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An Overview on Design Parameters of Practical Lithium-Ion Capacitors

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Lithium-ion capacitors (LICs), composed of a lithium ion battery (LIB)-type electrode and an electrochemical capacitor (EC)-type electrode (non-Faradic), operating in a lithium ion-containing electrolyte, have the potential to deliver high energy density, high power density and long cycle life simultaneously. In this minireview, we focus on the development of practical LICs, which has been barely introduced in previous reviews, to supplement their development course. This minireview includes

the introduction of fundamentals, analysis of the key parameters, and review of the key technologies of practical LIC systems. The practical LIC technologies have been summarized and discussed in contrast to the commercial ECs. Finally, we propose the future research for LICs in terms of materials and their properties, which aims to provide guidelines for the researchers in the fields of LICs.

1. Introduction

Renewable energies, such as wind and solar power, have been extensively explored during the last several decades. These intermittent sources of power are necessary to stimulate the development of suitable energy storage technologies with the characteristic of versatility, iniquitousness, high power as well as high energy density, which enables the integration of renewable energy into different energy sectors, particularly electric-mobility, public transportation, and stationary (grid) storage.^[1–3]

Electrochemical capacitors (ECs), one of the most promising electrochemical energy storage systems, store the charge via fast, surface-confined processes, which can be electrostatic or faradic in nature, in satisfying the demands for high-rate harvesting, storage and delivery of electrical energy in an operation time of tens of seconds to minutes. Such surface storage causes only minor, if any, volume change of the electrodes during operation, resulting in a long cycle life. Currently, the commercial ECs composed of two symmetrical porous carbon electrodes with high specific surface areas, such

as activated carbon (AC), can deliver a high power density of over 10 kW kg^{-1} and a long cycle life up to 1,000,000 cycles.^[4] Unfortunately, the energy density of ECs is still lower than 10 Wh kg^{-1} in non-aqueous electrolyte and even lower in aqueous electrolyte, less than one-tenth of that of lithium (Li) ion batteries (LIBs), hence unable to fully meet the various performance demands required by the markets and limiting their applications. In the last two decades, a major effort has been devoted to increase the energy density of ECs to a target value in the vicinity of $20\text{--}30 \text{ Wh kg}^{-1}$.^[5–7]

Since the energy density is a product of capacitance and voltage, increasing the voltage is necessary to enhance energy density. Increasing the voltage is more effective because the energy density increases in proportion to squared voltage. Essentially, there have been three main approaches to achieve this goal: the first is to develop alternative carbonaceous or redox material with higher capacitance; the second is to develop a novel electrochemically durable electrolyte or an ionic electrolyte with large, stable voltage window; and the third and most promising approach under serious investigation is the development of non-aqueous Li ion capacitors (LICs), also called hybrid Li ion supercapacitors, which have the potential to essentially increase the voltage.^[5–7]

The first LIC system (2.5 V) was proposed in 1987 using a polyacenic semiconductor (PAS) as the active material in both cathode and anode electrodes.^[8] Since then, the typical LIC systems using AC as cathode, graphite, $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO), hard carbon (HC), or soft carbon (SC) as anode, in a Li ion-containing non-aqueous electrolyte have been developed one after another. With a considerable progress on the LICs having been made by researchers during the last two decades, the LIC technologies have been successfully extended to the practical level. In this context, to supplement the development course of LICs, in this mini-review, we focus on the progress of practical non-aqueous LICs, which is barely touched in previous reviews.^[8–10]

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 An invited contribution to a Special Collection dedicated to Metal-Ion Hybrid Supercapacitors.



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2. Evaluations of Practical LIC

In general, a LIC is composed of a LIB-type electrode (Faradic) and an EC-type electrode (non-Faradic), operating in a Li ion-containing electrolyte. More detailed definitions and classifications of LICs have been made in our previous review.^[9] Herein, we mainly pay attention to practical LIC systems using AC as cathode and pre-lithiated HC as anode. In this section, the working principles of practical LIC systems will be introduced in detail, and the key technical design in practical LIC system will be carefully discussed and compared with ECs, based on which the key parameters of current practical LIC are also evaluated.

