Electrified Vehicles and the Smart Grid: The ITS Perspective

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***Abstract*—Vehicle electrification is envisioned to be a significant component of the forthcoming smart grid. In this paper, a smart grid vision of the electric vehicles for the next 30 years and beyond is presented from six perspectives pertinent to intelligent transportation systems: 1) vehicles; 2) infrastructure; 3) travelers; 4) systems, operations, and scenarios; 5) communications; and 6) social, economic, and political.**

***Index Terms*— Energy efficiency, intelligent transportation systems, smart grid.**

I. Introduction

THE impact of the interaction and integration of intelligent vehicles and the power grid is envisioned to be penetrating in multiple dimensions [1]. Initiated by the IEEE Standards Association, the IEEE Smart Grid (SG) Vision is intended to be a long-term vision of what the SG will look like 20 to 30 years from now. In the Intelligent Transportation Systems (ITS) society, the SG Vision for Vehicular Technologies Project was kicked off in mid 2011 [2]. The joint forces of technological leaders with diverse expertise related to ITS and SG have resulted in the creation of a rich set of forward-looking use cases, application scenarios, and corresponding enabling technologies for future SG–ITS integration. In this paper, we selectively present some of the key characteristics of the SG–ITS paradigm and aspire to stimulate research and development of ITS technologies enabling this paradigm.

The foremost interface between the SG and the ITS consists of vehicle-charging units, which offer assurance for users and flexibility for the utility [3]–[5]. Their networked intelligence will enable more efficient and effective vehicle–grid systems, but will most likely require bidirectional battery chargers [6], [7]. Compared with unidirectional charging, the bidirectional alternative will provide improved flexibility and overall energy efficiency in the long run [8]. In addition, mobile inductive charging may overcome the basic range limitation of plug-in electric vehicles (EVs) [9].

Incorporation of this foremost interface, however, urgently calls for the development of an integrated smart infrastructure; the challenge lies in the assurance of synchronized energy flow, transportation flow, and communication flow [10]. This is only possible via the modernization and unification of the existing transportation, energy, and communication infrastructures. The key technology breakthroughs include battery technology and its economics, seamless and stable integration of various renewable energy sources [11], and high-bandwidth high-performance highly versatile cloud service platforms. It is also envisioned that automated and coordinated parking and driving will be at the heart of the infrastructure unification [12].

Adapting to such macroscale development, individual travelers' role will also evolve rapidly from the traditional picture: Travelers as mobile nodes will be able to optimize their route/time schedules in a multidimensional grid based on considerations including energy, travel time, environmental impact, and data connectivity [13]. Such seamless system connectivity may lead to privacy issues. Variable user tolerance may also arise from the system complexity and intensive customizability.

To achieve the aforementioned traveler, transportation, and energy optimization objectives, it is essential to jointly manage

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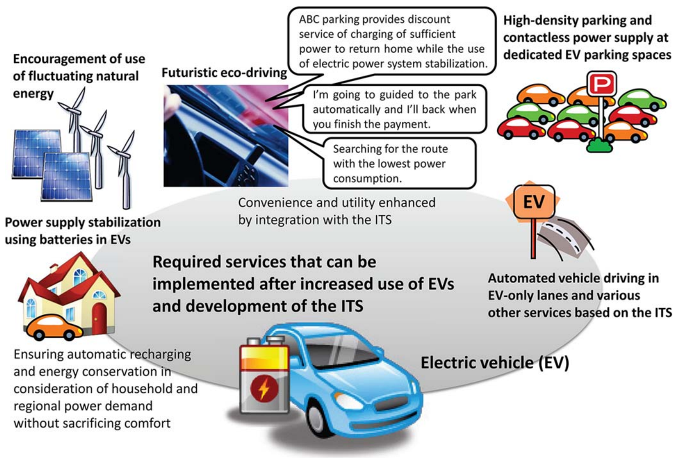

Fig. 1. Example structure of future EV driving and living under the support of ITS.

the ITS and SG information from both the system and operation perspectives [14]. To cope with the vast scale of such integrated information, it is recommended to enable real-time processing of the converged system via hierarchically distributed cloud service and content-centric communications [15], [16].

At the core of the information flow, the envisioned communication and networking infrastructure is highly heterogeneous, with hierarchically distributed quality of service (QoS)-oriented routing, high-mobility high-fidelity connections, and extensive information sharing [17]. Due to the unique characteristics of ITS scenarios [20]–[31], the design of such communication and networking infrastructure has to deal with fast time-variant vehicle channels and thus consists of a critical challenge [17]–[19], [32], [33]. It is also envisioned that new communication technologies will be jointly developed with nontraditional charging technologies, such as wireless mobile charging [34].

As with any technological innovation, the vehicle–grid integration will profoundly transform the economy and society (see Fig. 1) [36]. We will discuss how the electrified transportation system envisioned will become a critical part of future smart cities as a business platform with an open architecture for third-party applications.

Following respective sections focusing on these distinct perspectives, conclusive remarks will be provided overviewing the interconnections among all sections. Discussions on key technologies dictating future of the evolution of vehicle electrification will also be included. We hope that the joint efforts of the authors will serve the purpose of stimulating the readers' keen interest, as well as inspiring the readers' imagination on vehicle electrification and electrified vehicles as part of the SG.

II. Vehicles

A. Global Power Market Player

EVs today have already evolved to include functionalities such as kinetic energy recovery system and regenerative brake to improve the energy efficiency and travel range [35], [37]. For future EVs, an intelligent vehicle-charging unit will play much more critical roles for these purposes. From the user perspective, it offers assurance about when a battery pack is fully charged and ready, and includes diagnostics to monitor the vehicle and the battery. It can manage the timing of charge in a manner that reduces energy cost, optimizes battery life, and maintains safe conditions. From the utility perspective, it offers flexibility: A vehicle is parked most of the time, and the timing of a charge process can be adjusted if that provides benefits. It can serve as an energy storage resource to the grid, or it can interact more directly with a time-varying renewable resource such as wind or solar power. Electric and plug-in hybrid vehicles that support intelligent grid interaction are generally termed as "plug-in vehicles." The intelligent interaction between a plug-in vehicle and the power grid falls into the broad category of vehicle-to-grid (V2G or G2V) concepts [39]–[41].

A key issue for plug-in vehicles is the management of their utility interaction. It is well established that uncontrolled on-demand battery charging turns vehicles into uncontrolled loads on the grid and tends to overload distribution equipment [5]. Several studies suggest substantial life reduction in grid transformers and reduced customer reliability, when charging is not subject to control [4], [42]. However, there is a good reason to expect that consumers will be motivated to take advantage of controlled charging. In many systems, for example, the ratio of peak daytime electricity prices to late night prices is four to one, six to one, or even more. Even during the day, real-time prices tend to be the highest during just one or two hours; therefore, even limited flexibility can lead to noticeable economic benefits.

