international cases also provide numerous useful experiences regarding the integration of EVs and the grid. Our study examined four EV pilot projects in the United States and Germany (See Appendix E), which set up objectives and took actions according to relevant factors under local context, such as electricity consumption, the penetration level of EVs, and the market volume. Research from these projects offers feasible recommendations on issues such as how best to tackle the fluctuations in the power grid caused by EV charging, utilize clean electricity generated by renewable energy, and develop EV market and the ancillary infrastructure.

5. MARKET MECHANISMS AND BUSINESS MODELS

5.1 Power Sector Reform and Electric Vehicles

International experiences demonstrate that spot electricity markets (which bid in balancing intervals ranging from every 5 minutes, 15 minutes or 1 hour) improve the flexibility of the power system, despite the difference in electricity pricing mechanisms in individual cases. The reason is that spot markets allow flexible generation resources across the spectrum of technologies to bid in and be dispatched throughout the day, thus helping to maintain the availability of supply with optimal economics. With flexible generation resources at their dispatch, system operators can achieve load leveling and keep voltage/frequency within safe bounds. In addition, short bidding intervals enables grid operators to dispatch the flexible resources in a timely manner, balancing the grid in real-time.

In recent years, China's electricity generation fuel mix has become substantially more diversified with the rapid growth of renewables, nuclear power, pumped hydro and a host of distributed generation technologies. Expanded energy resource diversity creates more uncertainties on both the demand and supply sides of the grid. Furthermore, flexible generation resources that can be called on in short notice to balance the grid are becoming scarcer. However, the resource diversity can also provide significant levels of complementarity to and perhaps even lessen the need to call on generation resources for grid balancing. [12]

There are two structural reasons why the planned power system can account for the growing scarcity of flexible grid resources. First, the default tool of current grid operators to deal with imminent grid imbalances remains mandatory load curtailment, as per the Measures for the Orderly Use of Electricity. Under the current mechanism, curtailed customers need to bear economic losses, but the potential of demand-side resources as a grid balancing resource cannot be properly recognized. So while EVs have great potential as a flexible grid resource, they are not fully utilized as such. Second, electricity rates in China are set by the government with a long rate setting cycle. The rates, therefore, cannot reflect short term balancing needs, such as day-ahead or hourly-based. Without market-based price signals, flexible resources like EVs, which could respond to the grid's needs instantly any time of the day, are overlooked.

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[12] Find further related in-depth analysis: Renewable Electricity Futures Study, http://www.nrel.gov/analysis/re_futures/

The existing ancillary services in China indeed help to increase the flexibility of the grid to some extent. Generators providing ancillary services are paid for their service, while those not providing are charged a fee, as per the “Two Implementation Rules”. Today generators providing ancillary services consist primarily of coal-fired and hydroelectric generators, leaving emerging flexible resources like EVs with little room to play a role as an ancillary service resource. However, for hydroelectric plants, the capacity to provide ancillary services is constrained by the seasonal availability of water resources, and for coal plants, the need to meet heating demands. Particularly, the growing volume of renewable energy integration into the grid will make the ability to increasingly utilize flexible resources like EVs essential. When EVs become an ancillary service resource to the grid, current ancillary service categorization and relevant technology standards, policies and regulations will all need to be expanded. EVs as an ancillary service resource will also add complexity to the cost-benefit dynamic, and it will be difficult for the cost-based accounting to capture the changing values of various ancillary services from different sources at different times of the day.

In summary, energy and ancillary services markets characterized by their robust pricing mechanisms are better at channeling the economic values of flexible resources. Thus, those markets are fundamental to incentivizing electric vehicles to join the grid operators’ portfolio of balancing solutions.

5.2 A Comparison of EV Commercial Operation Model

Similar to conventional demand response resources, EVs are spatially scattered and irregular in terms of geographical distribution and availability as a grid resource. It is therefore difficult for individual EVs to directly provide service to the grid. Business models should be in pace where aggregation of EVs increase its values as a flexible and valuable grid resource.

