Power Tools: Batteries

W Weydanz, Siemens AG, Erlangen, Germany

Introduction

The name 'power tool' originally describes a tool that is powered by an electrical motor. Thus, the effort needed by an operator is reduced through using this tool.

Today the term 'power tool' or 'cordless tool', as it is also called sometimes, is most commonly used for an electric tool, which is powered by batteries. This makes the user independent of power outlets. Power tools include drills and screwdrivers as well as hammers, saws, grinders, etc. They replace their electric power grid–connected equivalents.

The first electrified drill was patented by Arthur James Arnot (1865–1946) on 20 August 1889, in Melbourne, Australia. In 1895, Wilhelm Emil Fein (1842–1898) produced the first power tool in Stuttgart, Germany. This is an electric hand drill to be operated on a workbench (**Figure 1**).

On 6 November 1917, the pistol grip and trigger switch on an electric drill were patented by S. D. Black and A. G. Decker of Black & Decker Co., Baltimore, Maryland, USA. In 1925, FEIN GmbH launched the first electrical screwdriver. Today, power tools are cordless electric tools, powered by a rechargeable battery pack. A modern power tool with a pistol grip and trigger using a nickel–cadmium (Ni–Cd) battery pack is shown in **Figure 2**.

Power Tool Operation Requirements

A current profile for a traditional power tool battery pack is shown in **Figure 3**. It is taken from a screwing application. A very short high initial peak in the current for the start of the electric motor is followed by a medium-current phase where the screw is gradually working its way into the material. The final rise of current up to a shutoff current marks the tightening of the screw towards the end of the process. Peak currents are around 20–25 A and mean operation current is about 8 A for this application. Average power is about 50–100 W, where peak power can be up to 250 W.

Resulting from the above current requirement, temperature rise of the battery pack is a consideration. This is especially true for continuous use or in fast charging of the battery pack. In use, medium currents are about 4 *C*–5 *C* rate and peak current can be well over a 10 *C* rate. Charging currents can be up to 2 *C* rate, allowing charging of the pack in about 1 h.

The ambient temperatures can be in the range of -30 to $+50\,^{\circ}\mathrm{C}$ when the power tool is used. However, for cold-temperature applications, battery performance might be drastically reduced. This is especially true for nickel–metal hydride (Ni–MH) and lithium-ion packs.

Different applications require different voltage levels to deliver the power needed for the application. Power tools like cordless screwdrivers operate at voltages from 7.2 to 16.8 V traditionally (see **Table 1**). The first lithium-ion-powered tool, the IXO (**Figure 4**), operated at only 3.6 V. However, some modern high-end tools like hammers and saws operate at voltages between 24 and 36 V. Power for these applications can be greater than 500 W. Pack volume and size are defined by the power tool manufacturer. The complete battery packs are usually assembled and supplied by the cell manufacturers to the power tool producer.

Figure 1 First electric hand drill from 1895 by Wilhelm Emil Fein. Source: Fein GmbH.

Figure 2 Modern power tool with a pistol grip and trigger. Source: Hilti Corp.

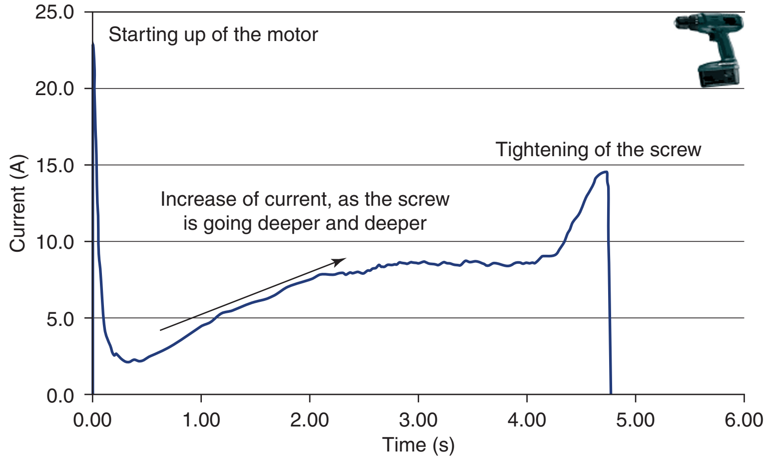

Figure 3 Current profile for a power tool when tightening a screw. Source: BaSyTec GmbH.

