Exemption for the use of cadmium in portable batteries and accumulators intended for the use in cordless power tools in the context of the Batteries Directive 2006/66/EC

Final Report (revised)

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Consortium **ESWI**
Expert Team to **S**upport **W**aste **I**mplementation

umweltbundesamt

ENVIROPLAN
Consultants & Engineers

BiPRO
Beratungsgesellschaft für integrierte Problemlösungen

Executive Summary

Background

The Batteries Directive 2006/66/EC (repealing Directive 91/157/EEC) entered into force on 26 September 2006[1]. The Directive sets out rules applicable to all batteries and accumulators that are put on the European Union market.

These rules include, among others, restriction on the use of cadmium in portable batteries and accumulators (PBA) according to Article 4(1)(b) of the Directive. Portable batteries and accumulators, including those incorporated into appliances, that contain more than 0,002% of cadmium by weight shall not be placed on the market.

However, according to Article 4(3) of the Directive the above requirement shall not apply to portable batteries and accumulators intended for use in: (a) emergency and alarm systems, including emergency lighting; (b) medical equipment; or (c) cordless power tools.

Furthermore, based on Article 4(4) of the Directive the Commission shall review the exemption from the cadmium ban for use in cordless power tool with a view to the prohibition of cadmium in batteries and accumulators. The Commission shall submit a corresponding report to the European Parliament and to the Council by 26 September 2010, together, if appropriate, with relevant proposals. The review should be based on the experience of the application of the Directive, the developments in science and technology, environmental requirements, and the functioning of the internal market. It should assess the environmental, social and economic impacts in an integrated manner.

Objective

Based on this background the general objective of the study is to assess and synthesise available data and information, identify and address remaining needs with a view to assisting the Commission services with the review in prohibition of cadmium in batteries and accumulators intended for use in cordless power tools taking account of available technical and scientific evidence.

Market analyses

The task of the market analyses was to provide an overview on the EU and worldwide market of portable batteries intended for the use in cordless power tools as a basis for the technical and impact assessment of a possible ban of NiCd batteries intended for the use in CPTs (see chapter 3).

The 2008 world market for portable rechargeable batteries (9200 million US $) is dominated by Japan (5100 million US $), China (2300 million US $) and Korea (1800 million US $). Sales in the rest of the world are below 100 million US $. The market of portable rechargeable batteries used for CPTs is increasing and was in 2008 13% of the world market value.

In the dynamic and growing CPT sector, the trend for NiCd batteries is decreasing whereas it is increasing for Li-ion-batteries and more or less stable for NiMH batteries. Other battery technologies are currently not used in CPTs.

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[1] OJ L 266, 26.9.2006, p. 1., as last amended by Directive 2008/103/EC (OJ L 327, 5.12.2008, p. 7–8).

In total a number of around 1060 million cells (of all relevant types) have been used in cordless power tools (CPTs) worldwide in 2008. This corresponds to a value of about 1400 million US $.

The number of cells used in CPTs in Europe in 2008 is about 41 % of the world market and estimated to amount to 436 million cells[2]. These were used in about 12.9 million CPT units related to a market value of 1440 million $.

The following table summarises shares of battery technologies applied in Europe in cordless power tools (CPTs):

Table 0-1 : Shares of battery technologies applied in cordless power tools (Europe)

NiCd	Li-ion	NiMH	Information and source
55%	36%	9%	Current share [EPTA 2009a]

A recent EPTA survey has shown that for 9 EPTA member companies (which represent a significant proportion of the market), the total share of battery technologies was NiCd 49%, NiMH 11% and Li-ion 40%. For the professional CPTs the corresponding shares were 42%, 19% and 39%. For the DIY CPTs the corresponding shares were 54%, 6% and 40% [EPTA 2009d]. These data indicate that the share of NiCd technology may actually be lower and that of Li-ion be higher than shown in Table 0-1 (Table 3-7 respectively) and that the penetration of Li-ion technology is higher in the segment of professional CPTs compared to DIY CPTs.

The number of NiCd cells used in CPTs in 2008 was about 515 million cells worldwide and 240 million cells within the EU. This corresponds to a world market share of 47%.

The average mass of a NiCd cell used in CPTs is 55 g resulting in a total mass of 13,200 tonnes of NiCd cells used in CPTs in Europe in 2008.

SAFT is the last European producer of NiCd cells. Applications of portable NiCd batteries from SAFT are for example medical equipment, radio communication and tracking equipment, military equipment, emergency lighting units or security devices[3]. The production of NiCd cells by SAFT has decreased to 8% of the world market in 2008 i.e. to approximately 56 million US $ or about 84 million portable NiCd cells. SAFT does not produce any more NiCd cells for batteries intended for the use in CPTs in the EU. All portable NiCd batteries used in CPTs are imported to the EU.

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[2] All relevant cell types, i.e. NiCd, Li-ion and NiMH cells

[3] See http://www.saftbatteries.com/Technologies_Nickel_NiCd_293/Language/en-US/Default.aspx

Technical assessment

The task of the technical and the impact assessment was to elaborate what would be the consequence of a ban of NiCd batteries for their application in cordless power tools (CPTs) or more exactly what would be the consequence of limiting the cadmium concentration in the energy storage system of cordless power tools at 0,002% by weight (see chapter 4).

Current market trends and the technical assessment let expect that:

- For existing NiCd-driven cordless power tools[4] NiMH power packs would be used as replacement (power tools that are sold today can be driven by either NiCd or NiMH batteries, only a different charging equipment may be necessary)
- New cordless power tools[5] would be driven by Li-ion power packs
- In the medium to long term, improved Lithium or Lithium-ion batteries, Nickel-zinc batteries, Carbon Nanotube Enhanced Supercapacitors may substitute the Li-ion battery of today
- In the long term possibly portable fuel cells or redox flow batteries may substitute the Li-ion battery of today.

However, already today's Li-ion battery is a more than good substitute for NiCd batteries in cordless power tools (CPT). Li-ion batteries are:

- lighter,
- lose less energy during storage,
- have a better energy efficiency,
- store more energy per volume and
- Li-ion batteries having three times the cell voltage of NiCd batteries, will allow to design much more powerful CPTs in future.

Shortcomings of Li-ion batteries in comparison to NiCd batteries are the limitation in operations below 0 °C and a yet uncertain lifetime.

The poor sub-zero °C performance of Li-ion batteries, however, does not keep professionals from preferring Li-ion batteries over NiCd batteries even in cold areas such as Northern Sweden.

The uncertain lifetime is less a technical as an economic restriction. Even a more conservative estimate [EPTA 2009b] reports Li-ion batteries of having 62 % of the NiCd's life-time-energy storage capacity. Other sources [Bosch 2009a] attest Li-ion batteries to have the same life-time-energy storage capacity as NiCd batteries. Consequently the lifetime system costs of Li-ion batteries are:

- 49 % higher than NiCd-system costs (when assuming as [EPTA 2009b] an average life-time of 4.3 years for the Li-ion power pack)
- or only 10 % higher (when assuming as [Bosch 2009a] an average lifetime of 7 years for the Li-ion power pack).

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[4] Existing CPTs means CPTs manufactured and placed on the market prior to a ban of NiCd batteries for CPTs

[5] New CPTs means CPTs manufactured and placed on the market after a ban of NiCd batteries for CPTs

In practice the Li-ion batteries (and to a minor extent the NiMH batteries) already have replaced the NiCd batteries in the segment of professional cordless power tools and in many DIY CPTs. Here the technical advantages of Li-ion batteries are more important than the additional costs.

Particularly in the low-price DIY segment the NiCd battery still keeps a hold.

Impact assessment

The main policy objective of a prohibition of cadmium in batteries and accumulators intended for use in CPTs is to avoid negative environmental impacts that are related to this use. The most important objective of an assessment of the impacts related to a prohibition is to assess the impacts which will be caused by technical substitutes, i.e. by a possibly increased use of NiMH and particularly Li-ion technologies. The previous studies, mainly performed during the period from 2000 to 2004, are to a certain extent outdated due to the technological development of substitutes which took place after the elaboration of the mentioned studies.

Therefore, the previous studies could particularly not appropriately consider the availability and maturity of Li-ion technologies as these were not significantly represented in specific market segments including the market of cordless power tools (CPTs) before.

The impact assessment of the present study takes the current state-of-the-art in battery development into account.

The environmental, economic and social impacts have been systematically identified along the supply chain of portable rechargeable batteries and CPTs and all involved actors. Most important stakeholders are raw material suppliers for battery manufacturers, battery manufacturers, consumers (users of CPTs), battery recyclers, CPT manufacturers and the society and the environment as a whole.

The environmental impact assessment considers the properties, health and environmental effects, the exploitation and the recycling of the materials contained in the NiCd, NiMH and Li-ion batteries (see chapter 5.3).

The materials assessed are:

- The electrode materials
    - Cadmium (anode of NiCd)
    - Cobalt (cathode of Li-ion)
    - Lithium (electrodes of Li-ion)
    - Manganese (cathode of Li-ion)
    - Nickel (Cathode of NiCd and NiMH)
    - Rare-earth-metals (Lanthanides) (as representative material for the NiMH anode)
    - Carbon/Graphite (anode of Li-ion)
- And the electrolyte materials
    - Alkali (in NiCd and NiMH)

  - Aprotic salts and solvents, such as $LiPF_6$ and di-etyhl carbonate (in Li-ion)

The impacts from the NiCd, NiMH and Li-ion batteries themselves are assessed in a second step (see chapter 5.4).

Environmental impacts

- When only NiMH batteries replaced the NiCd batteries in European Cordless Power Tools,
  - 2,200 t/year of very toxic (also and especially to aquatic organisms), accumulating and category 2 carcinogenic cadmium

  would be replaced by roughly:

  - 4,900 t/year of toxic and category 3 carcinogenic nickel
  - 750 t/year of harmful cobalt and
  - 2,400 t/year of low to moderate toxic mischmetal alloy.
- When only Li-ion batteries replaced the NiCd batteries in European Cordless Power Tools,
  - 2,200 t/year of very toxic (also and especially to aquatic organisms), accumulating and category 2 carcinogenic cadmium

  would be replaced by roughly:

  - 835 t/year of very toxic lithium hexafluorophosphate (or 1,600 t of fluorine) and
  - 2,600 t/year of harmful cobalt.

All three technologies, NiCd batteries, NiMH batteries and Li-ion batteries contain hazardous substances. By far the most hazardous substance to health and environment, however, is the cadmium contained only in the NiCd batteries.

Available information sources indicate that the emissions related to NiCd batteries would be small compared to the emissions from oil/coal combustion, iron and steel production or phosphate fertilizers. Thus NiCd batteries would only be responsible for 1.35 % of the atmospheric cadmium emissions, 1.51 % of the cadmium emissions into water and 0.65 % of the total emissions ([EC 2003b] cited in [Recharge 2004]).

Based on the fact that 1 % of the cadmium which is brought into Austria is emitted over its lifetime, it can be estimated that the total cadmium emissions connected to NiCd batteries for CPTs over its total lifetime is also approximately 1 % (by mass) of the cadmium contained in these batteries. This results in an amount of cadmium emissions of 22 tonnes connected to the 2,200 tonnes of cadmium brought into the European Union in 2008 by NiCd batteries for CPTs. A big share of these emissions occurs outside the European Union e.g. during processes related to mining, processing, manufacturing and transport of the cadmium.

Irrespective of these considerations, **NiCd batteries used in Europe in CPTs are responsible for 10.5 % of the total cadmium which is brought into the economy worldwide intentionally**. A ban of NiCd batteries in cordless power tools (CPT) would substantially reduce the amount of cadmium annually brought into the European economy and used in everyday products and the corresponding risk of cadmium releases to the environment.

Current market developments let expect that the NiCd batteries would be replaced by NiMH batteries in existing cordless power tools and by Li-ion batteries in new cordless power tools. This would for some years increase the nickel- and mischmetal-alloy (rare-earth) turnover and on the long term the cobalt, lithium and fluorine turnover.

The high chemical reactivity of the Li-ion system in general and of lithiumhexafluorophosphat ($LiPF_6$) in particular is a matter of concern especially for the collection and treatment of power packs and power pack containing waste.

Economic impacts

(1) Raw material suppliers

A replacement of all NiCd batteries used in CPTs worldwide by NiMH batteries would increase:

- The cobalt market by 2.5 %
- The lithium market by 1.8 %
- The nickel-market by 1.0 % and
- The rare-earth-market by 4.1 %

A replacement of all NiCd batteries used in CPTs worldwide by Li-ion batteries would increase:

- The cobalt market by 8 % and
- The lithium market by 3.4 %

The analysis of the corresponding markets has shown that for all mentioned materials the reserves are large enough to guarantee enough supply for the decades to come. Due to the concentration of the exploitable and production ores in few countries (cobalt in the Democratic Republic of Congo and China, lithium in Chile, and rare-earth oxides in China), however, high future price volatilities for cobalt, lithium and rare-earth oxides have to be expected.

Primary cadmium is generally not mined on its own but recovered as a by-product from zinc concentrates [USGS 2009]. Relevant impacts on miners are not expected.

(2) Battery manufacturers

SAFT is the last European producer of NiCd cells. SAFT does not produce any more NiCd cells for batteries intended for the use in CPTs. All NiCd batteries used in CPTs are imported to the EU, mainly from Asia.

In any case the rechargeable NiCd-market is shrinking, leading to shrinking profit margins. Thus, on the medium to long term, NiCd batteries for cordless power tools (CPTs) has no good business perspectives even if it is not banned. A ban of NiCd batteries for CPT would only accelerate an existing development.

If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) it can be expected that a ban of NiCd batteries for CPTs may contribute to the creation of new jobs in the manufacturing of current and future substitutes. A ban might support the market development.

(3) CPT manufacturers

There could be a relevant economic impact on CPT manufacturers if the use of substitutes would make the appliances less attractive to potential purchasers. However, as the technical performance of NiMH or Li-ion batteries is usually equal or better compared to NiCd batteries and the expected cost increase for CPTs is low to moderate[6] it is not expected that CPT appliances will become significantly less attractive if NiCd batteries for CPTs will be banned.

- A ban of NiCd batteries for CPTs would, on the one hand, cause costs for CPT manufacturers to technically adapt assembly lines due to changing from NiCd battery technology to Li-ion systems (approximately 60 million € one time costs in Europe);
- reduce turnover of CPT manufacturers due to a shortened natural product life cycle for some NiCd based CPT models (not quantified);

on the other hand, however,

- increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for more powerful and expensive CPTs (ranging from 65 to 326 million €/year and including all costs for required system changes; these costs will decrease over the years);
- increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for the replacement of charging equipment for existing tools (approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced).