Consumers are likely to take advantage of low off-peak and controllable electricity prices, provided two conditions are met: 1) The charger that interacts with the vehicle is highly automated and easy to set up; and 2) the consumer is able to invoke an energy guarantee, by which a battery pack will be assured of a certain target energy state no later than a specified target time. An intelligent plug-in vehicle acts as an "energy load," in the sense that the typical requirement is for a specific amount of energy, but to be delivered over a relatively flexible time interval (e.g., "provide 10 kWh total no later than 6:00 A.M. tomorrow"). Energy loads are relatively rare in residential systems but are actually fairly typical on the supply side, where the concept is common for large-scale energy exchange (e.g., "deliver 200 MWh between 2:00 P.M. and 4:00 P.M. next Tuesday").

The implication of both conditions is that an intelligent plug-in vehicle, although a significant consumer of energy, can sell flexibility to the grid operator [43]. From a consumer perspective, if a car is connected at 7:00 P.M. with a requirement to have 10 kWh provided by 6:00 A.M. the next morning, it makes little difference whether the energy is delivered at a rate of a 10 kW in an interval of one hour, at a rate of 1 kW delivered over ten hours, or at a more complicated schedule that tracks a regional wind generator provided the correct total level is delivered. Intelligence is essential here: A car that merely plugs in and draws charge offers no suitable benefit to exchange with a utility provider. The nature of this intelligence ranges from near trivial (e.g., timer-based charging) to comprehensive adaptive learning. An adaptive learning charger might evaluate past patterns, examine published day-ahead electricity prices, consider the weather forecast, and then draw the desired energy in a manner most likely to minimize cost.

Interactive energy storage is widely discussed as a possibility for more advanced V2G systems [44], [45]. The potential benefits are to use vehicle battery packs as a tool for smoothing the rapid fluctuations experienced with many renewable resources [46]. There are two fundamental alternatives for interactive storage. [47]

- If a battery charger is unidirectional, it only delivers charge to the battery and never discharges it. Then, the "storage" function is a virtual one, based entirely on flexibility. For example, if a cloud passes over a solar array, a corresponding number of plug-in chargers are throttled back or turned off until energy production is restored.
- If a battery charger is bidirectional, the energy stored in the pack is potentially available for use by the utility.

At present, there are many reasons to prefer the unidirectional alternative. Since it never discharges batteries, the grid does not put extra cycling stress on a battery pack. Unidirectional charging avoids safety issues such as grid outage and islanding protection, the potential for high power flow backfeeding, extra bidirectional metering issues, and extra cost in the charger itself [48]. It can be an effective strategy provided there are enough vehicles, and provided their batteries are not full such that the load on the grid can be altered quickly by turning some off. Bidirectional energy flow makes any parked plug-in car a potential grid resource. By simply plugging in a vehicle, fast dynamic energy exchange and the associated benefits immediately become possible.

By 2030, flexible billing methods that permit plug-in vehicles to draw energy from nearly any electrical outlet in the world will probably be routine, with rates and costs governed by a contract between the vehicle owner and a utility company. The model, as in existing mobile phone systems, is likely to provide time-sensitive rates, various types of energy guarantees, roaming capabilities, and even battery diagnostics. At locations where energy storage provides premium value for interaction with renewable energy, there will be incentives to connect vehicles whenever they are parked [49]. Owners of parking garages and apartment complexes may also have entered the market as infrastructure providers. Similar to cell tower owners, they may obtain some economic benefits by providing suitable outlets. Notice that the theme is flexible billing. The intelligence is in the vehicle and the communications infrastructure and not necessarily in the outlets or utility infrastructure.

It is a matter of debate whether inductive charging devices that do not require a plug connection will be widely used by 2030 [9], [47]–[51]. These devices are inherently expensive, associated with substantial energy loss, and merely avoid the (conventional) limitation of plug-in cords. It seems more likely that convenient cord reels and robust connectors will be used in private and public garages. Today, even outdoor outlets associated with parking spaces are ubiquitous in many climates, and it seems logical that this familiar infrastructure will be extended for plug-in vehicle applications. Inductive charging has more interesting applications to mobile chargers [47]–[51].

By 2050, bidirectional plug-in vehicles, capable of providing active energy support services to the grid, may be popular. Well before that time, the processes and algorithms needed to support comprehensive bidirectional V2G services, while preserving or at least properly valuing battery life impacts, will become available. This will have the vital benefit of rapid coordination between solar resources and energy storage, resolving the most fundamental limitation of renewables. In this time frame, it will be feasible to develop roadway energy technology that can maintain battery charge in a plug-in vehicle during long-range driving on intercity expressways, most likely based on mobile inductive charging. Rapid management of chargers is a necessary development to support mobile charging of this type. If this can be implemented at reasonable cost, it will overcome the basic range limitation of plug-in vehicles and allow wide adoption of electric cars.

III. Infrastructure

Electrified Infrastructure + Wireless Dynamical Charge = Charge in Motion: To facilitate these new roles of EVs, a key aspect is the interaction between transportation vehicles and the road, energy, and communication infrastructures. Intelligent vehicles need to collaborate with smart infrastructures in order to optimize transportation-related tasks [52]. Thus, energy flow, transportation flow, and communication flow are synchronized.

Over the next decades, the energy demand will dramatically shift from the established regions in the world to the emerging regions due to economic development growth and population growth. This will have significant influence on the infrastructure development for transportation [53]. On one hand, aging infrastructure has to be modernized to support energy-efficient, safe, and fast transportation [54]; on the other hand, new infrastructure is created in new urban areas.

A. Impact of Transportation Electrification and Renewable Energy

First of all, due to transportation electrification and renewable energy generation, the need to establish an intelligent SG infrastructure in the context of intelligent transportation systems will be developed in all major transportation markets. Transportation electrification is linked to the electrification of the powertrain of vehicles, which ultimately requires new forms of energy storage and new forms of energy transfer. Battery systems with very high power density levels and the ability to quickly absorb large quantities of energy will be required to reduce the current dominant role of internal combustion engine (ICE) vehicles. However, the charging systems needed in the future must be able to transfer energy at comparable speeds to gasoline fuel pumps. This will trigger the development of automotive standards to support high-power transfer via wired and wireless interfaces between the vehicle and the charging infrastructure. It is essential to find ways to make batteries more cost competitive and to reduce the huge weight penalty that affects vehicle dynamics and vehicle energy efficiency. Only breakthrough developments on the battery technology and battery economics will ultimately stimulate the demand for a charging infrastructure that supports both stationary and dynamic charging. The production of energy from renewable sources is desirable from a true zero-emission philosophy. However, it is more difficult to integrate these sources into an energy grid system with predictable usage patterns combined with random demand peaks. A potential approach is to combine renewable energy sources with charging infrastructure in low-density and remote locations or at locations where solar and/or wind energy is plentiful. Suitable energy storage solutions need to be developed to buffer the energy that cannot be consumed immediately [55], [56].