2.1. Working Principles of LIC

LIC combines various mechanisms into one configuration, where the cathode undergoes a physical adsorption/desorption process and the pre-lithiated anode undergoes chemical intercalation/de-intercalation or insertion/extraction process. Due to the pre-lithiation treatment on anode, the open-circuit potential (OCP) of HC is relatively low (~0.2 V), therefore, the open-circuit voltage (OCV) for LIC being close to the OCP of AC (~3.0 V) as shown in Figure 1. During the first charge process, the anions (e.g. PF_6^-) in electrolyte adsorb onto the cathode and the cations (e.g. Li^+) are injected into the anode simultaneously. In this process, the electrolyte works as charge carrier and an important active material, called "ion-consumption mechanism" similar to ECs. With the voltage increasing, the electrolyte concentration decreases gradually, which indicates that the capacity of this LIC is not determined by the natures of the electrodes but also by the initial ion concentration of the electrolyte. During the next discharge process,

the ion-transport mechanism is reversed and the ion concentration in the electrolyte recovers gradually. When the voltage is lower than OCV, an extra Li ions transport mechanism occurs, called "rocking-chair mechanism". With the voltage decreasing from OCV to lowest voltage, the Li ions adsorb onto the cathode and are extracted from anode (which is supplied by pre-lithiated) simultaneously, keeping the overall electrolyte concentration constant. During the next charge step, this process is totally reversed. In the charge and discharge process of a LIC, the anions and cations both play important roles for the energy storage and conversion.^[11]

2.2. Key Characteristics of LICs

In comparison with ECs, LICs exhibit major differences both in the distinct energy storage mechanism and cell setup as shown in Figure 2. The key characteristics of LICs and the distinction to ECs can be summarized as follows:

- 1) LIC is a hybrid electrochemical energy storage system in which the potential of negative electrode (anode) is lower than that of EC as shown in Figure 2. Currently, the voltage of the practical EC is about 2.5–2.7 V, therefore, the anode has a lowest potential of 1.65–1.75 V. In contrast, the potential of pre-lithiated HC for LIC is always working at the potential of ~0.2 V. Due to the lower working potential of anode, the voltage of the LIC has an overall improvement, which is beneficial to the energy density and power density simultaneously.^[12]

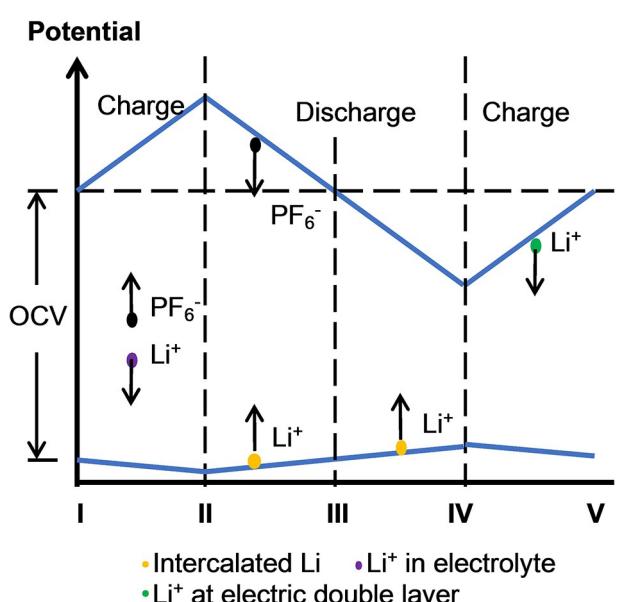


Figure 1. The working mechanism of LIC. The anions and cations diffusion process during charge and discharge. Reproduced from Ref. [11] with permission. Copyright (2016) American Chemical Society.

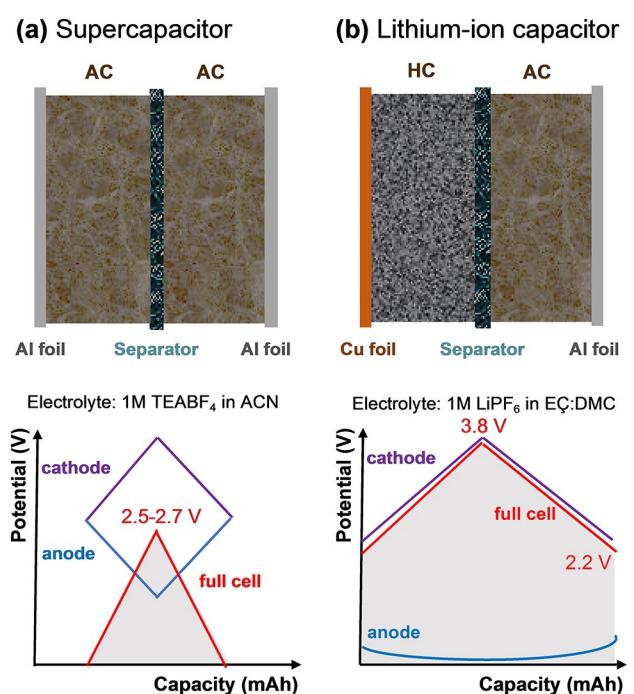


Figure 2. Schematic illustration of the cross-sections and corresponding charge/discharge profiles of a) ECs and b) LICs. The porosity of AC electrode are 70% and 50% respectively.