The availability and values of EVs as a grid resource largely depends on travel hours, parking hours, charging frequency, charging time, etc. As demonstrated in Chapter 4, managed charging would maximize the potential and value of EVs as a reliable and controllable grid resource. Charging load aggregation greatly improves the predictability and controllability of EVs as grid services, which would in turn enhance the economic values of the resource.

When aggregated, charging service providers can play a role as a DR load aggregator, where grid operators send signals to charging service providers to procure load resources when the system is in need of additional flexible resources. Charging service providers respond to grid requests with available aggregated charging loads or load shifts, procured through real-time communications with EV owners or through charging price incentives. One advantage of EV load aggregation is that grid companies seeking DR resources now need only to interface with charging service providers, instead of having to contract with individual EV owners that are, again, spatially scattered and random in charging times/energy volumes.

Charging service providers and load aggregators can choose either to invest in and operate charging infrastructures or to engage in the aggregation part of the business only. Other business models also see aggregator design strategies for the sequential usage of batteries in passenger cars, transit buses, and energy storage power stations. Transit operators and car rentals outsource all battery-related operations to the aggregators, as exemplified by the contracts between the Shenzhen transit authority and a local charging service provider that also runs all of the electric bus charging stations in the city.[71]

The development of the “internet of vehicles” enhances the incorporation of additional vehicle fleet operations into the aggregators’ business model, such as vehicle purchases, operations and maintenance, insurance and so on, which help to turn the aggregators into an one-stop shop for transit consumers. In this integrated business model, consumers share compensation from the electricity market while avoiding the technical details of the transactions. In this regard, electric vehicle rental markets have good potential. [72]

5.3 EV Charging Rates

Charging rates are important economic incentives to shape charging behaviors. Currently, charging and battery swapping station operators in Shanghai charge customers volumetric rates as well as a service fee. Facilities servicing electric transit buses implement time-of-use rates for “industrial and other purposes”. Other centralized commercial charging stations are subject to industrial power rates for the “ferroalloy, caustic soda (including ion-exchange membrane)” class. Average residential rates are applied to home charging facilities installed by State Grid, which implement average residential rates. Other charging facilities are subject to rates that correspond to their geographic locations. Service charges are capped by the government at RMB 1.3 per kWh.

Issues exist with the three components of EV charging rates in Shanghai: capacity rates, energy rates, and service fees.

EVs in Shanghai are exempt from capacity charges until 2020. However, such exemptions, combined with the low utilization rate of chargers (1-2 hours on average per day particularly for those charging facility with special purposes), will require other end-users to pay higher capacity charges in order to compensate the EV chargers. Charging rates made cheaper with the exemption of capacity charges may also weaken incentives for off-peak charging. Additional research is needed to assess whether EVs should also pay capacity charges and how the rates should be set.

With respect to energy charges, more and more EV chargers are equipped with demand response capabilities, enabling EVs to respond to the price signals and shift charging needs to off-peak hours even on a real-time basis. However, the quick response capability of EV charging load may cause new spikes when shifting the loads under the current static TOU structure. In the high-growth scenario introduced in Chapter 4, if the majority of EVs in Shanghai start charging at 22:00, the total load at that time on the Shanghai power grid would surge to upwards of 40 GW, far exceeding the daytime peak. Therefore, static TOU rates might be no longer compatible with the growing volume of EVs in Shanghai; real-time electricity rates or charging service providers would work better to effect managed charging.

The service charge capped at RMB 1.3 per kWh is meant to help recoup the costs to build out charging infrastructures and to incentivize further infrastructure investments. However, as DC fast chargers cost significantly more than AC slow chargers (Table 5-1), a unified service charge may fall short of encouraging the expansion of fast charger networks in Shanghai. The anticipated mass deployment of next-generation charging technologies (e.g. smart charging, wireless charging, etc.) also calls for more robust adjustments to service charges.

