# Importance of Next-Generation Batteries

**Kiyoshi Kanamura and Yuto Yamada**

**Abstract** Rechargeable batteries have been utilized in Natural Energy System and Electric Vehicle Applications, in order to reduce the production of carbon dioxide in our society. Lithium-ion battery has been utilized in these applications due to its highest energy density among rechargeable batteries. However, a higher energy density of rechargeable batteries is needed for future energy society. In this section, a background of development of next-generation batteries is introduced to understand the present status of rechargeable lithium-ion battery and next-generation batteries. Especially, some specification and performance of batteries for electric vehicles and electric power plant with natural energy are described. In addition, life cycle assessment of carbon dioxide from four kinds of vehicles, such as gasoline vehicle, diesel vehicle, hybrid vehicle and electric vehicle, is compared and discussed to know a proper direction of next-generation battery development. Moreover, some of the fundamental electrochemical aspects of rechargeable battery are basically discussed to realize real batteries with higher energy density, with other reasonable performance, such as power density, safety and life.

**Keywords** Carbon dioxide · Natural energy · Electric vehicle · Rechargeable batteries · Next-generation batteries

## 1 Reduction of Carbon Dioxide

A global warming is a big problem now, which has been caused by huge carbon dioxide production by human activity. This problem results in a rising temperature of atmosphere and abnormal weather. Therefore, reducing carbon dioxide production is an important task for all mankind. There are so many kinds of technologies for reducing the carbon dioxide release rate. Energy technologies, which are independent of fossil fuels, should be developed for future society. One of the possible solutions for new energy system is an introduction of natural energy such as solar energy and

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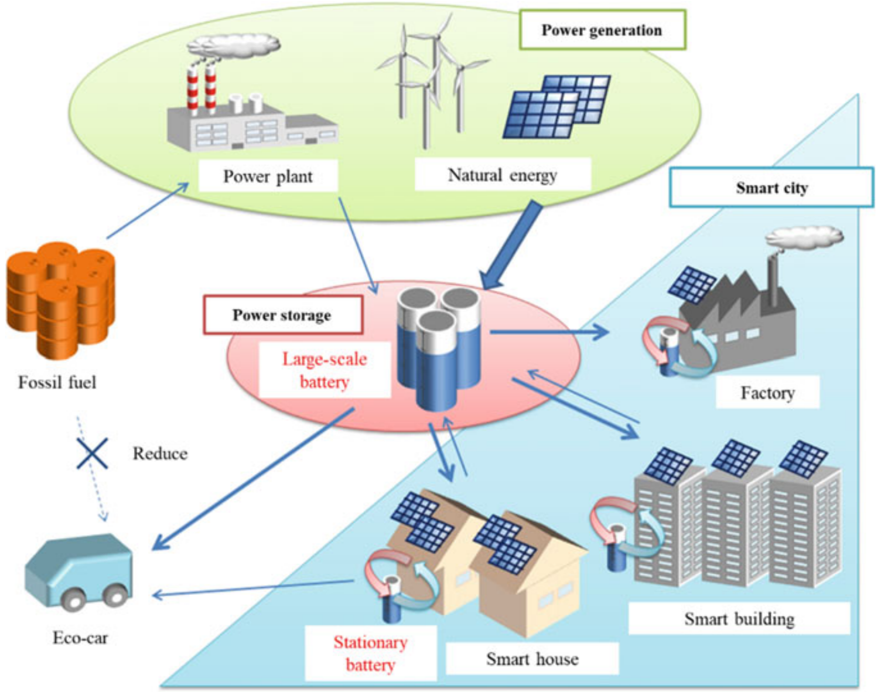