- 2) In LIC, due to the lower potential of pre-lithiated anode, the swing potential window of cathode is enlarged. EC is a symmetrical electro-chemical system so that the swing potential of cathode is from OCP to highest potential, e.g. AC (3.0–4.35 V). Since the potential of anode has been moved to a lower value, the swing potential window of cathode has the prospect of being extended. For instance, the theoretical swing potential of AC could be 2.0–4.35 V in LIC (2.4–4.0 V in practical application). The enlarged swing potential window enables higher capacity, which is significant for improved energy density and power density. It should be noted that the potential boundary is determined by the durability of the cathode and electrolyte interphase. In our previous report, we have demonstrated that side-reactions occur when the potential is over the designated boundary, e.g. the electrolyte oxidation (above upper boundary), SEI formation on cathode (below lower boundary), etc., resulting in poor cycle life.^[13]
- 3) LIC exhibits a lower leakage current behavior than EC. In comparison with physical ion adsorption mechanism, the Faradic electrochemical energy storage mechanism is more stable in charged state. When the anode of EC is replaced by the LIB-type anode as per LIC system design, the self-discharge behavior improves delivering lower leakage.^[12,14]
- 4) The capacity of anode is generally much higher than cathode, e.g. HC (200 mAh g⁻¹) as anode and AC (40–50 mAh g⁻¹) as cathode. Therefore, the thickness and weight of the anode is thinner than cathode in theoretical design (similar in practical application). On the other hand, the porosity of LIB-type anode is much lower than AC, which will reduce the usage of electrolyte. In general, the weight of the LIC cell will be largely reduced resulting in higher energy density and power density.^[15,16]
- 5) In an EC, the potentials of cathode and anode are always higher than 1.0 V and thus the aluminum (Al) foil is selected as current collector for both cathode and anode. In contrast, the anode potential in a LIC is reduced to values lower than 1.0 V vs Li/Li⁺ and even 0.1 V vs Li/Li⁺. Since the Al current collector is not stable within this potential range, therefore, the copper (Cu) foil will be desirable substitution for anode.

2.3. Key Technical Design in Practical LICs

The major differences between LICs and ECs have been discussed both in the distinct energy storage mechanism and cell setup. We discuss here some technical designs of practical LICs, which are of great significance to the performance of the LICs. In detail, the key technical design in practical LICs includes:

2.3.1. Pre-Lithiation Treatment of Anode

As mentioned previously, the pre-lithiation treatment of anode has multiple benefits which transform directly into improved energy density.^[9,17–21] Currently, the promising practical pre-

lithiation technologies are classified into two categories (Figure 3a–3e), *i.e.* *in-situ* electrochemical method (IEC) and *in-situ* short circuit method (ISC) as introduced in our previous review.^[9] IEC method is proposed by JM energy in Japan for the LIC application. The advantage of IEC method is that the pre-lithiation rate can be controlled externally, but the disadvantages are long pre-lithiation time and all current collectors must be made with densely packed pinholes for Li-ion passing through during pre-lithiation, hence additional processing costs.^[22] Figure 3f exhibits the relationship between the pre-lithiation time and pre-lithiation capacity of graphite with hole diameters of 20 (blue line), 100 (red line) and 200 (black line) μm in a laminated cell. The cells with larger hole diameters (200 μm) have faster pre-lithiation rate. Figure 3g shows the relationship of pre-lithiation capacity of each anode for the cells with three electrodes. The cells with smaller hole diameters (20 μm) process the best balancing effect. Generally,

