Designing for Li-ion Battery Longevity

Lithium-ion batteries (Li-ion) is a group of rechargeable batteries where lithium ions moves between the negative and positive electrodes during discharge and charging. Lithium-ion polymer batteries (abbreviated LiPo) is a subgroup of Li-ion batteries in a soft package or pouch. For most practical purposes, a LiPo battery behaves like a Li-Ion battery with similar chemistry.

There are different chemistries used in Li-ion batteries, providing different characteristics. Here we focus on the most common type, lithium cobalt oxide (LCO). This is widely used for consumer and regular industrial applications, because LCO offers high energy density at the expense of somewhat lower safety. Most other Li-ion chemistries behave similarly, although they tend to be more robust, supporting higher cycle counts and higher pulse currents at the expense of specific energy.

Even though this document describes methods to extend the battery life-length, Celltech does not warrant batteries for any longer period or more cycles than defined in the product specification.

For a quick checklist of things that affects the life-length of a Li-Ion or LiPo battery please refer to the section “Summary: long life-length for Li-ion batteries” at the end of this document.

Life-length

The life-length of a Li-ion battery depends mainly on following aspects:

1. Number and type of charge/discharge cycles
2. Discharge and charge currents
3. Temperature
4. Maximum charge voltage
5. Cell balance in multi-cell packages

The lithium-ion battery is based on ion movement between the positive and negative electrodes. In theory, such a mechanism should work forever, but cycling, elevated temperature and aging decrease the performance over time. Manufacturers take a conservative approach and specify the life of Li-ion in most consumer applications between 300 and 500 discharge/charge cycles.

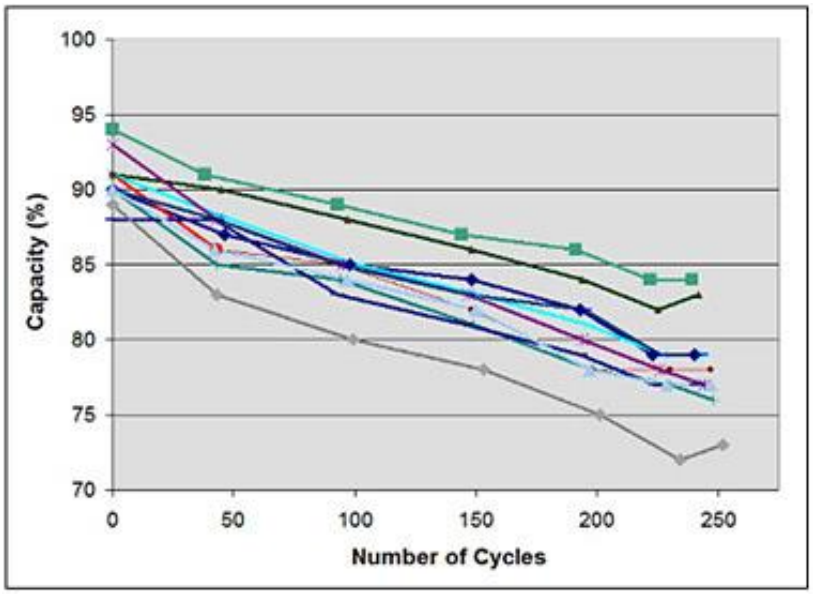
Evaluating battery life by counting cycles is not conclusive because a discharge may vary in depth and there are no clearly defined standards of what constitutes a cycle. Some device manufacturers suggest battery replacement based on a date-stamp, but this method does not consider usage.

The performance of a battery is measured in capacity, a leading health indicator. Internal resistance and self-discharge play a role, but these are less significant in predicting the end of battery life with modern Li-ion chemistries.

Figure 1 illustrates the capacity drop of 11 Lithium polymer batteries that were cycled at a Cadex laboratory. The 1500 mAh pouch cells for mobile phones were first charged at a current of 1 500 mA (1C) to 4.20 V/cell and then allowed to saturate by 0.05C (75 mA) as part of the full charge saturation. The batteries were then discharged at 1 500 mA to 3.0 V/cell, and the cycle was repeated. The

expected capacity loss of Li-ion batteries was uniform over the delivered 250 cycles and the batteries performed as expected.

