ELEC6095 Smart Grid

Electric Vehicles –

Hotspot or Cold-spot in Smart Grid

Content

Group Members

Ming Him	LAI	3035273084	perspect@hku.hk
Hok Lim	CHAN	3035279040	hlchan19@connect.hku.hk
Kin Ming	WONG	3035735941	ming0623@connect.hku.hk
Kwok Wai	NG	3035736957	u3573695@connect.hku.hk
Chun Lung	CHAN	3035515418	u3551541@connect.hku.hk
Wai Lok	WONG	3035179056	u3517905@connect.hku.hk
Chun Sing	HO	3035736763	u3573676@connect.hku.hk
Ka Shing	MUI	3035632137	ksmui@connect.hku.hk

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This report, written for the course ELEC6095 Smart Grid in University of Hong Kong, is solely for educational and institutional purpose.

1. Introduction

Electric Vehicles (EV) have been in the news a lot in recent years, especially in the stock markets, investors demonstrated a huge enthusiasm towards some of the electric vehicle company like Tesla and BYD Auto since pursuing electric vehicles is a trend around the globe, given that electric vehicles can be connected with technical advancements, such as Internet of Things, Autonomous Vehicles, and it fulfils the concept of sustainable development when electric company are adopting more Renewable Energy (RE) or cleaner fuels to generate electricity. While it is necessary to review the matching facilities for the electric vehicles when the demand for electric vehicles has been growing rapidly, the idea of PEV Charging Hotspots or Cold-spots due to renewable energy emerges at the same time.

This paper will first describe the concepts of Smart Charging (V1G), Vehicle-to-Grid (V2G) and Vehicle-to-Building (V2B), then discuss how optimal charger location, charger schemes and charging scheduling can help limit effect of EV Charging Hotspots or Cold-spots in the first part. In the second part, Smart Grid Technologies will be evaluated, in terms of Demand Response with EV + RE, Grid Infrastructure and Planning Consideration. In the end, a conclusion will be given to tell whether the issue of PEV Charging Hotspots or RE Cold-spots can be solved with the help of Smart Grid Technologies.

2. Smart Charging (V1G), Vehicle-to-Grid (V2G), Vehicle-to-Building (V2B)

V1G is also called Managed Charging or Smart Charging. According to California Independent System Operator (CAISO) definition, V1G refers to the unidirectional power flow enabling EVs to charge from the grid.[1] The difference from traditional electric vehicle charging is that V1G can meet the needs of the grid and adjust charging time and charging rate for electric vehicles.

V1G can be divided into two charging management systems, User-managed charging (UMC) and Supplier-managed charging (SMC).[2]

For UMC, Time of Use (TOU) method is applied. The customer schedules EV charging based on the price and their needs. This method can make most drivers decide the charging time in off-peak and low-price periods. Compared with the peak EV charging curve caused by uncontrolled charging, UMC will delay peak charging load formation to a specific later time, usually between 9:00 pm and 10:00 pm, depending on electricity price regulations.[3]

For SMC, the charging and decision is made by an electric utility or another third party. Utilities controls charging time and rate with real-time energy production, local energy consumption and charging status of nearby EV and other electric devices.[4]

A survey in the UK on the acceptance rate of UMC versus SMC shows that current and former EV owners are twice more likely to adopt to UMC than SMC.[5] Figure 1 shows an interview result that most driver prefers UMC than SMC. This interview had 60 drivers took part. The result showed that most drivers chose UMC for smart charging, as UMC has more strength of preference for personal control. [7]

The pros and cons of UMC and SMC:

	UMC	SMC
Charging Behavior	Customer have more initiative and flexibility of charging EV	The EV's battery percentage at every use becomes unclear
Load Balancing / Demand Response	Not effective, because charging time depends on customers' needs.	More significantly effective, due to charging time managed by utilities.

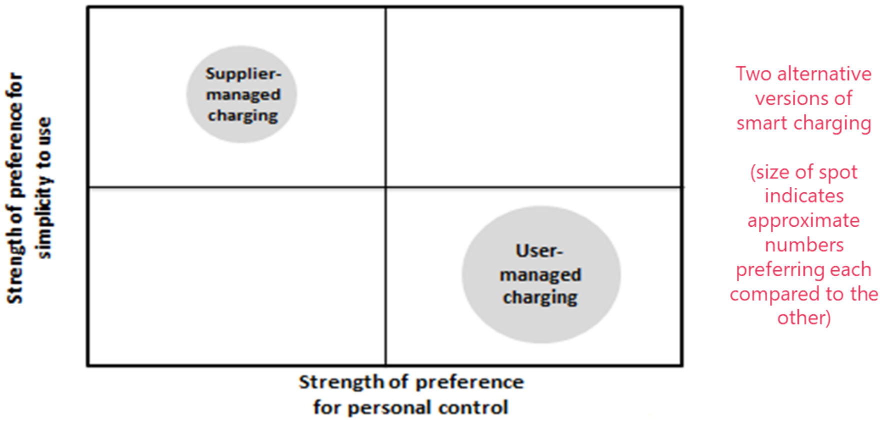

Figure 1 – Smart Charging – Theoretical Segmentation

V2G means Vehicle-to-Grid, According to the definition of CAISO, V2G refers to the bidirectional flow of power enabling EVs to charge from the grid and to discharge back to the grid.[1]

V2G vehicles can help load balancing in grid at different periods of time. It charges load demand is low at night, i.e. valley filling[6], and discharges back to the grid during peak hours, i.e. peak shaving. Peak load adjustment provides flexibility to grid owners to regulate voltage and frequency and undergo maintenance with spare network reserve. Charger Controllers and Intelligent Distribution Autonomous Power System (IDAPS) works with Smart Meters to calculate charging and discharging power in real time for load balancing and load shifting. Smart meters enable buying (charging) and selling (discharging) power from EV at cost optimal point. In the current development, it is proposed to use V2G electric vehicles as a buffer for renewable energy power generation equipment (such as wind power and solar power). It can provide load shifting and ramp rate control by absorbing fluctuating output from PV and Wind. V2G can effectively stabilize the power grid when the power source has intermittent characteristics.

Vehicle-to-Home (V2H), Vehicle-to-Building (V2B) or Vehicle-to-Everything (V2X) will not affect performance of main grid. It can supply power in a regional environment. EVs are used as a backup power source at home when parking. When demand reaches at a certain level, load can be switched to electric vehicles to avoid charging for excessive power demand.

3. Charger Location and Optimization

There are main considerations for the charger location for PEVs. Typically, charging stations are located at business complexes, stores, workplace, leisure facilities and colleges.