		Configurations	**Capacity (kW)**	**Price (RMB)**
AC	Star Charger	Wall mount	6.6	2,299
	DH Technology	Column	7	3,200
	Charging Home	Wall mount	7	2,500
	Diandian	Column	3.2	960
DC	Guanghe	Column	20	48,000
	Lanhai	Column	30	32,000
	Titans	Column	60	69,000

Table 5-1 Charging Capacities and Prices of Selected Chinese Domestic Brands

6. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Through an evaluation of Shanghai's power system peak load and electric vehicle users' driving patterns, this study has produced an analysis of the city's electric vehicle charging demand and load characteristics and the potential of electric vehicle charging and discharging technologies. Based on an EV charging behavior survey in Shanghai, this study found that although the peak load of unmanaged EV charging would not appear during the original system peak period, a large number of EV could still cause a new system peak in the evening. Therefore, the unmanaged EV charging load would lead to a significant increase in Shanghai's peak load during evening hours, thereby putting pressure on the grid. Next, this study found that different types of vehicles have distinct charging management potentials. Electric passenger cars and government owned EVs could be the main contributors of demand response due to their relative long parking time and if managed charging is undertaken by these vehicles, the peak load will be significantly reduced because of the large market share of these vehicles. Given the expected increase of clean power import, the ramping up capacity of EVs could even provide a higher value for Shanghai's power grid than that from ramping down. Furthermore, electric vehicle integration and improved demand response will not only prove economically beneficial to users and power companies, but will also bring about considerable social and environmental benefits. Compared with other conventional demand response resources, EVs could also offer a cost competitive solution through managed charging. The cost of V2G, in contrast, is presently very high due to the apparent battery degradation caused by delivering discharging services. In order to fully identify the demand response potential from EVs, a developed power spot market with a lower market threshold for demand side resources would be helpful. An EV charging services provider who aggregates distributed EV customers would also improve efficiency of grid integration of EVs. In addition, a better design of charging infrastructure deployment could further induce a system friendly charging pattern. In summary, there is a great potential for the integration of electric vehicles in Shanghai's power system, and the full realization of this potential depends on factors including charging technologies, modes of operation, electricity market, charging facilities, and pricing mechanisms

6.1 Strengthening Research on Managed Charging Technology

Most of the currently operating charging infrastructure is poorly suited to supporting a managed charging system, and even with facilities that do support managed charging, their link with the grid can often run into problems. The large-scale use of electric vehicles will make them a distributed energy storage resource, which will create a more pressing need for managed charging. The implementation of managed charging depends on the cooperation of vehicle users, charging infrastructure and grid companies, and thus, research on managed charging systems should focus on integrating the stakeholders. For grid companies, charging facilities should be viewed as electric power facilities, and the charging network should be viewed as an integral part of the distribution network. Companies should consider the charging infrastructure along with grid planning, design and construction, in order to promote the managed development of the grid.

6.2 The Implementation of Managed Charging for Load Adjustment

Large numbers of randomly distributed electric vehicles make it difficult to predict the charging load at any given time, resulting in a loss of value for the power system. The introduction of charging service providers that use managed charging systems can improve the regularity of charging patterns and fully realize the potential of electric vehicles' power system applications. In practice, however, the path toward implementing managed charging faces many challenges and thus charging service providers and other market stakeholders will need to conduct more research and experimentation in the future.

6.3 Establishing a Market that Values Flexible Resources

Electricity markets allow for interaction between electric vehicles and the grid. The current price scheduling system provides little room for the development of flexible system resources. For example, the lack of a reasonable pricing mechanism with which the grid companies procure electricity from the generators has been unable to duly reflect the value of flexible grid-balancing resources. Therefore, as part of the solution, a competitive electricity spot market is recommended to replace the current approach of planned dispatch and price scheduling. Furthermore, more research is needed on market mechanisms that can reflect the value of flexible resources such as electric vehicles, and that can lower the threshold for electric vehicles to participate in ancillary services and access the market.

6.4 Accelerating Residential and Office Charging Facilities

Charging infrastructure is an important factor in determining the potential applications of electric vehicles in adjusting load. In order to enhance charging flexibility, the construction of residential and office charging facilities should be given priority in order to ensure that electric cars have regular parking and charging options and to provide sufficient opportunities for electric vehicles to help balance load and generation. In addition to managed charging, the use of smart charging software and hardware infrastructure should be increased so that electric vehicle users can play a larger role in regulating load.