Figure 1



Capacity drop as part of cycling

Eleven new LiPo batteries were tested on a Cadex C7400 battery analyser. All packs started at a capacity of 88–94 % and decreased to 73–84 % after 250 full discharge cycles. The 1 500 mAh pouch packs are used in mobile phones.

Courtesy of Cadex

Similar to a mechanical device that wears out faster with heavy use, so does Depth of Discharge (DoD) determine the cycle count. The shorter the discharge (low DoD), the longer the battery will last. If possible, avoid full discharges and charge the battery more often between uses. Partial discharge of Li-ion batteries is fine. There is no memory effect and the battery does not need periodic full discharge cycles to prolong life. The exception is a periodic calibration of the fuel gauge on a smart battery or intelligent device.

Table 1 compares the number of discharge/charge cycles Li-ion can deliver at various DoD levels before the battery capacity drops to 70 percent. All other variables such as charge voltage, temperature and load currents are set to average default setting.

Table 1

Depth of discharge	Discharge cycles
100 % DoD	300 – 500
50 % DoD	1 200 – 1 500
25 % DoD	2 000 – 2 500
10 % DoD	3 750 – 4 700

Cycle life as a function of Depth of Discharge

A partial discharge reduces stress and prolongs battery life. Elevated temperature and high currents also affect cycle life.

Obviously, a 50 % DoD means that only 50 % of the capacity is used each cycle, but the total energy that can be withdrawn from the battery during the lifetime grows to 1.5 to 2 times compared to the 100 % DoD case. On the other hand, 10 % micro-cycles does not provide more total energy than nominal cycles, mainly due to the stress of always being fully charged.

Another factor that shortens the battery life is charging or discharging at higher than nominal charging or discharging current. Quick-charge and pulse discharges are often allowed per the specification, but all currents higher than nominal will shorten the battery life-length to some extent. Do not use higher than maximum pulse currents as this may compromise the safety. Please check with the manufacturer regarding specific use cases.

Lithium-ion suffers from stress when exposed to heat, so does keeping a cell at a high charge voltage. Temperatures above 30 °C are considered *elevated temperature* and for most Li-ion a voltage above 4.10 V/cell is deemed as *high voltage* (for batteries with higher charging voltages than 4.20 V/cell the limit is correspondingly higher). Exposing the battery to high temperatures and keeping it in a full State-of-Charge (SoC) for an extended time can be more stressful than cycling. Table 2 demonstrates permanent capacity loss as a function of temperature and SoC.