**Fig. 1** Schematic illustration of clean energy society with natural energy

wind power energy. Figure 1 shows a schematic illustration of clean energy society with natural energy. The introduction of natural energy has been already started in a small scale. Solar energy or wind power energy is unstable, depending on change in weather and time zone. Such an unstable energy cannot be directly introduced in electric power system network. Therefore, the energy from solar power and wind power should be stored in rechargeable battery before deliver to main gird according to demand from users [1]. This means that a rechargeable battery plays an important role in a smart grid system. So far, traditional batteries, such as lead-acid battery, have been utilized in the smart grid system. However, the power storage system with lead-acid battery needs a vast land. In the small size solar power generation system, lead-acid battery may be applicable. The large-scale smart grid system cannot use lead-acid battery because of a vast land for battery system. Figure 2 shows a photograph of battery system for large-scale solar power plant [2]. The battery system, which is set inside a large size container, is placed in a vast land. When the energy density of rechargeable battery increases, the land used for battery system decreases. Even for the stationary application, the rechargeable battery with higher energy density is strongly demanded.

Another application contributing to reducing carbon dioxide production is an electric vehicle. Figure 3 shows a summary of $CO_2$ production from various fields

**Fig. 2** Photograph of battery system for large scale solar power plant

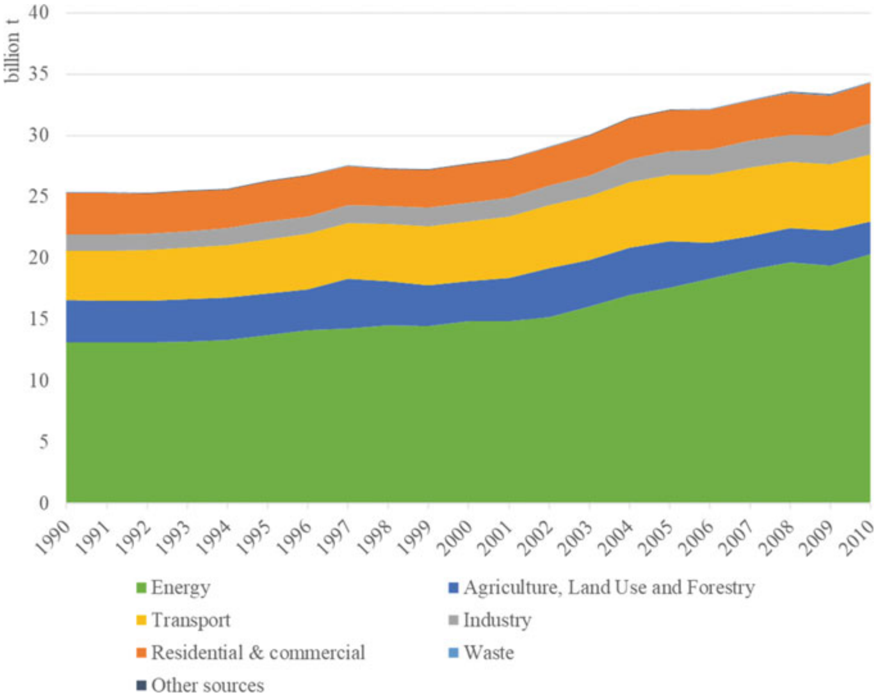



**Fig. 3** Summary of $CO_2$ production from various fields

[3]. The field of transportation produces relatively larger amount of carbon dioxide. Electric vehicles are useful to reduce carbon dioxide production. Automobiles with thermal engines are consuming fossil fuels for long time and release carbon dioxide to air atmosphere. Instead of thermal engine, motor with rechargeable battery has been utilized to automobile, namely electric vehicles (EVs), to reduce the production