The charging station location should[8]:

Provide simple and affordable pricing - For charging outside peak hours, it is usually cheaper in public spaces and workplace, payment by credits is simple to be employed. However, the billing system is difficult to be constructed when the infrastructure of charging stations in some countries are not well-developed yet.

Provide convenience - The location should attract transportation electrification customers such that a wide net is constructed around the community where most PEVs users will pass through when they travel within their countries.

Reduce emission - If there are renewable energy sources at the proximity of charging stations, such as solar panels and wind farms, it can form a charging network using renewable energy sources, it can greatly reduce emission generated by traditional diesel engines, such as CO2, SO2, etc.

In general, there are two types of charging stations, Curbside Charging Stations and Off-Street Charging Stations. They both offer Electric Vehicle Supply Equipment (EVSE) which can deliver energy to electric cars by recharging through plug-in methods.

Curbside Charging Stations[9]

It refers to charging stations located at curbside, which allows vehicles from street traffic to a designated place in a public space. There are criteria when locating curbside charging stations.

First, it should be constructed before the intersection for vehicle travel directions to avoid chaotic scenarios, as managing in-and-out is problematic at charging stations. In addition, the vehicle should access the EVSE from a diagonal or perpendicular position relative to the charging station, but it depends on the width of the road.

A minimum width of 3 ft should also be reserved to have an accessible aisle to the EVSE. There should be sidewalk clearance of minimum 3 ft for pedestrian movement between the EVSE and the built area. For charger clearance, the EVSE should have a minimum of 2 ft from the curb and it should be protected with barriers for vehicles which are going to access the EVSE from perpendicular or diagonal from the curb.

Off-street Charging Stations

Charging stations NOT locating at public area near roadside, i.e. dedicated fuelling or parking spots, are off-street charging stations.

Requirement:

Height of EVSE could not exceed more than 4 ft from the surface area. Equipment with a retractable cord is recommended. The station should have appropriate signs to indicate the station location and suitable lighting for users to access the EVSE. In the US, there are standards for service signs related to EV stations, indicating the location and size for the station.

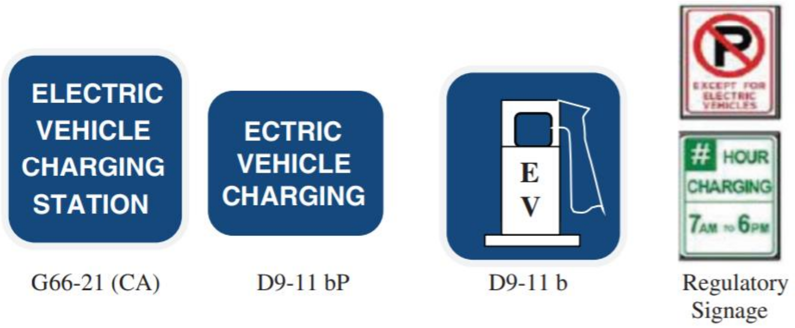

Figure 2: Standards for regulatory signs used in the US for EV charging stations

The charging station site and sizing are:

Standards	Charging station	Conventional road	Freeway	Expressway
G66-21 (CA)	12" x 12"	24" x 24"	-	-
D9-11 bP	-	24" x 18"	30" x 24"	30" x 24"
D9-11 b	-	24" x 24"	30" x 30"	30" x 30"

Charging optimization [10]

There are two algorithms implemented to ensure appropriate control for PEV charging scheduling, which are centralized and decentralized algorithms. A set of constraints and limits set for local control of PEVs are shown in Figure 3. When charging begins, Data Management System (DMS) receives data from PEVs such as plug-in and plug-out time, battery statistics.

For centralized algorithm, it performs 2-stage dynamic programming, which gives insights on how to schedule PEV charging such that price and network constraints can be met.

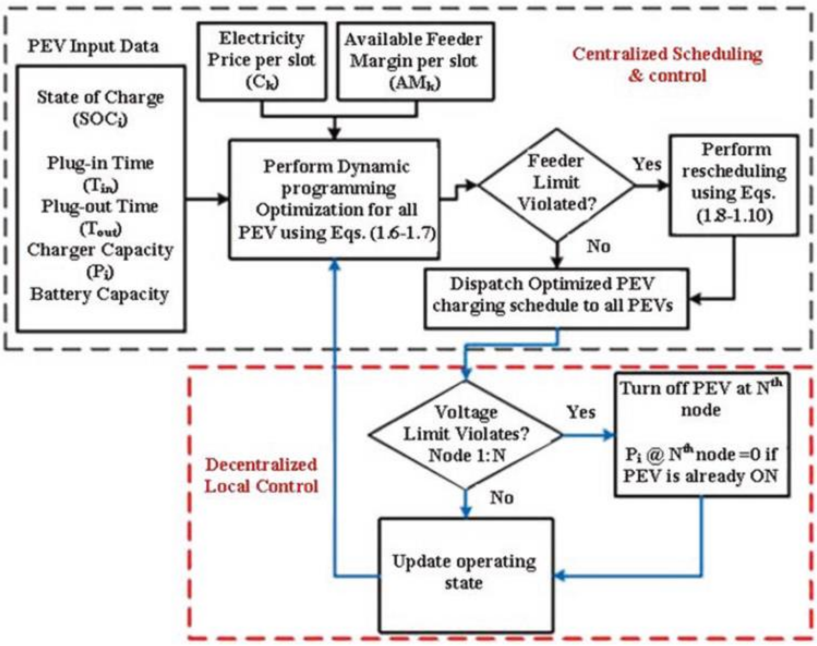

Figure 3: PEV charging coordination

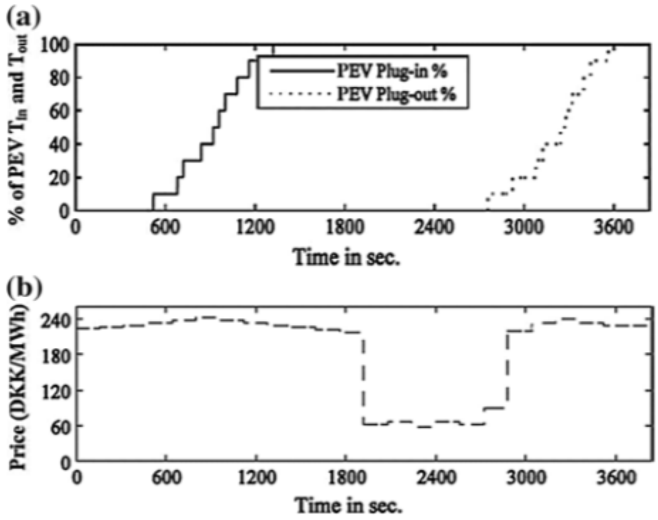

Figure 4: (a) Plug-in and Plug-out Profile, (b) Price Profile

Optimization Result:

Price based Optimization – This PEV scheduling algorithm aims to minimize the cost. For example, PEV charging is scheduled at a lower price as shown in Figure 4a. The energy profile is high between 1800 and 3000s when the electricity price is relatively low, as shown in Figure 4b.