B. Impact of Information and Communication Systems on Transportation Infrastructure

Another important long-term trend to consider is the massive expansion of a broadband wireless network infrastructure that will establish a close interaction between data centers, mobile devices, transportation vehicles, and transportation energy distribution infrastructure [53], [57]. The hyperdynamic growth of smartphones and tablets over the last few years is only the beginning of a longer transition period of connecting mobile and stationary processors and data storage items in a worldwide information and communication network. This development is an excellent opportunity to implement a physical Internet where not only physical goods but also people can be transported in a more efficient manner by using standardized technology and interfaces [58]. There is no doubt that connected vehicles will generate large amounts of data that can be mined (big data) to optimize traffic flow [59], [60], increase safety, and optimize the energy used. Traditional passive information sources to impact traffic (e.g., FM radio) will be replaced by active control mechanisms (e.g., speed control).

From a safety perspective, vehicle-to-vehicle communication will become very relevant but might be replaced or at least complemented by low-latency vehicle-to-infrastructure (V2I) solutions in the long run [61], [62]. There is no doubt that energy efficiency in combination with safety becomes the major driver of active traffic flow control. This requires bidirectional communications between the vehicles being monitored and the control data centers. The key question is to what degree manual driving will be possible in highly automated traffic flow scenarios of the future. A potential answer is that it is very likely that highway traffic will be largely automated, as well as high-density roads in urban areas; whereas in rural areas, as well as on low-density urban roads, manual driving will still prevail. This means that the transition from automated to manual driving and *vice versa* is the most vulnerable situation from a safety perspective. Fully automated driving is of course highly desirable for specific groups such as children, senior citizens, and people with severe medical handicaps. However, fully automated driving requires an information and communication infrastructure that guarantees a safety level that is significantly superior to manual driving scenarios. Whether true driverless operation on public roads will ever be permitted largely depends on the penetration level of autonomous-enabled vehicles on the road and legal considerations in terms of liability.

C. How to Finance the Transportation Infrastructure of the Future

The cost to finance transportation infrastructure improvements and new infrastructure development require new means to generate revenue in public–private partnerships. The key challenges of transportation infrastructure cost are as follows.

1) As vehicles become in general more fuel efficient and the maturity level of overall growth of transportation is high, the revenue potential from the gasoline tax as the main funding source for road maintenance and expansion is at least limited if not shrinking.
2) Connectivity to the power grid and the communication grid is essential for the transportation of the future and needs to be considered in the transportation infrastructure cost calculation.
3) Active control of traffic via V2I technologies requires ICT (information and communication technology) services that need to be included in the transportation infrastructure cost calculation [63].
4) Vehicle original equipment manufacturers need to invest in vehicle components that are designed to interact with the intelligent transportation infrastructure via standardized interfaces [64], [63].

A promising concept is to collect road usage fees based on vehicle miles traveled (VMT) instead of collecting gas tax. A VMT fee could be categorized according to the emission level (where zero-emission vehicles would pay the lowest fee). Once the VMT system is installed, it can also be used to collect fees for additional communication and energy-related services (e.g., infotainment services or charging services). Evidently, a major question to answer is whether the VMT system should be operated by a public or private agent or in a public/private partnership.

D. Role of Smart Charging

With the development of a smart charging infrastructure, the further expansion of vehicle electrification can be supported. While pure EVs will have their primary markets in urban areas due to range limitations, plug-in hybrids can be utilized in both rural and urban areas. With the introduction of dynamic wireless charging (charging of electrical vehicles that are in motion) and quasi-dynamic charging (charging of electrical vehicles that stop while enroute, e.g., by a traffic light), the range limitation of electrical vehicles can be overcome but the cost of the infrastructure is still being influenced by length of charging lanes and power levels required for energy transmission. As the transportation electrification further develops, it is important to make the right decisions on positioning charging sites. An area of future research might be the introduction of mobile charging sites to react to changes in the demand patterns. In particular, smart parking systems in urban areas need to be developed in order to map the charging needs of EVs with charging capabilities and available parking capacities. As indicated earlier, renewable energy sources in combination with energy storage systems used as a temporary buffer can play a significant role in enabling zero-emission transportation scenarios [66]. Integration of renewable energy sources into the zero-emission transportation energy concept will require the implementation of SG components.

E. M2M System Architectures as Driver of Intelligent Transportation Infrastructure

With the traditional transportation concept, the human–machine interface is essential for the control of a vehicle. In the future, machine-to-machine (M2M) system architectures will turn vehicles more into mobile robots that are able to communicate among each other and with data centers individually or in clusters [67]–[71].

Autonomous and remotely controlled vehicles will play a much bigger role in the future as it can extend road trips significantly in a safe manner and relax critical traffic situations. Furthermore, it is possible to optimize the fuel efficiency of a vehicle by utilizing an autopilot mode similar to an airplane.

If we compare automotive vehicles with cell phones, we can find interesting analogies. First, originally, cell phones were primarily used for voice communication, but now, they are used for a variety of services such as social networking, navigation, e-mail, media streaming, and electronic payment. Voice communication becomes a small part of many available services, Second, automotive vehicles are currently used primarily to drive from A to B. Future transportation services will be bundled in an intelligent manner across multiple transportation modes to minimize traveling time and optimize energy efficiency. Furthermore, drivers and passengers can leverage their transportation time by utilizing all communication services of mobile devices without compromising on either vehicle safety or quality of connectivity.

The automotive industry is following the telecommunication industry in building a variety of services that have a major impact on the lifestyle of the consumer and providing more choices. Transportation is commoditized without compromising individuality; however, the individual needs will be defined more by software and content than by hardware (including the vehicle itself).

The transition of the transportation ecosystem from a primarily class-layered model (public transportation for the masses, and individual transportation with differentiation of the vehicle choice as status symbol) to a service-oriented multimode model suited to everybody's need is largely enabled by the pervasive establishment of information and communication infrastructure where mobile devices and cloud-based services are providing the backbone in managing transportation needs and transportation flows in the most efficient way. Vehicles can be considered mobile communication nodes communicating with fixed ones via a secure intelligent high-performance network.

Data centers and the associated wired and wireless communication infrastructure will become as important as the physical road infrastructure in solving future transportation problems. All payment-related activities that are required during transportation are accomplished wirelessly and without the need of cash or physical credit-card payment. The time and location of refueling vehicles will be optimized by the information network considering the specific energy needs and range constraints of the vehicle (gasoline, alternative fuel, electrical energy, or hydrogen); a multifuel infrastructure will be developed according to the needs of the transportation market.

IV. Travelers

i–Travelers on e–Social Networks: With the development of such a smart transportation ecosystem, the role of the traveler is also changing rapidly. Physical transportation and participation in a virtual collaboration space can be blended without compromising the safety of the traveler. However, keeping the privacy of the traveler regarding his/her travel status and consumption behaviors during travel comes at a price. This can be shared with third parties if the traveler wants to share certain services for free.