The European CPT market is already in the transitions towards Li-ion battery technology as the most important energy source for CPTs. However, without a ban of NiCd battery application for CPTs this transition will likely be long lasting and incomplete. It is to be expected that imported cheap NiCd battery driven CPTs would stay on the market for a long time without such a ban.

The NiCd batteries ban for CPTs could support the transition of the European CPT industry towards the Li-ion technology and (due to the properties of Li-ion batteries) allow CPT producers to develop new, more powerful applications, to develop new markets, to generate more revenue and to create new jobs.

Industry expects non-quantified economic and social impacts on EU CPT battery pack assemblers because their business would be taken over by Asian companies if NiCd batteries would be banned for CPTs.

(4) Consumers

The cost increase of retail prices for CPTs depends on the lifetime of the used battery technologies. According to different information sources the lifetime of Li-ion batteries ranges from 4.3 (source: [EPTA 2009b]) to 7 years (source: [BOSCH 2009a]). The final consumer over the lifetime of the

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[6] Li-ion driven CPT systems are 10 to approximately 50% more expensive compared to NiCd systems.

cordless power tool (CPT) has to pay 57 % more in Euros (€) with NiMH than with NiCd systems, and 49 % more in Euros (€) with Li-ion than with NiCd-systems, when assuming that the life-time of the NiMH and of the Li-ion power packs are 4.2 and 4.3 years respectively. When, however, the actual lifetime of the Li-ion power packs after regular use is 7 years, the final consumer has to pay only 10 % more in Euros (€) with Li-ion than with NiCd, while having a lighter tool and, at least in the beginning, power packs which need to be recharged less frequently.

When assuming that the additional costs for Li-ion battery systems are 10 to 49 % compared to NiCd systems, the additional costs for final consumers caused by a ban of NiCd-batteries in cordless power tools (CPT) lie between 65 and 326 million €/year.

It, however, needs to be stressed, that:

- that part of the additional costs is caused by the necessary system changes (such as product development and waste management) and will become smaller over the years and,
- that part of the additional costs for final consumers is for the benefit of cordless-power-tool-producers in Europe.

(5) Waste management sector

Waste amounts resulting from the use of NiCd batteries and Li-ion batteries in CPTs depend on the lifetime of the Li-ion technology. When the lifetime of Li-ion batteries according to the more conservative estimation by [EPTA 2009b] is 4.3 years, this would lead to a mass increase of 12 % as compared to NiCd batteries, if the lifetime is the same as NiCd batteries (= 7 years) as stated by [BOSCH 2009a], the mass of the Li-ion batteries would be 30 % less than the mass of NiCd batteries. Relevant economic impacts due to altered amounts of waste to be treated are therefore not expected.

Additional costs may however be considered for the disposal of NiCd batteries as hazardous waste (costs are estimated in a range from 0.26 to 0.4 million €/year on average over a period of 10 years).

In the waste management sector, the three European companies which today recycle NiCd batteries (Accurec from Germany; SAFT and SNAM from France) would be most affected. The estimates range from 20 to 30 million €/year loss of turnover and loss of 70 to 90 workplaces.

A ban of NiCd batteries for CPTs would cause a slow disappearance of waste NiCd batteries from the recycling market. The recycling of NiCd batteries would have to continue for several years for decreasing amounts of NiCd batteries.

The amount of waste from NiCd batteries for 2008 is estimated to amount to 16 500 tonnes. Due to a current slowly reduction of ~ 1.6% per year the amount for 2010 is estimated to amount to 16 000 tonnes. This can be considered the current amount of NiCd batteries waste.

A scenario of the future quantities of NiCd batteries waste after a NiCd battery ban in CPTs is shown in Table 0-2. The NiCd battery waste would go down continuousely after 2010 and almost become 0 in the year 2026. It, however, has to be noted, that only part of the battery waste arisings is collected separately and treated for recycling.

Table 0-2 : Scenario of NiCd battery waste arisings from CPTs in Europe after a NiCd ban in CPTs in 2010

Year	2010	2015	2020	2025	2030
Amount of NiCd-battery waste in tonnes/year	15,986	10,272	5,210	817	0

Part of the market share of NiCd recyclers would shift to recyclers of other battery-types.

In the medium term the waste management sector may profit from the elimination of one of the most hazardous substances they have to deal with.

Social impacts

According to Recharge [2009b], the recycling industry expects to lose 70 to 90 jobs if a NiCd battery ban for cordless power tools (CPT) becomes effective, as there are 70 to 90 employees which work exclusively for the recycling of NiCd batteries. However, also the majority of Li-ion-battery types contain valuable materials worth for being recycled. Therefore, it is expected that jobs lost for the recycling of NiCd batteries would be related to the creation of jobs for the recycling of Li-ion batteries. Thus in balance no negative impact for the jobs in the overall recycling industry is expected.

If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion batteries) this may contribute to the creation of new jobs in battery manufacturing (not quantified).

The CPT industry will profit from the increased costs for consumers. It is expected that the corresponding additional turnover will among other be related to the creation of new workplaces (not quantified).

In total the authors estimate that by a NiCd battery ban for cordless power tools (CPT) more jobs will be created than lost.

Impacts on management of risks

Currently about 2,200 tonnes of cadmium are imported yearly into Europe by the NiCd-batteries used in cordless power tools (CPT). This is by far the biggest source for intended cadmium imports and mobilisation.

As a consequence of a ban of NiCd batteries in CPTs in Europe:

- The intentional world extraction of cadmium from primary resources would be reduced by more than 10 %;
- The emissions of cadmium during the extraction and processing of cadmium, as well as during the preparation of the nickel-cadmium (NiCd) cells would be reduced accordingly;
- The cadmium content in residual household waste would be reduced in a range between 50 % [according to EC 2003b] and 75 % [according to CEU 2004];

- The cadmium emissions from waste incineration and landfills would be reduced by between 50 % [according to EC 2003b] and 75 % [according to CEU 2004]

This will reduce the health risk for thousands of people and the environmental risk (partly in Europe but more importantly in the countries of cadmium and NiCd-cell production) to a big extent.

However, also the alternatives to NiCd batteries contain hazardous substances. In addition to the heavy metals nickel, cobalt and rare-earth metals the fluorine containing electrolytes of the Li-ion-battery are of concern.

Li-ion batteries are more and more in use in the segment of entertainment and information technology. Therefore a ban of NiCd batteries would only strengthen a trend towards more Li-ion batteries which develops anyway. Risk management has to acknowledge this trend and to care for high safety standards in the production, retail, use, collection and treatment after use of Li-ion batteries. A high separate collection rate spent Li-ion batteries (and other batteries) is an important contribution of keeping the risks connected to these technologies at bay.

Conclusions

From the point of view of the environment, a NiCd ban would eliminate cadmium as the most hazardous substance from the portable battery segment and to a large extent (between 50 % (according to [EC 2003b]) and 75 % (according to CEU [2004]) reduce the concentration of the very toxic cadmium in waste streams which contain battery wastes, such as the residual fraction of municipal solid waste.

The cadmium would be replaced by less toxic, but partially still harmful substances such as nickel, cobalt, rare-earths or fluorine containing compounds. These (besides nickel) new substances require adaptations by the waste management sector. Due to the fast market penetration of Li-ion batteries in information- communication and entertainment technologies, these adaptations are required in any case (that is with or without NiCd ban).

The efficiency of the collection of spent NiCd batteries used in cordless power tools (CPTs) is a critical factor to maintain the control of the flow of these batteries in the economy and to avoid high environmental impacts. With currently achieved collection rates (estimation for NiCd battery collection rates in Germany lie between 38 and 44%, see chapter 5.4.1) the majority of the very toxic cadmium contained in NiCd batteries is not treated in specialised battery treatment plants. The only long-term efficient measure to limit the cadmium release from NiCd batteries into the environment is a ban of NiCd batteries also in its use in cordless power tools.

In total the authors conclude that a ban of the application of NiCd batteries in cordless power tools:

- would be of substantial benefit for European health and environment;
- would not be related to substantial technical problems (only in applications where the temperature lies below 0°C additional equipment to warming the Li-ion batteries before start up might be necessary);

- would not cause inacceptable economic[7] and social impacts[8];
- could support the economy to be more competitive and to gain higher profit margins[9].

The expected benefits from a ban of NiCd batteries for application in cordless power tools (CPTs) exceed its costs.

In order to achieve all environmental benefits from keeping batteries out of the household waste streams both are necessary:

- A ban of the most hazardous substances and
- High battery collection and recycling rates.

This is also in line with the waste hierarchy as specified in the Waste Frame Directive (2008/98/EC).

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[7] The identified quantifiable costs for final consumers are additional annual costs of 65 to 326 million €/year for the more expensive Li-ion battery based CPT systems. A part of these additional costs will be used to cover the one time adaptation costs for final consumers, CPT manufacturers, waste management and recycling ranging from 107 to 128 million €. The corresponding quantifiable one time benefits sum up to a range from approximately 45 to 64 million €. The health benefits are estimated to amount up to 25 billion €/year. The environmental benefits could be in a comparable range. Without taking account of any health and environmental benefits the expected one time cost benefit ratio ranges from approximately 1 to 2. Taking also the expected health and environmental benefits into account, it can however be assumed that the overall cost benefit ratio lies significantly below 1 because health and environmental benefits related to a ban of cadmium in batteries for the use in CPTs are expected being significantly higher than the corresponding costs.

[8] It is expected that job losses will be balanced out by the creation of new jobs.

[9] The EU CPT manufacturers could profit from the additional costs for final consumers ranging from 65 to 326 million €/year. A NiCd battery ban for CPTs could accelerate the transition to the Li-ion technology.

The results of this study are compared to the conclusions of four other NiCd impact assessment studies:

- The study “Impact Assessment on selected Policy Options for Revision of the Battery Directive“ from Bio Intelligence Services published in 2003 [Bio 2003],
- The Extended Impact Assessment of the Batteries Directive published by the European Commission in 2003 [EC 2003],
- The “Impact assessment of key Council amendments to the Commission proposal for a Batteries Directive” from Council of the European Union published in 2004 [CEU 2004],
- The report “Cadmium in power tool batteries - The possibility and consequences of a ban” from the Swedish Environmental Protection Agency, published in 2009 [SE EPA 2009].

The comparison is shown in Summary Table 0-3.

The impacts of a NiCd battery ban in cordless power tools (CPT) on the different concerned actors is shown in Summary Table 0-4.

Summary Table 0-3 : Impacts related to a ban of NiCd batteries in cordless power tools (CPT) expected by different sources

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
Environmental Impacts					
- NiCd batteries are an important source of cadmium circulating in the economy - Impact of NiCd ban - Total environmental impact of NiCd ban for cordless power tools (CPT)	A ban has no relevant impact on general human cadmium exposure. Portable NiCd batteries may pose relevant environmental risks, these may be reduced due to a partial ban: (a) possible risk due to air emissions; (b) Cd concentration levels in sediment already cause adverse effects; (c) non-EU-conform landfills pose risk for groundwater.	The amount of total cadmium releases during the life-cycle of NiCd batteries is 607 to 2,566 kg per year (in EU-15) The replacement of NiCd batteries by NiMH and Li-ion batteries would result in decreased environmental impacts.	NiCd batteries account for 75% of the total use of refined cadmium in products on the market within the Community. Refined cadmium accounts for a small proportion of total discharges of cadmium to the environment, with the application of fertilizer being the main source. Batteries create a risk of releases of cadmium to the environment during production and, more significantly, disposal of NiCd, particularly via incineration residues and inputs to groundwater from landfill sites. Estimate for 2002 indicate that 2000 tonnes of portable NiCd batteries end up in the MSW stream and cause the input of 13 to 66 kg cadmium to groundwater.		[EC 2003] figures may not include emission during mining and processing in foreign countries. European NiCd batteries in cordless power tools (CPT) are responsible for 10.5 % of the total cadmium which is brought into the economy worldwide intentionally. Thus it is expected that a ban has a relevant impact on human cadmium exposure. When NiCd batteries would be replaced in European Cordless Power Tools, 2,200 t/year of very toxic accumulating and category 2 carcinogenic cadmium would be replaced by other, generally less hazardous substances. NiCd batteries create a risk of releases of cadmium to the environment during production and, more significantly, disposal of NiCd batteries. It is estimated that from 2,200 tonnes of cadmium annually imported to the EU in NiCd batteries for CPTs 22 tonnes are released per year to the environment during the life cycle

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					The replacement of NiCd batteries by NiMH and Li-ion batteries would result in decreased health and environmental impacts. The monetarisation of the environmental and health benefits of a ban of NiCd batteries is related to high uncertainties. However it is estimated that the benefits are 1 to 2 orders of magnitude higher than the corresponding costs.
Recycling instead of a ban for NiCd batteries in CPTs			The Commission's proposal (a specific collection target for portable NiCd batteries of 80% of the amount of such batteries collected and disposed of) implies that up to 20% of NiCd batteries - or more than 400 tonnes based on the estimate mentioned above - would continue to be disposed of with MSW year on year. A partial ban would stop several hundred tonnes of NiCd batteries ending in MSW each year.	A considerable amount of cadmium is used in batteries for cordless power tools (CPT). Even if the collection of spent batteries lives up to the requirements of the Battery Directive which is 45 % collected by 2016, this means that more than half of all the cadmium in portable batteries will not be collected and dealt with in a secure fashion. The consequence of a ban would be that the cadmium leakage into the environment from spent batteries would decrease and would, in	An 80 % recycling target seems to be rather optimistic when compared to recycling rates of established systems and is no substitute for a NiCd-ban.