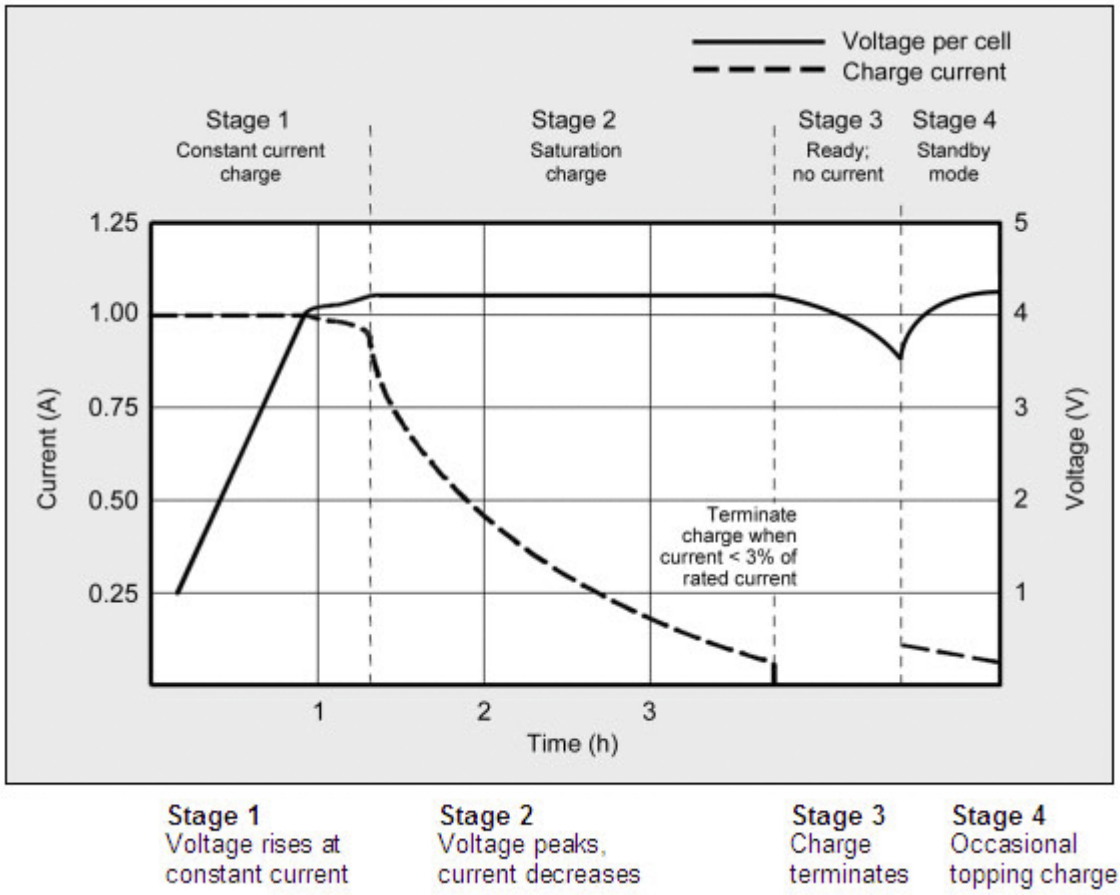
Table 2

Temperature	40 % charge	100 % charge	*Estimated recoverable capacity when storing Li-ion for one year at various temperatures* Elevated temperature hastens permanent capacity loss. Not all Li-ion systems behave the same.
0 °C	98 %	94 %	
25 °C	96 %	80 %	
40 °C	85 %	65 %	
60 °C	75 %	60 % (after 3 months)	

Charging

For battery longevity and safety, it is of utmost importance that Li-ion batteries are charged with an appropriate charging method. Li-ion with the traditional cathode materials of cobalt, nickel, manganese and aluminium typically charge to 4.20 V/cell. The tolerance is ±50 mV/cell. Some nickel-based varieties charge to 4.10 V/cell; high-capacity Li-ion may go to 4.35 V/cell and higher. Boosting the voltage increases capacity, but when going above specified maximum the cell deteriorates and delivers a reduced service life. More important is that safety is being compromised when going beyond the limits. Figure 2 shows the voltage and current signature as lithium-ion passes through the stages for constant current and topping charge.

Figure 2



***Charge stages of lithium-ion**. Li-ion is fully charged when the current drops to a set level. In lieu of trickle charge, some chargers apply a topping charge when the voltage drops. Data courtesy of Cadex.*

The charge rate of an ordinary Energy Cell is between 0.5C and 1C (1C is same current in Amperes as capacity in Ah); the complete charge time is about 2–3 hours. Manufacturers of these cells recommend charging at 0.8C or less to prolong battery life. Most Power Cells can take a higher charge. Charge efficiency is about 99 percent and the cell remains cool during charge.

Li-ion does not need to be fully charged, as is the case with lead acid. In fact, it is better not to fully charge because a high voltage stresses the battery. Choosing a lower voltage threshold or eliminating the saturation charge altogether, prolongs battery life but reduces the runtime. To achieve maximum runtimes, most chargers for consumer products are designed for maximum capacity; extended service life is perceived less important.

