Construction of the renewable energy eco-system: strategic distributions along the chain of “photovoltaics-energy storage-electric vehicles”

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Abstract. The “photovoltaics (PV)-energy storage system-electric vehicles (EV)” industry is taken as an instance in this paper to depict the blueprint of the renewable energy eco-system: (1) As the headstream of the whole industry chain, clean energy source is first discussed. Taking full advantage of low cost in the photovoltaic lifetime, the highway PV plant is supposed to be a promising, cheap power supply for new energy vehicles, and to conducive to less traditional energy consumption and carbon emission. (2) Two-level energy storage systems, including power-grid energy storage and customer-side energy storage, would be established by developing novel energy-storage devices, high-capacity materials of EV batteries and standardization of battery manufacturing. Also, with the aid of “internet of things (IOT)”, a network of monitoring, maintenance, recycling and echelon utilization will be established to cover the EV batteries’ whole life. (3) As for the new energy vehicles, novel manufacturing standards will be formulated including modular design and production. Instead of the integrated battery modules, the exchanging mode will be applied to vehicle batteries, accompanying with the construction of the gas-station-like battery supply network, which provides power access and battery charging/exchanging/maintenance. In addition, it is also briefly described that hydrogen evolves from water electrolysis by utilizing surplus photovoltaic and wind power and serves as a significant supplement of the present electricity-dominant renewable energy industry. An ecology is hopefully formed through synergetically developing renewable energy supply, storage and applications in the following years. Thereafter, the energy consumption will be thoroughly changed via the construction of a fossil-fuel-independent new energy eco-system, supported mainly by renewable energy sources.

1. Introduction
Along with human’s civilization, science and technology proceeding, the world energy supply has undergone twice revolution with substitution of coal for fuelwood and oil for coal, and is on the way from fossil fuels to renewable energy sources by force of energy crisis and environmental pollution. However, new challenges emerge at the same time as the expansion of the new energy industry, especially in the EV industry.

With the aid of policies [1], capital and market demands, the basic framework of the new energy industry has already been constructed in the field of EVs, consisting of three sections: renewable energy supply, energy storage and renewable energy application. Nevertheless, a well-established new energy eco-system as well as a more complete layout is urgently required in EV industries to break the
constrains of synergetic development issues, such as the high cost of electricity supply from renewable sources, low energy density of EV batteries and absence of unified EV standards.

Following the energy flow, problems are identified throughout the renewable energy industry [2]: (1) as for the energy source, large amount of solar/wind/water power is discarding due to their unstable supply, geographically uneven distribution and difficult transmission, although renewable energy only accounts for a small proportion in the current energy supply structure; (2) in the aspect of energy storage, lack of technologies for large-scale energy storage accounts for solar/wind/water power discarding, and the capacity and the efficiency of power batteries are far from the market demands and limit the wide spread use of EVs; (3) thus, in the application market, thermal power from coal donates more than 70 % electricity consumption, and the goal of CO₂ emission reduction is not achieved yet; fuel vehicles still dominate the automobile industry because of EVs’ short duration and slow charging, and petroleum import rate exceeds 70 % in China, which threat the natural environment and national energy security.

In the view of aforementioned problems, herein is proposed the industry chain of “highway photovoltaics—energy storage—electric vehicles” as an instance to describe construction of a well-established eco-system of renewable energy: the new energy supply/transmission issues for EVs can be solved via building highway photovoltaic power stations, and predicaments in the energy-storage segment will be overcome through development of high-capacity batteries or other energy storage devices, while a breakthrough in the wide range of EV application is anticipated by implementing standardization and modularization of EV manufacture and promoting battery-exchanging modes.

2. Electricity from renewable energy source

In terms of renewable energy supply, besides traditional hydropower, solar and wind power exhibits the most rapid development. Owing to the continuous technological advancement and scale expansion of China’s polysilicon industry, the cost of photovoltaic power is remarkably reduced by 92 %, 87.5 % and 82 %, respectively, in terms of the prices of PV modules, PV systems and PV electricity. In addition, the average CO₂ emission in PV lifecycle is only 49 g kWh⁻¹, much less than that of the thermal power 1000 g kWh⁻¹. Therefore, the low-cost and environment-friendly advantages enable PV to be the largest source of electricity in the future, as shown in figure 1. What’s more, PV generates direct current (DC), which can be used to propel EVs directly and reduce the EVs’ usage charges significantly. Howbeit, the present PV electricity has to be converted as alternating current (AC) via inverters before transmitting to customers because of the geographic disadvantages of PV power plants, which are usually far away from habitations, and the AC electric power is rectified to DC at EV charging stations. The PV power supply becomes so complicated after twice transformations between DC and AC and long-distance transmission that not only energy loss but also investment is greatly increased. The consequence is a rise of over 55 % in PV electricity cost, which assigns a minus point to the renewable industry.