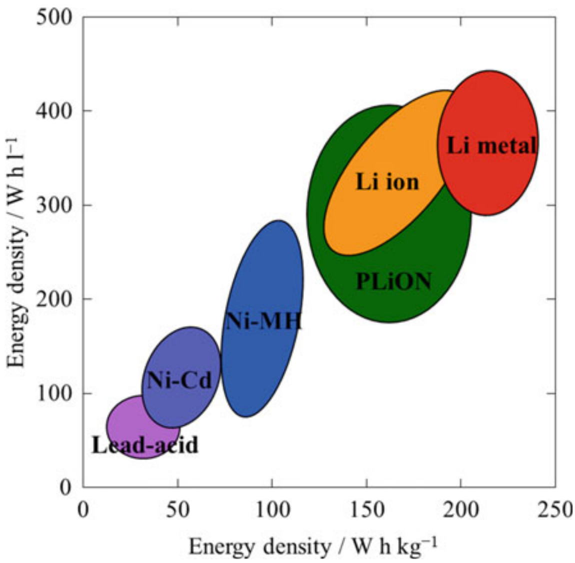



**Fig. 4** Comparison of the different batteries

of carbon dioxide. In fact, Lithium-Ion Battery (LIB) has been already utilized in EVs. Tesla car, Leaf (Nissan) and other EVs have been already commercialized. A size of the rechargeable battery (LIB) depends on electric power consumption by EVs. An electric vehicle can travel 8 km per 1 kW h of rechargeable battery energy. The EV with 20 kW h rechargeable battery can travel 160 km. The EV with 80 kW h can travel 640 km. Among existing rechargeable batteries, LIB has the largest energy density, as shown in Fig. 4 [4]. LIB for EVs has 400 W h $L^{-1}$. The volume of 20 kW h battery is 50 L. The volume of 80 kW h battery is 200 L. The volume of car is around 3000 L. It is not so easy to equip such a large battery (200 L) to automobile. New rechargeable battery with higher energy density is really needed for new EVs. One of the energy density targets is 1000 W h $L^{-1}$, leading to 40 L battery volume. By the way, a reduction of carbon dioxide production depends on the kind of electricity used in EVs. How can we obtain electricity? When the electricity is produced by thermal power station, EVs do not highly contribute to the reduction of carbon dioxide production. In order to investigate the contribution of EVs to carbon dioxide production, Life Cycle Assessment (LCA) was calculated for various kinds of automobiles. The carbon dioxide production from automobiles can be calculated from a sum of carbon dioxide from production process, battery production process and consumption of gasoline during traveling of car. All data used in this calculation are summarized in Tables 1, 2 and 3 [5–13]. Figure 5 shows the calculated results for LCA. Here, electricity produced from various electric power generation systems is utilized by cars. LCA of gasoline vehicle, diesel vehicle, hybrid vehicle and electric vehicle (20 kW h or 80 kW h battery is installed) was calculated. At the initial stage (zero traveling distance), LCA of EVs is larger than that of gasoline vehicle. This is due to carbon dioxide generation by a battery manufacturing process.

**Table 1** The data of $CO_2$ emission

| Item | | $CO_2$ emission(kg) | Reference |
|---|---|---|---|
| Vehicle body | Manufacturing gasoline vehicle (1300 kg) | 2824 | [5] *1, 2 |
| | Manufacturing gasoline or diesel vehicle (x kg) | $2824 \times (x/1300)$ | *3 |
| | Manufacturing HV including battery | 5571 | [7] *4 |
| | Manufacturing EV without battery (x kg) | $2824 \times [(x-10.4 \times y)/1300]$ | *5 |
| Battery | Manufacturing 1kWh battery | 75 | [5] *6 |
| Driving (gasoline) | Consumption of 1L gasoline | 2.32 | [8] |
| $CO_2$ emission by 1kWh Power generation | Current power generation method in Japan | 0.54 | [9] |
| | Solar energy | 0.038 | [10] |

*1: Scale ratio of Fig. 3, *2: Vehicle weight is estimated from fuel combustion in car and 2nd page in [6], *3: Calculation assuming that emissions are proportional to vehicle weight, *4: Calculation from the scale ratio, *5: 10.4 = battery weight per 1 kWh, y = battery capacity (kWh), *6: Scale ratio of Fig. 2