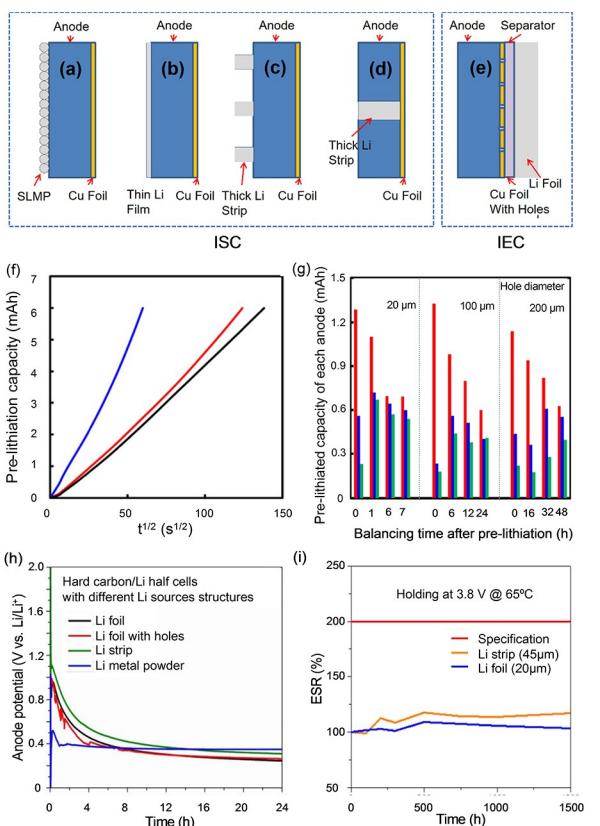


Figure 3. The schematic illustration of pre-lithiation treatment. a–d) ISC with different Li source structures; e) IEC. f) The relationship between pre-lithiation time and pre-lithiation capacity of graphite in a laminated cell using IEC with the hole diameters of 20 (blue line), 100 (red line) and 200 (black line) μm for current collector and electrodes; g) Pre-lithiated capacity of each graphite anode in a laminated cell after the pre-lithiation and capacity balancing. Red bar: anode 1, blue bar: anode 2 and green bar: anode 3. (f) and (g) are reproduced from Ref. [22] with permission. Copyright (2019) Elsevier Ltd. h) The relationship between anode potential and pre-lithiation time of ISC with various Li source structures. Reproduced from Ref. [23] with permission. Copyright (2017) The Electrochemical Society. i) The relationships between ESR and time of LIC full cell using ISC with Li strip and Li foil as sources. Reproduced from Ref. [25] with permission. Copyright (2017) The Electrochemical Society.

the hole diameter should be of the order of electrode thickness so as not influence much the electrode resistance. ISC method is proposed by our group,^[23–27] for which the pre-lithiation efficiency is relatively higher and the Li source structures are optional. In particular, the stabilized Li metal powder (Figure 3a) and thin Li foil (Figure 3b) can be used to uniformly cover the surface of the anode electrode, thick Li strips to partially cover the surface of the anode electrode (Figure 3c), thick Li strips embedded in the anode electrode (Figure 3d) in the case of cylindrical cells. The advantage of having Li metal directly in contact with the anode electrode (Figure 3a-3d) is that these techniques can be applied to most ordinary electrodes; while the disadvantage is that the pre-lithiation rate cannot be well controlled since the internal short circuit between Li and the anode electrode is self-driving once initiated. The time to pre-lithiation, the resistance and stability of pre-lithiated anode are key parameters to evaluate the pre-lithiation method.^[23,25,26] It has been demonstrated that the Li source structure has huge effects on the pre-lithiation time. The stabilized Li metal powder (SLMP) disappears rapidly while the Li strip and Li foil disappear relatively slow, which is also detected by the potential of anode as shown in Figure 3h. The resistance and stability of pre-lithiated anode are demonstrated by charge and discharge behavior in full cell. It is demonstrated that the pre-lithiated anode using Li film with 20 μm as Li source exhibits lower resistance and better cycling durability as shown in Figure 3i.

2.3.2. Anode/Cathode Capacity Ratio (A/C Ratio)

Due to the distinct energy storage mechanisms of cathode and anode, the high-rate performance and cycling durability of anode are not comparable to cathode, which will result in low power density and poor cycling lifespan. Therefore, a general method to improve the power density and cycling lifespan is to construct an unbalanced system, i.e. the capacity of anode is higher than cathode, which enables the anode to be working at low area current density and low state of charge even when the cathode is working at higher values. The reduced current density on anode makes it work well even at high cell current condition, improving the power density of LICs. The low charge state can reduce the volume change and lattice strain of anode, resulting in improved cycling durability. As shown in Figure 4a, b, the cell with higher anode capacity (three times higher than AC capacity), exhibits comparable high-rate behavior to AC, while the cycling performance is still unsatisfactory. In order to further improve the cycling durability, the capacity of anode should be much higher. It has been demonstrated that when the A/C ratio reaches to 7 (where the mass ratio of anode to cathode is about 1), the cycling performance can achieve over 250,000 cycles as shown in Figure 4c, d. However, this method will inevitably decrease the energy density of the LICs due to the overweight anode materials. In general, current methods to improve the power density and cycling lifespan basically scarifies the energy density of the LICs. Hence, the final