![Figure 1. The tendency in the variation of global energy structure.](image-url)
2.1. Exploration for solution of PV land predicament
The majority of commercial PV modules are made of silicon cell wafers, whose highest conversion efficiency of solar energy is only around 24% [3], so the total area of module installation must be big enough to ensure sufficient electricity output, and the land use for PV plants turns into a tricky problem. Consequently, new schemes of distributed PV stations are put forward to make full use of the highway utilities and two of them have been carried out. The first one aims to utilize the non-functional areas along highways (including the greenbelts, median strips, service area roofs, car sheds and so on) for PV cell installation [4]. But, the installation area is still not big enough and the power generation can never satisfy the EVs’ demand anyhow. The second trial is carried out by paving a PV road surface on the expressway. In spite of experiment implementation, it is already proved to be a complete failure because of the extremely high cost just with regards to the PV modules, which require abrasion-resistant high-strength materials and specially designed roadbeds. Simultaneously, those wearing-resisting protective layers greatly reduce the light exposure intensity of PV cells, and the calculated conversion efficiency is merely 5.06% [5], which would be much smaller when the traffic flow is high. Other than the low ratio between conversion efficiency and construction cost, maintenance fees would be unimaginably high due to the fast deterioration of pavements.

2.2. A practical highway PV scheme
Learning lessons from the foregoing failures, a more practical scheme is proposed, overhead highway PV stations, as illustrated in figure 2. We conceive of taking full advantage of the overhead space and settling PV modules on those stilts along the express way. Except for installation height, overhead highway PV stations have nothing different from the traditional PV plants, so almost every parts of the current PV power plants can be transferred to our proposal, including modules, installation procedures, light tracing technology and maintaining & recycling systems, which guarantee effective control of construction/operation/maintenance investment. Furthermore, massive DC electrical power output can be achieved since complete PV coverage can be easily realized along the motorways except for some tunnel regions. And we can even anticipate more potential improvements based on the highway PV infrastructures such as inductive wireless charging devices for EVs in the future.

2.3. Supply capacity of highway PV
In order to clarify the feasibility of the overhead highway PV, its power supply capacity in Henan province is estimated as follows. Taking the 4-lane highway with a 24 m wide roadbed as an example, 1/3 coverage of PV modules is adopted to ensure enough light shedding on the road. Considering the variation of daylight time and sunshine intensity with weather and seasons, those PV cells work equivalently at least 1100 h (apart from the maintenance time) per year at full capacity (0.1 kW m⁻²). In Henan province, the total motorway length is over 7300 km, and then more than $6.43 \times 10^9$ kWh electrical power can be harvested from the highway PV facilities.

In order to be more intuitionistic, such a big number is interpreted in another way as follows. The electricity consumption of one Tesla EV is 18 kWh per hundred kilometres and it travels 20 thousand kilometres per year, then electrical power generated by highway PV stations in Henan can satisfy energy demands of 1.78 million Tesla EVs, which means around 13% of fuel vehicles can be replaced by EVs, given the present car ownership of 13.27 million in Henan. In addition, the PV electricity charge can be
as low as 0.6 ¥ kWh⁻¹ as a result of no DC-AC conversion and no long-distance transmission. Then, the payment for energy consumption of one Tesla EV per year is as low as 1200 ¥, less than 10 % of that of the fuel vehicle (15000 ¥, given an average gasoline consumption of 10 L per hundred kilometers). Besides highways, more PV facilities can also be installed along ordinary roads to enhance PV’s contributions in EV applications.

3. Energy storage

Despite the rapid PV expansion benefiting from fast development of the polysilicon industry, the intrinsic randomness and intermittence of energy supply hampers its further applications [6]. Therefore, energy-storage devices need to be added between PV and energy-consumption terminals. As the key connection between energy source and consumers, energy-storage systems not only play vital roles in electricity peak cutting but also act as the buffer to neutralize the shock from the unstable power supply [7]. According to the difference of scales and transportability, energy-storage systems are divided into power-grid energy storage and customer-side energy storage.

3.1. Power-grid energy storage

The basic duty of power-grid energy storage systems is to balance the temporal and spatial uneven distribution of energy supply by storing it in certain media during the summit of power generation while releasing it during the surge in electricity demand. Thus, such an energy storage system shall satisfy the following qualifications [8]: (1) high gravimetric/volumetric specific capacity to store as much energy as possible; (2) flexible tenability to release energy in accordance with users’ demands; (3) high efficiency to save the driving force or energy dissipation during charging and discharging with maximum rates; (4) high reliability and low cost to preserve the economy of large-scale applications.