Most Li-ions charge to 4.20 V/cell and every reduction of peak charge voltage with 0.10 V/cell is said to double cycle life, see Table 3. On the negative side, a lower peak charge voltage reduces the capacity the battery stores. As a simple rule-of-thumb, every 70 mV reduction in charge voltage lowers the overall capacity by 10 percent. Applying the peak charge voltage on a subsequent charge will restore the full capacity.

Table 3

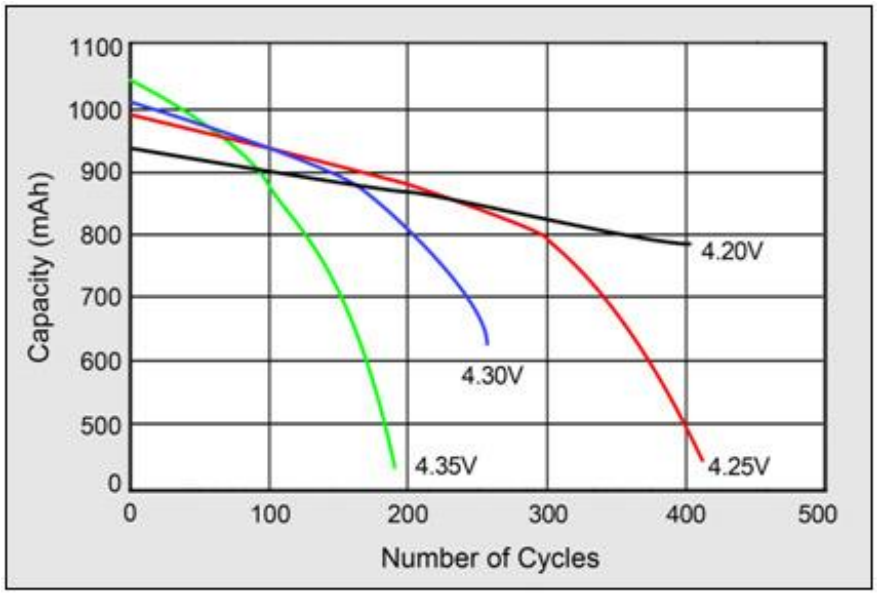
Charge V/cell	Estimated no. of charge cycles	Capacity at cut-off voltage	Charge time	Capacity with full saturation
4.20	300 – 500	85 %	180 min	100 %
4.10	600 – 1 000	80 %	165 min	~90 %
4.00	1 200 – 2 000	75 %	150 min	~80 %
3.90	2 400 – 4 000	70 %	135 min	~75 %
3.80		60 %	120 min	~65 %

Typical charge characteristics of lithium-ion. *Adding full saturation boosts the capacity by about 10 percent but adds stress due to high voltage. High-voltage cells behave similar but have higher limits.*

In terms of longevity, the optimal charge voltage for a battery with a maximum charge voltage of 4.2 V is 3.92 V/cell. Battery experts believe that this threshold eliminates all voltage-related stresses; going lower may not gain further benefits but will induce other effects. Some equipment manufacturers therefore set the charge threshold lower on purpose to prolong battery life. Table 3 illustrates the estimated capacities when charged to different voltage thresholds with and without saturation charge.

For safety reasons, many lithium-ion chemistries cannot exceed 4.20 V/cell (some high-power and NMC chemistries are the exception). While a higher voltage boosts capacity, exceeding the voltage shortens service life and compromises safety. Figure 3 demonstrates cycle count as a function of charge voltage. At 4.35 V, the cycle count of a regular Li-ion battery is cut in half.

Figure 3



Effects of elevated charge voltages on cycle life

Higher charge voltages boost capacity but lowers cycle life and compromises safety.

Source: Choi et al. (2002)

Besides selecting the best-suited voltage thresholds for a given application, a regular Li-ion should not remain at the high-voltage ceiling of 4.20 V/cell for an extended time. A proper Li-ion charger turns off the charge current and the battery voltage reverts to a more natural level.