Optimization related to network constraints – To prevent network congestion, network constraints are added into the algorithm. Load profile is set to be lower than feeder capacity, and charging profile follows the price profile. Whenever the charging load is more than 300VA, the DMS records the triggering point and reschedule the charging scheme for PEV to reduce charging power, while maintaining its output below the feeder capacity limit[12].

4. Charging Schemes

Charging Scheme is the scheme available from EVSE service providers or grid owners to customers in which charging location, charging time, distribution of spare power to grid capacity limit and charging cost are concerned. Table 1 lists the charging strategies and the corresponding range anxiety, i.e. fear that battery does not have enough state of charge to reach its destination, and electricity tariff.

Intensive Charge is to charge after reaching the destination with maximum power; Plug-and-Play are scheme, e.g. EV-Charging at Home Subsidy Scheme at Hong Kong, which is to charge at night with maximum power to perform valley filling; Tariff Control is to operate charging, and even discharging, with cost optimal schedules; Smart Charging is to distribute power under aggregator control by considering network capacity.

Table 1: Charging Scheme & Strategy – Range Anxiety & Electricity Tariff [12]

Scheme	Charging Strategy	Range Anxiety	Electricity Tariff
Intensive Charge	At the end of each displacement	High	Constant
Plug-and-Play	At the end of the day	Medium	Cheaper at Home
Tariff Controlled	During the cheapest period	Low	TOU
Smart Charging	Under Aggregator Control	Low	TOU

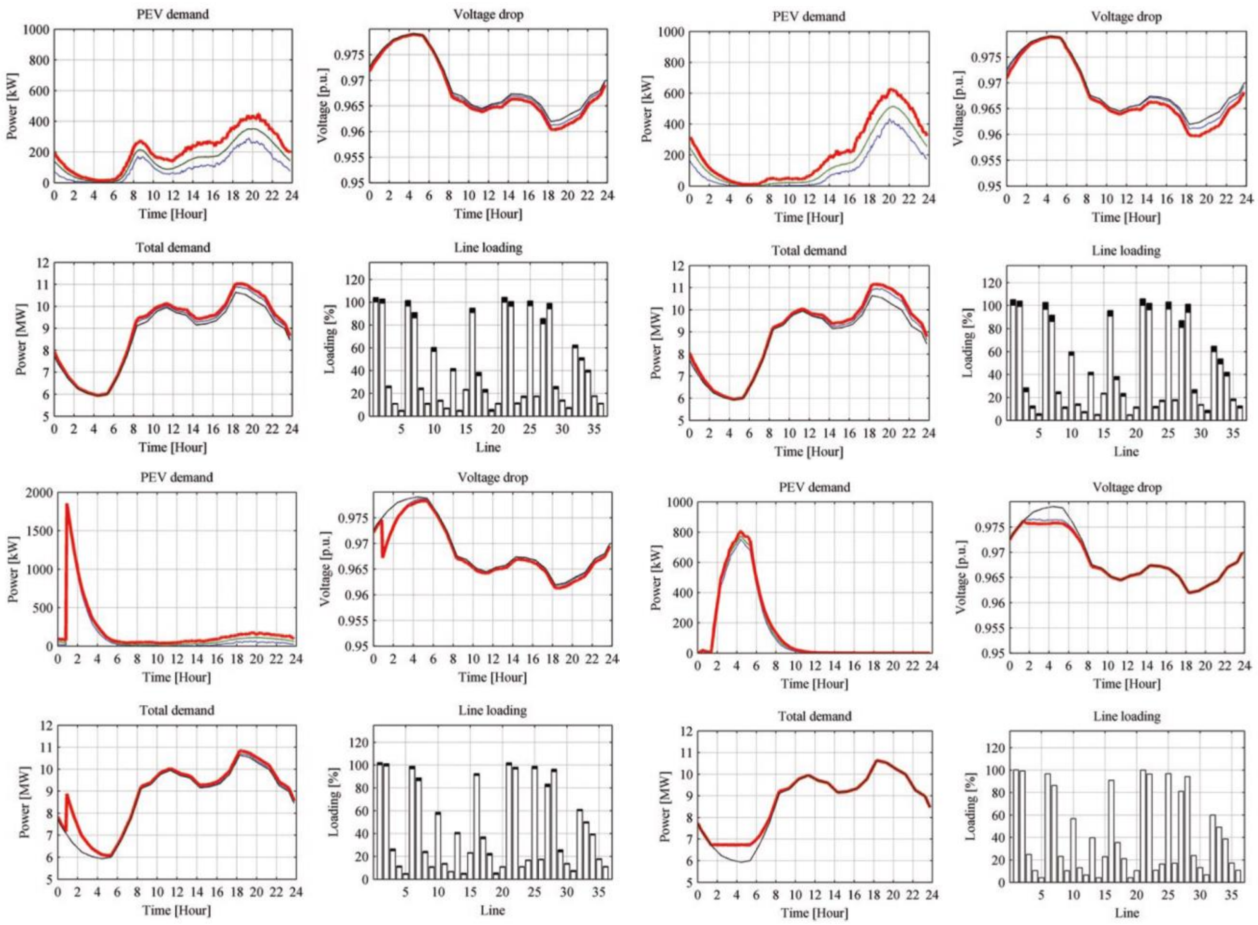

Figure 5: PEV Demand, Voltage Drop, Total Demand and Line Loading for (a) Intensive Charge, (b) Plug-and-Play, (c) Tariff Control & (d) Smart Charging [12]

Figure 5 shows the effect of charging schemes to grid voltage, network reserves and total demand. Intensive Charge tends to distribute the power uniformly in time, while Plug-and-Play is to charge at night, i.e. tends to night-time. These charging schemes are uncontrollable in nature and may create hotspot due to charging location, e.g. residential area with long feeders. They cannot provide flexibility in grid operation with more network reserves. Tariff Control and Smart Charging can distribute EV charging power in grid-optimal and cost-optimal, however, it requires smart grid infrastructures, such as managing agents in IDAPS and charge controllers to control charging/discharging speed, communication network, advanced metering infrastructure (AMI) and smart meters for cost control, and distribution automation, with the ability to connect and disconnect, or provide parameter control, e.g. degree of autonomy.

5. Charging Rate and State of Charge (SOC): Control and Coordination

In EVSE, charging rate has been improved to provide greater incentive for the usage of electric vehicles. Under current technology, there are several charging methods which are standard charging, medium charging and quick charging.