3.1.1. Flow batteries

Among a variety of grid-level energy storage options, the flow battery is one of the most promising schemes on account of its energy-power-independent properties, high safety and long lifetime. And its fast charging/discharging rate satisfies high-power input/output demands in practical application scenarios, since the charge transfer only happens at the electrode-electrolyte interfaces and there is no tardy charge migration within a solid medium. Furthermore, the all-vanadium flow battery, storing/releasing energy through the variation of vanadium ions’ valences, possesses a unique ability of valence balance to prevent the electrolyte degradation, so it would be a preferential option with long durability, high security and low cost for grid energy storage.

![Figure 3. Schematic of an all-vanadium redox flow battery [9].](image-url)
3.1.2. Liquid-metal batteries

Very similar with the flow battery, another potential solution of grid energy storage emerges as the liquid-metal battery, whose anodic and cathodic liquid metals are separated by a certain molten salt according the density difference between the working media, so there is no complex separator inside the cell, as shown in figure 5. Such a simple structure guarantees high operation stability and long cycle life and endues the liquid-metal battery with excellent reliability and easy industrial magnification. The degradation rate of the liquid-metal battery is so slow that the capacity retains 99 % after 10-year operation with 1 charging-discharging cycle every day. And one practical liquid-metal battery has been developed with the capacity of 1000 kWh, the charging/discharging power of 350 kW, the total weight and volume of 15 t and 18 m³, respectively [10,11]. Currently, the only disadvantage lies in additional energy consumption to maintain the high temperature and the molten state of working media, and a room-temperature technology would enable liquid batteries to possess superiorities competing with flow batteries in the future.

![Figure 4. Cell schematic of Li | Sb-Pb liquid metal battery [12].](image)

3.1.3. Secondary utilization of EV batteries

Besides development of new energy-storage systems, secondary utilization of EV power batteries offers another energy-storage route. The expansion of EV industries results in more and more retired power batteries with a 60-80 % residual capacity [13], which can be classified and applied to domestic energy storage, standby power source of base stations and microgrid systems etc., in the aftermath of performance diagnosis and safety estimation [14]. Echelon use provides a solution for environment pollutions from EV batteries, and there is no usage cost because the retired batteries are usually free.

3.1.4. Customer-side energy storage

EV, as the most important application terminal of renewable energy discussed herein, is one of the focuses in both scientific and industrial researches. Great efforts are made to break the bottlenecks in performance, price and production capacity of EV batteries [15]. Due to the superiority of high energy density, lithium ion batteries (LIBs) dominate the on-board battery industry, wherein the battery materials play decisive roles in performances of specific capacity, working voltages, cycling life and security. Poor physicochemical properties of materials account for those battery issues of limited capacity, big volume, heavy weight, slow charging and short durability. Additionally, the lagging standardization of power batteries leads to uncontrollable stability and uniformity. Thus, the development of power batteries in future will aim at large capacity, long lifetime and high standardization.

In order to break through the mentioned limitations, a roadmap of power batteries within next 10 year has been formulated in China. By synchronously investigating novel battery materials, management
& control technology, echelon utilization and materials recycling, large-scale standardized production of high-performance EV batteries is planned to be implemented gradually, which helps to achieve the energy density goals of 350, 400, 500 Wh kg\(^{-1}\) until 2020, 2025, 2030, successively, as listed in Table 1. However, Chinese government removed the index of 350 Wh kg\(^{-1}\) last year since the research progress is severely delayed in contrast to the expectation.

### Table 1. Target specifications of EV batteries in China

| Year   | 2020 | 2025 | 2030 |
|--------|------|------|------|
| Energy density (Wh kg\(^{-1}\)) | 350  | 400  | 500  |
| Cycle number | 4000 | 4500 | 5000 |
| Cost (¥ Wh\(^{-1}\)) | 1.0  | 0.8  | 0.6  |

3.2. Battery materials
Among the major materials of LIBs, the cost of anode, cathode, electrolyte and separator accounts for approximate 40 %. And technical breakthroughs are especially needed in anode and cathode materials, which are lithium-storage and capacity-decisive media in LIBs. Currently, the commercial graphite anodes exhibit the highest capacity of 370 mAh g\(^{-1}\), extremely close to the theoretical value of 372 mAh g\(^{-1}\) [16], hence novel anode materials with higher capacity are in urgent need. At room temperature, silicon can react with lithium forming Li\(_{11}\)Si\(_4\) alloy, whose theoretical gravimetric capacity is 3572 mAh g\(^{-1}\) [16], nearly 10 times as that of graphite, and it is widely recognized as the candidate for next generation of anodes. In future, more efforts will be made in developing new technologies like nanosizing and compounding for performance improvement in charging-discharging rate and cycling lifetime and thus promoting the large-scale commercialization of silicon anodes.