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
				the long term, cease.	
Economic impacts					
Risks for mining industry				The mining industry considers itself as a secondary stakeholder and will not be significantly affected by a ban on cadmium in batteries for cordless power tools	Cadmium is produced only as by-product. Therefore the mining industry will not be significantly affected.
Risks for producers of NiCd batteries	There is a risk of side effects for the NiCd batteries industry on other segments of the NiCd batteries	Industry estimates that a turnover of approximately € 1 billion is generated by the NiCd battery production activities. However, since the policy option is only limited to a small part of the NiCd battery market, the economic impacts for the manufacturers are expected to be less than this.	It is unclear whether there is any significant economic impact on EU producers of nickel and cadmium. SAFT is the last European producer of NiCd batteries with plants in DE, FR, ES, SE. Production of NiCd batteries in the EU concerns mainly industrial NiCd batteries. A ban on portable batteries should therefore not have a large direct impact on EU battery manufacturers.	A ban on NiCd batteries for use in CPTs in Europe will probably mean that NiCd batteries, which are currently produced to a certain extent in Europe, will be replaced by Li-Ion batteries produced in Japan.	The last European producer SAFT does not produce portable NiCd batteries for use in CPTs anymore. If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) this may contribute to the creation of new jobs in the manufacturing of current and future substitutes.
Risks for producers of cordless power tools (CPT) and other suppliers	There is a risk of domino effect for importers, assemblers and incorporators		There could be a relevant economic impact on manufacturers of appliances that include batteries (e.g. CPT manufacturers) if the use of substitutes would make	Manufacturers and retailers of CPT expect partly positive impacts (speed up of the development of other battery types, especially Li-ion) and partly	In total the market is a dynamic and an increasing market (with respect to numbers of cells and value). A ban of NiCd batteries for CPTs could: • Cause costs to technically

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
			the appliances less attractive to potential purchasers.	negative impacts (problems due to the replacement of batteries in older machines).	adapt assembly lines due to changing from Ni-Cd battery technology to Li-ion systems (approximately 60 million € one time costs) • reduce turnover of CPT manufacturers due to a shortened natural product life cycle for some NiCd based CPTs (not quantified) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for more powerful and expensive CPTs (ranging from 65 to 326 million €/year and including all costs for required system changes; these costs will decrease over the years) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for the replacement of charging equipment for existing tools (approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced) The NiCd batteries ban could support the transition of the European industry towards more

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					profitable products. Producers of cordless power tools (CPT) see Li-ion-technology as chance.
Risk for professional users				Professional users will not be affected by a ban of NiCd batteries in CPT. Interviews with professional users in northern Sweden indicate that the battery type is not relevant for them. Important are factors such as brand name, performance, capacity and the weight of the CPT	Professional users will not be affected
Risks for waste management sector and recyclers			A ban on portable NiCd batteries could affect the European recyclers of NiCd batteries. However, the factories concerned do not process only portable NiCd batteries, but also industrial NiCd batteries and other types of Nickel batteries.	Recyclers of NiCd batteries do not regard a possible ban of NiCd batteries for CPT as a problem. Management of surplus cadmium may be necessary.	The three European NiCd recycling companies (Accurec, Germany; SAFT, France; SNAM, France) would be affected. The estimates range from 20 to 30 million €/year loss of turnover. A ban of NiCd batteries for CPTs would cause a slow disappearance of waste NiCd batteries from the recycling market. The recycling of NiCd batteries would have to continue for several years for decreasing amounts of NiCd batteries. Part of the market share of NiCd recyclers would shift to recyclers

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					of other battery-types. In the medium term the waste management sector may profit from the elimination of one of the most hazardous substances they have to deal with.
Market distortion	Risk of market distortion if NiCd batteries are e.g. imported with equipment due to deficient control				May exist for no-name products. Not expected to be relevant.
Costs due to higher prices of substitutes	Yes	Substitutes for NiCd batteries in household appliances are more expensive than the NiCd batteries and have a shorter life-time, so this policy option could result in a price increase for rechargeable batteries used in household appliances for consumers. Estimates for additional costs for consumers range from 825 to 1,995 million € per year. The additional costs related to the fact that more waste is to be treated are estimated between 0 and 1.3 million €.	The principal reason why NiCd batteries retain a large market share for cordless power tools (CPT) for DIY users is their lower purchase price. The EIA (Environmental Impact assessment) quotes, in relation to the policy option of a complete cadmium ban, a Bio Intelligence estimate of additional annual costs for consumers of between € 825 and 1,995 million, equivalent to a rough additional cost per year per head of population of somewhere between € 2 and € 5. These figures are based on the dual assumption that portable NiCd batteries are cheaper	The price of a CPT is important for private persons buying a CPT	10 to 50 % higher life-cycle costs of Li-ion systems as compared to NiCd systems Additional costs for final consumers for more powerful and expensive CPTs range from 65 to 326 million €/year. This includes all costs for required system changes. These costs will decrease over the years) Additional costs for final consumers for the replacement of charging equipment for existing tools (costs amount to approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced).
Cost due to more frequent replacement of equipment					

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
			than those using substitute technologies and that they have a longer lifespan. However, these assumptions are open to challenge. The higher capacity of NiMH batteries compared to NiCd combined with equal charging cycles more than compensates the initial sales price. This means that the mentioned additional costs would not actually occur. Additional costs may arise due to the necessary replacement of chargers. Consumers often buy new appliances before they need to replace their batteries. In this case extra costs will not occur.		
Costs for waste treatment due to higher amounts of waste to be treated	Yes				Waste amounts resulting from the use of NiCd batteries and Li-ion batteries in CPTs depend on the lifetime of the Li-ion technology. When the lifetime is 4.3 years (as assumed by [EPTA 2009b]), this would lead to a mass increase of 12 % as compared to NiCd, if the lifetime is the same as NiCd (= 7 years), the mass of the Li-ion batteries

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					would be 30 % less than the mass of NiCd. Relevant economic impacts due to altered amounts of waste to be treated are therefore not expected. Additional costs may arise for the disposal of NiCd batteries as hazardous waste (in a range from 0.26 to 0.4 million €/year on average over a period of 10 years).
Costs to implement and monitor a control system	Yes				Monitoring and control costs for the NiCd ban in addition to the monitoring and control costs of the other Battery-Directive-requirements are expected to be irrelevant.
Social impacts					
Job creation	Job creation for production of substitutes and control system	Job creation for production of substitutes and control system			If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) this may contribute to the creation of new jobs in battery manufacturing (not quantified). The CPT industry will profit from the increased costs for consumers. This may be used for the creation of new workplaces (not quantified). Li-ion driven cordless power tools

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					(CPT) are manufactured by European companies and may create jobs (not quantified). Job creation is possible in the recycling of technical substitutes particularly in the case of Li-ion batteries (could be in the range of job losses in NiCd recycling, i.e. between 70 and 90 workplaces).
Job losses	Job losses at production, assembling, incorporation, distribution Impacts on indirect jobs. Risk of outsourcing of production outside the EU	The EU produces approximately one third of the global cadmium production and exports 40% of it. Industry estimates a job loss of 10,000 jobs in the zinc and cadmium production industry if a general cadmium ban in all battery applications were to be implemented. Furthermore, industry claims that 3,500 people are directly employed by NiCd battery producers in the EU. However, as all producers also produce the substitutes to the portable NiCd batteries in household appliances (such as NiMH and Li- ion batteries), this policy	Social impacts depend on whether the direct or indirect impacts will lead to job losses.		Europe in 2008 covered only 4.7 % of the world cadmium refinement (USGS 2009). Cadmium is produced as by-product and not on its own. A number of 70 to 90 workplaces will be lost at EU recyclers of NiCd batteries. It can be expected that job losses in the NiCd recycling sector will be balanced by new jobs related to the recycling of NiCd battery substitutes. NiCd batteries for CPTs are not produced within the EU. Impacts on workplaces in the EU batteries industry are not expected. No job effect is expected in the mining sector.

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
		option might eventually have limited negative effects on employment.			

Summary Table 0-4 : Concerned actors and identified relevant impacts related to a ban of cadmium in batteries (n.r. = not relevant)

Actors	Expected impacts
(A) Raw material supplier for battery manufacturers (in particular Ni, Cd, Li, Co and Mn industry)	Only a small part of the primary metals used in rechargeable batteries originate from Europe. Thus the impact will be mostly outside Europe. A ban would cause a shift from cadmium refinement to the mining of other metals. As cadmium is mined only as by-product of zinc-mining the effect on raw material suppliers will be small. With respect to cobalt and lithium (contained in Li-ion batteries) primary reserves are concentrated in few countries. Therefore high price volatilities are to be expected. However, there are also mature Li-ion technologies without cobalt.
(B) Operational equipment manufacturer (OEM) for battery manufacturers	n.r.
(C) Battery manufacturer of portable NiCd, NiMH, Li-ion and other technical substitutes (including manufacturer of battery packs for CPTs)	All NiCd batteries used in CPTs are imported to the EU, mainly from Asia. Economic or social impacts on the EU batteries industry are not expected. If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) this may contribute to the creation of new jobs in the manufacturing of current and future substitutes. European production of NiMH and Li-ion must take efforts to get a sustainable market share. A ban of NiCd might be of help for the market development.
(D) Battery retailer	n.r.
(E) DIY consumers of CPTs	Dependent on the actual lifetime of the Li-ion batteries, Li-ion-based cordless power tool systems are 10 to 50 % more expensive than the NiCd-based systems. Additional costs for final consumers for more powerful and expensive CPTs range from 65 to 326 million €/year. This includes all costs for required system changes. These costs will decrease over the years) Additional costs for final consumers for the replacement of charging equipment for existing tools (costs amount to approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced). However, the Li-ion may prove to be more comfortable for the user (lighter, no full discharge required, less frequent charging, more powerful tools).
(F) Professional consumers of CPTs	
(G) Battery collector	n.r.

Actors	Expected impacts
(H) Battery recycler	The three European NiCd recycling companies (Accurec, Germany; SAFT, France; SNAM, France) would be affected. Estimates range from 20 to 30 million €/year loss of turnover related to 70 to 90 workplaces. A ban of NiCd batteries for CPTs would cause a slow disappearance of waste NiCd batteries from the recycling market. The recycling of NiCd batteries would have to continue for several years for decreasing amounts of NiCd batteries. It can be expected that job losses in the NiCd recycling sector will be balanced by new jobs related to the recycling of NiCd battery substitutes.
(I) Disposal company that disposes of waste from battery recycling	Treatment of landfill leachate for cadmium may be eliminated. However, additional efforts for fluoride monitoring and control may be necessary.
(J) Raw material supplier for CPT manufacturers	n.r.
(K) Operational equipment manufacturer (OEM) for CPT manufacturers	n.r.
(L) CPT manufacturer (including importer, assembler, battery incorporator)	In total the market is a dynamic and an increasing market (with respect to numbers cordless power tools (CPT) and value). A ban of NiCd batteries for CPTs could: • cause costs to technically adapt assembly lines due to changing from Ni-Cd battery technology to Li-ion systems (approximately 60 million € one time costs) • reduce turnover of CPT manufacturers due to a shortened natural product life cycle for several CPTs (not quantified) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for more powerful and expensive CPTs (ranging from 65 to 326 million €/year and including all costs for required system changes such as product development and waste management; these costs will decrease over the years) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for the replacement of charging equipment for existing tools (approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced) The NiCd batteries ban could support the transition of the European industry towards more profitable products. Selected producers of cordless power tools (CPT) see Li-ion-technology as chance. Industry expects non quantified economic and social impacts on EU battery pack assemblers.
(M) CPT retailer	Depends from impacts on CPT manufacturer
(N) CPT collector	n.r.
(O) CPT recycler	n.r.

Actors	Expected impacts
(P) Disposal company that disposes of waste from CPT recycling	n.r.
(Q) Society and Environment	The replacement of NiCd batteries by NiMH and Li-ion batteries would result in decreased health and environmental impacts. The monetarisation of the environmental and health benefits of a ban of NiCd batteries is related to high uncertainties. However it is estimated that the benefits are 1 to 2 orders of magnitude higher than the corresponding costs. In total the NiCd ban will have either no effect on the jobs in Europe or a positive effect by supporting more innovative and profitable products (batteries and cordless power tools). The additional costs for the consumers are only partly caused by material costs. It can be assumed that parts of the additional costs create opportunities, profit and jobs for cordless power tool producers and battery producers. From the environmental point of view the NiCd ban is seen as the most efficient instrument to take one of the most hazardous substances out of the economic cycles in substantial quantities. This will not only be of benefit for health and environment but also make waste management to some extent less complex.
(R) Public authorities	Monitoring and control costs for the NiCd ban in addition to the monitoring and control costs of the other Battery-Directive-requirements are expected to be irrelevant.

Content

Abbreviations

AlkMn	Alkaline-manganese-battery
CAS	Chemical Abstracts Services
CPT	Cordless power tools
DEC	Dietyhl carbonate
DIY	Do-it-yourself
DMC	Dimethyl carbonate
DMFC	Direct Methanol Fuel Cell
EC	Ethylene carbonate
EDLC	Electric Double Layer Capacitors
EPTA	European Power Tool Association
EV	Electric vehicles
HEV	Hybrid electric vehicles
Li-ion	Lithium-ion-rechargeable-battery
Li-poly	Lithium-polymer- rechargeable-battery
MAK-value	Maximum working place concentration
MEC	Methyl ethyl carbonate
MH	Metal hydride
MIT	Massachusetts Institute of Technology
OSHA	U.S. Occupational Safety and Health Administration
OEM	Operation Equipment Manufacturer
PBA	Portable batteries and accumulators
PEL	Permissible exposure limit
PEM	Proton Exchange Membrane (Fuel Cell)
PVDF	Poly(vinylidene fluoride)
PVDF-HFP	Poly-(vinylidene fluoride – hexafluorpropene)
RAM	Rechargeable alkaline manganese battery
RECHARGE	International association for the promotion and management of portable rechargeable batteries through their life cycle
SAFT	Société des Accumulateurs Fixes et de Traction (Saft S.A.)
SEI	Solid electrolyte interface
SMES	Superconducting Magnetic Energy Storage
SNAM	Societe Nouvelle d' Affinage des Metaux

TDT	Total discharge time
TRAR	Targeted Risk Assessment Report
TRK-value	Technical compliance concentration
UPS	Uninterruptable Power Supply

The following abbreviations are part of the International System of Units (abbreviated **SI** from the French *le **S**ystème **i**nternational d'unités*)

Physical Measures According to SI

C	Nominal capacity of a battery in Ampere-hour (Ah)
I	Electric current
P	Electric power
Q	Electric charge
R	Electrical resistance
V	Electromotive force, commonly called "voltage"
W	Energy

Physical Units According SI

A	Ampere (unit of electric current)
Ah	Ampere-hour (unit of electric charge)
mS/cm	Milli-Siemens per centimetre (unit of electrical conductivity)
V	Volt (unit of electromotive force, commonly called "voltage" and of electric potential difference)
W	Watt (electric power unit)
Wh	Watt-hour (electric energy unit)

Abbreviations of Chemical Substances According to the Periodic System of Elements

C	Carbon
Cd	Cadmium
Co	Cobalt

F	Fluorine
Fe	Iron
H	Hydrogen
HF	Hydrogen fluorine (fluoric acid when dissolved in water)
Li	Lithium, lithium-battery
$LiPF_6$	Lithium hexafluorophosphate
Mn	Manganese
Ni	Nickel
NiCd	Nickel-cadmium- rechargeable-battery
O	Oxygen
P	Phosphorous
ZnC	Zinc-carbon-battery

These internationally used abbreviations are used in the present report despite the fact that some abbreviations are identical. However, it can be understood from the context what an abbreviation stands for in each specific case.