6.5 Formulation of the Vehicle Charging Pricing System

Currently, the charging price mechanism in Shanghai needs to be improved, particularly in terms of coordinating capacity charges, electricity charges and service fees. In order to maintain the advantages that electric vehicles have over conventional fuel vehicles in terms of fuel cost, it is necessary to establish grid friendly charging behavior, and simultaneously conduct further research on whether this will compensate for the massive investment in early stage of construction of charging infrastructure.

6.6 Research Limitations and Next Steps

This study brings together research on electric vehicles, the power system, and the electricity market, and employs concepts and research methods from sectors ranging from energy, economics, and transportation. It is inevitable that there are limitations to this research: for example, the study did not conduct research into how the integration of electric vehicles in Shanghai might lead to higher consumption of renewable energy, thus providing economic and environmental benefits. The current EV promoting policies both in Shanghai and in China as a whole are mostly focused on the scale of development. However, the integration of a large number of EVs within the power system and in particular, the synergy between EV growth and renewable energy penetration needs further investigation. This study also did not suggest specific recommendations for electric vehicle charging pricing systems which is also badly needed in the near term. Future studies should pick up where this study left off to strengthen research in these areas.

Appendices

Appendix A

The charging demand of electric vehicles is the aggregate demand across different vehicle types (private-owned vehicles, government-owned vehicles, transit buses, taxis, and logistics vehicles) and different technologies (battery electric and plug-in hybrids):

$$EC_{i,m,t} = \sum\nolimits_{model}\sum\nolimits_{tech}\frac{Stock_{i,m,t}\times Distance_{i,m,t}\times FE_{i,m,t}}{Charge_{i,m,t}}$$

Where, ECi,m,t: charging electricity demanded by electric vehicles of type m and technology t in year i (kWh);
Stocki,m,t: the number of electric vehicles of type m and technology t in year i (units);
Distancei,m,t: distance traveled by electric vehicles of type m and technology t in year i (km);
FEi,m,t: fuel economy of electric vehicles of type m and technology t in year i (kWh/km);
Chargei,m,t: the charging efficiency of electric vehicles of type m and technology t in year i (%).

Appendix B

The total load on the electric grid in hour i is the aggregation of the original load in hour i and the electric vehicle charging load in hour i, given by:

$$P_i = P_{o,i} + P_{v,i}$$

Where, Pi: the total load in hour i;

Po,i: the original load in hour i;

Pv,i: the electric vehicle charging load in hour i.

This study assumes the EV owners start charging once trips are finished. Therefore, the charging load in hour i can be dissected into the load that comes online in hour i, and the load that was initiated in previous hours (i-n) but continues into hour i because the underlying electric vehicles are yet to be fully charged as of hour i. The number of hours where there are overlapping charging loads depend on the amount of hours needed to fully charge individual electric vehicles:

$$P_{v,i} = \sum_{0}^{t} P_{v,i'} + P_{v,i'-1} \cdots + P_{v,i'-t}$$

where, t: the number of overlapping charging loads in hour i;

Pv,i': the load that comes online in hour i.

Obviously, battery capacities, fuel efficiencies, charging loads and travel mileages all impact charging time lengths. The higher the daily travel mileages, the lower the initial state of charge (SOC) and, holding charging capacity constant, the longer the required duration of charging will be. For instance, if vehicles that are plugged into the grid in hour i require 3 hours of charging, then their charging loads will last into the subsequent hours, i+1 and i+2. This study assumes that charging ends at 90% SOC. Therefore, the charging time of electric vehicles is given by:

$$t = CEIL\left[\frac{B\times 90\%\times\left(1-\frac{E}{100}\times D\right)}{P_c}\right]$$

where: B: rated battery capacity, assuming 30 kWh;

E: EV battery fuel efficiency, assuming 15kWh/100km;

D: daily distances traveled;

Pc: charging capacity, assuming 7 kW/charger.

Based on the load forecast for random electric vehicle charging, and assuming that managed charging strategies take full effect, then the charging loads are dispatched to the valley hours of the grid. The electric vehicle charging load in the current hour is given by the difference between the original grid load and the average daily load of the present day:

$$P_{v,i'} = \frac{\bar{P} - P_{o,i}}{\sum_i P - P_{o,i}}\times \mathrm{D}\times\frac{E}{100}$$

Where $\bar{P}$ is the average load of the daily base load.