**Table 2** The data of battery

<table>
<tr><td rowspan="2">Battery weight</td><td colspan="4" rowspan="2">LIB weight per 1 kWh</td><td>Weight(kg)</td><td>Reference</td></tr>
<tr><td>10.4</td><td>[11]</td></tr>
<tr><td rowspan="2">Battery for HV</td><td colspan="4">Battery capacity equipped in one HV (kWh)</td><td>Guaranteed distance (km)*7</td><td>Reference</td></tr>
<tr><td colspan="4">0.73</td><td>100,000</td><td>[12]</td></tr>
<tr><td>EV</td><td>Battery capacity equipped in one HV (kWh)</td><td>Utilization of battery capacity(%)</td><td>Electric efficiency (km/kWh)</td><td>Driving distance per one charge (km)</td><td>Cycle life (times)</td><td>Total driving distance(km)</td></tr>
<tr><td>EV (20kWh)</td><td>20</td><td>100</td><td>9</td><td>180</td><td>500</td><td>90,000</td></tr>
<tr><td>EV (80kWh)</td><td>80</td><td>100</td><td>9</td><td>720</td><td>500</td><td>360,000</td></tr>
</table>

*7: The distance promised free repair of battery

During traveling of car, an increase of LCA for EVs is smaller than that of other cars. From a comparison of LCA of gasoline vehicle with those of the EV with 80 kW h battery, the EV exhibits a larger carbon dioxide emission before 90,000 km traveling distance in Japan. If a vehicle is driven 10,000 km per year, the EV does not reduce a carbon dioxide emission during 9 years. If a life of EV is 9 years, the EV increases a carbon dioxide emission. On the other hand, a carbon dioxide

**Table 3** The estimation of LIB electric efficiency and cycle life

| | Battery capacity(kWh) | Driving distance(km) [13] | Electric efficiency(km/kWh) | Guaranteed distance(km) [13] *8 | Cycle life(times) |
|---|---|---|---|---|---|
| EV(40kWh) | 40 | 400 | 10 | 160,000 | 400 |
| EV(62kWh) | 62 | 570 | 9 | 160,000 | 280 |

*8: The limit of driving distance for free repair when battery capacity was below 90% under standard use condition

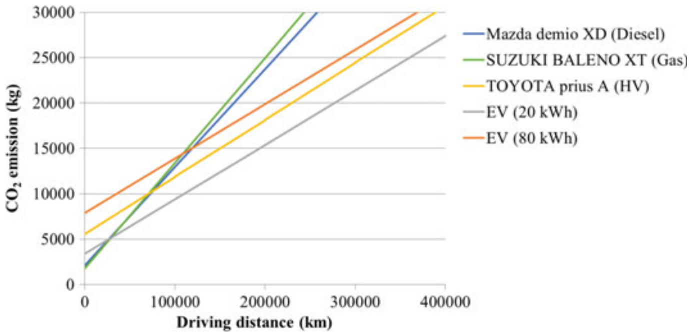



**Fig. 5** LCA using current power generation method, without battery exchange

emission can be reduced by EVs, when natural energy is utilized more and more. A battery exchange is needed according to a battery cycle life. By taking into account of battery exchange and utilization of natural energy, Fig. 5 was modified to Fig. 6. In this case, EVs are extremely useful for the reduction of carbon dioxide production. In a sense of suppression of carbon dioxide production by EVs, an introduction of natural energy must be done. Another important point of EVs is a carbon dioxide production at manufacturing process of battery. Even when the energy density of