A. Traditional Role of the Traveler

Let us first examine the traditional role of the traveler. The traveler is a person who wants to move physically from location A to location B under certain time and cost constraints with the need of a certain amount of space for physical storage. In general, the traveler has to make the decision on whether to use public transportation or personal transportation. In a public transportation system, travel plans are scheduled, and transportation processes are standardized; whereas, personal transportation allows more flexible travel plans and also comes typically with a higher level of convenience (including more freedom with physical storage). Personal transportation requires that at least one of the travelers using a specific transportation vehicle is also a driver, whereas in public transportation, the traveler is always a passenger. In the traditional role, the traveler is disconnected from all forms of real-time communication while traveling.

B. Modern Role of the Traveler

The modern role of the traveler is very different from the traditional one [72]: 1) The modern traveler is expected to be constantly connected with his/her professional and private networks and can respond in real-time if needed; 2) he/she is expected to be highly productive and able to work while traveling; 3) time and cost efficiency have a significantly higher priority than ever in the past; 4) Weather-, traffic-, or environment-related delays of physical travel need to be compensated with technology as much as possible, and new methods of real-time collaboration need to be facilitated if physical presence cannot be achieved in time; and 5) the traveler has access to the latest mobile technologies using multiple state-of-the-art high-performance broadband wireless networks.

The traveler becomes a mobile node that can optimize its movement in a multidimensional space that takes into account the optimal energy, optimal travel time, minimum environmental impact, and optimal data connectivity. There is no doubt that the traveler has to balance among multiple conflicting objectives: 1) Reach the destination in a specific time; 2) keep the travel budget under a certain limit; 3) be compliant to any government rules that come with the utilization of a transportation device; 4) stay connected with key networks while traveling (human beings, data); and 5) minimize risks of self-implied travel delays or travel termination.

The modern traveler has more choices to optimize his/her travel activity according to his/her preferences due to the progress in technological development.

C. New Freedom of the Modern Traveler

The traveler has gained new freedom with respect to communication choices during travel, efficiency of travel itself, and services available during the travel process.

Example (Long-Range Driving): Autonomous driving technology will allow travelers to substantially extend the travel time of individual traveling without compromising the safety level. Autonomous driving laps can also be utilized for working sessions, personal entertainment, or resting/sleeping periods. Even automated refueling stops could be integrated into the autonomous driving sections.

Example (Navigating Through Urban Areas): The traveler can move through an urban area to a defined destination with higher certainty of being there in time while optimizing the resources being involved. Route optimization and automated parking, including automated information of critical collaborators about the status of the travel, will become the norm.

Example (Organizing Breaks and Overnight Stops): Ordering food and beverages at drive-through restaurants from the vehicle in a safe manner, including payment automation or arranging a hotel stay while you are driving, will be significantly simplified. Digital coupons will be automatically identified and can bring down the cost of the travel.

D. Public Versus Private Traveler Information

The modern traveler can count on the seamless integration of services that manage both the physical travel needs and the personal needs. This is enabled by a smart infrastructure that connects the personal information stored in mobile devices and the backend systems with information generated by the transportation systems he/she is using to move from A to B. Some of such information can be shared with trusted parties of his/her social network (private or professional). In emergency situations, some critical information can be shared with first responders. However, information can also be shared with commercial or governmental entities. Protecting the information space of the individual traveler becomes therefore naturally a very important issue. To what degree personal/private information is shared is also the choice of the traveler himself. For example, some services the traveler consumes might be linked to a subscription or transaction fee to protect privacy. Accepting commercials accompanying free services might be a price the traveler has to pay.

V. Systems, Operations, and Services

Cyberspace Counterparts for Each Physical Component: As indicated repeatedly in preceding sections, the integration and interactions of the vehicle, the infrastructure, and the traveler inevitably occur in the cyberspace. Hence, in this section, we will envision the features of the cyberspace counterparts for each of the aforementioned physical components (see also Fig. 2 for the future model).

A. EV Integrated Energy Management System

The penetration of EV makes an impact on the future building energy management and the development of the net-zero energy buildings (NEZB) [73]. Most of the current study of EV charging strategies focuses on nighttime residential charging and valley filling problems for power demand. Meanwhile, the parking-lot charging at commercial buildings would be a

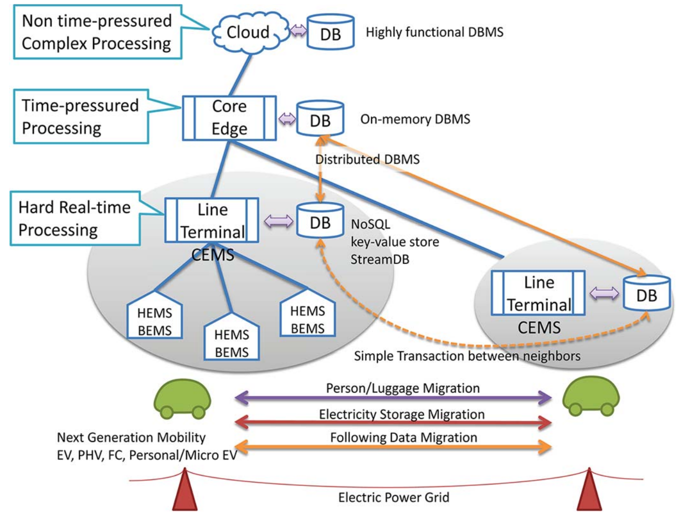

Fig. 2. Future model of systems, operations, and services.

very attractive solution for commuters who would park their EVs at the attached parking lots. For the customers/employees, such possibility can reduce the onboard battery capacity need from round-trip to one-way, which would dramatically improve the payback economy and eventually promote the ramification of EVs. However, it will also bring forth challenges at the distribution level. Building energy management would be (interestingly) more complicated; thus, the daytime power demand for a commercial building will have to incorporate the battery charging. Within the foreseeable future, the limited distribution-level transformer capacity will force a more collaborative optimization between conventional building power usage (e.g., lighting, office equipment, and, particularly, the high-voltage alternating-current systems) and the EV charging. By interfacing the onboard GPS and V2I communication with the existing building control network (e.g., BACNET), provided the existence of necessary cyber security, the scheduling of building energy management will move towards a new level [74]. On the other hand, the parking-lot charging should not merely become a burden of building operation. Under the inevitable trend of NEZB, local renewable/conventional power generation would be dramatically developed. The significant onboard battery storage and the controllable charging process will be a plus for the power quality control and arbitrage, among others, particularly considering the fluctuated renewable power source [75]. The vehicle-borne ITS and communication system, SG and building control system, building information management systems, and even the cooperate enterprise resource planning (ERP) system would be nicely merged for a win-win situation for better vehicle charging, better building operation, and better enterprise in the future [76].