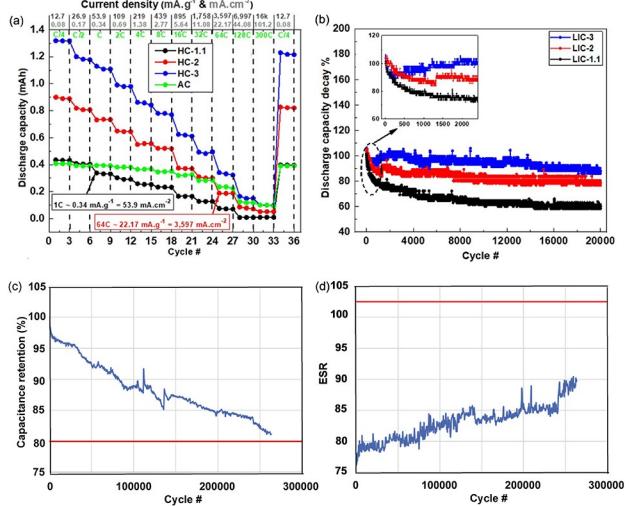


Figure 4. The electrochemical performance of AC//HC LIC system with various A/C ratio. a-b) Multi-rate and cycling performance with A/C ratio of 1.1-3.0. Reproduced from Ref. [28] with permission. Copyright (2019) The Electrochemical Society.; c-d) cycling performance and ESR evaluation with A/C ratio of 7.

performance of LICs are a trade-off between the energy density and power density, cycling durability.^[16,28–30]

2.3.3. Optimal Potential Range of Anode

We have demonstrated that the anode capacity of LICs should be higher than cathode for better power density and cycling durability. With this design, when the cathode and anode profiles are superimposed, the cathode can only match with a part of anode profile. Therefore, it is of significance to design the cathode to match with that part of anode profiles which has the best reaction kinetics and cycling durability. As shown in Figure 5, the anode materials at lower potential range exhibit poor reaction kinetic behavior and cycling durability due to the

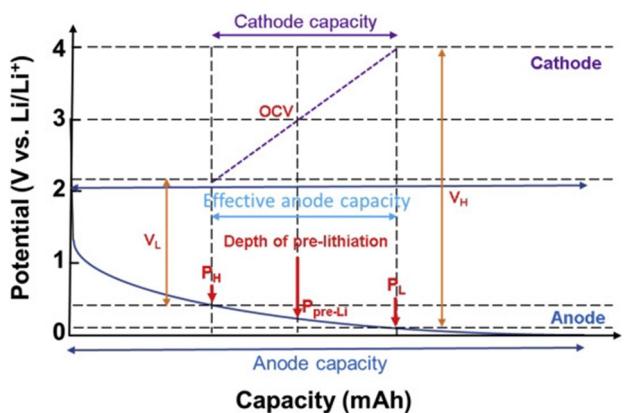


Figure 5. Schematic illustration of cathode and anode profiles and their matching for high performance LIC, in which the pre-lithiation degree, voltage range can be determined. Reproduced from Ref. [15] with permission. Copyright (2019) Elsevier Ltd.

extreme volume change and lattice strain; while at higher potential range with low kinetic behavior due to small lattice distance. By means of pre-lithiation treatment, the middle part with better kinetic behavior and cycling stability is selected to match with cathode for better power density and cycling lifespan, in which, energy density is also sacrificed due to the narrowed voltage range.^[15,31]

2.3.4. Modified Electrolyte

By balancing the energy density, power density and cycling lifespan, the LIC configuration (including A/C ratio, pre-lithiation method and degree, etc.) is basically settled. More research on the modified electrolyte has been undertaken to further improve their electrochemical performance, e.g. energy density, power density, high temperature performance, high voltage stress performance, etc.^[32–35]

2.4. Key Parameters of LICs

Similar to the LIBs and ECs, some of the performance evaluation characteristics for practical LICs include cell voltage range, energy density, power density, cycling lifespan, self-discharge behavior, temperature range, etc., which will be discussed in this section:

2.4.1. Cell Voltage Range

The maximum cell voltage is determined by the difference between maximum allowed potential of cathode and minimum allowed potential of anode. The activated carbon can be cycled at potentials below 4.0 V vs. Li/Li⁺ without significant degradation after hundreds of thousands of cycles. The anode is designed to be operated near or above 0.2 V vs. Li/Li⁺ by controlling the degree of pre-lithiation. The purpose of avoiding the operation of the anode in a potential range <0.2 V vs. Li/Li⁺ is to ensure the high power characteristics of the LICs. Therefore, when the LIC is charged at high currents, the potential of the anode will not exceed to values lower than the potential of Li and hence, no Li plating occurs. Combined the maximum allowed potential of cathode and minimum allowed potential of anode, the maximum cell voltage of LICs is 3.8 V. The minimum cell voltage is limited by the minimum allowed potential of cathode due to its extremely high specific surface area. It was found that when the potential of the activated carbon cathode is lower than 2.2 V vs. Li/Li⁺, the cycle life of LICs reduces and internal resistance increases significantly due to solid electrolyte interface (SEI) layer growth at the surface of activated carbon.^[12]