Table 1 Operating conditions and lifetime parameters for a cordless screwdriver

Ambient temperature	− 30 to + 50 °C
Battery (pack) voltage	3.6–18 V, dependent on application
Pack maximum discharge current	20–25 A (>10 *C* rate)
Pack medium discharge current	8 A (∼4–5 *C* rate)
Pack charge current	4–6 A (∼2–3 *C* rate)
Calendar lifetime	>3 years needed (2-year warranty required)
Cycle lifetime	>500 cycles requested (full DoD)

Note: DoD: depth of discharge.

Figure 4 First lithium-ion-powered cordless tool, IXO, by Bosch. Source: Robert Bosch GmbH.

For recycling of power tool battery packs, different options exist. They may be recycled through the normal battery recycling infrastructure. Further, power tool manufacturers and many home supply stores are starting to offer recycling facilities. In any case, battery packs have to be properly recycled by the user.

Power Tool Battery Chemistries

Cordless power tools use rechargeable batteries as a source of energy. The Ni–Cd batteries were for the longest time the most commonly used battery type for this application. Some tests were made earlier with high-power wound or spiral lead–acid batteries in power tools. However, the cells do not exhibit sufficient cycle life at high power and high depth of discharge to make this battery chemistry useful for the power tool application. Power tools do also exist with Ni–MH batteries. Packs with lithium-ion chemistry are rapidly gaining popularity. The three types of batteries, Ni–Cd, Ni–MH, and lithium-ion, used today in power tools are addressed with their advantages and disadvantages.

Nickel–Cadmium Batteries in Power Tools

The most common battery chemistry for power tools are Ni–Cd cells. This battery type is ideal for power tools in that it delivers high currents over a large number of cycles. This is even true when deep-discharging the cells at a high discharge current. The Ni–Cd cells with sintered electrodes are used for this application. Using sintered electrodes in comparison to pasted electrodes reduces the internal resistance and makes the cells more high-power-stable. Thus, they can provide the high currents needed for operation of the power tool over a long lifetime. Most cells are made in the standard cell size of a sub-C cell. The internal resistance of an individual cell is about 5 mΩ. Their capacity is around 2000 mAh with a nominal cell voltage of 1.2 V.

The Ni–Cd cells show good low-temperature (below freezing) behavior. They also show good performance on higher-temperature charging at 60 °C or above. At the same time, they are less expensive than Ni–MH and lithium-ion cells. No control electronics is required, though normally a thermocouple reads the pack temperature. High-quality Ni–Cd cells show a very good calendar lifetime of more than 10 years as well as a cycle lifetime of more than 1000 cycles.

Some drawbacks are the low energy values and high self-discharge. The specific energy density of high-power Ni–Cd cells is only about 40–50 W h kg^{-1} and the energy density about 100–140 W h L^{-1}. Their self-discharge rate can be up to 20% per month, depending on storage temperature. This is mainly a disadvantage for occasional users. Low-temperature storage is recommended. The memory or lazy battery effect, which can be found in this battery chemistry, might further require some considerations in use, that is, a charging regime preventing this disadvantageous effect. Charger price is about US$6–8 for a 12-V charger and about US$ 15 for an 18-V charger.

Marketing restriction for nickel–cadmium batteries

One topic heavily discussed is the reduction of cadmium in products as it is an environmental hazard. Thus, a cadmium ban was published by the European Union in the 2006 Battery Directive, dated 26 September 2006. It prohibits the marketing of batteries with more than 0.002% cadmium. However some exceptions apply, Ni–Cd batteries for cordless power tools being one of them. These only have to be clearly labeled to contain cadmium. Proper recycling is also required for packs containing Ni–Cd cells.

This battery directive has to be transferred into each European country's law. Countries like Denmark and Finland already have laws prohibiting cadmium batteries altogether. As an alternative, Ni–MH cells have been used in the past in these countries.