Standard charging provides general charging for electric vehicles where it provides 13A charging current. In EVSE of Hong Kong Electric[11], the standard charging consumes 6-7 hours for fully charging 18kWh battery. For Medium Charging, a single phase 32A charging current is provided. It can charge up to 18kWh battery within 2-3 hours. Quick Charging has the fastest charging rate as it provides the highest output power for. A 18 kWh battery can be charged up to 80% in 30 minutes.

Since there are different charging rates, it is important to set up a control scheme for the charging coordination in G2V/V2G. Centralized PEV Scheduling is introduced to coordinate the charging process as shown in Figure 6 [9].

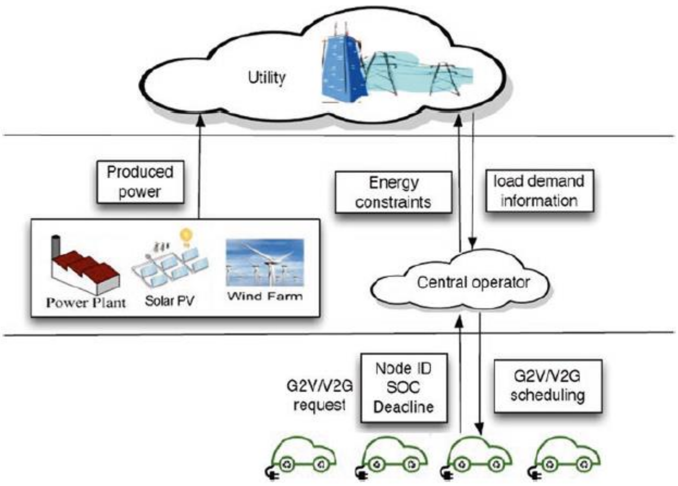

Figure 6: Centralized PEV Charging

All PEV charging schedules are planned and controlled by central operators. They are dependent on final SOC, charging cost and permissible charging interval from the customer side [9]. Central operators also calculate the load variability, local generations and PEV requirements. Combining information from smart grid, charging schedule is provided to EV. Yet, its implementation is expensive and inflexible for the specific customer. Therefore, decentralized local control is adopted as shown in Figure 7 [9].

Customers can choose their own charging profile regarding their own charging pattern. Charging becomes more flexible and independent, but grid stability will be affected. Since the control decision returns to customers, EV may be switched in simultaneously without arrangement. It will cause serious voltage oscillation to the grid which may threaten grid stability.

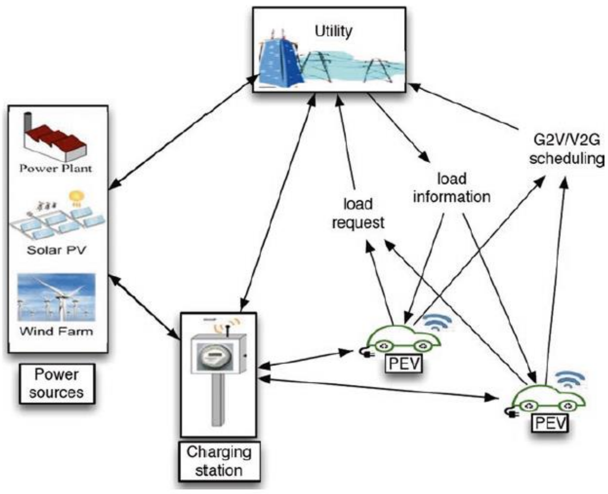

Figure 7: Decentralized Local Control for PEV Charging

6. Demand Response (DR) in Electric Vehicles and Renewable Energy (EV+RE)

With an increasing demand for EVs, peak demand for electricity is surging. Power utilities operate inefficient generating units to meet increasing peak demand. DR can perform peak curtailment at critical times when demand outstrips capacity. With DR, it improves energy efficiency in Figure 8.

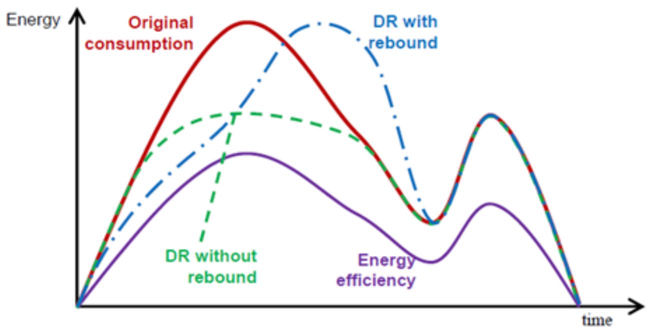

Figure 8: Impact of Energy Efficiency vs Demand Response[12]

Different DR programs are improved for load regulation of EVs. For the incentive-based, Direct Load Control (DLC) is highly adopted according to FERC's 2006 survey [13]. For time rate based, Time-of-Use (TOU) mentioned is commonly adopted, and it is to reduce power consumption by increasing electricity price during the peak time. TOU has been used effectively in the US, Germany, the U.K., Japan, and other regions [14]. However, TOU can cause unintentional higher peaks in "off-peak" periods than in the peak periods as shown in Figure 9 [15]. Dynamic Rates and Rewards are introduced to mitigate the side effects of TOU by offering different rates and rewards to different customer groups [16].

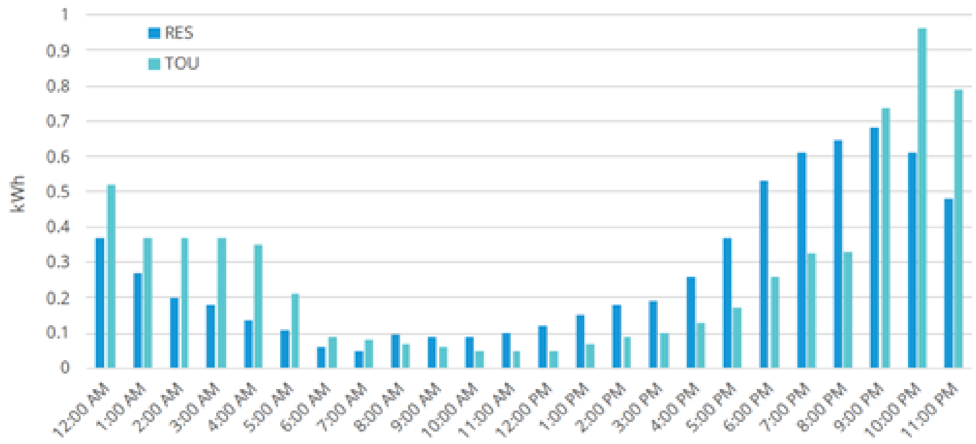

Figure 9: Charging Patterns with (TOU) and without (RES) during summer weekdays [4]

By adopting smart charging and Advanced Metering Infrastructure (AMI), Demand Response Program can reduce operational cost of power utilities and improve energy efficiency.