Li-ion cannot absorb overcharge. When fully charged the charge current must be cut off. A continuous trickle charge would cause plating of metallic lithium and compromise safety. To minimize stress, keep the lithium-ion battery as short time as possible at the peak cut-off voltage. Once the charge is terminated, the battery voltage begins to drop, and this eases the voltage stress. Over time, the open-circuit voltage will settle to between 3.70V and 3.90V/cell. Note that a Li-ion battery that received a fully saturated charge will keep the higher voltage longer than one that did not receive a saturation charge.

If a lithium-ion battery is left in the charger for operational readiness, some chargers apply a brief topping charge to compensate for the small self-discharge the battery and its protective circuit consume. The charger may kick in when the open-circuit voltage drops to 4.05 V/cell and turn off again at 4.20V /cell. Chargers made for operational readiness, or standby mode, often let the battery voltage drop to 4.00 V/cell and recharge to only 4.05 V/cell instead of the full 4.20 V/cell. This reduces voltage-related stress and prolongs battery life.

Some portable devices sit in a charge cradle in the ‘On’ position. The current drawn through the device is called the parasitic load and can distort the charge cycle. Battery manufacturers advise against parasitic loads while charging because it induces mini-cycles, but this cannot always be avoided; a laptop connected to the AC mains is such a case. The battery is being charged to 4.20 V/cell and then discharged by the device. The stress level on the battery is high because the cycles occur at the voltage threshold, often also at elevated temperature.

A portable device should ideally be turned off during charge, or at least be put in a low-power mode. This allows the battery to reach the set voltage threshold and current saturation point unhindered. A parasitic load confuses the charger by depressing the battery voltage and preventing the current in the saturation stage to drop low by drawing a leakage current. A battery may be fully charged, but the prevailing conditions will prompt a continued charge, causing stress.

Charging at extreme temperatures

Rechargeable batteries operate at a wide temperature range but this does not mean they can be charged at extreme temperatures. Extreme cold and high heat reduce charge acceptance, and the battery must be brought into moderate temperature conditions before charging.

Table 4 summarizes typical charge and discharge temperatures of Li-ion batteries. The table excludes specialty batteries that are designed to be charged and used outside these conditions.

Table 4

Charge Temperature	Discharge Temperature	Charge Advisory
0 °C to 45 °C	–20 °C to 60 °C	No charge permitted below freezing. Good charge/discharge performance at higher temperature but shorter life.

Typical permissible temperature limits for Li-ion batteries. *Batteries can be discharged over a large temperature range but charge temperature is limited. For best results, charge between 10 °C and 30 °C. Limit the charge current when cold.*

Li-ion batteries offer reasonably good charging performance at cooler temperatures and allow fast-charging in a temperature range of 5 to 45 °C. Below 5 °C, the charge current should be reduced, and no charging is permitted at freezing temperatures. During charge, the internal cell resistance causes a slight temperature rise that compensates for some of the cold. With all batteries, cold temperature raises the internal resistance.

Many battery users are unaware that normal-grade lithium-ion batteries cannot be charged below 0 °C. Although the pack appears to be charging normally, plating of metallic lithium can occur on the anode during a subfreezing charge. The plating is permanent and cannot be removed with cycling. Batteries with lithium plating are more vulnerable to failure if exposed to vibration or other stressful conditions.

Cell manufactures seek ways to charge Li-ion below freezing. Charging is indeed possible with most lithium-ion cells but only at very low currents. According to research papers, the allowable charge rate at -30 °C is 0.02C. At this low current, the charge time would stretch to over 50 hours. It is for this reason that manufacturers prohibit the charging below freezing.

Specialty Li-ion can charge at temperatures down to –10 °C or even lower at a reduced rate. For example SAFT Batteries' 17065 Integration range of Li-ion batteries can be charged down to -30 °C

under certain conditions. To charge at a higher rate, Li-ion systems for automotive propulsion systems require a heating blanket.

Cell matching and balancing

Quality cells are the best foundation for a lasting battery pack.