Nickel–Metal Hydride Batteries in Power Tools

Less than 10% of all power tool packs sold in 2007 were equipped with Ni–MH cells. The standard size for Ni–MH cells is also the sub-C type with a nominal cell voltage of 1.2 V. The capacity increases from 2.0 A h for the Ni–Cd version to >3.0 A h for the Ni–MH version. The energy density of high-power Ni–MH cells is about 80–100 W h kg^{-1} and 180–220 W h L^{-1}. The cell voltage is 1.2 V. Alternative battery packs for power tools with the same dimensions as Ni–Cd packs exist (e.g., for the power tool shown in **Figure 2**).

Some high-end, high-capacity models are sold with Ni–MH cells, which can achieve about 50% longer run time. The improvements in high-power stability of Ni–MH cells as well as a drastic capacity increase in Ni–MH battery technology in recent years have helped this development.

The biggest problem of the Ni–MH cells is their behavior at low temperature. Discharging below freezing temperatures is problematic with these cells. This is due to a reduced diffusion of hydrogen out of the storage alloy at low temperature. Self-cooling of the alloy, that is, the effect that the hydrogen storage alloy cools on discharge, further worsens the problem. These effects reduce dramatically the power capability of Ni–MH cells at low temperatures. However, professional users have learned to keep the power tool warm, that is, within a heated environment, until use. This is especially true for the Scandinavian countries in Europe, where these tools are extensively used, mostly due to restrictions imposed on using Ni–Cd cells.

A further disadvantage is a lower cycle life at high-power discharge for Ni–MH cells compared to Ni–Cd cells. Additionally, some users report lower battery performance of Ni–MH packs after repeated complete discharging of the pack. Another disadvantage is the high self-discharge of Ni–MH cells, which is even higher than for Ni–Cd cells. Memory and lazy battery effects can also be found in this battery chemistry.

Lithium-Ion Batteries in Power Tools

In fall 2003, the first lithium-ion battery-operated power tool was introduced to the market. It was the IXO by Bosch (**Figure 4**). It is powered by a single lithium-ion cell.

Lithium-ion cells were developed to be suitable for high-power applications. Coating thicknesses were reduced to achieve this. Today, round cells of size 18650 (18 mm diameter and 65 mm length) are manufactured as high-power versions. The nominal cell voltage is 3.3–3.6 V. Internal resistance of such a cell is about 15–25 mΩ, depending on cell chemistry. Energy density is about 220–350 W h L^{-1} and specific energy 100–130 W h kg^{-1}, depending on the cell chemistry, current capability, and manufacturer. There are normally an ultra-high-power (20 C discharge rate) and a high-power (10–15 C discharge rate) version of the cells. The capacities of these cells are about 1.2 and 1.6 A h, respectively, depending on the cell manufacturer. Some manufacturers also offer 26650-size cells as high-power versions.

The main advantage of lithium-ion packs is the greatly increased energy density of the cells, allowing longer run time on a single charge. The high-power stability of lithium-ion cells has been improved to make them similar in cycle life to Ni–MH cells. Lithium-ion cells show self-discharge of only a few percent per month. There is no memory or lazy battery effect. Partial discharging or charging is no problem. No periodic conditioning of any kind is required. Fast charging of these cells can be performed within 1 h to a minimum of 80% capacity, making them similar to Ni–MH packs in this respect. Mention has to be made here, that the cell voltage is 3 times as high as for Ni–Cd or Ni–MH systems, resulting in only one-third of the number of cells being required for a battery pack with a certain voltage.

Disadvantages are still higher cost, partially due to higher cell manufacturing cost and additionally due to some control electronics being required for this type of battery chemistry. Protection electronics are required when using lithium-ion cells. Also, more expensive charging technology may be needed. The temperature sensitivity of lithium-ion cells is not quite as strong as that of Ni–MH cells, especially in the low-temperature range. In the higher-temperature range, stricter control of temperature, especially during charging, is needed for lithium-ion cells. Lithium-ion cells of second generation can well fulfill the power tool needs.

Cells using lithium manganese spinel and lithium manganese nickel cobalt oxide or mixtures of these materials as cathode material are well established. New and even more robust lithium-ion cells are entering this market segment. They are using lithium iron phosphate ($LiFePO_4$) as the active material. The trade-off here is a safe and robust chemistry at the price of a loss in energy density. This is partially due to a lower average cell voltage, resulting in an energy density only slightly better than the best Ni–MH cells. The cells have good cycle stability. These cells are commonly made in 18650 or 26650 cell sizes with a nominal cell voltage of 3.3 V.