7. Impact of Electric Vehicles (EV) to Grid and How to Solve?

With the growing market share of EVs, planning and operations of power system will be affected significantly [17]. It results in the increase of energy consumption and peak demand, complexity of network and difficulty of power system control. In other words, EVs in large scale penetration can have a detrimental impact on the power quality, performance, reliability and stability of the grid, especially with the integration of DERs. [18]

Voltage Stability

EV charging may lead to a sudden increase in the loads and cause grid stability issues such as voltage instability. Voltage Sensitivity Factor (VSF) and Voltage Stability Index (VSI) are used for voltage stability analysis. The effect of intermittent nature of EVs is analysed with VSF from PV curve.

From the PV curve in Figure 10, when the active power increases, the voltage decreases up to a point where the active power is highest (Pmax, Vcritical). The nose point corresponds to a critical operating condition known as the limit of stable operation. VSF is the ratio of change in voltage to change in loading. Mathematically, it is expressed as

$$VSF = \left|\frac{dV}{dP}\right| \quad \forall P < P_{\max} \tag{1}$$

VSI is calculated as Equation (2), to determine voltage stability. Increasing P, VSI decreases up to a limit and the system goes unstable [19].

$$VSI = 2V_j^2 V_{j+1}^2 - 2V_{j+1}^2\left(P_{j+1}r + Q_{j+1}x\right) - |Z|^2\left(P_{j+1}^2 + Q_{j+1}^2\right) \geq 0 \tag{2}$$

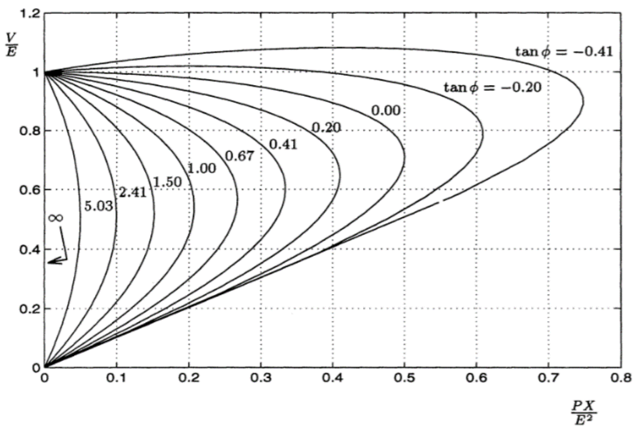

Figure 10: Active Power to Voltage Curve (PV curve).

Logic flow for VSF and VSI computation is as shown in Figure 11(a) and 11(b).

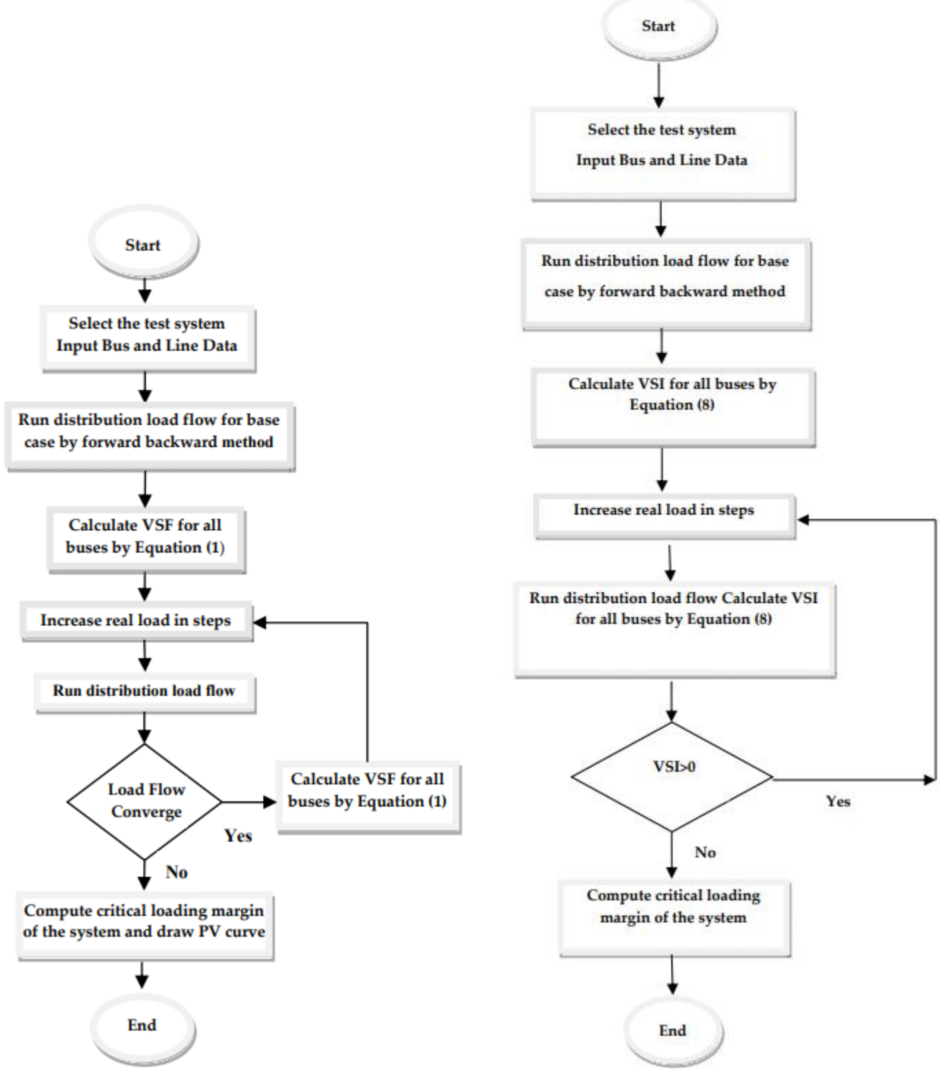

Figure 11: Flowchart for Computation of (a) VSF and (b) VSI

From the analysis, it shows that charger location at the weakest bus caused limited margin to voltage stability (from the P-V curve). Thus, determining which feeders have a higher sensitivity of real power transfer to voltage drop, i.e. $S_V^P = \Delta P(\%)/\Delta V(\%)$, and avoiding placing chargers at high sensitivity location can help soothe this issue. Voltage sensitivity can also be included in Hosting Capacity Analysis (HCA) for distribution planning.