2.4.2. Energy Density

Due to the electrolyte consumption process, similar to the cases of ECs, the energy density of this LIC has a theoretical maximum limitation as demonstrated in our previous reports,^[36] i.e., when the ion concentration of the electrolyte is 1 M, the theoretical specific energy of LICs can be 120 Wh kg⁻¹ and 50 Wh kg⁻¹ based on the electrode materials and added electrolyte, as shown in Figure 6, respectively. Due to the high porosity of electrode materials, the weight of electrolyte is greater than that of electrodes. For examples, the typical porosities of activated carbon and hard carbon are respectively 70% and 50%. In order to match the rate and cycle life with the activated carbon cathode, the capacity of the anode is usually greatly increased. For example, the capacity of anodes are 7 and 10 times greater than that of cathode when the hard carbon and graphite are used as anodes, respectively. For longer cycling lifespan, higher capacity of anode is required, which will further sacrifice the energy density of LICs. Adding the additional necessary materials including current collectors, separator, metal tabs, and package materials, the specific energy achieved is a trade-off between energy density and power density/cycling lifespan in a range of 10–30 Wh kg⁻¹ for commercial LICs, which is higher than current ECs with an energy density of 7 Wh kg⁻¹.^[36]

2.4.3. Power Density

The maximum power density can be calculated based on Equation (1):

$$P_{\max} = \frac{V_{\max}^2}{4 \times ESR_{DC} \times M} \quad (1)$$

where ESR_{DC} is the DC-equivalent series resistance (ESR), V_{\max} is the maximum voltages of cell, and M is the total mass of the electrode active materials. From the equation, it can be seen that the rate capability is determined by the maximum cell voltage and the internal resistance of the cell. For ECs, the

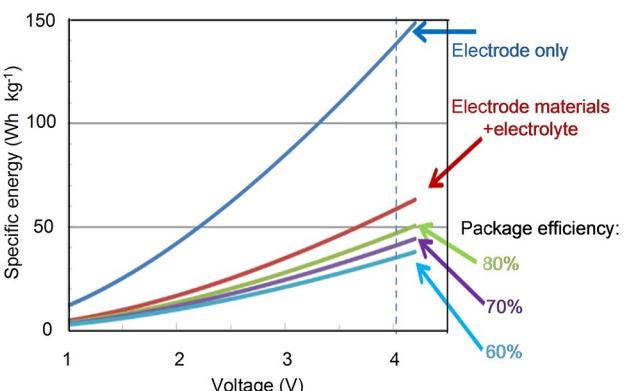


Figure 6. Estimated energy density of LIC in terms of electrode only, electrode materials and electrolyte, and with various package efficiency.

internal resistance is mainly ionic resistances from ion diffusion through the separator and porous electrodes. For LICs, there are additional resistance on anode due to charge transfer and Li diffusion; however, it was found that when the capacity of hard carbon anode is three times greater than that of activated carbon, the rate capability of anode could match with cathode as shown in Figure 4a, b, since both charge transfer and Li diffusion rates increase with increasing the surface area of the electrode. Since the ionic resistance in both ECs and LICs play a dominating role, the ionic conductivity of the electrolyte commands major influence. For ECs, it can be beneficial in using acetonitrile based electrolyte, because the ionic conductivity of acetonitrile based electrolyte is almost double that of common carbonate based electrolyte used by LICs. On the other hand, LICs are benefited by a significantly higher cell voltage (3.8 V) than that of ECs (2.7 V). Therefore, the maximum specific power of LICs is as high as 10 kW kg^{-1} , which is comparable to ECs.

2.4.4. Cycling Lifespan

AC always has extremely stable characteristics. With good electrode fabrication technique and proper cycling, ECs can be cycled hundreds of thousands even over a million cycles. For LICs, the capacity degradation rate of anode determines the final cycle life; therefore, the cycle life increases with increasing the capacity ratio between the anode and the cathode. For example, for a LIC using hard carbon anode and activated carbon cathode and having a capacity ratio of 7, the cycle life can be over 250,000 cycles as shown in Figure 4c, d. At the same time, in order to increase prolong the cycle life, the specific energy has been sacrificed.