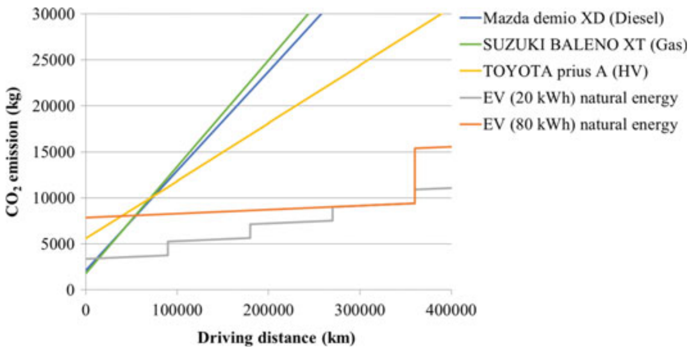



**Fig. 6** LCA using solar energy, with battery exchange

rechargeable battery becomes twice larger, a carbon dioxide production from battery manufacturing process does not increase very much. The carbon dioxide emission from the manufacturing can be reduced in a unit of $CO_2$ amount/Wh. In addition, the production cost of battery is also reduced by higher energy density battery. From these points, the higher energy density of battery should be achieved. In other words, the improvement of energy density of battery is an eternal theme.

## 2 Energy Density of Battery

Figure 7 shows an essential structure of rechargeable battery consisting of cathode, electrolyte and anode. The longer distance between cathode and anode results in a high resistance of electrolyte part, so that the electrolyte part should be thin. A separator is a key material to reduce the distance between cathode and anode. In general, the separator consists of porous polymer film. Of course, a solid electrolyte system may not need a separator.

By using separator or solid electrolyte, the distance between cathode and anode has to be reduced as possible as we can. The energy density of rechargeable battery is determined by capacity densities of cathode and anode materials. $LiCoO_2$ and graphite are used as cathode and anode materials in LIB, respectively. Non-aqueous electrolyte is used in LIB. Electrochemical reactions taking place in LIB are described as follows.