### Table 2. Comparison between graphite and silicon anode materials of lithium ion batteries [16]

| Anode materials | Lithiated phase | Theoretical specific capacity (mAh g\(^{-1}\)) | Cost (¥ kg\(^{-1}\)) |
|-----------------|-----------------|---------------------------------------------|---------------------|
| Graphite        | Li\(_6\)C       | 372                                        | 20-50               |
| Silicon         | Li\(_{11}\)Si\(_4\) (RT) | 3572                                    | 80-100              |
|                 | Li\(_{22}\)Si\(_5\) (HT) | 4212                                    |                     |

Notes: (1) RT— room temperature, HT— high temperature; (2) The specific capacity of commercial graphite materials already reaches 370 mAh g\(^{-1}\), close to the theoretical capacity; (3) Silicon anodes suffer from severe volume change (more than 300 %), leading to fast degradation of mechanical and electrochemical performances.

Similarly, the cathodic materials are also faced with problems of limited performances. For a long time, the cathodes of EV batteries are mainly based on LiFePO\(_4\) due to its high stability and security, but the sustainable increasing demands in energy density and power density impel the advent of ternary materials (LiNi\(_{1-x-y}\)Co\(_x\)Mn\(_y\)O\(_2\)), which combine the high capacity of Co- and Ni-based cathodes and the safety of Mn-base cathodes. Except the superior specific energy and power than LiFePO\(_4\), ternary cathode materials have a moderate cycling number as well as low toxicity and price compared with its LiMn\(_2\)O\(_4\) and LiCO\(_2\) counterparts, benefiting from the synergy of Ni, Co, Mn elements [17,18]. Ternary-cathode batteries will be the general trend in the EV market, and the key issue is how to raise the dosage of Ni to achieve the highest capacity under the prerequisite of safe operations.

### Table 3. Properties of different cathode materials [17,18]

| Parameters                        | LiMn\(_2\)O\(_4\) | LiFePO\(_4\) | LiNi\(_{1-x-y}\)Co\(_x\)Mn\(_y\)O\(_2\) | LiCO\(_2\) |
|-----------------------------------|------------------|--------------|--------------------------------------|------------|
| Theoretical gravimetric capacity (mAh g\(^{-1}\)) | 148       | 170          | 280                                  | 274        |
| The highest actual capacity (mAh g\(^{-1}\))    | 120      | 160          | 150                                  | 155        |
| Average discharge voltage (V)     | 3.70   | 3.20          | 3.60                                  | 3.7        |
| Cycling number                     | ≥300   | ≥1500         | ≥600                                  | ≥300       |
| Price (10\(^4\) ¥ t\(^{-1}\))    | 5-6   | 15-18         | 16-20                                 | 18-20      |
3.2.1. Standardization of EV batteries
A lot of attention is paid to the development of novel materials, while what is equally important but usually overlooked is the battery standards [19]. Non-uniform specifications of cell units become one of the main obstacles between EV manufacturers and battery producers, and significantly slow down the expansion rate of EV battery industries. Difficulty lies in the module assembly, which is traditionally accomplished by welding processes. Shortages of the welding assembly have been identified that the welding equipment and operations require high investment, the induced surface protuberance and internal pores would threaten the battery safety, and the integrated modules are difficult to be recycled. Modularization assembly techniques are thereupon put forward, such as the pressure connection method to fast assemble and disassemble modules. Test results from Original Equipment Manufacture (OME) indicate that the new assembly method not only requires much shorter operation time but also has comparable assembly density, reliability and stability compared with the welding method. Moreover, this pressure connection can turn the fixed-capacity batteries into variable-capacity products containing a series of standardized modules, which provide battery suppliers and EV manufacturers a simple and cheap technique to efficiently produce EV batteries with any capacity demanded by the clients, and also reduce the risks during market validation of the new assembly method.

![Figure 5](image1.png)

**Figure 5.** Illustration of the pressure connection method for battery module assembly [20].

3.3. EV battery management
Advanced materials and reasonable standards render batteries excellent properties, while the battery management system (BMS) is the key factor to bring those properties into full play to achieve the best performance in practical operations [21]. With the support from IOT, we suppose to set up a fully interconnected intelligent management system, covering the whole lifetime of EV batteries “registration-charging/usage record-maintenance record-recycling/scrapping treatment” and monitoring electricity output, energy storage and security state in real time [22]. With the assistance of artificial intelligence and big data analysis, the BMS can predicate the potential risks to prevent serious accidents like battery self-ignition, and prejudge the rest lifetime for manufacturers to make appropriate recycling plans in advance.