1 Introduction

This report deals with cadmium containing portable batteries and accumulators as energy sources of cordless power tools (CPT) and alternative portable energy sources for the operation of cordless power tools. For the ease of reading this report will use the term batteries for both, batteries and accumulators.

Background

The Batteries Directive 2006/66/EC (repealing Directive 91/157/EEC) entered into force on 26 September 2006[10]. The Directive sets out rules applicable to all batteries and accumulators that are put on the European Union market.

These rules include, among others, restriction on the use of cadmium in portable batteries and accumulators (PBA) according to Article 4(1)(b) of the Directive. Portable batteries and accumulators, including those incorporated into appliances, that contain more than 0,002% of cadmium by weight shall not be placed on the market.

However, according to Article 4(3) of the Directive the above requirement shall not apply to portable batteries and accumulators intended for use in: (a) emergency and alarm systems, including emergency lighting; (b) medical equipment; or (c) cordless power tools.

Furthermore, based on Article 4(4) of the Directive the Commission shall review the exemption from the cadmium ban for use in cordless power tool with a view to the prohibition of cadmium in batteries and accumulators. The Commission shall submit a corresponding report to the European Parliament and to the Council by 26 September 2010, together, if appropriate, with relevant proposals. The review should be based on the experience of the application of the Directive, the developments in science and technology, environmental requirements, and the functioning of the internal market. It should assess the environmental, social and economic impacts in an integrated manner.

Already in the year 2000 about 25 % of all power tools were cordless [Rentz et al. 2001]. The current share is estimated at 36% [EPTA 2009a]. Examples of cordless power tools are tools that consumers and professionals use for turning, milling, sanding, grinding, sawing cutting, shearing, drilling, making holes, punching, hammering, riveting, screwing, polishing or similar processing of wood, metal and other materials, as well as for mowing, cutting and other gardening activities. Due to frequently upcoming new appliances the market for cordless power tools is constantly changing. In several of the cordless power tool applications cadmium free alternatives are used. However, in some applications the share of cadmium batteries is still high.

Cordless power tools are currently operated with rechargeable portable NiCd, Li-ion or NiMH batteries. According to different information sources, in 2008 the share of these battery chemistries in the cordless power tool market were in the ranges of 48 to 56% for NiCd, 30 to 37 for Li-ion and 7 to 22% for NiMH technologies. The trend for NiCd batteries is decreasing whereas it is increasing for Li-ion batteries and more or less stable for NiMH batteries.

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[10] OJ L 266, 26.9.2006, p. 1., as last amended by Directive 2008/103/EC (OJ L 327, 5.12.2008, p. 7–8).

Objective

Based on this background the general objective of the study is to assess and synthesise available data and information, identify and address remaining needs with a view to assisting the Commission services with the review in prohibition of cadmium in batteries and accumulators intended for use in cordless power tools taking account of available technical and scientific evidence.

Contents of the study

The draft final report contains:

1) A detailed analyses of the market (EU and worldwide) of portable NiCd batteries and its commercially available technical substitutes intended for the use in CPT. Technical substitutes other than NiMH and Li-ion batteries which are mature enough and show the technical properties required by cordless power tools have not been identified in the technical assessment. A relevant market for such alternatives does not exist (chapter 3);
2) An assessment which new technical substitutes are likely to be developed in the future (chapter 4);
3) An assessment whether from a technical point of view, the use of cadmium in portable batteries and accumulators intended for the use in CPT can be limited to 0.002% of cadmium by weight, including a technical evaluation for each identified alternative on the market and in the pipeline (chapter 4);
4) An assessment of the environmental, economic and social impacts of the use of the (possible) cadmium substitutes in portable batteries and accumulators intended for the use in CPT (chapter 5);
5) A comparison of the identified impacts of the use of the cadmium substitutes with the impacts of the use of cadmium in portable batteries and accumulators intended for the use in CPT; for the latter impacts the analyses is built on the impact assessments and studies underpinning the Directive including the Commission’s and Council’s impact assessments[11] (chapter 5).

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[11] see http://ec.europa.eu/environment/waste/batteries/index.htm and http://register.consilium.eu.int/pdf/en/04/st14/st14372.en04.pdf

2 Methodology

Definition of cordless power tools

According to the Batteries Directive (2006/66/EC) Article 3(16) the term “cordless power tool” means any hand held appliance powered by a battery or accumulator and intended for maintenance, construction or gardening activities.

Examples of cordless power tools are tools that consumers and professionals use for turning, milling, sanding, grinding, sawing, cutting, shearing, drilling, making holes, punching, hammering, riveting, screwing, polishing or similar processing of wood, metal and other materials, as well as for mowing, cutting and other gardening activities (source: Batteries Directive, recital 11).

A non exhaustive list of current applications of cordless power tools is given in Table 3-4.

Definition of energy sources for cordless power tools and of portable batteries and accumulators

According to Article 3(3) of the Batteries Directive (2006/66/EC) the term “portable battery or accumulator” means any battery, button cell, battery pack or accumulator that:

(a) is sealed; and

(b) can be hand-carried; and

(c) is neither an industrial battery or accumulator nor an automotive battery or accumulator.

Examples of portable batteries and accumulators, which are all-sealed batteries and accumulators that an average person could carry by hand without difficulty and that are neither automotive batteries or accumulators nor industrial batteries or accumulators, include single cell batteries (such as AA and AAA batteries) and batteries and accumulators used by consumers or professionals in mobile telephones, portable computers, cordless power tools, toys and household appliances such as electric toothbrushes, razors and hand-held vacuum cleaners (including similar equipment used in schools, shops, restaurants, airports, offices or hospitals) and any battery or accumulator that consumers may use for normal household applications (source: Batteries Directive, recital 10).

Cordless power tools are currently operated with rechargeable portable NiCd, Li-ion or NiMH batteries (source: [Takeshita 2008]). Rechargeability is considered as technical requirement for technical substitutes of energy storage systems for cordless power tools. Primary (non-rechargeable) batteries are therefore not considered in the present report (for more details see chapter 4.2.1).

According to the project objective and related tasks the methodology to achieve the project objective is divided in five work packages (WP) as illustrated in Figure 2-1.

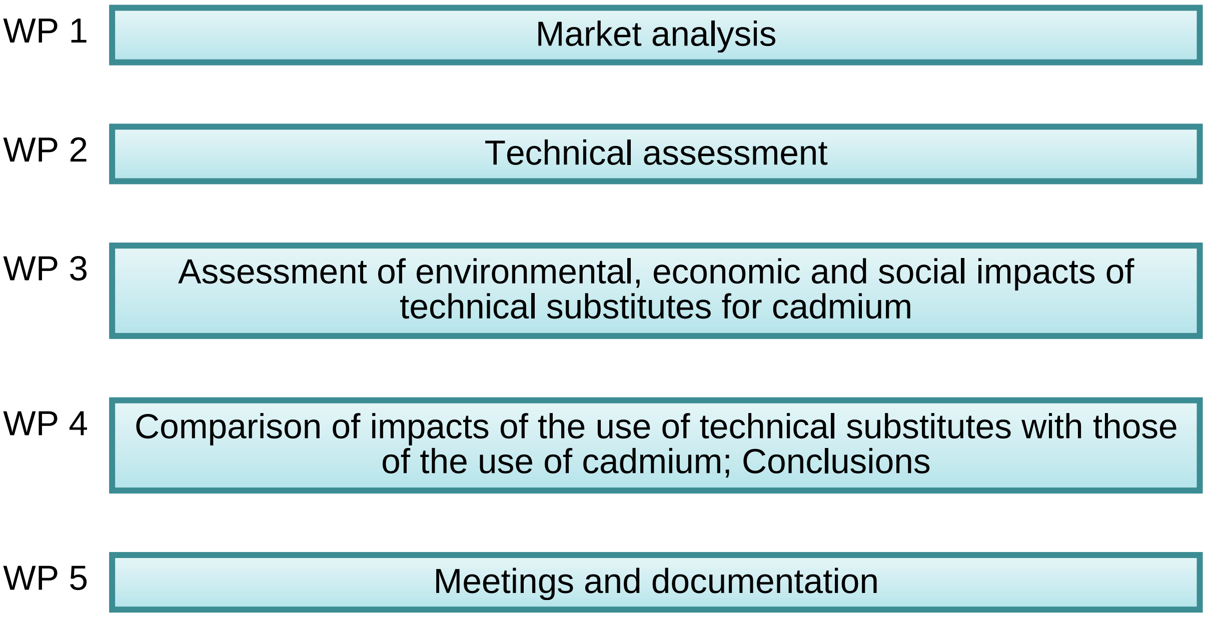

Figure 2-1: **Project work packages (WP)**

On the basis of specific properties as required for the use of batteries in cordless power tools a pre-selection of relevant alternatives is carried out. The selected alternatives will be subject to a subsequent market analyses and the assessment steps (technological assessment and impact assessment). The outcome of the market analyses and the assessment steps is the basis for the comparison of the impacts between the current status (no limitation for Cd-batteries used in cordless power tools) and a Cd limitation of 0.002% by weight for batteries used in cordless power tools (CPT). This approach is illustrated in Figure 2-2.

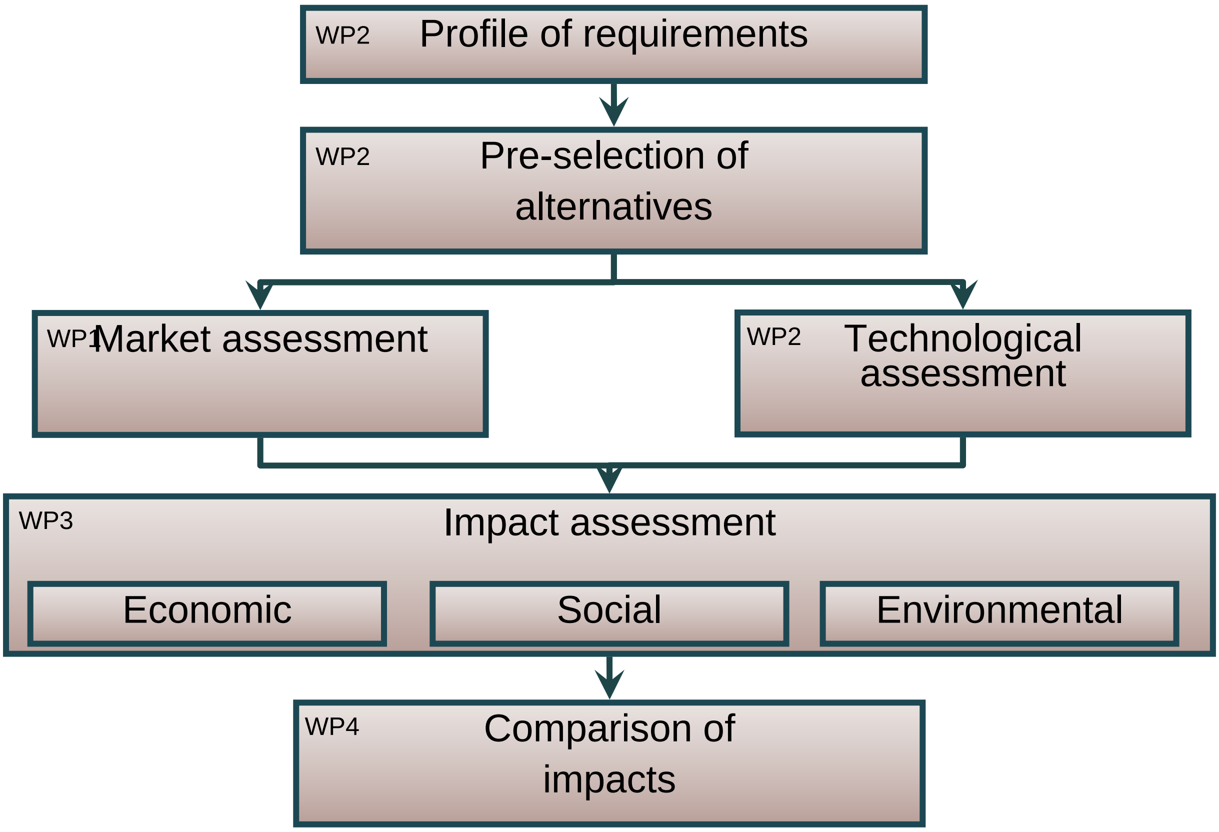

Figure 2-2 : **Illustration of the project approach**

3 Market analysis

3.1 Market of Portable Rechargeable Batteries Intended for Use in Cordless Power Tools

3.1.1 Characterisation of the Cordless Power Tool Market

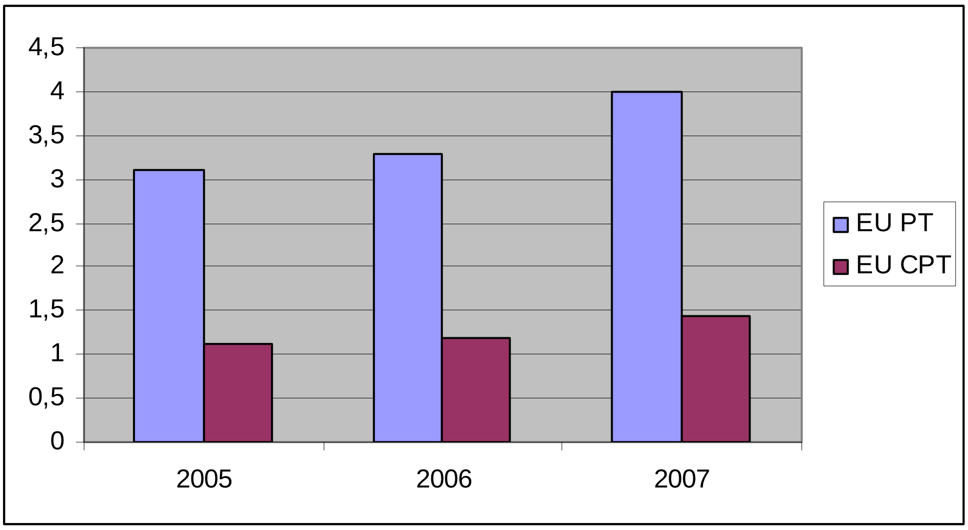

Figure 3-1 : **European market for portable electric power tools (PT) and cordless power tools (CPT) from 2005 to 2007 (market value in billion €; based on EPTA website)**

Figure 3-1 illustrates the development of the European market value for portable electric power tools (PT) and cordless power tools (CPT) from 2005 to 2007 in billion €.