Lithium-ion cells have enabled more applications to become cordless. For example, power tools with very high power drain in excess of 500 W and battery pack capacity requirements are becoming possible now. Only with lithium-ion-based systems, pack voltages of 24–36 V can be achieved while the device can still be operated and handled with respect to weight consideration. Thus, the development of cordless devices is speeding up with lithium-ion cells. They enable hammer drills, cordless saws, reciprocal saws, cordless vacuum cleaners, and the like. These battery packs are also sold for powering high-power work lights. **Figure 5** shows a state-of-the-art high-end power tool with a 36-V lithium-ion battery pack.

Battery cost for lithium-ion is rather high. Packs cost about US\$0.5 $(W\ h)^{-1}$. This results in a share of battery pack cost for the power tool from about one-fourth to around one-third. Charger price is about US\$8 for a 12-V charger and about US\$15–20 for an 18-V charger.

Summary and Comparison of Battery Chemistries for Power Tools

A summary of the different cell chemistries used today for power tool applications is shown in **Table 2**. Performance parameters of Ni–Cd, Ni–MH, and lithium-ion cells are compared in this table. The performance of the different cells has been discussed above.

Figure 5 High-end hammer drill with 36-V operating voltage powered by a lithium-ion battery pack. Source: Hilti Corp.

Table 2 Comparison of performance parameters for battery chemistries nickel–Cadmium (Ni–Cd), nickel–metal hydroxide (Ni–MH), and lithium-ion for use in power tools

	Ni–Cd cells	*Ni–MH cells*	*Lithium-ion cells*
Power capability	+ +	+	+ +
Energy density	–	+	+ +
Specific energy	o	+	+ +
Cycle life	+ +	o	o
Calendar life	+ +	+ +	+
Price	+ +	+	–
Self-discharge	–	–	+ +
Temperature behavior	+ +	o	o
Reliability	+ +	+	o
Fast charging	+ +	+	o

+ +, very good; +, good; o, neutral; –, disadvantage.

Application Notes for Power Tools

The first Ni–Cd-powered cordless power tools started using battery packs with nominal voltages of 7.2 or 8.4 V, consisting of six or seven cells, respectively. Today these pack voltages are still used for low-power applications. Standard voltages for Ni–Cd battery-powered tools are currently in the range from 12 V through 14.4 to 18 V, using 10, 12, and 15 Ni–Cd cells, respectively. The same voltage levels and cell numbers per pack are standard for Ni–MH battery packs.

Figure 6 schematically shows a 12 V pack with 10 Ni–Cd cells connected in series. It also contains a thermo-element at a central location, possibly in contact with one of the inner cells for detecting the pack temperature. The thermal element is ideally located at the spot with the highest temperature in the pack.

The thermal element reports a temperature to the power tool and/or charging station and can thus control operation of the power tool. Lately, a more advanced charging and cooling technology has entered the market. An example of a clever charging station with temperature control and management for a lithium-ion battery pack is shown in **Figure 7**. The battery pack has small air inlet holes in its bottom (top side in the figure). An air duct connects the pack to the fan in the charging station, which sucks the air through the pack. The air leaves the charging station through outlet slits.

The pack has to be below a certain maximum temperature before the charging process is started. During use a battery pack becomes hot. Temperature control before charging by limiting the maximum pack temperature as well as homogenization of individual cell temperatures by cooling can extend the lifetime of a power tool pack by 50–100%. The immediate benefit for the user is the reduction of the charging time by up to 30% due to cooling during charge.

Many users require a longer operating time and shorter downtime. Thus, for Ni–Cd-powered tools especially, several power tool manufacturers have adopted the policy of delivering the tool with two battery packs. This is only possible due to the low price of Ni–Cd cells. Continuous operation is thus possible with one pack being charged while the other pack is being in use.