2.4.5. Self-Discharge

LIC has a self-discharge rate which is almost an order of magnitude lower than that of the EC, as shown in Figure 7. This enhanced performance of LIC is due to the faradic charge storage mechanism in its anode. The energy barrier for the charge to escape from an intercalating host (such as hard carbon or graphite) is much higher than that from an electric double-layer.^[12]

2.4.6. Temperature Range

Usually the stable temperature range of the electrolyte determines the operating temperature range of the capacitor, particularly for the ECs. If the temperature is too high, the electrolyte will decompose; and if it is too low, the electrolyte will freeze. For ECs using acetonitrile based electrolyte, the temperature range is -40 to 60°C . For LICs using ordinary carbonate based electrolytes, the temperature range is -20 to 60°C ; therefore, when an additive was integrated into the

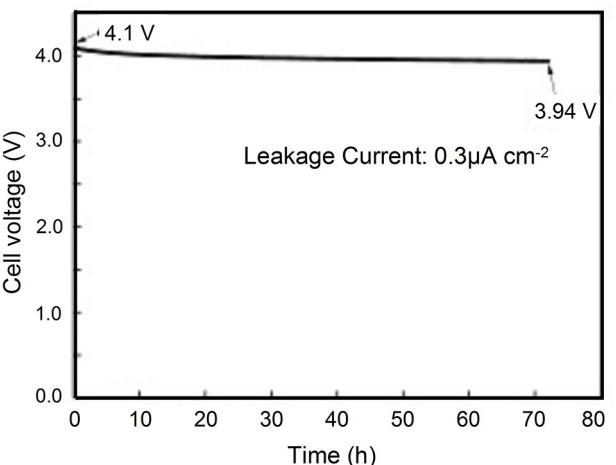


Figure 7. The self-discharge behavior of LIC at 25°C . Reproduced from Ref. [12] with permission. Copyright (2014) Elsevier Ltd.

electrolyte, the temperature range increased to -40 to 60°C as shown in Figure 8.^[32,33]

2.5. State-of-the-Art Practical ECs and LICs

The performance of the state-of-the-art practical EC and LIC is shown in Table 1. By making good trade-offs among energy density, power density and cycling lifespan, the LIC can achieve higher energy density, comparable power density and cycling lifespan in comparison with ECs as the performance of CLQ1100S1B and BCAP1200. Increasing the energy density will sacrifice the power density and cycling lifespan as CLE2100S1B. Besides, the DC-IR, temperature ranges as well as self-discharge behavior are also summarized. These practical parameters will give important guidelines for the development of practical LICs.

3. Future Research for LICs

LICs have achieved great progress in last several years. Nonetheless, there are still many challenges to be tackled, both at fundamental levels as well as at practical application levels to enable high performing LICs in terms of materials and their properties.

3.1. Cathode Materials

The AC, as the cathode material in LIC, has the advantages of an extremely stable performance within certain potential range such as 2.0 – 4.0 V vs Li/Li⁺ and a high rate capability; the main disadvantages are low specific capacity compared to anode materials and high porosity. The future development of AC should focus on achieving high specific capacitance but low porosity, so as to realize high volumetric specific capacitance (or capacity) of AC (F cm^{-3} or mAh cm^{-3}) in order to increase

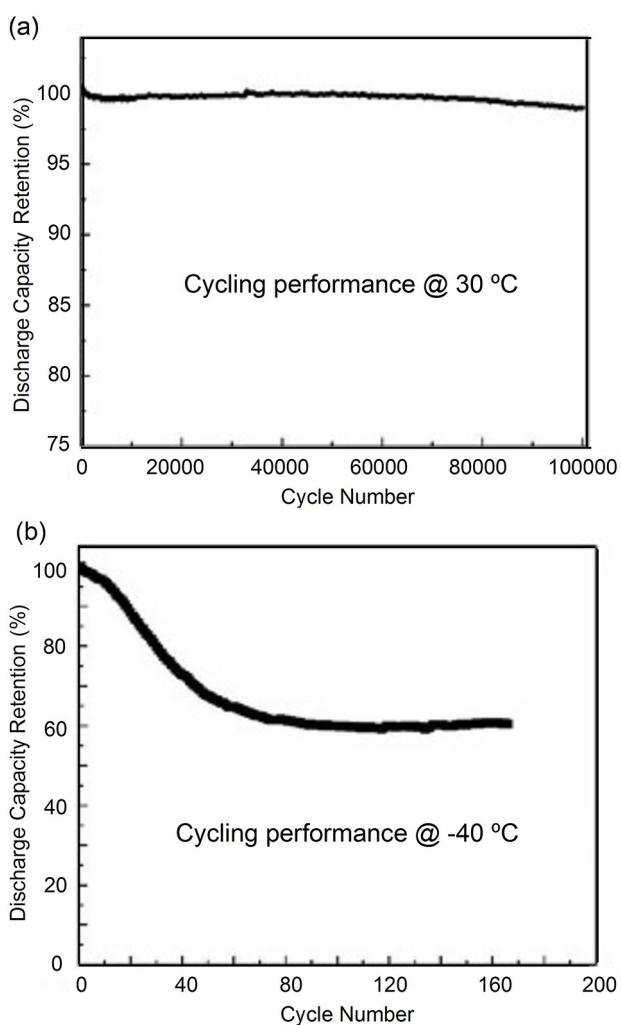


Figure 8. The cycling performance of LIC at 30 °C and –40 °C with 1.0 M LiPF₆ in EC/EMC/MB (20:20:60 by vol) and 0.1 M LiFOB as additive. Reproduced from Ref. [32] with permission. Copyright (2017) Elsevier Ltd.