The European market for portable electric power tools (PT) increased in 2005 by 2 percent to 3100 million € (source: EPTA website[12]).

In 2006, the worldwide market for portable electric power tools (PT) was approximately 8000 million €, of which 3300 million € is from Europe, 2900 million € from North America and 1400 million € from the Far East (source: EPTA website).

In 2007, the worldwide portable electric power tool (PT) market had a value of 8500 million € at 170 million sold units[13]. The biggest market was Europe with around 4000 million € (source: EPTA website).

It is estimated that in the EU and worldwide market currently 36% of the electric power tool market is related to cordless power tools (CPT). Accordingly in 2007, the worldwide market value for cordless power tools (CPT) is estimated at 3500 million €. The European market value of the cordless power tool (CPT) sector was 1440 million € [EPTA 2009a].

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[12] source: http://www.epta.eu/Home.AxCMS?ActiveID=1029 (accessed on 21.8.2009)

[13] estimation according to [EPTA 2009a]: global turnover for total power tools 9500 million €

According to an EPTA forecast from January 2008 it was expected that in 2008, the market growth in Europe will slow down, which partly results from the collapse in the construction industry in Spain and Italy, and the real estate development in Great Britain that is similar to the one in the USA. For 2008, a worldwide growth of 2.5 percent of the market value is expected for the power tool market in general. For 2009 though, the market development is seen rather sceptical in comparison with the prospects for 2008, from today's (note: beginning of 2008) point of view (source: Press release EPTA: Pr – 02/2008).

The market for CPT is estimated to grow at 5% per year from 2010 to 2020 [EPTA 2009e].

Table 3-1 : **Overview on the worldwide and regional market development of corded and cordless electric power tools (market value in billion €; sources: [EPTA 2009a], [EPTA 2009d] and EPTA website)**

Market (billion €)	2004	2005	2006	2007	2008
Worldwide portable electric power tools (PT)			**8.0**	**8.5**	
Europe		3.1	3.3	4.0	4.3*
North America			2.9	3.0	2.5*
Far East			1.4		
Worldwide cordless power tools (CPT)				**3.5**	
Europe		1.05	1.1	1.44	1.5*

* indicative figures that are subject to assumptions, such as exchange rates, sector classifications etc.

Table 3-1 shows the data that are available from EPTA on the worldwide and regional market development of corded and cordless electric power tools.

Cordless power tools (CPT) are powered by rechargeable batteries. They are the fastest growing segment of the sector and have been so for many years. While sales of corded tools have maintained modest growth, cordless products have grown at twice the rate of corded tools, depending on the market segment [EPTA 2009d].

Table 3-2 : **Overview on the 2007 market of professional and DIY cordless power tools (market value in billion €; units in million units [EPTA 2009a]**

EU Market data	2007	
	(billion €)	(million units)
EU Market cordless power tools	1.44	13.3
EU Market professional cordless power tools	0.96	4,8
EU Market DIY cordless power tools	0.48	8,4

Cordless power tools (CPT) are used by professionals on the one hand and by "Do-it-yourself" (DIY) users. The EU average retail prices for a professional cordless power tools in 2007 was 198 € and for a DIY cordless power tools it was 57 € [EPTA 2009a]. In 2007 the professional cordless market was about twice the size of the DIY cordless market by value. According to the average retail prices, this translates to about 1.7 times as many DIY cordless products as for cordless products.[14] Table 3-2 gives an overview on the EU market of professional and DIY cordless power tools for the year 2007.

There is a considerable amount of international trade in this sector. It is estimated that approximately 65% - 70% of the European market by value is served by EPTA member companies. However, not all of these products were made in Europe (source: EPTA website). Approximately 30% to 35% are placed on the market by non-EPTA member companies or by importers of CPT. The share of CPT products which are actually made in the EU is not accurately known. However, more professional CPTs are made in Europe than DIY CPTs, with Bosch, Hilti, DeWalt, Makita, Hitachi, Metabo, Sparky all having a significant manufacturing presence [EPTA 2009d].

Employment by EPTA member companies excluding direct sales staff in EU27 is approximately 17000 workplaces in Europe out of an estimated total 20000 workplaces for the whole industry [EPTA 2009a]. Significant employing Member States are UK, Germany, Czech Republic, Austria, Hungary, Romania, Bulgaria, Ireland, Belgium, Netherlands [EPTA 2009d]. Considering that about 36% of the turnover of the electric power tool industry is related to CPTs it can be estimated that about 7200 workplaces are related to the EU CPT industry.

The following EPTA members sell cordless power tools (CPT):

Table 3-3 : Overview on companies that sell cordless power tools

EPTA members which sell cordless power tools	
Black & Decker/DeWalt*	Fein
Bosch*	Festool
Hilti*	Flex
Hitachi*	Mafell
Makita*	Sparky
Metabo*	
Techtronic Industries (TTI)*	

*companies which have a significant share of the market

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[14] Personal communication from EPTA, Brian Cooke, 1.10.2009

Table 3-4 lists current applications of cordless power tools. The list is not exhaustive, and is likely to increase as the performance of cordless technologies continues to improve [EPTA 2009a].

Table 3-4: Current applications of cordless power tools (non exhaustive list; source [EPTA 2009a])

Current applications of cordless power tools	
Drills	Drill/drivers
Percussion drills	Right angle drills
Sealant guns	Impact wrenches
Impact drivers	Screwdrivers
Pneumatic hammer drills	Chipping hammers
Nailers	Sanders
Circular saws	Mitre saws
Compound mitre saws	Plunge saws
Reciprocating saws	Flash lights
Shop wet/dry vacuum devices	Hand held wet/dry vacuum
Rotary lasers	Heavy duty shears
Finishing grinders	

Drills, drill/drivers and screwdrivers occupy a significant portion of the market for both professional and DIY sectors [EPTA 2009d].

Looking at the sales figures by battery chemistry for the various CPT applications shows that NiCd batteries still dominate the DIY and outdoor (lawn and garden) cordless sectors, whereas the professional sector is moving now quite quickly towards Li-Ion batteries, with the NiMH battery share declining. NiMH batteries have a small share currently of the DIY and outdoor sectors (<10%) and this is expected to fall further with the predicted increase of Li-ion batteries in these sectors. Assuming no further legal market restrictions, EPTA predicts that the NiCd battery share will fall further in DIY, Outdoor and Pro sectors, but is expected to retain significant residual share (>25%) in the medium term for those applications where cost, robustness, ability to fast charge, operating temperature range are customer priorities [EPTA 2009d].

3.1.2 Market of portable rechargeable batteries

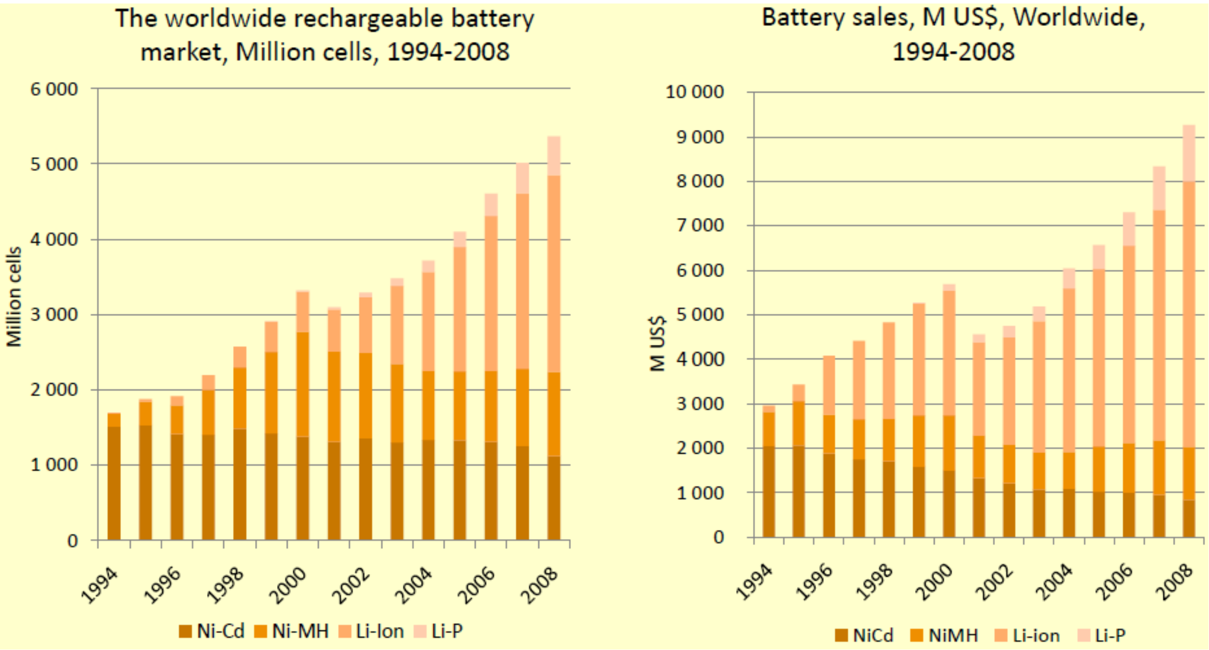

Figure 3-2: **Worldwide rechargeable battery market development 1994 to 2008: (left) volume in million cells; (right) value in million US $ for NiCd, NiMH, Li-ion and Li-poly batteries [Pillot 2009]**

Figure 3-2 shows the worldwide rechargeable battery market development from 1994 to 2008 in terms of volume (million cells) and value (million US $). It demonstrates increasing trends in terms of volume and value for the worldwide rechargeable battery market (source: [Pillot 2009]).

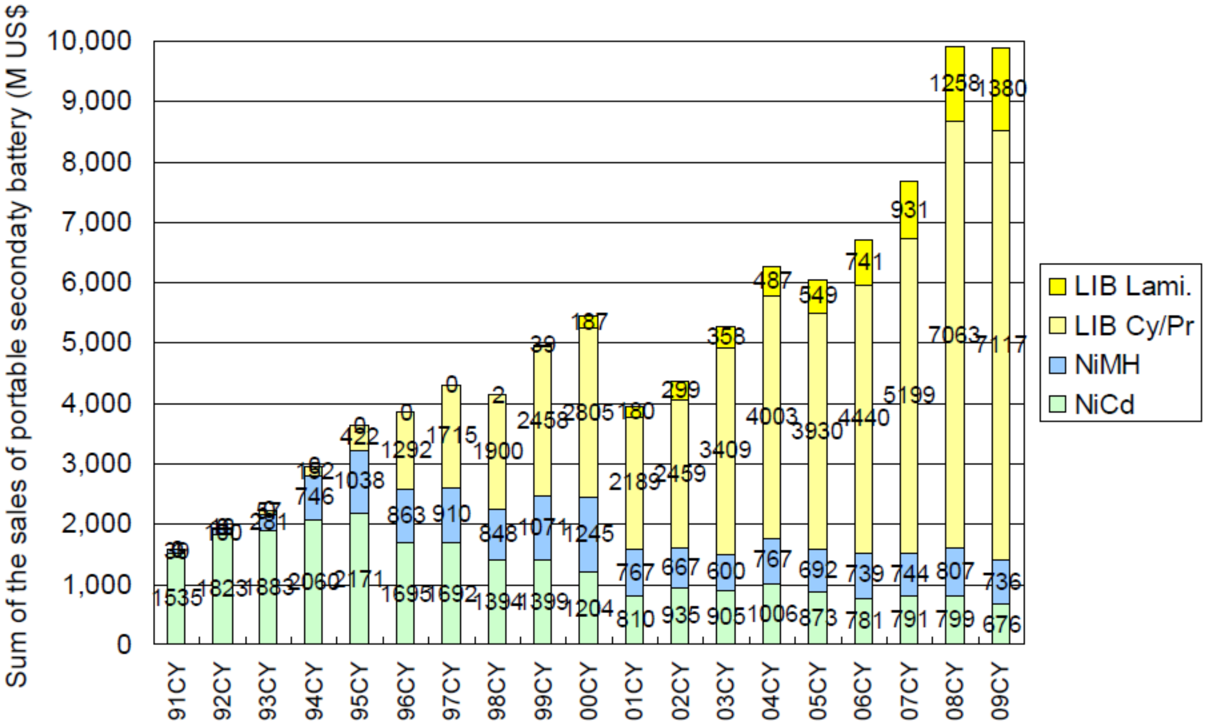

Figure 3-3 : **Worldwide rechargeable battery market development 1991 to 2009: value in million US $ for NiCd, NiMH, Li-ion (LIB Cy/Pr) and Li-poly (LIB Lami.) batteries [Takeshita 2008]**

Figure 3-3 shows the worldwide rechargeable battery market development from 1991 to 2009 in terms of value (million US $) according to another information source [Takeshita 2008].

The data differ a little from the data shown in Figure 3-2 from [Pillot 2009]. Compared with these, the figures from Takeshita for the year 2008 are more or less identical for NiCd (799 vs. 800 M US $), lower for NiMH (807 vs. 1200 M US $), higher for Li-ion (7063 vs. 6000 M US $) and slightly higher for Li-poly (1258 vs. 1200 M US $). However the general trends are identical according to both information sources:

- increasing trends in terms of volume and value for the worldwide and European rechargeable battery market;
- increasing trends for the Li-ion and Li-polymer batteries;
- comparatively stable situation for NiMH batteries and
- decreasing trends for NiCd batteries.