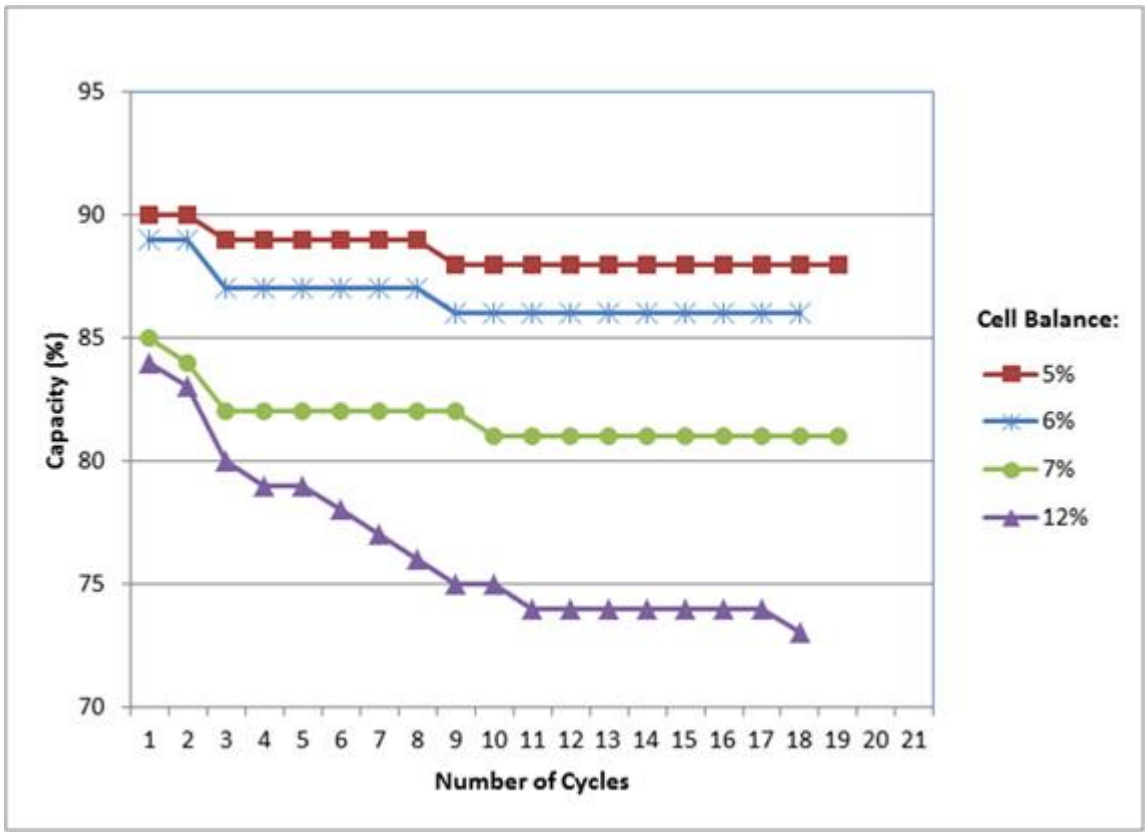
A cell manufacturer cannot predict the exact capacity when the cell comes off the production line. As part of quality control, each cell is measured and potentially segregated into categories according to their capacity levels. The buyer should be aware of differences in capacity and quality, which often translate into life expectancy.

In a multi-cell battery pack, a high-quality cell continue to perform longer than the lower-quality counterpart does, and fading is more even and controlled. Lower-grade cells, on the other hand, diverge more quickly with use and time, and failures due to cell mismatch are more widespread. Cell mismatch is a common cause of failure in industrial batteries. Manufacturers of professional power tools and medical equipment are careful with the choice of cells to attain good battery reliability and long life.

Let us look at what happens to a weak cell that is connected to stronger cells in a pack. The weak cell holds less capacity and is discharged more quickly than its strong brothers. Going empty first causes its strong brothers to overrun their feeble sibling to the point where a high load can push the weak cell into reverse polarity. On charge, the weak cell reaches full charge first, and then goes into heat-generating over-charge while the strong brothers still accept charge and stay cool. The weak cell experiences a disadvantage on both charge and discharge; it continues to weaken until giving up the struggle. There is a strong correlation between cell balance and longevity.