B. Simple Visualization and Simple Operation

Although visualized systems offer much information, most of them have little utility value. A system is required to show not the complicated information but the exactly required information appropriately, which is highly processed and sophisticated. This is also the case in an operation. It is not the essence of home energy management systems to operate all household appliances from terminals or panels, such as a personal digital assistant (PDA). The interface of the remote controller of the air-conditioning machine is an excellent example because it is instinctive and intelligible enough to be used both by a child and an old person. A cooling down button is pressed when it is hot, and the warming up button is pressed when it is cold. HEMS control should follow the same concept. You may turn the control knob of HEMS to the comfortable mode or to the saving mode if you are home alone [38]. EV charging and discharging control is achieved automatically under consideration of tariffs, calendar, and status of power consumption. Namely, the system should carry out the automatic control of air conditioning or the household appliance operation according to the optimized calculation based on abstract indexes, such as charge condition of the battery of an EV, an operation schedule or the usage profile of a household appliance, and the indoor comfort desire. A simple interface to control system and its envisioned complex background computation with clear indexes are indispensable.

C. Integrated ITS and Smart Grid Data Center

When the SG observes a local balance of electric power supply and demand, it should give a command to navigate EV to the optimal battery charger. Hence, the ITS and SG information should be managed together [66], [77]. An EV quick charger should also have both connections of an ITS center for navigation and an SG center for reserving the electricity required in an EV charging. Some EV quick charger may have a battery to achieve very quick charging. The state-of-charge information of this battery becomes useful information for electric power system stabilization. The control of these batteries should consider the local electricity balance and interact with a SG system. The prediction of electricity demand should be conducted by using the information of when and how long the EV is parked and charged, and this information is given by the ITS.

Moreover, another infrastructure management system will be required to achieve precise demand prediction. An air conditioner in an EV has to operate intensively in winter compared in summer. This is because an EV does not have a heat engine, and the difference of temperature between cabin and outside in winter is greater than that in summer. Accordingly, the cruising distance of the EV is shorter in winter. For example, according to the real usage history of an EV in an experimental EV town, an EV that runs 90 km on average in summer reduces its mileage to 60 km on average in winter. It is necessary to calculate the cruising distance correctly by measuring indoor comfort and predicting the outside air temperature. Moreover, by integrating the information of the local electric power grid, the optimal EV charger can be selected and used in navigation not only for the charge cost but also based on the electricity demand and supply. In some situations, the system may recommend the EV driver to reduce the power consumption in air conditioning. In order to build a system for providing such services, it is indispensable to manage the integrated information in ITS, SG, and other infrastructures. The core of the service is the benefit for end users. Appropriate system operation should be accomplished to meet specific requests of EV drivers.

D. Hierarchically Distributed Cloud Service

Unifying the information on both ITS and SG infrastructures may cause the increase in data size. Although it will be possible to manage these big data in a cloud, it may cause the increase in management and calculation costs if all local information is centralized into a cloud and sent back to the local. As a result, it becomes difficult for the current cloud system to facilitate real-time or time-critical services because of the increase in calculation and communication delay. Moreover, privacy management should be considered, particularly in the case of data concentration through cloud service [79]. The Internet and telecommunication infrastructure has a hierarchical structure. For example, the structure of the Internet is composed of xDSL, Wi-Fi infrastructure, and passive optical network of fiber-to-the-home in a local area. The edge area of the structure is a tree, and core area is composed of a mesh network. By using this hierarchy, effective management of time-critical operation and privacy control can be accomplished [78].

At each layer of the hierarchical structure, pertinent information should be handled directly with content-based processing. In this processing, it sends the simplified and abstracted information to a cloud for compression. Simultaneously, it feeds back the control command to the lower layer to accomplish low-latency processing within a local area in critical cases. This real-time processing is enabled by using a distributed cloud system. In the future, such distributed cloud system will integrate the information of ITS and SG. The stabilization of electric power grid typically requires a delay of 10 ms or less. Such hard real-time applications can be attained by the cooperation of distributed cloud services.

E. Content–Centric Communications

SG standards, such as IEEE 1888, use extensive markup language (XML)-based protocol, which becomes popular and is highly desired for the affinity with modern web services because XML-based messages provide flexibility to applications [81], [82]. However, processing complexity is increased compared with the common simple bit-operation-based protocols. In some cases, advanced string manipulation may be needed for the text-based communication, such as XML, and specified embedded hardware is required for processing a lot of character strings at high throughput. On the other hand, this text-based protocol has some clear merits. Message passing communication establishes a communication path between a sender and a receiver with a predetermined purpose. In content-centric communications, an information sender may send it to a cloud service, without limiting the distribution while permitting intermediate observation of the contents. The area of EV information distribution will be typically limited in a town area. HEMS information distribution is generally in the dedicated house. These can be varied by the layer of its hierarchical structure and its target application. In the future, the purpose of the data usage will not be defined beforehand. In other words, if the user who owns the information permits its use in certain applications, the size is varied according to the layer that handles the XML message. While a message ascends to the upstream of the network hierarchy, an appropriate layer inspects the message, and the layer uses the message to solve the problem in an application. As a result, a message-passing system that communicates with a specific purpose, a clear destination, and an initiator address will be generally changed into multipurpose unspecified-target communications by the content-centric strategy. As a result, an open system will be required. The infrastructure, including ITS and SG, becomes a soil to habit unique and useful services continuously, as well as the Internet services by the open system.

Penetration of the text-based protocol requires the advancement in string-processing hardware. A Modern microprocessor has a function of an XML parsing accelerator. As an enhancement of this function, stream-based string-processing accelerator or compression–decompression hardware and wire-rate key-value store management with stream database will be required in the future network traffic. These accelerator devices will be embedded in network modules everywhere [80].

F. From Smart Grid to Smart Community

As described, SG and ITS have particular affinity in providing integrated services. Examples include the meteorological data for obtaining an exact cruising distance, medical data of a driver in an accident, and taxes or cost management information brought by an electric government dedicated to an EV. Since this information is used mainly in a local area, it can be elevated to the concept of smart community. This leads to future city designs and can facilitate many applications on future highway and power demand-supply balancing. Moreover, to achieve effective service of battery sharing and EV sharing, the infrastructure should be unified to support all these services.

VI. Communications

Mobile Information Platform: Interweaving these cyberspace counterparts is the communications backbone. Starting from a brief description of some very unique ITS–SG functionalities envisioned toward achieving the aforementioned objectives, and then based on their particular requirements, we will extract the expected features and trends of the facilitating communication infrastructure.

A. Unique ITS–SG Functionalities

1) Electronic and Automatic Transactions: Traditionally, the only monetary transaction involved in ITS is the electronic toll collection (ETC), where users purchase an in-car ETC device that is uniquely linked to a customer account and communicates with the toll station via dedicated microwave short-range communications [84]. Although ETC has been shown both by research and practice to be beneficial both in saving travel time and to alleviate the bottleneck of manual toll collection, some people still opt not to use the ETC device due to the deep rooted faith in paper-based transactions. This is expected to change drastically in 30 years. In fact, with the frequent charging and discharging activities necessitated by the EVs together with the dynamic electricity pricing, human intervention into each transaction is unrealistic and unbearable to customers. As described in Section V, it is envisioned that the end user only needs to set preference via a largely simplified interface, and then the electricity trading transactions will be automatically optimized and electronically accomplished jointly with route planning.