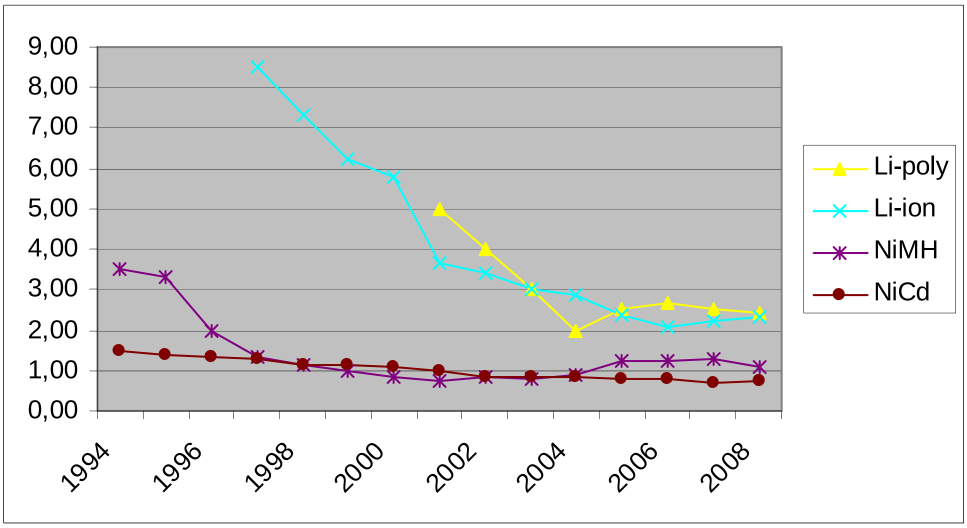

Figure 3-4 : Development of the average prices for NiCd, NiMH, Li-ion and Li-poly batteries (worldwide market; US $ per cell; based on [Pillot 2009])

The development of the market volume and value as illustrated in Figure 3-2 allows to estimate the price development for individual cells of the relevant battery chemistries. Figure 3-4 shows an estimation of the development of the average prices for NiCd, NiMH, Li-ion and Li-poly batteries. It illustrates generally decreasing trends for the average prices per cell. In 2008 the average prices per cell were for NiCd cells (~ 0.76 US $), followed by NiMH cells (~ 1.09 US $) and Lithium cells (~ 2.31 US $ for Li-ion and ~ 2.40 US $ for Li-poly cells). To conclude, comparing the 2008 prices of NiCd cells with those for NiMH and Li-ion cells, the price for NiMH cells was about 1 and a half times higher (~143%) and the price for Li-ion cells was about 3 times higher (~303%).

The prices are most representative for the corresponding main applications of the different technologies, i.e. in the case of NiCd batteries for cordless power tools (CPT), in the case of NiMH batteries for hybrid electric vehicles and in the case of Li-ion batteries for mobile phones, digital cameras, laptops, etc.

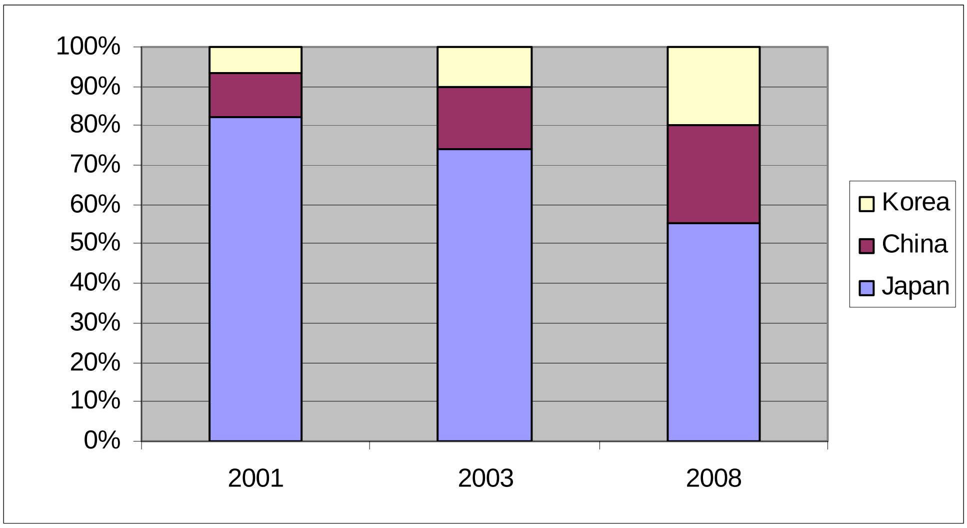

Figure 3-5 : **Market shares of the worldwide rechargeable battery market by countries (in % of the market value; based on [Pillot 2009])**

Figure 3-5 illustrates the market shares by countries of the worldwide rechargeable battery market. The market (value ~ 9200 million US $) is dominated by sales from Japan, China and Korea. Sales in 2008 from these countries were from Japan 5100 million US $ (~ 55% market share), from China 2300 million US $ (~ 25% market share) and from Korea 1800 million US $ (~ 19.5% market share). Sales in the rest of the world were below 100 million US $ (< 1% market share) (source: [Pillot 2009]).

Table 3-5 : **Overview on the market shares of battery manufacturers in the worldwide rechargeable battery market (shares in %; source [Pillot 2009]**

Company	Head office location	Share in production in %		
		NiCd	NiMH	Li-ion/ Li-poly
Sanyo	Japan	53	23	25
MBI (Matsushita Battery Industrial)	Japan	8	9	6
BYD	China	24		6
SAFT	France	8		
Others NiCD		7		
Panasonic EV	Japan		29	
GP batteries	China		14	
Yuasa	North America		10	
Others NiMH			15	
Sony	Japan			16

Company	Head office location	Share in production in %		
		NiCd	NiMH	Li-ion/ Li-poly
SDI (Samsung SDI)	Korea			17
MBI	Japan			
LG Chemical	Korea			8
Lishen	China			4
Maxell	Japan			5
Others Li-ion/Li-P				13
Total value in million US $		**800**	**1200**	**7200**

Table 3-5 gives an overview on the market shares of the most relevant rechargeable battery manufacturers in the worldwide rechargeable battery market. Only one of the most relevant producers is based in the EU (SAFT from France). The table shows also that except SAFT all major players producing NiCd batteries have also major market shares of the NiMH and/or Li-ion or Li-poly battery market.

However, also SAFT produces alternative technologies (NiMH and Li-ion), mostly for niche markets (source: [Bio 2003]). Also, currently SAFT offers among its products NiMH and Li-ion batteries and it can therefore be concluded that SAFT is also engaged in the corresponding market[15].

At the beginning of the decade, SAFT produced primarily NiCd batteries (more than 85% of its yearly sales according to industry sources). At that time SAFT was the last European producer, with two plants producing both portable and industrial NiCd batteries, one in France and one in Sweden, and plants producing industrial NiCd batteries in Spain and Germany. According to industry sources, in France and Sweden, SAFT yearly sales were 600-700 million €, approximately 2/3 for industry batteries segment and 1/3 for portable batteries segment. To produce both industrial and portable batteries, 2000 to 3000 persons were employed by SAFT[16]. Other producers (Varta, Panasonic, Moltech… - see table in section 3.6.3.1.4 page 164 (note: of [Bio 2003]) either produced outside Europe (mainly Asia) or imported portable NiCd batteries produced with low costs in China for instance (source: [Bio 2003]).

In 2008 SAFT had a share of 8% of the NiCd production which corresponded to a market value of approximately 56 million US $ or to a number of 84 million cells.

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[15] Source: http://www.saftbatteries.com/Technologies_Nickel_NiMH_329/Language/en-US/Default.aspx and http://www.saftbatteries.com/Technologies_Lithium_Liion_301/Language/en-US/Default.aspx accessed on 24.09.2009

[16] This corresponds to average sales ranging from 233,000 to 300,000 € per working place.

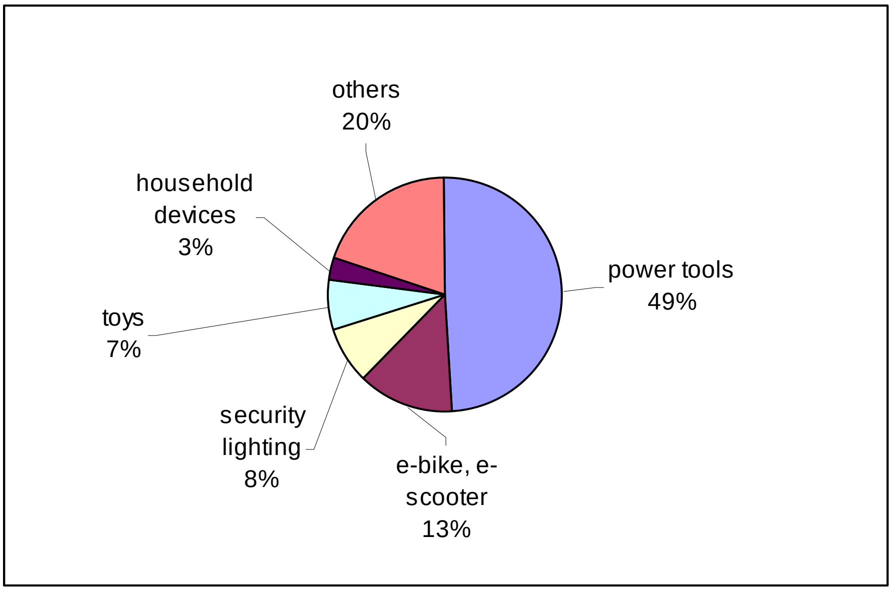

Figure 3-6 : Rechargeable NiCd batteries by applications worldwide in 2008 (source [Pillot 2009])

The worldwide market of rechargeable NiCd batteries in 2008 is characterised by 1050 million cells sold and a market value of 800 million US $. The trend from 2003 to 2008 is an average decrease of 4% per year in volume and 6% per year in value. The price per cell in 2008 was approximately 0.76 US $. The application of NiCd batteries in power tools worldwide has increased from 38% (433 million cells or 365 million US $) in 2003 to 49% (515 million cells or 392 million US $) in 2008. This increase is not due to an increasing share of NiCd batteries in the cordless power tool market but to the growing cordless power tool market itself. All application segments are stable or slowly decreasing except e-bikes and scooters, which is increasing. It is remarkable that in 2004 NiMH were estimated to be strong competitors of NiCd in the sector of power tools whereas in 2009 strong competition in this sector is Li-ion (sources: [Pillot 2004] and [Pillot 2009]).

The market of NiMH is characterised by 1110 million cells sold and a market value of 1200 million US $. The trend from 2003 to 2008 is an average increase of 2% per year in volume and 8% per year in value. The price per cell in 2008 was approximately 1.09 US $. In 2008 53% of NiMH cells were applied in Hybrid Electric Vehicles (source: [Pillot 2009]).

The market of rechargeable Li-ion/Li-poly batteries in 2008 is characterised by 3100 (Li-ion 2600 and Li-poly 500) million cells sold and a market value of 7200 (Li-ion 6000 and Li-poly 1200) million US $. The trend from 2003 to 2008 is an average increase of 22% per year in volume and 17% per year in value. The price per cell in 2008 was approximately 2.32 US $. All applications such as cellular phones, portable PCs, power tools, camcorders, digital cameras, mp3-players, games and other are increasing since several years.

3.1.3 *Market of portable rechargeable batteries for Cordless Power Tools*

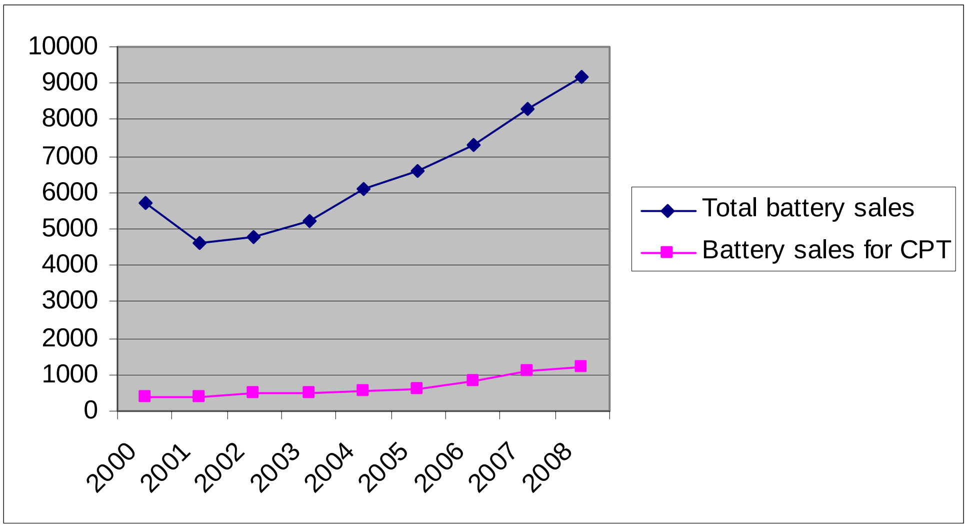

Figure 3-7 : Development of the worldwide rechargeable battery sales and sales of rechargeable batteries for cordless power tools from 2000 to 2008 (value in sales of batteries in M US $; based on [Pillot 2009])

Figure 3-7 illustrates the development of the worldwide rechargeable battery market in comparison with the sales of rechargeable batteries for cordless power tools during the years 2000 to 2008. The figure illustrates the increasing trend of the worldwide market (see also Figure 3-2). The market value of batteries for the use in cordless power tools and its share of the worldwide market is increasing. In the year 2000 the share was approximately 7% of the worldwide market and it has increased to approximately 13% of the worldwide market in 2008.

In the cordless power tool (CPT) sector, the trend for NiCd batteries is decreasing whereas it is increasing for Li-ion batteries and more or less stable for NiMH batteries. In total a number of around 1060 million cells have been applied in cordless power tools worldwide in 2008. This corresponds to a value of about 1400 million US $ (source: [Pillot 2009]).