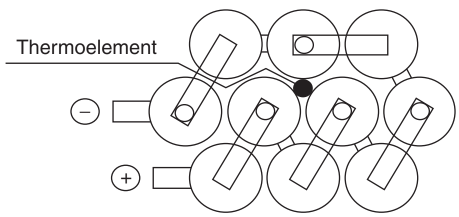

Figure 6 Schematic drawing of a power tool cell pack consisting of 10 nickel–cadmium (Ni–Cd) cells and a thermal element.

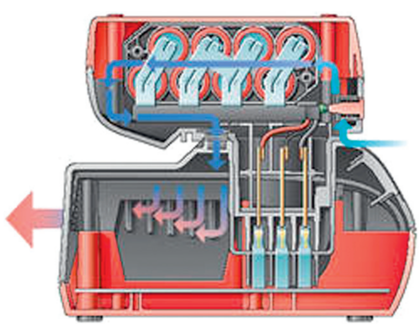

Figure 7 Power tool pack with charging station and integrated cooling function. Source: Metabowerke GmbH.

Market Overview

As mentioned above, Ni–Cd still is the most commonly used cell type for power tool applications. The amount of Ni–Cd cells used in the power tool industry, however, is decreasing even though the total market is growing by about 5–10% per year. In 2007, about 600 million Ni–Cd cells were sold for power tool applications. Ni–MH has kept a rather stable market share for the last 10 years. However, its market share has started to decrease now. About 36 million Ni–MH cells were sold for power tool applications in 2007.

High-power lithium-ion cells are catching on fast. It is only since 2005 that a large number of power tools with lithium-ion cells have been sold. The number of these cells sold for power tool applications is rising by 10% per year (**Figure 8**). In 2006, lithium-ion batteries for the first time surpassed Ni–MH in demand of cells for power tools. The year 2007 saw 120 million lithium-ion cells being sold into power tool applications.

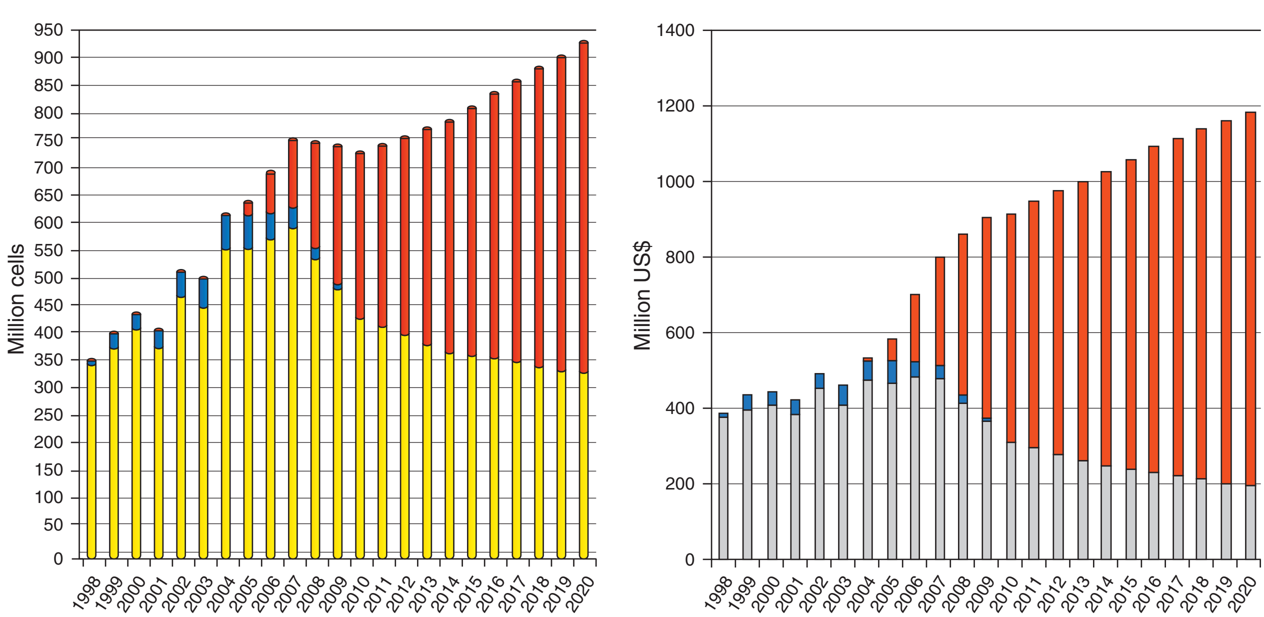

Figure 8 Worldwide battery market by amount of tools sold and by value (grey/yellow: nickel–cadmium (Ni–Cd); blue: nickel–metal hydroxide (Ni–MH); red: lithium-ion. Source: Avicenne compilation.