Figure 4 illustrates cycling performance of five aged Li-ion packs as a function of cell match. The cells are connected in a 2P4S (2 parallel, 4 in series) arrangement with a centre tap, forming two battery sections that in our example are poorly matched. The capacity differences between the two sections are 5, 6, 7 and 12 percent. When cycled, all batteries show large capacity losses over 18 cycles, but the greatest loss incurs with the pack exhibiting 12 percent capacity mismatch.

Figure 4



Cycling performance as a function of cell match. *Battery packs with well-matched cells perform better than those in which the cell or group of cells differ in serial connection. A 5 Ah prismatic Li-ion cell is connected in 2P4S (14.8 V, 10 Ah) configuration with centre tap. Courtesy of Cadex*

Quality Li-ion cells have uniform capacity and low self-discharge when new. Cell balancing is beneficial especially as the pack ages and the performance of each cell decreases at its own pace. A problem arises when a cell in a string loses capacity or develops elevated self-discharge. This can be attributed to high-temperature spots in a large battery. Low-quality cells may also be prone to unequal aging.

For multi-cell packs, the recommendation is to use quality Li-ion cells that have been factory-sorted on capacity and voltage. This works well for Li-ion packs up to 24 V; packs above 24 V should have balancing. Most balancing is passive; active balancing is complex and is only used in very large systems.

All Li-ion cells require a protection circuit that assures that serially connected cells do not exceed 4.25 V/cell (most Li-ion) on charge, and disconnect when the weakest cell drops to 2.80 V/cell or lower. The discharge disconnect prevents the stronger cells from pushing the depleted cell into reverse polarity. The protection circuit acts like a guardian angel that shields the weaker siblings from being bullied by the stronger peers. This may explain why Li-ion packs for power tools last longer than nickel-based batteries without a protection circuit. The protection circuit also safeguards the battery from excessive load current.

Summary: long life-length for Li-ion batteries

1. Decide whether maximum capacity or long life is more important. If capacity is significantly more important, accept a normal number of cycles and life length.
2. Make sure that the charging method is appropriate for the type of chemistry. Do not charge or discharge a battery at higher currents than specified. A lower current will extend the battery life to some extent.
3. Avoid high temperatures during storage and use. Recoverable capacity after one year at 40 °C is only 65-85 % (Table 2).
4. Never charge ordinary Li-ion batteries at temperatures below 0 °C without the manufacturer's approval – this will cause permanent damage and may compromise safety.
5. Do not store batteries for extensive periods at full charge. After one-year storage, 20 - 35 % of the capacity is permanently lost when stored as fully charged at 20 - 40 °C temperatures (Table 2).
6. Limit the Depth of Discharge if possible. Cycling at an average of 50 % DoD increases the number of cycles to 3-4 times, and the total energy output increases to 1.5 to 2 times compared with 100 % DoD cycles (Table 1). With smart batteries or in an intelligent device one potential scheme is to initially cycle the battery only between 20 % and 80 % charge, and once the battery wears down take more of the full range into use.
7. Consider reducing the maximum charge voltage. Every 0.10 V drop of charge voltage per cell is said to double the number of cycles (Table 3). This will give lower capacity, but the lost capacity can be later recovered by charging with maximum charge voltage.
8. If the battery is used for operational readiness, please consider to let the voltage drop significantly before recharging (for example to 4.00 V for a battery with nominal charge voltage of 4.20 V).
9. Avoid parasitic load by turning off the device or having it in low-power mode during charging. Parasitic load may confuse charging algorithm to continue charging the battery even when it is full, shortening life-length significantly.
10. Use high-quality cells in a multi-cell battery package. For bigger packs, especially with a nominal voltage above 24 V, cell balancing is needed.

Sources:

Battery University: http://batteryuniversity.com/

Cadex Electronics, Manufacturer of battery analysers: http://www.cadex.com/en

Celltech: internal cell and battery pack specifications: https://celltech.fi/en/

Saft Batteries: http://saftbatteries.com/