Reliability

Reliability of power system refers to the probability that a system performs correctly during a specific time duration, and it also relates to customer satisfaction. With more load attached, including EV charging load, the customer minutes loss (CML), which multiplies interruption time and number of affected customers, is larger when there is fault, i.e. at a higher impact. There are indices to indicate reliability of a power system. [19]

Table 2: Definition, Formula and Significance of Different Reliability Index [19]

Index	Definition	Formula	Significance
SAIFI	Units of interruptions over a certain time period per customer	$\frac{\sum \lambda_i N_i}{\sum N_i}$	Condition of the system, units of interruption per customer
SAIDI	Average interruption during per customer served	$\frac{\sum U_i N_i}{\sum N_i}$	Shows the duration of interruption as the condition of the system
CAIDI	Average interruption time for those customers interrupted over a year	$\frac{\sum U_i N_i}{\sum \lambda_i N_i}$	Offers the average outage duration that any given customer would experience.
ENS	The total energy not supplied by the system	$\sum U_i L_i$	An indicator of Energy deficiency of the system
AENS	Average system load curtailment index	$\frac{\sum U_i L_i}{\sum N_i}$	Represent how much energy is not served over a certain time.

Reliability indices collapses on centralizing fast chargers at weak buses. Moreover, uniformly distributing charging stations among buses is better than concentrating charging stations at a single bus in terms of reliability, same as voltage sensitivity consideration. Thus, carrying out a voltage and reliability sensitivity analysis to network with hosting capacity analysis is a must.

Peak Demand, Load Shifting and Energy Storage

If EV charging is left uncontrolled, its adverse impact to the peak demand is problematic, as it can worsen voltage profile and overload transformers at a sudden.

40% EV penetration can lead to 40% increase in peak demand as illustrated in Figure 13. Thus, charging management, load shifting and installation of distributed energy storage are suggested to reduce peak demand. [20]

Charging Management: Time of Use (TOU) program to passively control customer loads and encourage people to perform plug-and-play, i.e. charging at night. Smart charging, where active control of EV charging is handled by utilities or services providers, can be dynamically avoid going beyond limits and overload transformers by price signals, as discussed in previous section. [18]

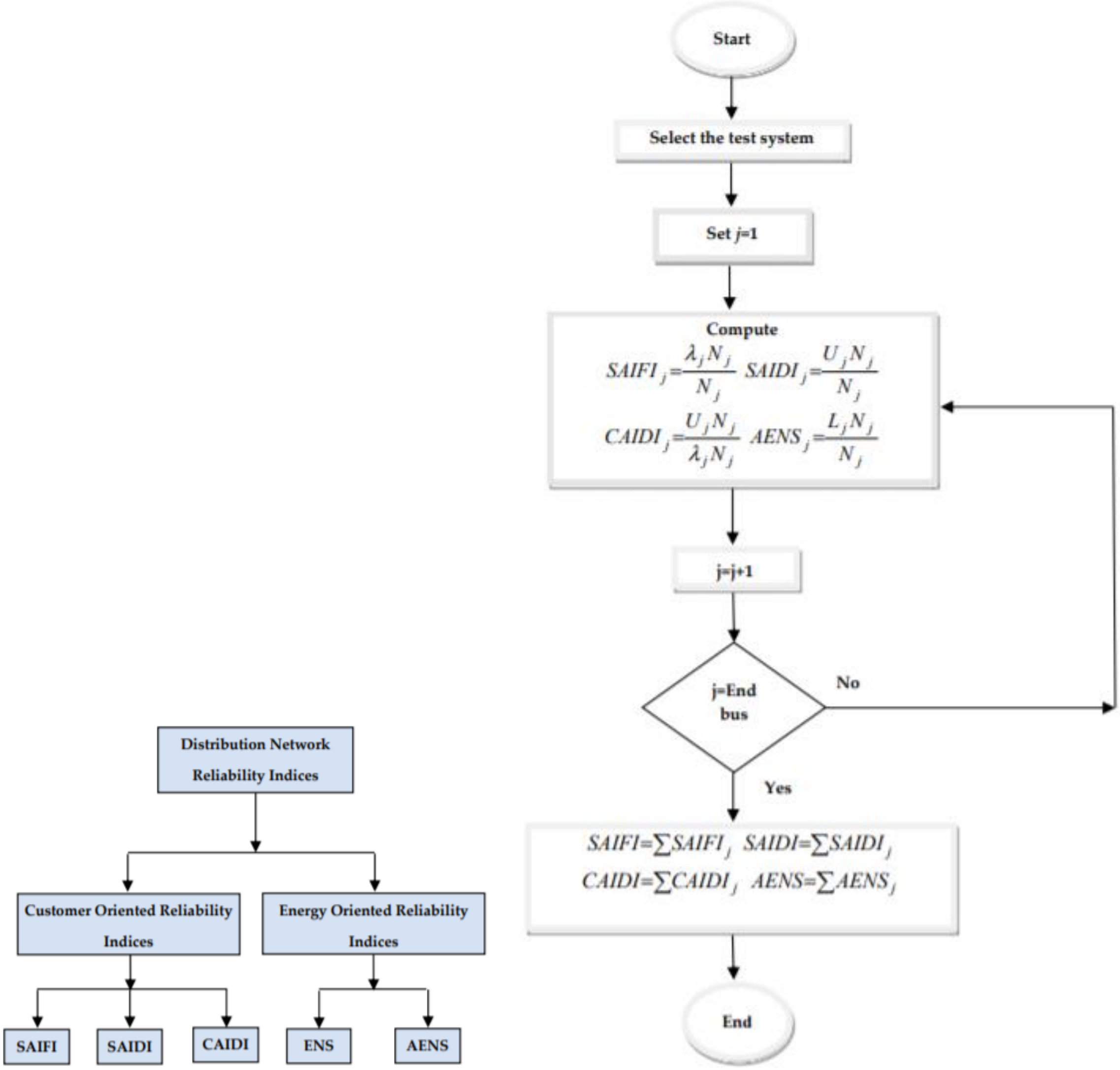

Figure 12: Flowchart for Computation of Reliability Indices

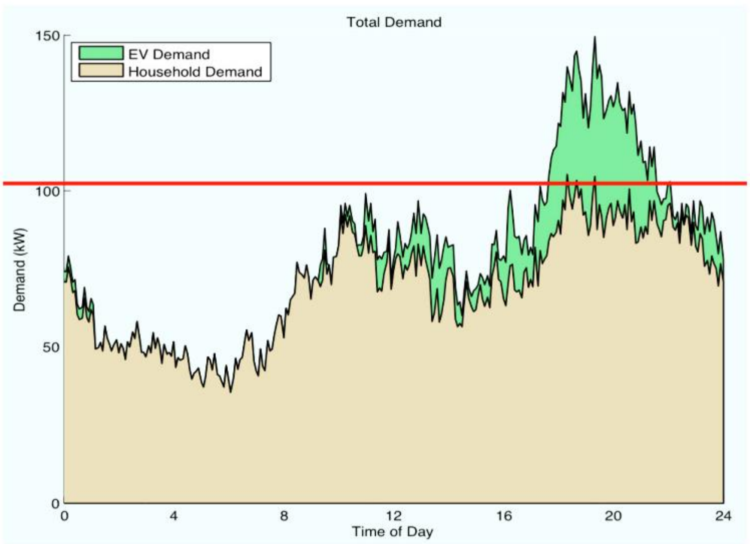

Figure 12 Impact of EV Charging at Peak Demand

Load Shifting: It is a process to mitigate the effects of large load blocks during a period by advancing or delaying their effects until the system has network reserves to accept additional load[19]. It is by minimizing generation capacity requirements by regulating load flow[12], as shown in Figure 14.