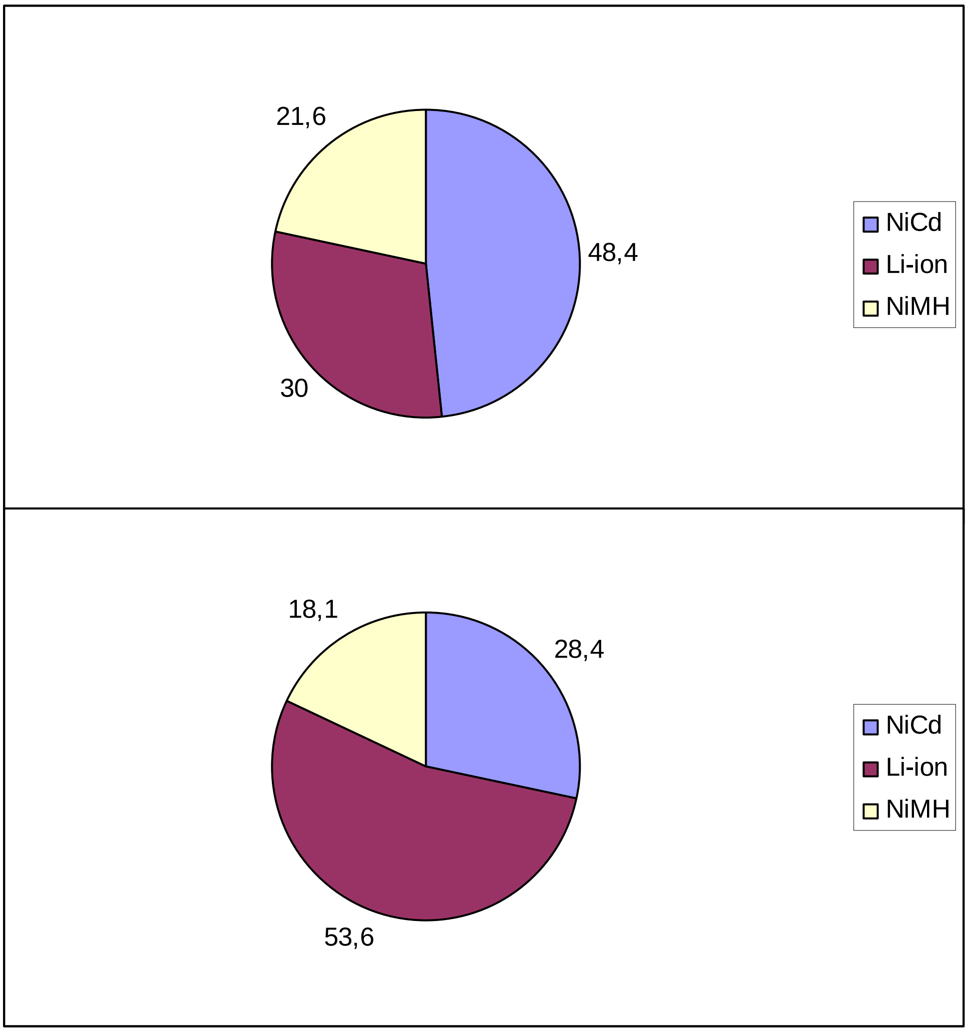

Figure 3-8 : **Estimation of the market volume (top; percentage of number of cells) and market value (bottom; percentage of market value) of NiCd, Li-ion and NiMH batteries of the worldwide cordless power tool market in 2008 (estimation based on [Pillot 2009]).**

On the basis of the worldwide market shares of NiCd batteries and Li-ion batteries in cordless power tools (CPT) in 2008 in terms of numbers of cells an overall picture of the worldwide market shares of NiCd, NiMH and Li-ion batteries applied in cordless power tools (CPT) can be estimated[17]. According to the estimation, in 2008 the share of these battery chemistries in the worldwide cordless power tool market was approximately 48% NiCd, 30% Li-ion and 22% NiMH in terms of numbers of cells and approximately 28% NiCd, 54% Li-ion and 18% NiMH in terms of market value (see Figure 3-8; estimation based on [Pillot 2009]).

It could be concluded that the Li-ion batteries are more expensive than the NiCd batteries. The development of prices is illustrated in Figure 3-4 above. Cost impacts and life-time costs are discussed in chapter 5.5.5.

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[17] Assuming that the rest of the 2008 market is supplied with NiMH cells

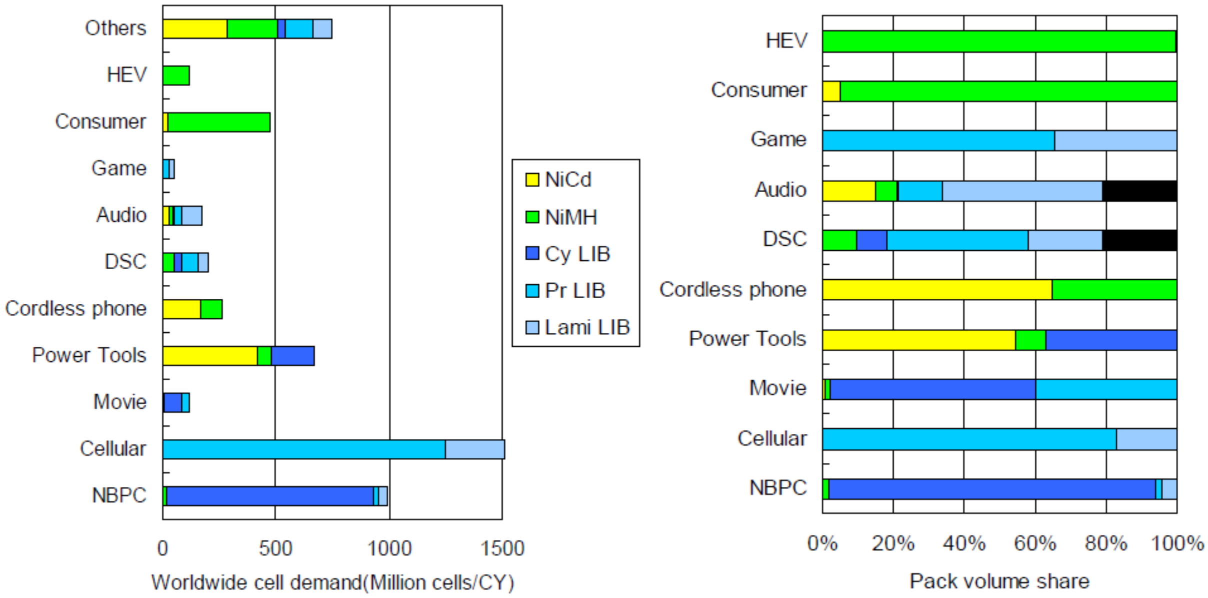

Figure 3-9 : **Worldwide portable rechargeable cell demand in million cells (left) and pack volume share (percentage of packs in the market) in the calendar year (CY) 2008 by application (source [Takeshita 2008])**

Figure 3-9 illustrates the worldwide portable rechargeable cell demand in million cells (left) and the pack volume shares in percentage of packs on the market (right) in 2008 by application. According to this figure the 2008 worldwide cell demand for cordless power tools (CPT) is approximately 680 million cells (~420 NiCd, ~60 NiMH, ~ 200 Li-ion[18]) and the pack volume share is approximately 56% NiCd, 37% Li-ion and 7% NiMH (source: [Takeshita 2008]).

The following table summarises shares of battery technologies worldwide applied in cordless power tools (CPT) according to different information sources:

Table 3-6 : **Shares of battery technologies applied in cordless power tools (CPT) (Worldwide)**

NiCd	Li-ion	NiMH	Information and source
56%	37%	7%	Pack volume share for 2008 [Takeshita 2008]
48%	30%	22%	Estimation of the cell volume share for 2008; based on [Pillot 2009]

According to EPTA information on the share of battery technologies used in Europe in 2008 in cordless power tools (CPT) the share of NiCd was 55%, of Li-ion 36% and of NiMH it was 9% [EPTA 2009a]. However, it is noted that, based on a recent EPTA survey of 9 companies, the share of NiCd in Europe appears lower than this and Li-ion higher (source: [EPTA 2009a]).

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[18] Li-ion batteries are designated as ''Cy LIB'' in Figure 3-9.

The following table summarises shares of battery technologies applied in Europe in cordless power tools (CPT):

Table 3-7 : Shares of battery technologies applied in cordless power tools (Europe)

NiCd	Li-ion	NiMH	Information and source
55%	36%	9%	Current share [EPTA 2009a]

A recent EPTA survey carried out in 2009 has shown that for 9 EPTA member companies (which represent a significant proportion of the market), the total share of battery technologies was NiCd 49%, NiMH 11% and Li-ion 40%. For the professional CPTs the corresponding shares were 42%, 19% and 39%. For the DIY CPTs the corresponding shares were 54%, 6% and 40% [EPTA 2009d]. These data indicate that the share of NiCd technology may actually be lower and that of Li-ion technology be higher than shown in Table 3-7 and that the penetration of Li-ion technology is higher in the segment of professional CPTs compared to DIY CPTs.

Recent data from 2009 from GfK made available via Bosch show the proportion of Li-ion batteries used for CPTs sold through “traditional trade” outlets (professional CPTs) at 42% in 6 EU Member States. The equivalent proportion in Hungary is 15.3%. Li-Ion CPTs sold through DIY superstores (DIY CPTs) in 25 EU countries was 25%, whereas the equivalent proportion sold in Hungary was 10.5% [EPTA 2009d]. These data indicate that in specific Member States (under worse economic conditions) the market penetration of Li-ion seems to be lower compared to other Member States (under better economic conditions).

On the basis of the information from [Pillot 2009] and [EPTA 2009a] an estimation of the number of NiCd cells used in cordless power tools (CPT) in Europe in 2008 can be made.

Table 3-8: Estimation of the number of NiCd cells used in cordless power tools (CPT) in Europe in 2008 based on several pieces of information from [EPTA 2009a] and [Pillot 2009],

		Source
Value of CPTs sold worldwide in 2007 (in million US $)	3500	[EPTA 2009a]
Value of CPTs sold in Europe in 2007 (in million US $)	1440	[EPTA 2009a]
Share of Europe in worldwide market of CPTs (in %)	41,1	
Assumed share of Europe for all cell types for CPTs in 2008 (in %)	41,1	
Total number of all cell types sold for CPTs worldwide in 2008 (in millions)	1060	[Pillot 2009]
Estimated number of all cell types sold for CPTs in Europe in 2008 (in millions)	436	
Share of NiCd cells sold for CPTs in Europe in 2008 (in %)	55	[EPTA 2009a]
Estimated number of NiCd cells used in CPTs in Europe in 2008 (in millions)	**240** [19]	

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[19] Considering that the number of NiCd cells sold worldwide in 2008 for CPTs was 515 million cells [Pillot 2009] this corresponds to an estimated share of Europe on the worldwide market for NiCd cells in CPTs of 47%.

Considering that in 2008 about 13.3 million CPT units have been sold, it can be estimated that on an average level approximately 33 cells are used per sold CPT unit.

According to [Bio 2003] SAFT produced at the beginning of the decade in France and Sweden NiCd batteries which corresponded to sales of 600-700 million €, approximately 2/3 for the industry batteries segment and 1/3 for the portable batteries segment. This means at that time SAFT produced about 200 million NiCd cells for cordless power tools (CPT).

According to [Pillot 2009] the production of NiCd cells of SAFT has decreased to 8% of the world market in 2008 i.e. to approximately 56 million dollars or about 84 million cells number. At present SAFT does not produce any more NiCd cells for batteries intended for the use in CPTs[20]. According to [EPTA 2009d] NiCd cells used in CPT in Europe are mainly produced in the Far East. To conclude, currently all NiCd batteries used in CPTs are imported to the EU mainly from Asia.

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[20] Personal Communication, telephone conversation with Recharge, 11.12.2009

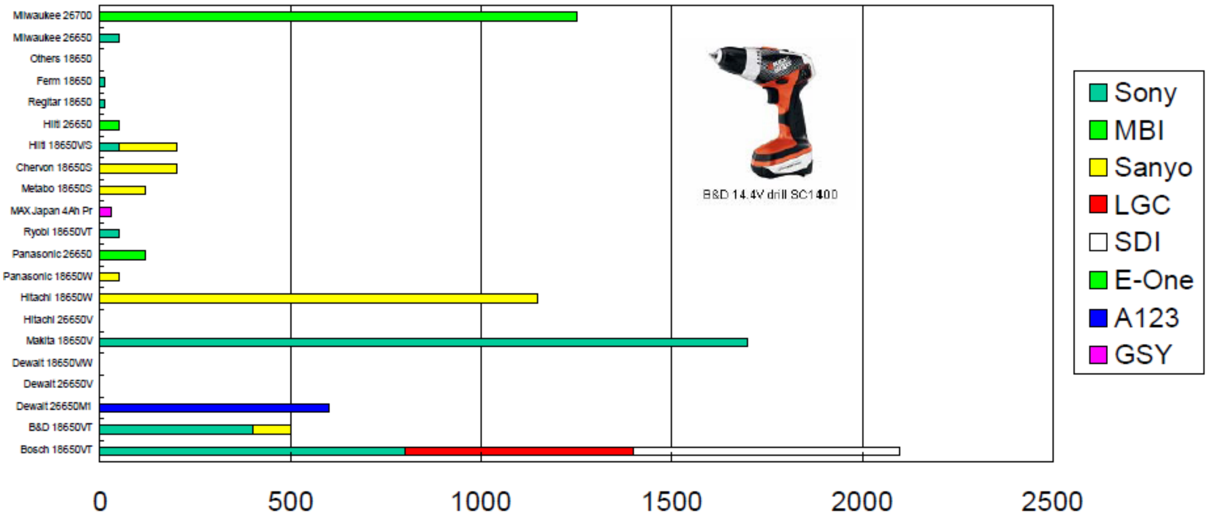

Figure 3-10 : **Shipment of Li-ion batteries (x-axis: cells per month) by suppliers to users for CPT (y-axis: names of companies using Li-ion batteries for CPTs[21]) (source [Takeshita 2007], chart 12)**

Figure 3-10 illustrates the shipment of Li-ion batteries by suppliers to users for cordless power tools (CPT). From this figure it can be concluded that already in 2007 all EPTA members who have a significant share of the European market of cordless power tools (except Techtronic Industries) already applied significant amounts of Li-ion batteries in cordless power tools (CPT).

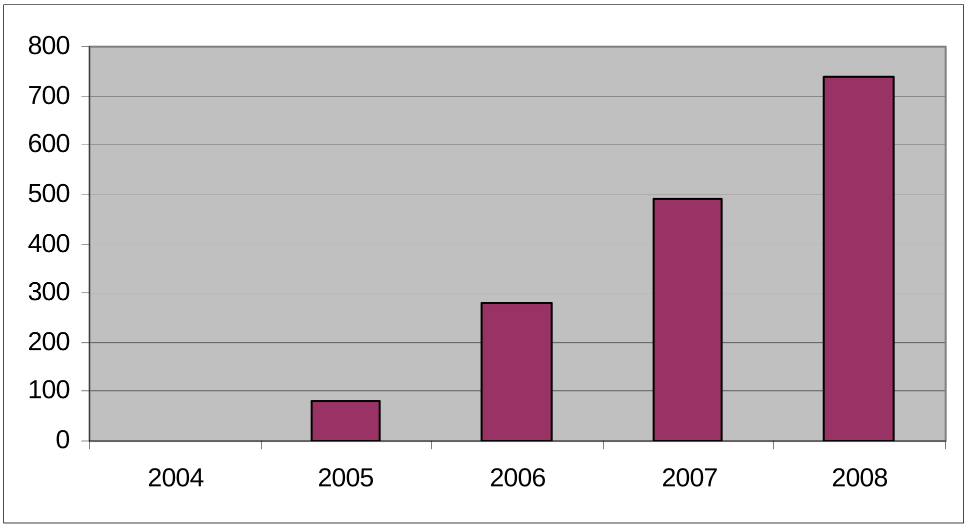

Figure 3-11 : **Worldwide market of Li-ion batteries in cordless power tools (CPT) from 2004 to 2008 (market value in million US $ on the basis of [Pillot 2009])**

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[21] The suppliers listed on the y-axis are: Milwaukee 26700, Milwaukee 26650, Others 18650, Ferm 18650, Regitar 18650, Hilti 26650, Hilti 18650V/S, Chervon 18650S, Metabo 18650S, MAXJapan 4Ah Pr, Ryobi 18650VT, Panasonic 26650, Panasonic 18650W, Hitachi 18650W, Hitachi 26650V, Makita 18650V, Dewalt 18650V/W, Dewalt 26650V, Dewalt 26650M1, B&D 18650VT, Bosch 18650VT

Figure 3-11 illustrates that the worldwide application of Li-ion batteries in cordless power tools (CPT) has increased from zero in 2004 to approximately 321 million cells[22] or a value of approximately 740 million US $ in 2008 (source: [Pillot 2009]).