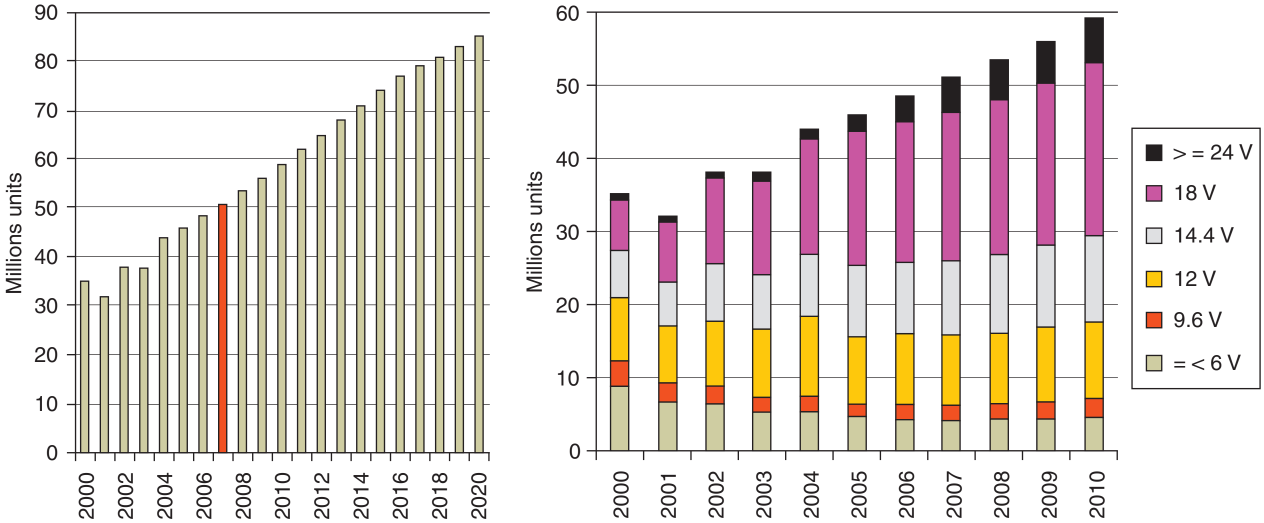

Figure 9 Worldwide power tool market and split of pack size in respect to voltage. Source: Avicenne forecast.

The total market has a volume of about 750 million cells (2008, estimate). However the market share of the lithium-ion chemistry, based on packs sold, is about 22%, where Ni–Cd still holds 68% and Ni–MH roughly 10%. This is due to a smaller number of cells needed when making packs with lithium-ion cells.

The trend toward higher pack voltages can clearly be seen from **Figure 9**. In 2000, 25% of the packs had a voltage of 6 V. This has decreased to 8% in 2007. The number of 12 V packs has slightly decreased, from 25% market share to 18% in the same time. However, 14.4 V packs and 18 V packs have gained from 18 and 20% to 20 and 40%, respectively. The 24 V packs were nearly not existent in 2000 and today have a market share of 9% with a rising tendency.

The main players in 2007 were TTI/Milwaukee and Black & Decker, each with a 12% worldwide market share. Bosch and Jingding are following with 6 and 5% market share, respectively. Makita shows a clear commitment toward lithium-ion technology with 90% share of their products being lithium-ion-powered. The other big players offer a share of 20–30% in lithium-ion-powered tools. Further, 75% of all power tools sold in 2007 were made in China. A number of manufacturers are exclusively producing there.

The respective market share of major power tool battery pack producers is shown in **Figure 10**. Market leaders are Sony, Sanyo, and E-One Moli, where Sanyo and E-One are using manganese spinel-based chemistry in their cells.