2) Optimum Routing and Charging: In traditional optimum routing, the decision is usually made based on parameters such as the real-time location, traffic condition, and user preference [85]–[87]. In 30 years, EVs and the SG overall could benefit significantly from the optimization of charging in terms of the charging level and charging site. The latter is clearly intervened with the task of optimum routing. It is even more so in the case of wireless charging along the road. As a result, ORC calls for the joint consideration of the aforementioned ITS parameters with the SG parameters such as load distribution and prediction, dynamic electricity pricing, power balancing concerns, and the actual charging capability of the road. In other words, ITS information and SG information should be managed together and should allow for real-time sharing.

3) Automatic Parking and Electricity Leveling: The main purpose of existing automatic parking in ITS is to save parking time, improve facility utilization, and reduce pollution [88], [89]. Usually, this is achieved by identifying parking slot availability, distributing such information via visualization or electronic dissemination, incorporating such information into the routing algorithm, and even allowing for remote parking slot reservation either manually or automatically. It is envisioned that, by 2050, automatic parking facilities will be equipped with electricity leveling capability to benefit the EV owners, the SG, and the parking facilities. Individual vehicles are too small in an electrical sense, for interactive storage to function autonomously. It take groups of coordinated EVs to effect reasonable control mechanisms at the grid level. In other words, parking in an empty lot may not be very rewarding in terms of the potential electricity leveling incentives. Hence, the location where a particular EV with a certain charging profile should park needs to be optimized in coordination with the actual parking lot utilization, local power system status, user preference, and traffic conditions.

4) ADC: Today's ADC capabilities include mutual impact warning, lane shift assistance, traffic data and risk warning, pre- and postaccident warning, traffic congestion forecast, and emergency vehicle priority [26], [90], [91]. By 2050, fully automatic driving coordination (ADC) will become reality, where the transportation safety, traveling speed, and road utilization efficiency are all expected to improve significantly. These not only rely on much more penetrating real-time communications of neighboring vehicle intentions and the timely availability of the overall traffic condition but also need to account for the status of wireless charging of certain vehicles as the latter may not allow for flexible and swift lane shifting or speed alteration, etc.

5) Connected Travelers: Last but not least, once the travelers are relieved from the tiring tasks of maintaining safety, selecting route, making charging decisions, etc., they will be willing to and should be able to work productively while traveling. With the explosively growing cloud-based productivity services, the travelers will need to be constantly connected with his or her professional and private networks, and be responsive in real time if needed.

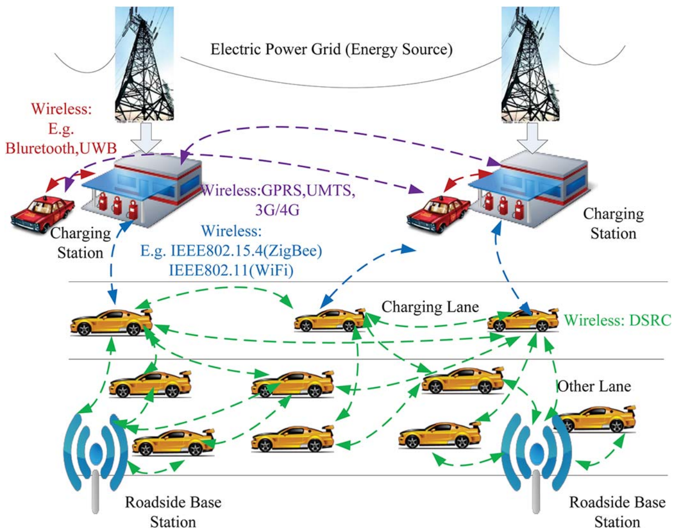

Fig. 3. Example of the highly heterogeneous communications architecture.

B. ITS–SG Communication Infrastructure

In order to meet the aforementioned ITS–SG objectives, the communication and networking infrastructure supporting the ITS–SG integration with various unique functionalities is expected to have the following key features: highly heterogeneous architecture, hierarchically distributed QoS-oriented routing protocols, high-mobility high-fidelity connections, and extensive information sharing among multiple entities.

1) Highly Heterogeneous Architecture: As stated above, the communication and networking infrastructure needs to support a broad array of services. All these call for communication services at various granularity, reliability, bandwidth, and latency. Based on the physical laws governing the frequency versus distance, bandwidth versus data rate, and user number versus latency, it is doubtful that, by 2050, one ubiquitous and universal wired or wireless technology will be capable of supporting all these needs simultaneously (see also Fig. 3 for an example of a highly heterogeneous architecture).

It is henceforth envisioned that heterogeneous communication technologies are required to meet the diverse needs of such a complex system integrating SG and ITS [83], [92]. Many of such technologies are already in place today. For example, short-range wireless technology similar to Bluetooth or ultrawideband could be used for the communication between parked vehicles or power grid interface and charging stations, IEEE802.15.4 (ZigBee) and IEEE 802.11 (WiFi) could be used for communication between low speed vehicles and charging stations in the form of local area networks, dedicated short range communication (DSRC) can facilitate high-speed vehicle-to-vehicle or V2I communications, and cellular wireless (e.g., General Packet Radio Service, Universal Mobile Telecommunications System, third/fourth-generation technologies) may be used for the communication of vehicle–grid or among charging stations [93]–[100], [110]–[112]. By 2050, more advanced versions of these technologies with improved data rate and multiaccess capacity, powernperformance tradeoffs, and even energy scavenging capability are expected to be available.

In addition, the integration of ITS and SG via EVs and the charging infrastructure provide new venues for communications [101]. For example, at charging stations, parking lots, or home garages, the EVs will often be connected to a charging interface that leads to the power grid. Information exchange can then take place via the media of the power line [102]. Today, the field of power-line communications is already starting to receive attention from various academic and industrial sectors [103]. The inevitable integration and interaction with the SG will undoubtedly bring such research and development to a whole new level. Another yet to be investigated communication medium is the wireless charging interface [104]. As the vehicles are to be charged wirelessly on the road, such well-secured and relatively long-term connection can potentially be exploited for simultaneous data access. Both technologies have the potential to resolve some challenging issues the ITS is facing. For instance, precise localization in a parking garage often requires extra hardware and careful calibration. An EV-capable parking garage could easily solve this problem by mapping charging interfaces with physical parking slots. Lane tracking is another touchy issue in ADC. Roads equipped with wireless charging capabilities can help resolve this issue by incorporating the necessary tracking and correcting functionality in the wireless charging link to the EVs [34], [104], [116], [118], [119].