Distributed Energy Storage: It is another solution to solve the problem of peak demand by scheduled charging and discharging. Energy Storages with different energy density and power density which have their own benefits and appropriate application. This helps EV charging more cost effective with renewable energy resources. [22]

As a result, charging schemes, load shifting and distributed energy storage approaches could reduce the peak demand in the grid network.

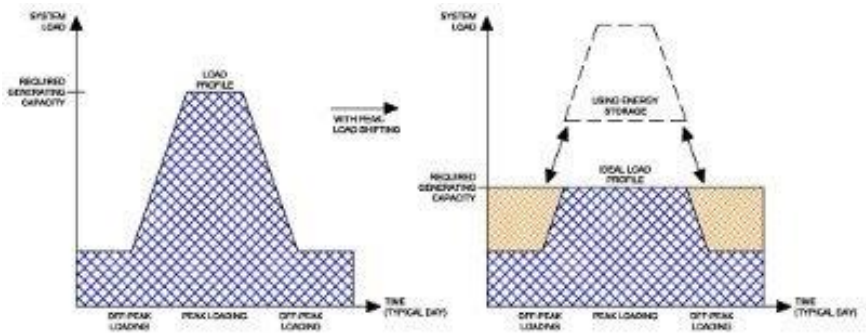

Figure 14: Peak-load shifting approach

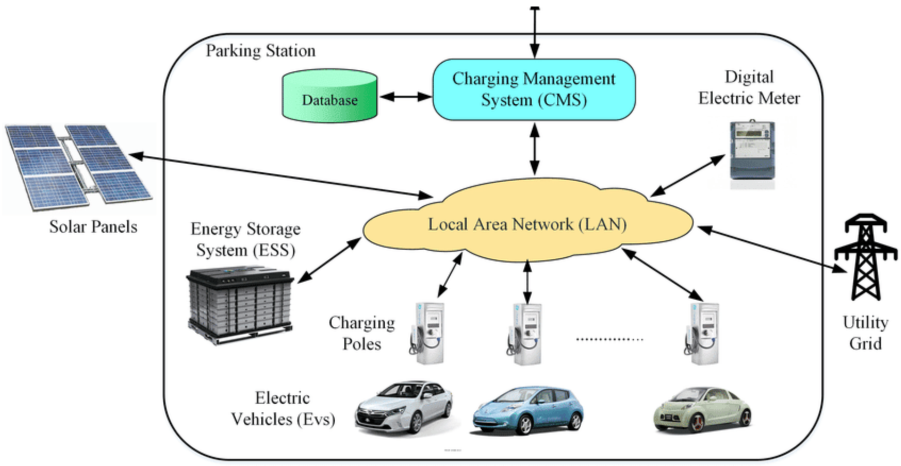

Figure 15: Integration between EV Charging and Energy Storage

8. Grid Planning Consideration

Grid planning is the frontline to face RE and EV integration. It foresees the aggregated behavior and sets up policies and models to allow, and reject, if necessary, grid connection applications of smart grid components, e.g. distributed energy resources (DER), battery energy storage (BESS), electric vehicles supply equipment (EVSE) and distributed FACTs. From the utility experience in Hong Kong and Singapore, the major considerations in the first glimpse of EV integration are the diversity factor and ratio of fast charger to slow charger. It is location and charging behavior dependent, as discussed in the previous section. Another concept to be considered in the planning stage is the possibility of static and dynamic re-configuration.

Diversity Factor (DF) is defined as

$$DF = \frac{\max \sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} \max P_i}$$

which is the percentage of load operating simultaneously [16].

SA Power Network considers a diversity factor of 30% or less at zone-substation level, which is 30 of 100 chargers operating at maximum [16]. It also means that the allowed EVSE installation capacity is 3.3 times of spare capacity of the distribution transformers, e.g. for a dedicated 1.5MVA transformer, the allowed EVSE capacity is 5MVA, with some safety factors. In fact, the off-board charging controllers should be able to perform load curtailment according to local RE generation and real time transformer loading. Utilities in Hong Kong have NOT set any limits to EVSE installation, as the aggregated effect of EVSE is not large in the network. Yet the preferred DF would be *larger than* 30%. SP Group in Singapore has even developed a mobility model to observe the charger location effect (from home to work) [24].

Another parameter is the Ratio of Fast Charger to Slow Charger (FC/SC). The actual effect of charging speed and charging scheme have been discussed in previous section. Yet, it is planners' responsibility to restrict the percentage such that expected power ramping and power quality issues with stochasticity are limited, while satisfying the charging needs of EV owners.

After standardizing locally the hardware requirement of chargers, the percentage of rapid chargers in planning comes in. The figure below presents the rapid chargers and regular charger distribution, in which China has more rapid chargers (40%) while Netherlands has smaller than (5%), and other countries have too few chargers to observe this ratio. It depends on the expected travelling distance and governmental policies to implement EVSE with grid reinforcement. However, the thumb rules for the ratio is around 15%, or the chargers should be well coordinated, with smart grid technologies, to avoid power ramping and aggregating at instants.