Appendix C: Residential Tariffs (Time-of-use) in Shanghai

Tier	Hours	Rates（RMB/kWh）
First Tier	Peak	0.617
	Off-peak	0.307
Second Tier	Peak	0.677
	Off-peak	0.337
Third Tier	Peak	0.977
	Off-peak	0.487

Appendix D: International Experiences for Integrating Electric Vehicles to the Grid.

All international cases in this appendix are selected from Creating the Grid-Connected Car – International Experiences Using Demand Response with Electric Vehicles, a report prepared and published by Natural Resources Defense Council in July 2016.

http://www.nrdc.cn/english/E_info_library_info.php?id=2173&down=1&cid=210

SDG&E Electric Vehicle Grid Pilot Programs

San Diego Gas & Electric (SDG&E), one of California's three largest investor-owned utilities, is developing a handful of EV-grid integration projects to promote the integration between EV and the grid. In 2014, SDG&E set up a ten-year EV and grid integration pilot program within its service area to mitigate EV's negative impact on the grid, encourage charging at off-peak hours, and explore other potential benefits of the EV-Grid integration.

SDG&E developed two projects to meet the above objectives, which are SDG&E Application Vehicle Grid Integration Rate Pilot and SDG&E Optimized Pricing and Resource Allocation Pilot, respectively. The components of these two projects are outlined in more detail below.

- Construct EV charging stations in multi-unit dwellings: Although over 50 percent of San Diego residents live in residences with more than one tenant, 88 percent of current EV drivers live in single-family homes. In order to expand EV ownership opportunities beyond people living in detached houses, SDG&E proposed to build 3,500 charging installations in a mix of workplace and multi-unit dwellings within SDG&E's service area. These new charging stations will also provide data for the rest of the project.

- Establish a variable pricing rate for EV charging: In order to encourage off-peak EV charging and test the potential for charging to be integrated with DR, SDG&E has developed a variable Vehicle Grid Integration (VGI) Pilot Rate for EV owners, which will display hourly differences in electricity rates on a day-ahead basis. Differences in electricity prices will reflect different grid conditions, such as peak vs. off-peak generation and availability of renewable energy. Customers can view these rates on the VGI Pilot Program smart phone application or website and plan their charging accordingly. SDG&E plans to collect data from the impact of this variable pricing structure to understand how it affects charging behavior and grid utilization.

- Integrate EVs into the grid as a service provider: SDG&E is attempting to "aggregate" EV fleets in five locations throughout San Diego County to act as a single grid resource in California's electricity markets. The EV chargers are equipped with remotely controlled software that allows the charging schedule of participants to be adjusted in order to provide DR services to the grid. The adjustments are made according to wholesale energy prices: participants agree not to charge their EVs during certain high-price periods and are paid the marginal energy price during those hours. By developing the connection between grid conditions and customer response, SDG&E ultimately hopes to not only use EVs to reduce charging during peak hours but also to begin charging when signals from the grid show that renewable energy is available.

For more detailed information please refer to the full report of SDG&E project, available at:
http://bit.ly/194csaQ.

BMW i ChargeForward Program

The BMW i ChargeForward program is a joint program between vehicle manufacturer BMW and California utility Pacific Gas & Electric (PG&E) Company. PG&E is the largest investor-owned utility (IOU) in California and one of the largest in the US, providing electricity and natural gas to 16 million people in Northern and Central California. BMW served as the intermediary between PG&E and the EV users, using the electricity demand from their EVs as a resource for PG&E's DR program. The specific actions taken by BMW include:

- Expand communication with EV customers: BMW allowed 100 owners of BMW i3 EVs to sign up for its initial 18-month program. During periods when PG&E must curb customer demand, these participants receive alerts through a smartphone app asking them to delay charging of their EV. The participants can decide either to accept the delay or to continue charging. If they accept, software in the charging equipment allows BMW to halt the charging remotely. Participants are paid $1,000 up-front (in the form of a BMW gift card) as well as additional payments depending on how many charging delays they accept.