With all these evolutionary and revolutionary communication technologies available by 2050, interoperability becomes one of the most essential issue for the communication infrastructure supporting the integration of SG and ITS. In fact, it may likely be that, instead of the development of any specific communication technology, the bottleneck of an enabling communication platform will be the interoperability agreement and compatible interface hardware and packet formats that can seamlessly bridge the different standards of various communication technologies. To this end, generic application programming interfaces (APIs) and middleware will also play critical roles [105].

2) High–Mobility High Fidelity: By 2050, highly or fully ADC is expected to bring the transportation safety, travel speed, and road utilization efficiency to a whole new level. The high mobility and high density of EVs raise challenges that are unprecedented in the history of terrestrial wireless communications. It is well understood that high mobility will lead to nonnegligible Doppler shift. In a broadband high-data-rate communication system, which is a must for the always-connected travelers, such effect becomes Doppler spread that consists of one main cause of channel variation. When the surrounding environment is packed with other EVs made of metallic materials and at comparable speed, the time variation of the wireless communication channel will be further accompanied with significant multipath propagation. All these render the wireless communication conditions very reminiscent to one of the most challenging environments, namely the underwater acoustic communication environment [106]. As regular ADC and electronic and automatic transactions are becoming necessities for EVs, high fidelity of the transmitted and received information also has to be guaranteed for both physical safety and cyber-security concerns. Hence, it is expected that research and development of these high-mobility high-fidelity communication technologies will be taken jointly with, and benefit from, the nontraditional technologies such as wireless charging.

3) Extensive Information Sharing: All aforementioned ITS–SG functionalities entail extensive information sharing through a highly heterogeneous communication network. This makes content-centric or content-aware communication a very attractive solution. Such content awareness is also expected to penetrate both the selection of communication technology based on the reliability and latency concerns, and the determination of routing protocol based on the QoS consideration.

In many occasions, information exchange not only occurs at the interface between ITS and SG, after they each collect the corresponding information from the EVs, but also may occur among EVs to facilitate, e.g., ADC functionalities or even electricity loaning activities under special circumstances. With content-centric communications, there may be an elevated risk of leaking critical private or secure information and rendering the pertinent EVs and/or their drivers vulnerable against various levels of privacy/security attacks [107]. This is even more so particularly when information exchange occurs among EVs that are within each other's geographical proximity, which is often the case than not.

At the individual level, EVs and their drivers are to be protected from financial or physical attacks. At the ITS and SG system level, highly sufficient authentication is a must since both systems can potentially pose drastic safety risks to the entire society if inappropriately manipulated [106], [109]. Fortunately, the recent popularity of smart meters has already raised a lot of interests from various government, academic, and industrial sectors [110], [113]. Although many solutions have been proposed to date for the security and privacy issues related to smart meters, these are far from sufficient in solving similar problems in the integrated ITS–SG with EVs. The main issues are: 1) smart meters are fixed, whereas EVs are highly mobile; and 2) smart meters are designated to a handful of functions, whereas EVs will be involved in a lot more different ones spanning the entire gamut from personnel safety, financial security, and all the way to societal safety and stability. By 2050, we are expecting some paradigm-shifting advancement in this field to devise security-ensuring mechanisms that facilitate all aforementioned ITS–SG functionalities with enormous scale and highly mobile-networked entities.

VII. Social, Economic, and Political

Open and Fair Societies: There is never a stand-alone technological world. On the one hand, the development of technology at this scale will undoubtedly impact the society [114]. On the other hand, the envisioned technological transformation would not be possible if not strongly backed by the societal needs and empowered by business models deeply rooted in the society. In this section, these societal perspectives will be analyzed and discussed from three aspects.

A. Sustainable Electrified Transportation Pathway

The vision for 2030 includes a sustainable electrified transportation pathway that incorporates renewable energy generation. The transportation pathway originates from offshore energy sources such as wind, wave, and/or tidal, and ends at EV charging stations. Adoption and proliferation of electrified transportation is contingent upon availability of charging stations [115]. Meeting energy sustainability and security significantly depends on the energy storage capacity of charging stations. The sustainable transportation infrastructure in 2030 will have suitable technologies that provide for electrical energy production from renewable sources along with both bulk and distributed storage capabilities [116]. The sustainable pathway thus envisioned is shown in Fig. 4.

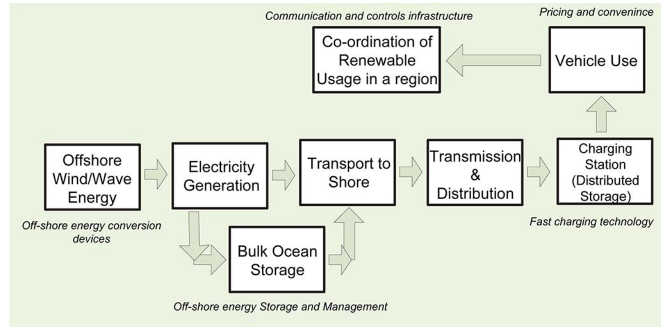

Fig. 4. Sustainable transportation pathway with offshore energy extraction.

The enhancements of various types of bulk energy storage are required to overcome the challenges of variability in renewables. Renewable energy generation plants are not typically located close to population centers. The availability of bulk energy storage mechanisms is essential for successful integration of renewable energy sources. The bulk storage technology can be either high-energy-density batteries or compressed hydrogen or compressed air. The bulk storage can be either offshore or land based. The concept of secondary battery usage is also expected to be prevalent in 2030. Secondary batteries are those that ran their life in an EV but still have significant life for use in stationary storage facilities. As plug-in vehicles continue to gain market share, concerns about battery recycling or disposal have become increasingly important. Since batteries are designed to last the life of the vehicle, there may be substantial residual battery life remaining at the end of the vehicle life. The battery performance requirements in a vehicle are significantly more stringent than in stationary applications. Therefore, there is the opportunity for a secondary use for these batteries to support the power grid so that their useful life is extended and costly recycling is deferred. This secondary battery usage will enable greater electric service reliability, better power quality, and higher penetration levels of renewable generation such as wind, solar, and ocean waves.

The distributed storage in the charging stations will interface with customers and facilitate power exchange between vehicles and the station. In comparison to utility-scale energy storage, charging station storage has the advantage of being closer to the point of use, thus improving efficiency and alleviating local distribution bottlenecks. The combined capacity of numerous charging stations, when controlled in concert as a fleet, parallels the capacity of utility-scale energy storage.

Conventional EVs that can only be charged while being stationary limit their functionality, raise infrastructure demands (requiring more charging stations, for example), and increase battery size and cost. If the EV is designed for a longer range, vehicle efficiency is reduced due to the added weight of the energy storage unit. Currently, two methods have been proposed to extend the vehicle range: vehicle hybridization with an ICE and battery swapping. Hybridization increases the vehicle weight, cost, and complexity, in addition to introducing the use of hydrocarbons. On the other hand, with battery swapping, there are logistical problems, question of battery ownership and standardization, the cost of the additional batteries (which is the most expensive component in the vehicle), and significant swapping infrastructure cost.