the energy density of LICs. If the stability of the interface between activated carbon and electrolyte at high potentials can be improved, it will not only increase the energy density of LICs, but also enable activated carbon to be benefited from

compositing with high-performance/high potential cathode materials of LIBs such as Li nickel manganese cobalt oxide (NMC) and Li nickel cobalt aluminum oxide (NCA) to achieve higher energy densities.^[37,38]

3.2. Anode Materials

In current LICs, the anode materials include graphite, HC, SC, and LTO. The biggest disadvantage of these materials is their cycle life being too low compared to AC. Additionally, their working potentials are also not in the preferred moderate range. For example, the potential of LTO is too high, graphite is too low, HC and SC do not have a moderate potential plateau. The ideal anode material should have a much higher cycle life than existing anode materials and a moderate potential plateau, such as 0.3–0.7 V vs Li/Li⁺.

3.3. Electrolytes

The ordinary carbonate based electrolytes are used in LICs. Although the modified electrolyte with an additive can make the lowest operating temperature of the LIC to be –40 °C, the rate capability of LICs at such low temperatures is not as good as that of ECs that use the acetonitrile based electrolyte. The future electrolytes used in LICs need to make breakthroughs in two aspects: 1) not just reduce the freezing point of existing electrolytes, but also increase the ionic conductivity at low temperatures; and 2) improve the stability at high potentials, so that AC can be stable at high potentials, thereby increasing the energy density of LICs.

3.4. Pre-Lithiation

Since both cathode and anode of LICs do not act as sources of Li ions, the pre-lithiation has become a unique characteristic of the LIC. This article has introduced the commonly used pre-lithiation methods and their advantages and disadvantages. The development of scalable, safe, cost effective, and reliable

Table 1. The performance comparison of state-of-the-art practical LICs (Musashi Energy Solutions Co., Ltd.)^[39] and EC (Maxwell).^[4]

Specifications	LIC (Laminate) CLQ1100S1B	LIC (Laminate) (CLE2100S1B)	EC (BCAP1200)
Voltage	2.2~3.8 V	2.2~3.8 V	2.7 V
Capacitance	1100 F	2100 F	1200 F
DC-IR	1.2 mΩ	6.2 mΩ	0.58 mΩ
Gravimetric energy density	10 Wh kg ⁻¹	24 Wh kg ⁻¹	4.7 Wh kg ⁻¹
Volumetric energy density	20 Wh L ⁻¹	40 Wh L ⁻¹	5.8 Wh L ⁻¹
Gravimetric power density	14 kW kg ⁻¹	4 kW kg ⁻¹	5.8 kW kg ⁻¹ (max. 12 kW kg ⁻¹)
Volumetric power density	27 kW L ⁻¹	6 kW L ⁻¹	7.2 kW L ⁻¹ (max. 14.9 kW L ⁻¹)
Maximum discharge current	800 A	200 A	930 A
Operating temperature range	–30~70 °C	–20~70 °C	–40~65 °C
Voltage drop after 10,000 h stored	< 5 %	< 5 %	2.7 mA (~20 % after 72 h)
Cycle counts required to 80 % capacity retention	> 1,000,000 cycles	> 300,000 cycles	> 1,000,000 cycles

pre-lithiation methods to introduce extra Li sources into LICs need further attention in realizing high performing practical LICs.

4. Conclusions

In this minireview of LICs, we introduce the fundamentals, evaluate the key parameters, and review the key technologies of LIC systems, which are of great significance to supplement the development cycle of LICs. The current practical LICs have been carefully discussed, including cell voltage range, energy density, power density, cycling lifespan, self-discharge behavior and temperature range. The developed practical LICs have been summarized and discussed in contrast to the commercial ECs. Finally, we propose the future research for LICs in terms of energy density, power density, cycling lifespan and other key properties, which aims to provide guidelines for the researchers in the fields of practical LICs.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: supercapacitor • lithium-ion capacitor • pre-lithiation • hard carbon • activated carbon

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