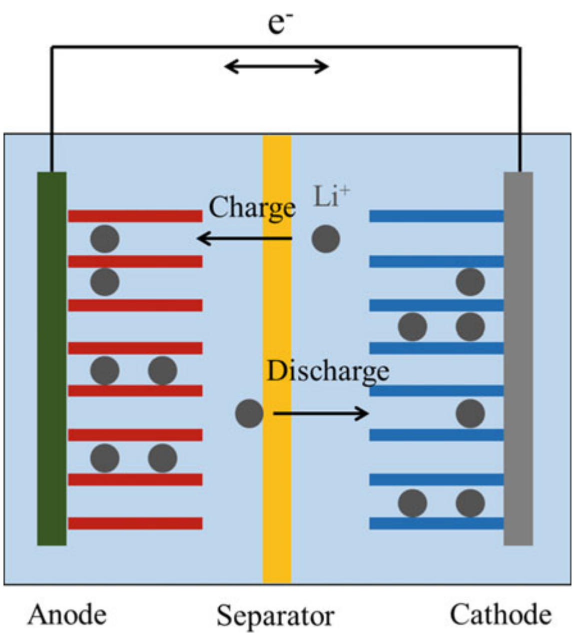



**Fig. 7** Structure of rechargeable battery

Cathode reaction $LiCoO_2 \leftrightarrow xLi^+ + xe^- + Li_{1-x}CoO_2$

Anode reaction $C_6 + xLi^+ + xe^- \leftrightarrow LixC_6$

Total reaction $LiCoO_2 + C_6 \leftrightarrow Li_{1-x}CoO_2 + Li_xC_6$

When $Li^+$ ion is extracted from $LiCoO_2$ by $x = 0.5$ during the charging process, the capacity of 140 mA h $g^{-1}$can be released during the discharge process. $Li^+$ ion is intercalated into Graphite (one $Li^+$ ion per 6C) corresponding to 372 mA h $g^{-1}$. The capacity of 1 g of $LiCoO_2$ is equal to that of 0.38 g of graphite. The total weight of cathode and anode materials is 1.38 g, corresponding to 140 mA h. The battery voltage is 3.7 V. From this estimation, the energy density of this battery can be calculated to be 375 W h $kg^{-1}$. However, electrolyte, current collector, cell case and other materials used in LIB are not included in this calculation. The real energy density of LIB is estimated at 150 W h $kg^{-1}$. The energy density of battery is different from the capacity density of active material. This is a very important point for the production of rechargeable battery. Even when active materials have very high capacity density, the battery consisting of these materials does not have high energy density. The energy density of battery strongly depends on both materials and cell structure. The next-generation batteries should be developed with the design of electrode structure and cell configuration. In this way, the above simple estimation only based on active materials misleads the energy density of battery. The volumetric energy density of LIB can be also calculated to be 300 W h $L^{-1}$ from density of LIB. Here, the energy density calculation for LIB with different thickness of electrodes is introduced as an example. Electrode A consists of 100 μm cathode thickness and the 60 μm thickness of anode. Electrode B consists of 50 μm cathode thickness and 30 μm anode thickness. The batteries with Electrode A and Electrode B have the same capacity. Electrodes A and B need current collectors for cathode and anode. Al and Cu foils are used as cathode and anode current collectors in LIB, respectively. Figure 8 shows the schematic illustration of both electrodes. In both cells, the same separator and electrolyte are used. From this figure, it is clear that the energy density of battery with electrode A is larger than that with electrode B. Both gravimetric and volumetric energy densities are increased with increasing thickness of anode and cathode. In this way, the energy density of battery depends on the structure of electrode, even when the same active materials are utilized in the cell. By the way, another important characteristic of battery is the power density. This depends on reaction mechanisms occurring in LIB. The battery reaction is not so simple and usually involves several kinds of elemental reaction process. Figure 9 shows a summary of elemental reaction process for porous cathode or anode. Among these reactions, the slowest reaction becomes a rate-determining step for battery reaction. For example, the diffusion of $Li^+$ ion in solid active materials is sometimes the slowest reaction process. Another possible rate-determining step is a charge transfer process at the interface between electrolyte and active material. Both reaction steps depend on particle size of cathode and anode. The apparent resistance due to both diffusion in solid matrix and interfacial reaction can be reduced by decreasing particle size (larger surface area). More or less, in practical batteries, the particle size of active materials

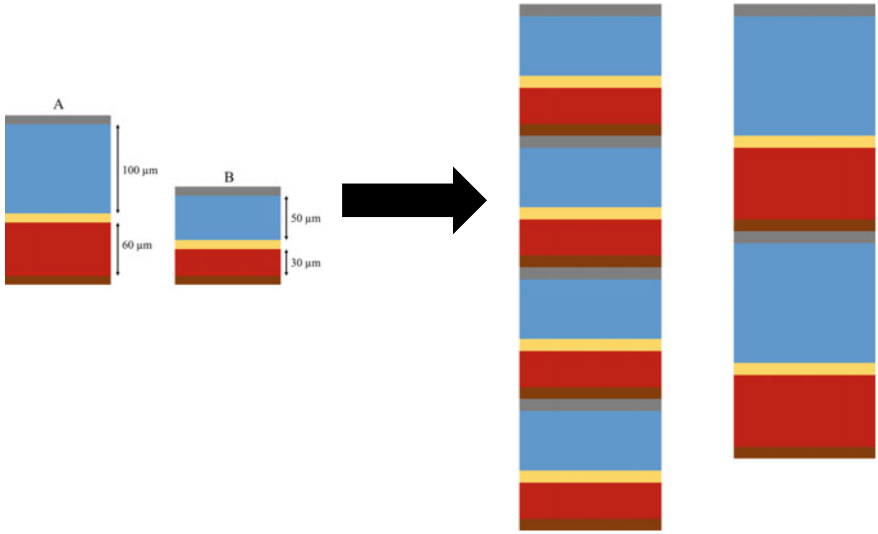
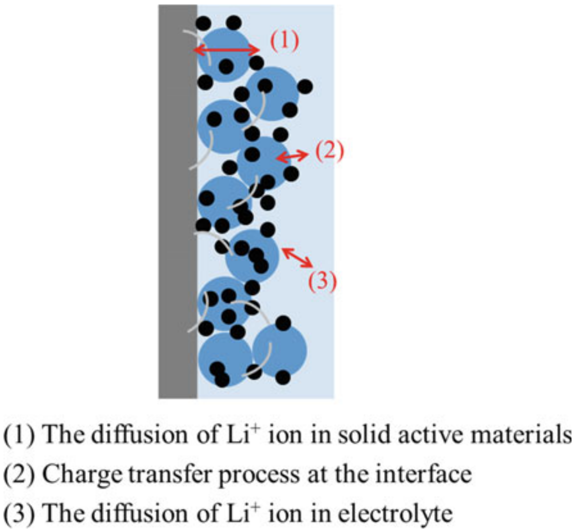