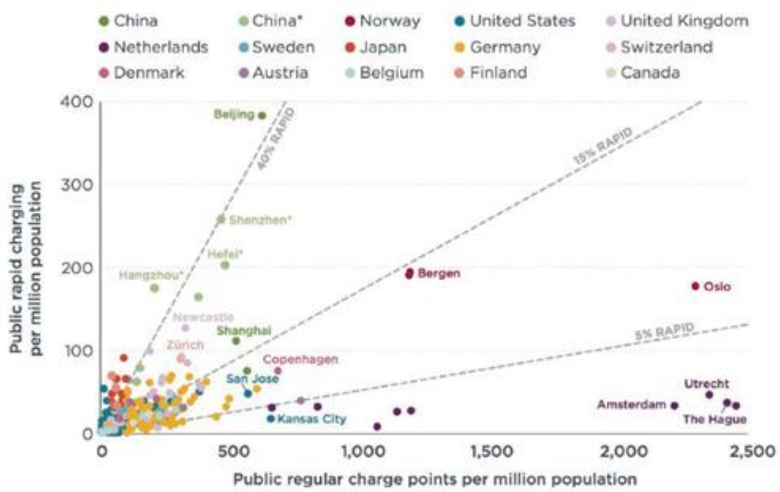

Figure 16: Public Rapid Chargers to Regular Chargers Benchmarking [16]

Static and Dynamic Reconfiguration is to reconfigure the grid topology under operator control (infrequent) and automatic control (frequent) respectively. Currently the distribution network in Hong Kong has interconnectors in ring networks, which connect from leg to leg, from ring to ring, or even from a primary substation to another primary substation. Yet, the connection is set to be normally opened (N.O.) and it is for contingency restoration purposes. However, in smart grid topology, it could also divert power and control power flow to designated locations, e.g. responsive load or utility-owned battery storages.

Dynamic Reconfiguration allows real time optimization and automatic control with cost, loss and hosting capacity optimal solutions, depending on the setting of objective functions, and constrained by voltage, capacity and SOC limits in grid. This in one way reduces the voltage drop / rise by diverting power to energy storage or to sources through different path, performs power conditioning (THD, ramp rate, power factor) by reconfiguring reactive power resources, i.e. distributed FACTs, to the required location, or even performs load shaping and grid stabilizing with energy storage through designated connection designs.

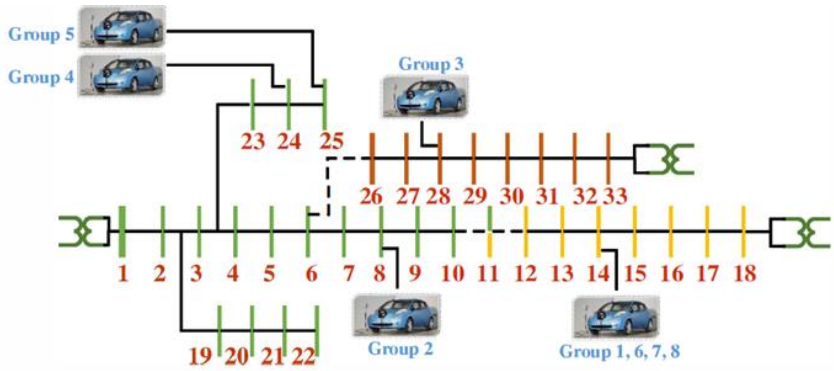

Figure 17: A Typical Radial Distribution Network [23]

9. Conclusion

This report discusses the effect of uncontrolled EV charging to controlled charging (e.g. smart charging, vehicle-to-grid and vehicle-to-building), such as hotspot issues, grid instability, deferral or rejection of RE and EVSE installation. Charger Location Optimization, Charging Scheduling, Charging Scheme, Demand Response Program and Distribution Planning are ways to improve integration of EVSE with RE, without creating hotspot and absorb excessive and fluctuating renewable energy, i.e. heating the coldspot, as well.

This requires placing chargers with optimization of transportation model and distribution network, understanding of driving behaviour modelling to investigate optimal use of state-of-charge, setting schemes and programs with cost optimal, grid optimal and user-experience optimal solutions.

All of these requires the controllability and observability of smart grid, including smart meters and advanced metering infrastructures to see real time information, hardware of distributed energy storage, controllable loads and renewable energy to provide flexibility to zero balance, ramp-rate control and voltage and frequency regulation, energy market to passively control effects of EV charging and peak loads with price signals, distribution automation to provide centralized or decentralized control in charging such that different charging scheme is implemented.

Smart Grid is a yet-to-be-reached solution and goals in which digitalization is embraced for decentralized world. Customer Engagement and System Automation is a win-win situation between customers and utilities in the foreseeable world.

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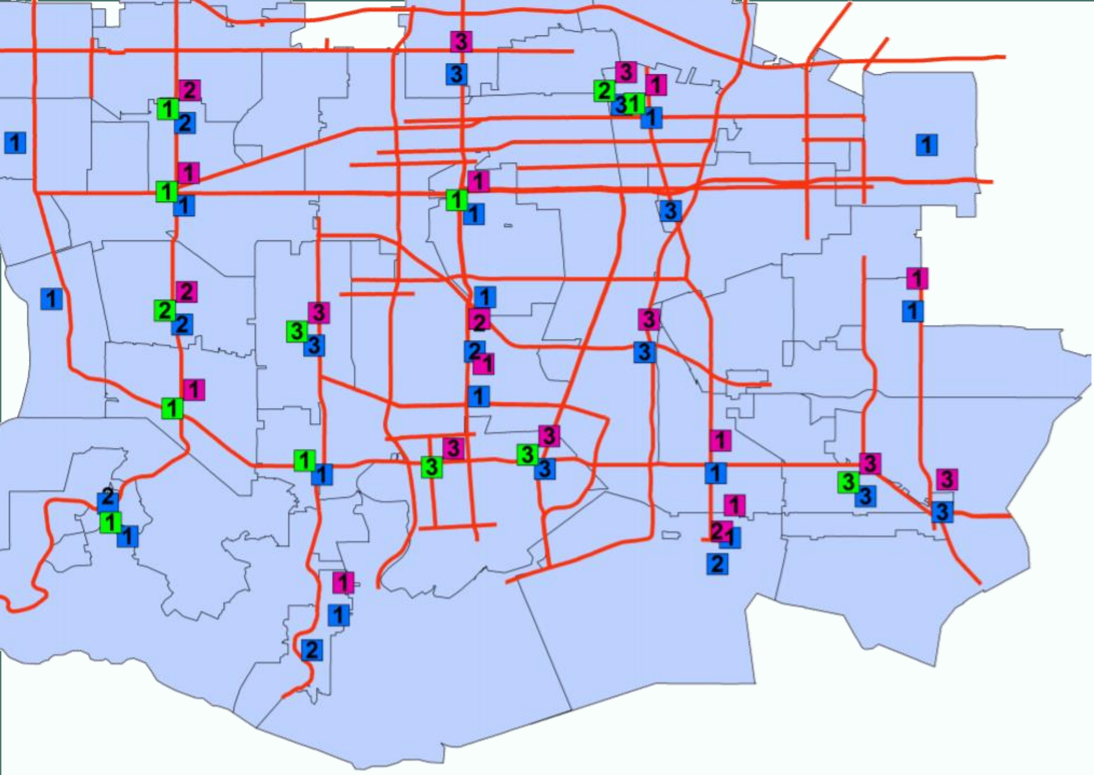

“Charger Location is an art of Compromise,
between Cost, Network Performance and User Experience”

- Teams of Smart Grid, ELEC6095