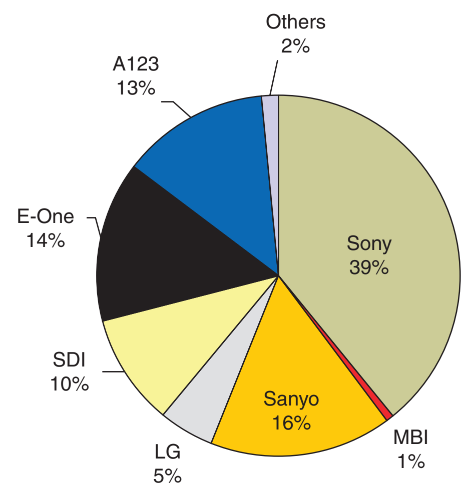

Figure 10 Market share of cell manufacturers for lithium-ion power tool cells 2007. Source: Avicenne compilation.

The lithium-ion penetration of the market is faster than expected and has accelerated dramatically in recent times. This can be seen from **Figure 11**. The Ni–Cd market share is predicted to fall by 5% per year in the next years. The Ni–MH user is decreasing and it is predicted to vanish from the market completely after 2010–12. For lithium-ion, growth in cell amount is predicted to be 30% per year and growth in power tools is estimated to be 18% per year.

About two-thirds of all power tools are sold at a middle price level for private users for home use. Roughly 20% of the tools are sold to professional users with frequent and regular use patterns. The rest of the power tools are sold at entry-level prices for infrequent use.

Concluding Remarks

It can be concluded that lithium-ion power tool packs successfully entered the market and are taking a fast lead. This technology will continue to gain popularity fast and

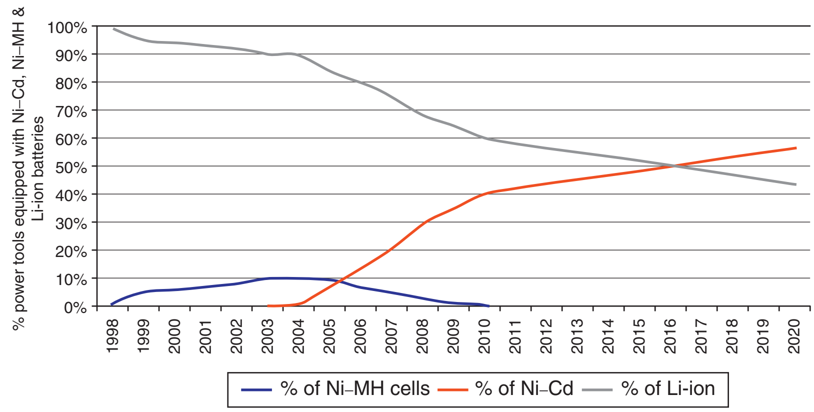

Figure 11 Share of power tools equipped with respective chemistry. Source: Avicenne compilation.

enable further new applications to become cordless. New safer and cheaper materials like lithium manganese spinel and lithium iron phosphate will become more popular.

The Ni–Cd-operated power tools will remain interesting for cost as well as high-power and lifetime considerations. However, their market share is decreasing steadily. The use of Ni–MH cells will further decrease and they are predicted to vanish from the market after 2010–12. Lithium-ion packs will take their role in regions, where marketing restricting for Ni–Cd cells exist.

Further points in development are reduction of charging time to less than half an hour (80% capacity) as well as extension of cycle life (for lithium-ion cells) to well above 500 cycles. Cost reduction is still an issue, because lithium-ion cells are rather expensive.

Nomenclature

Abbreviations and Acronyms

DoD	depth of discharge
Ni–Cd	nickel–cadmium
Ni–MH	nickel–metal hydride

See also: **Secondary Batteries – Lithium Rechargeable Systems – Lithium-Ion:** Overview; **Secondary Batteries – Nickel Systems:** Nickel–Cadmium: Overview; Nickel–Metal Hydride: Overview.

Further Reading

Besenhard JO (ed.) (1998) *Handbook of Battery Materials*. Weinheim Germany: Wiley-VCH.

Jossen A and Weydanz W (2006) *Moderne Akkumulatoren richtig einsetzen*. Germany: Reichardt Verlag.

Market Study (2008). Rechargeable Batteries for Power Tools 2000–2020, 17th edn. Avicenne Development, June.