Vehicles enabled with power exchange between the vehicle and the grid while the vehicle is moving would draw power from the grid as they move, and not just when they are stationary. These vehicles are called roadway-powered EVs [113]. The benefits are substantially simpler and lighter vehicle designs and all-electric propulsion with a much smaller battery investment. For roadway vehicles, it is not possible to transmit power using contact systems since roadway vehicles do not move along a predetermined path; a dynamic wireless charging infrastructure is required. A noncontact or wireless power transfer for both stationary and roadway vehicle charging is going to bring a change in the social behavior in the not so distant future [119]–[121].

The charging infrastructure envisioned will allow both stationary and roadway vehicle charging through wireless chargers that would cater to the societal need of convenient charging during off peak and at a charging station at reduced rates, and fast charging on the roadway available at a premium, respectively. The vision allows simultaneous optimization of both the cyber and the physical sides where the communications and control side will include physical/electrical constraints and state variables. The physical and cyber aspects of the electrified transportation pathway will need to be jointly formulated, logically integrated, and jointly optimized and controlled. The queuing and inventory models for vehicle distribution (routing) policies, control algorithms, and scheduling techniques already started to emerge and will become mature by 2030 [122]. The cyber–physical resource allocation involving pricing and incentive signals will have a joint energy and communication utility function in the future. Vehicles will receive navigation signals based on the conditions of the grid, and incentives will be designed to ease grid congestion. Drivers will have the option of accepting or declining the rewards based on their personal preferences.

B. Societal Implications

The electrified transportation pathway will require broad societal adaptation to this sustainable provision of energy for vehicles (see Fig. 5). While the image of driving home in a vehicle charging lane seems highly futuristic, the engineering solutions are emerging, and positive signs of social acceptance are visible for such a system in 2030. Research, education, and outreach must continue at an accelerated pace for the vision to become reality. Early adaptation may be incremental due to the initial cost of renewable energy and wireless fast charging. However, costs will fall with broader adaptation of renewables,

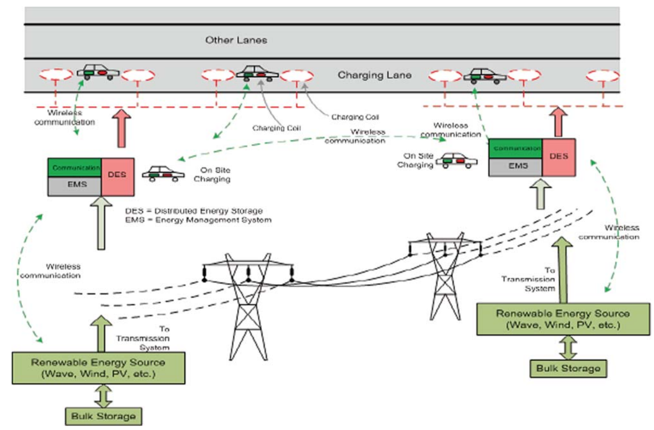

Fig. 5. Sustainable electrified transportation pathway with communications and control.

innovations in the renewable energy, and transportation sector and societal acceptance.

The charging station infrastructure and interface with the consumer is a critical societal aspect of electrified transportation. The density of stations and the price of charging at these stations, whether stationary or roadway, will dictate the social acceptance of electrified transportation in the future. A dense network of fast-charging stations acts to increase the range of an EV by allowing charges at any time and any location, The critical societal factor will be the household's willingness to pay (WTP) for convenient charging, which includes increased density of stations, fast charging and roadway charging, and the portion of renewable content. The WTP will vary widely among different societies in different cities around the world. The average driving distance to work among the cities will dictate the charging infrastructure in a particular city. While roadway charging stations will be more prevalent in cities with longer daily commutes, home overnight charging will be sufficient in smaller cities. Roadway charging stations are essential in the highway systems for an acceptable electrified transportation pathway.

C. Evolution From Smart Grid to Smart City and Its Service

The electrified transportation system is going to be an integral part of the Smart City in the future. Although clear definition of Smart City has not yet been established, the paper published from VU Universiteit Amsterdam in 2009 says that the Smart City is a concept for improving quality of life of the citizens by using the human resources infrastructure, social capital, and traditional infrastructures in addition to the investment in information and communication technology (ICT) infrastructure. The SG in which electrified transportation is an essential technology is also based on ICT [123], [124]. In the sophistication processes of the various infrastructures, the fusion of information technologies is essential. The definition of Smart City can be narrowed down to the synergy of sophisticated water supply and sewerage, gas, electric power, building structures, medical, and other infrastructures based on ICT.

In a variety of infrastructures for daily living, the smarter process is being established. The improvement of traffic congestion and its safety by ITS have been achieved. In the future, efficient use of distributed electric power generation, including

EV quick-charging infrastructure associated with the spread of EVs will be established through the analysis and optimization of these devices for grid stability and power demand control by the charging and discharging of the EV batteries. This is known as the V2G technology. EV personal mobility is expected to provide a senior-friendly society, addressing the problems associated with aging.

The smart next-generation infrastructure is a business platform with an open architecture for third-party applications. That is, the business ecosystem is no longer closed with limited players. Instead, many of the various service providers participate. Unlike the period of high economic growth, consumer demands in the 21st century are more diversified, and even infrastructure services, including water supply and sewerage, gas, and electric power will not be able to stand alone but should build a larger and open business ecosystem with various service providers which may satisfy those demands. With the standardized SG technologies and ICT, infrastructure works as a platform, EV as a terminal, and various third-party applications as service providers taking advantage of data obtained in the infrastructure. In addition to well-rounded creativity, different business models on each third party are required to satisfy various and fine-grain demands in a mature society.

The most important and required technological innovation in the ICT area is to develop the platform and protocols to transform existing infrastructure services into an open service platform. The challenge is to develop a common API to access data obtained by those infrastructure services. In addition, Internet of Things and M2M (machine to machine or machine to management) are technologies in the spotlight because they make it possible to connect every device to each other and to express the real objects in the real world.

SG is on the edge of the tide to realize the new society for providing unprecedented services by integrating the separated infrastructures, services, and systems and by transforming the generated data into contents. This has the power to change every citizen's lifestyle and soils transformation and flexibility to companies or organizations.

VIII. Conclusion

In this paper, multiple authors analyzed in different views their SG vision for vehicle technology assuming a time horizon of at least 2030. Reflecting all sections in context, we can see that the domain of ITS and SG will converge, while providing new opportunities to build an electrified transportation ecosystem. A key aspect dictating whether the projected scenarios actually become true is whether significant progress will be made in the battery and charging technology and the related economics. The information and communication technologies will further develop and are a key enabler to empower the converged infrastructures as well as the smart vehicles. In order to finance the transportation infrastructure improvements, new business models are also essential.

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