- Utilize retired EV batteries: This grid resource is supplemented by a collection of "second life" EV batteries, taken from BMW EV demonstration vehicles, which serve as stationary storage. They can fulfill similar functions to the customer-owned EVs and also provide grid balancing for intermittent renewable energies, absorbing the energy when demand for the energy is low and then releasing it when demand picks back up again.

For more information, please visit the project website at:

http://www.bmwichargeforward.com

eV2g Project

Many states within PJM's operation area have Renewable Portfolio Standards (RPS), which require that their energy providers include a certain amount of renewable energy in their supply portfolios, and as a result PJM is expecting a scale-up in the level of renewable energy in its operating area in the near future. The intermittent nature of renewable energy means that PJM will also have to expand its frequency regulation resources to maintain stability.

The eV2g Project is an attempt to develop commercial scale vehicle-to-grid (V2G) services, providing a direct financial benefit for customers who engage in grid balancing services through their EVs. The primary stakeholders are NRG Energy, a New Jersey-based electricity generator, and the University of Delaware (UD). These two entities created a joint venture called eV2gSM to commercialize a V2G technology developed by UD. In the face of emerging problems of a frequency regulation market during the project implementation, some key actions and measures are listed below.

- Develop a small-scale technology demonstration: UD initially tested its V2G technology in a trial project on UD's campus, where a small fleet of EVs were equipped with bi-directional V2G charging equipment and operated as a grid resource for PJM. In 2011, the pilot used seven vehicles and a large stationary storage system to take part in PJM's frequency regulation market, which required market participants to have at least 500 KW capacity. In 2014, the fleet had expanded to nine EVs and, following changes to PJM's capacity requirements (described below), was able to participate directly in PJM's markets without the assistance of a stationary storage system.

- Reduce the size of required frequency regulation generator: In order to allow UD's EVs to be incorporated directly into the frequency regulation market, PJM had to decrease the required size of service providers from 500 KW to 100 KW. This was changed in 2011, allowing the eV2g project's EV fleet to bid directly into PJM's frequency regulation market as a grid resource in 2013. Even with this change, however, the technology to aggregate multiple EVs into a single grid resource (also developed by UD) is critical for the project, allowing a single aggregator to control charging in multiple EVs and offer a frequency regulation resource large enough for the grid to use.

- Provide car leases for program participants: The eV2g joint venture offers two-year leases of BMW EVs to vehicle fleet owners in the greater Philadelphia area at rates comparable to their other vehicle leases. Those leasing the vehicles would be participants in the V2G pilot project and be incorporated into PJM's regional frequency regulation market. Participants would also receive a Level 2 charging device with each leased vehicle.

For more details please refer to the website at: http://bit.ly/1FSLzCD.

BMW Controlled Charging Berlin Pilot

As a major market for both renewable energy and electric vehicles, Germany enjoys the enormous environmental benefit of renewable power whereas it suffers an unstable grid caused by renewable intermittency. In collaboration with Swedish utility Vattenfall, German car manufacturer BMW implemented a two-year pilot project to examine the potential for managed EV charging to benefit grid functioning and integrating renewable energy into the grid. The program began in March 2013 and is scheduled to run through 2015. Some actions and measures are included as follows.

- Test pilot with BMW EV users in Berlin: The project looked at the charging behavior of a small sample of 30 BMW EV customers in three phases, testing how different incentives could promote grid-friendly charging behavior. Participants could take advantage of these incentives through a smartphone app. BMW compared the participant's charging time to the previous two years of charging data from BMW EV users and found that they were effective at shifting charging times to more ideal periods. The eventual introduction of V2G technology is expected to provide a sustainable business model for this type of project.

- Wind-to-vehicle-to-grid (W2V2G): Another aspect of the project looked at whether using vehicles as an intermediary between wind energy and the grid could improve uptake of renewable energy. In this portion, wind energy produced during periods of low demand was fed into electric vehicles, which are designated as Local Load Management service providers. The EVs held onto the power until demand rose, after which they could feed it back into the grid.

For more information please refer to the website at http://bit.ly/1SVW26V

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