![Figure 6](image2.png)

**Figure 6.** Framework of the battery management system [23]
4. Electric vehicles
Durability is the most concerned issue for EVs, which depends on both battery capacity and electricity replenishment. Due to the lack of charging stations and fast charging technologies [24], long-distance travelling would not be realized even if the energy density of EV batteries can be elevated to over 500 Wh kg\(^{-1}\) as expected. For the time being, the charging rate of EVs is still not comparable with the refueling of gasoline vehicles, and it is too slow to match the rapid development of EV industries [19]. There seems no possibility to replace fuel vehicles by EVs in the present EV recharging mode [25]. However, the successful operation mode of fuel vehicle industries offers us alternative solutions. One inspiration from the fuel vehicle industry is its widespread fuel supply network and gasoline stations. Similarly, charging stations should also be widely constructed to support the EV industry, but unlike direct charging therein, a battery exchanging/swapping mode (BEM/BSM) is adopted, wherein charged batteries are just substituted for discharged ones unloaded from EVs.

4.1. Standardization of EVs
The premise of battery exchanging is standardized power batteries and intelligent management [26]. Only with unified battery sizes, shapes and other specifications, the exchanging servicers can provide EV clients with authenticated batteries from any manufacturer. Assuredly, the BEM also requires standardization of vehicle manufacturing, including vehicle design modularization and battery module standardization (uniform installation position & charging port and standard loading/unloading procedure), in order to form a unified procedure for automatic battery exchanging operations. In addition, a set of communication protocols and interfaces is necessary to be added into the vehicle management system for data transmission with the battery management system, providing BEM servicers with basic information for battery charging and maintenance.

4.2. Business mode of battery exchanging
The EV battery exchanging mode is not just limited to engage in the running of the exchanging stations, but involves at least four aspects: EV manufacturers, battery suppliers, BEM servicers and EV users, who play their own roles in EV production & sale, battery supply, battery charging/rent/exchanging/maintenance & construction of exchanging station network, and EV use in the industry chain, respectively. Obviously, the battery exchanging service providers lies in the core position herein. However, the reality is that EV manufacturers are more active to test the BEM. Besides Pand (a ride-hailing servicer), Tesla, Baic and Chery already begin to provide battery exchanging service in some big cities. Once the BEM is approved comparable to the fuel vehicle mode in terms of efficiency and economy, a set of standardized battery exchanging network will be soon established to carry out overall planning and scheduling from electricity generation to consumption.

5. Hydrogen energy
In the field renewable energy, what has to be mentioned is hydrogen in addition to electricity. As another clean secondary energy, hydrogen has so many advantages, such as rich source, high energy density, high combustion value, renewability, storability, zero pollution, as to be regarded as the ultimate energy source in 21st century. With regards to its applications, the hydrogen fuel cell (HFC) is much more
efficiency than direct burning. Thanks to the ultra-high energy density of hydrogen, the HFC-driven vehicles shall have comparable or even longer durability than the gasoline vehicles, with the same rate of fuel recharging. However, the hydrogen energy technology is not yet refined, and the industry is faced with cost and technical challenges in hydrogen production, hydrogen storage and HFC catalysts. Anyway, the hydrogen supply issue can at least be well settled by the water electrolysis technology with further decline in the cost of PV/wind power electricity in the near future, and hydrogen can act as the medium to store surplus solar/wind/water power and a supplement for the current electricity-dominant renewable energy industries. Then, the development and improvement of the whole new energy industry chain will be promoted by accelerating progresses of fundamental and application researches in materials of hydrogen evolution, hydrogen storage and HFC catalysis as well as technologies of hydrogen-driven vehicles.

![Figure 8. Illustration of the hydrogen energy industry chain [29].](image)

6. Summary
Herein, the issues relating to the eco-system of renewable energy industries are discussed. The up- and down-stream sections of new energy vehicles (especially EVs) are taken as an instance to describe that how to construct the systems of energy supply, storage and recharging, and how to implement the production and operation of new energy vehicles. Also, hydrogen is briefly introduced as a supplement of the electricity-dominant renewable energy industry. Through synergic development of renewable energy source, energy storage and novel applications, a renewable energy system independent of fossil energy will be established to gradually reduce petroleum import and to guarantee the national energy security.

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