**Fig. 8** Schematic illustration of electrodes A and B

**Fig. 9** Summary of elemental reaction process for porous electrode




has been already optimized, so that the diffusion in solid matrix and interfacial resistance are not the rate-determining steps. Mostly, the diffusion of $Li^+$ ion in electrolyte involved in porous electrode is the slowest process, especially at high current discharge or charge [14] This reaction step strongly depends on the thickness of electrodes. The standard thickness of the electrode is 30 ~ 100 μm in LIB. The diffusion of $Li^+$ ion in electrolyte involved in porous cathode and anode determines the power density of LIB. The elemental reaction process relating to the thickness of electrodes is only a diffusion of $Li^+$ ion in electrolyte. The rate determining step for both cells in Fig. 8 is the diffusion of $Li^+$ ion in electrolyte. The diffusion resistance is proportional to the square of the thickness of porous electrode. Therefore, the power density of the cell with electrode A should be much lower than that with electrode B. In simply, the resistance of the cell with electrode A is four times larger compared with electrode B. The energy density of the cell with electrode A is larger than that with electrode B. This is very important point to develop practical battery. The design of electrode and battery must be considered very well. Otherwise, the battery does not work. A simple discussion on active material is not useful. The energy density and power density should be discussed based on the cell with adequate capacity needed by applications. In our ALCA-SPRING project, this point of view has been included to evaluate the materials.

## 3 Batteries for EVs

There are three kinds of EVs, such as HEV (Hybrid Vehicle), PHEV (Plug in hybrid vehicle) and EV (Electric vehicle). Table 4 shows a summary of characteristics of batteries used in these EVs. The capacity of module battery for HEV is not so large, but its power density is high. The current needed by motors in HEV, PHEV and EV is not so different each other. It only depends on a size of car. In the case of PHEV, vehicles have to travel at least 100 km for one time of battery charge. The module battery for PHEV should have a larger capacity than that of HEV. The power of battery for PHEV is smaller than that of HEV. In the case of EV, vehicles should travel more than 200 km (if possible 500 km). The capacity of battery becomes very large. The power of cell in module battery is so large. In this way, the battery characteristic depends on the kind of EV. The battery design should be optimized for each EV. In ALCA-SPRING project, the battery for EV is a main target, so that the energy density of battery must be increased by developing next-generation batteries, such as Li–Air battery, Li–Sulfur battery, all solid-state battery and Mg battery. These

**Table 4** A summary of characteristics of batteries used in these EVs

| | Battery capacity (kWh) | Battery weight (kg) | Current value (C) |
|---|---|---|---|
| HEV | 5 | 10 | 100 |
| PHEV | 10 | 20 | 50 |
| EV | 50 | 100 | 10 |

new batteries may provide higher energy density than LIB. The material science is not only important but also the battery technology is also very critical to realize real battery with high energy density 500 W h $kg^{-1}$ (1000 W h $L^{-1}$).

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