According to another information source the worldwide use of Li-ion batteries in cordless power tools has increased from 1 million cells in 2003 to 117 million cells in 2007 (source [Takeshita 2007], chart 8). This corresponds to an estimated worldwide market value of approximately 270 million US $[23] which differs from the value of approximately 490 million US $ as indicated by Pillot for the year 2007 (source [Pillot 2009], chart 9).

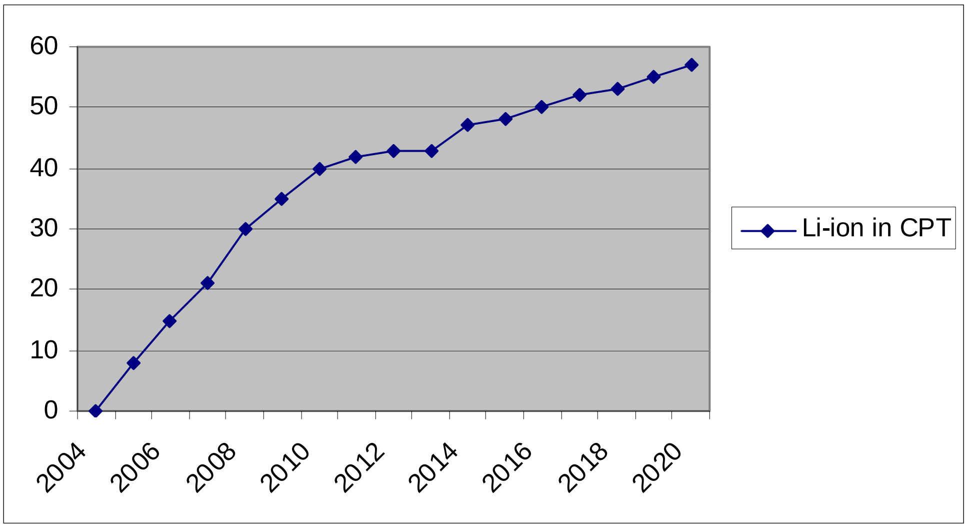

Figure 3-12 : **Worldwide market penetration of Li-ion batteries in the segment of cordless power tools (CPT); development from 2004 to 2008 and prognosis until 2020 (on the basis of [Pillot 2009])**

Figure 3-12 illustrates the actual and forecasted worldwide market penetration of Li-ion batteries in the segment of cordless power tools (CPT). Since the introduction in cordless power tools in 2004 the market share has increased according to this information source from zero to approximately 30% in 2008 and it is expected to further increase to approximately 55% in 2020 (source: [Pillot 2009]).

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[22] Estimation based on an average price per cell for Li-ion cells of 2.31 US $.

[23] Assuming an average cell price of 2.31 US $

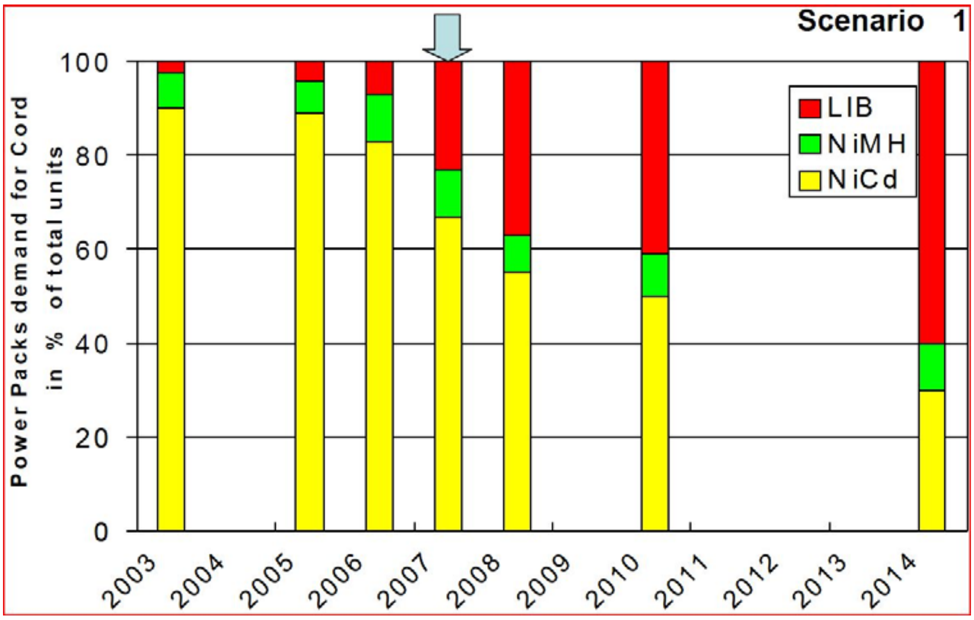

Figure 3-13 : **Worldwide market shares of Li-ion (LIB), NiMH and NiCd batteries in the segment of cordless power tools (power packs demand for cordless power tools in % of total units on a wet weight basis); development from 2003 to 2008 and forecast for 2010 and 2014 [Recharge 2009]**

Figure 3-12 illustrates the worldwide actual and forecasted market shares of Li-ion, NiMH and NiCd batteries in the segment of cordless power tools (power packs demand for cordless power tools in % of total units on a wet weight basis) according to another information source. Since the introduction in cordless power tools the market share of Li-ion batteries has increased according to this information source to almost 40% in 2008 and it is expected to further increase to approximately 60% in 2014 (source: [Recharge 2009]).

3.2 Specific Market Situation in Sweden

In 1997 an environmental charge on NiCd batteries was levied in Sweden (the equivalent of SEK[24] 300/kg which corresponds to approximately 30€/kg). The charge still remains in force. Producers and companies who manufacture or import batteries containing NiCd pay this charge into a fund administered by the Swedish Environmental Protection Agency. This charge is intended to cover the costs society pays for collecting, sorting, transporting and removing NiCd. [SE EPA 2009]

This charge has radically affected the sales of NiCd in Sweden. Sales statistics indicate a dramatic reduction in sales the same year the charge was introduced. The following year (1998) sales continued to decrease and are still doing so today. At national level sales of NiCd decreased to one third of previous levels between 1997 (328 tonnes) and 2004 (87 tonnes). In 2007, 56 tonnes of NiCd batteries were sold in Sweden.

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[24] SEK is the abbreviation for the Swedish currency; 1 SEK = 0,09791 €

The shares of the numbers of batteries sold by members of the Swedish Power Tools Association was in Sweden in 2007 approximately 7% of NiCd batteries, 58% of NiMH batteries and 35% of Li-ion batteries (estimation based on figure 6 of [SE EPA 2009]).

3.3 Market of Technical Substitutes

The market of portable NiCd batteries and its commercially available technical substitutes is analysed in detail in chapter 3.1. Technical substitutes other than NiMH and Li-ion batteries which are mature enough and show the technical properties required by cordless power tools (CPT) have not been identified in the technical assessment.

However, as a result from the technical assessment it can be summarised that in the medium to long term, improved Lithium or Lithium-ion-batteries, Nickel-zinc-batteries, Carbon Nanotube Enhanced Supercapacitors or possibly portable fuel cells or redox flow batteries may become appropriate portable energy sources for cordless power tools (CPT). These technologies in future may also find many other applications.

4 Technical Assessment of Alternatives to Cadmium-Batteries in Cordless Power Tools

The Resolution of the Council of the European Communities 88/C 30/01 [Council Resolution 88/C 30/01[25]] stressed the limitation of the uses of cadmium to cases where suitable alternatives do not exist. Consequently the Batteries Directive (2006/66/EC) limited the concentration of cadmium in portable batteries with 0.002 mass% (= 20 mg/kg), while exempting batteries intended for use in cordless power tools (CPT), among others. This exemption was based on the argument that in the year 2006 suitable alternatives did not exist.

The Batteries Directive (2006/66/EC), however, also requires review of this exemption.

The present technical assessment now shall examine if in the meantime suitable alternatives to NiCd batteries as energy source for cordless power tools (CPT) are available to an extent that NiCd batteries can be fully replaced without hampering the use of cordless power tools (CPT).

This technical assessment according to the project tasks shall not only describe what is available and mature now, but also give an overview of the technologies which are in the pipeline and of their core features.

4.1 Requirements for Energy Storage Systems in Cordless Power Tools

With respect to selection of the most appropriate energy source for cordless power tools there are three broad considerations:

- Technical performance;
- Environmental factors (including safety and recycling or safe disposal), and
- Cost.

Technical performance are affected by materials of construction, cell chemistry, design, ambient temperature, rate of discharge, depth of discharge before recharging, cut-off voltage on recharge, etc. Environmental performance and initial cost are mainly affected by materials used and by the production & recycling processes.

[Dell & Johnson 2002] list following desirable attributes as general requirements looked for in batteries:

- All batteries
    - High cell voltage and stable voltage plateau over most of the discharge
    - High stored energy content per unit mass (Wh/kg) and per unit volume (Wh/l)
    - Low cell resistance (mΩ)

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[25] Council Resolution of 25 January 1988 on a Community action programme to combat environmental pollution by cadmium (OJ C 30, 4.2.1988, p. 1.)

  - High power (= power discharge) per unit mass (W/kg) and per unit volume (W/l) (for definitions of these properties see Box 1)
  - High sustained power output
  - Wide temperature range of operation
  - Long inactive shelf life (years) corresponding to low self discharge[26] and low loss of capacity during storage
  - Long operation life
  - Reliable in use, rugged and resistant to abuse
  - Sealed and leak proof
  - Safe in use and under accident conditions
  - Made of readily available materials which are environmentally benign
  - Suitable for recycling
  - Low initial cost
- Secondary (rechargeable batteries)
  - High electrical efficiency (Wh output/Wh input in %)
  - Capable of many charge/discharge cycles
  - Ability to accept fast recharge
  - Will withstand overcharge and overdischarge
  - Sealed and maintenance free.

Box 1 : Definitions of electric energy, power and other terms used for describing batteries

In physics, **energy (W)** is a scalar physical quantity that describes the amount of work that can be performed by a force. The physical unit in which electric energy most often is described is either Ws (watt-second), Wh (watt-hour) or kWh (kilo-watt-hour). With respect to cordless power tools (CPT), the energy stored in the battery determines how many screws can be driven into a wall by a CPT screw driver till the battery is discharged.

Electric **power (P)** defines how much electrical energy is transferred by an electric circuit **per second**. The physical unit of power is the W (watt). With respect to cordless power tools (CPT), the power discharge of the battery determines if the cordless power tool has enough power to drive a screw also into a hard wall. The power discharge also determines how fast the screws can be driven into a wall.

Electric charge (Q) is the number of electrons stored in a battery which can be released during discharge. The physical unit of electrical charge used in this report is As (ampere-seconds) or Ah

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[26] **Self-discharge** is a phenomenon in batteries in which internal chemical reactions reduce the stored charge of the battery without any connection between the electrodes. Self-discharge decreases the shelf-life of batteries and causes them to have less charge than expected when actually put to use.

(ampere-hours). One ampere-second corresponds to 6.25 $*10^{18}$ electrons.

Electric current (I) is the number of electrons which are transported via a conductor per second. The physical unit of electrical current A (ampere).

Voltage (V) is the potential difference between 2 electrodes. The physical unit of voltage is V (volt)

The more electrons (or charge **Q)** can be transferred from one electrode of a battery to the other during discharge and the higher the voltage (V) the more energy (W) is released.

$$W = Q * V.$$

The more electrons can be transferred from one electrode of a battery to the other during discharge **per second** (the higher the current (I) is) and the higher the voltage (V) is, the more power (P) is provided.

$$P = I * V \text{ (Joule's law).}$$

The rate with which electrons can be delivered by a battery is determined by the internal resistance (R) of the battery (which in turn is determined by the kinetics of the electrode reactions and the kinetics of the internal ion-transport between the electrodes) and by the voltage of the battery:

$$I = V/R \text{ (Ohms law).}$$

Combining Joule's law and Ohms law gives:

$$P = V^2/R.$$

This means, the higher the voltage of a battery and the lower the internal resistance the higher the power discharge of a battery and the more powerful the cordless power tool it drives can be.

A battery for a cordless power tool (CPT) needs to have both properties, a high power discharge and a high energy storage capacity:

- If only the power discharge is high but the energy storage capacity is low (as for example with ultracapacitors (see Figure 4-3) one could drive a screw into very hard material, but only for seconds, and then have to stop for recharging the energy source.
- If only the energy storage capacity is high but the power discharge is low (as for example with fuel cells (see Figure 4-12) one could drive hundreds of screws but only very slowly and into very soft material.

For the energy source of a cordless power tool it is also necessary that:

- the energy is stored in a small mass (high gravimetric energy density) and in a small volume (high energy density)
- the power can be released by a small mass (high gravimetric power density) and by a small volume (high power density)

so that the battery pack is neither too heavy nor too big for an operation of the cordless power tool (CPT) during a couple of hours by one hand or two hands combined.

From the life-cycle point of view it is also desirable that the battery is easy to produce, that the production process is mature and imposes no risk on health and environment and that the battery is suitable for recycling.

A core requirement of cordless power tools (CPT) on their energy source is that high power drain of sometimes above 40 Ampere (corresponds to 960 W at a voltage of 24 V) is required, sometimes to be delivered also at low temperatures [Rentz et al. 2001]. The battery must be able to supply its charge in a short period of time and thus must have a high power discharge. According to Atlas-Copco, a professional cordless tool manufacturer, "the typical power drain in professional cordless power tools is 400 to 500 W/kg with peak powers up to 900 W/kg" [Noreus 2000]. Further properties important for the energy source of a cordless power tool (CPT) are low self discharge and low sensitivity with respect to over-discharge. Also low price and high robustness are important requirements [Rentz et al. 2001].

[Noreus 2000] reports that 6-12 V packs are required for low-price cordless power tools and 14-24 V packs for professional cordless power tools.

Table 4-1 summarises the requirements for the energy source of cordless power tools (CPT). As rechargeable NiCd batteries can be seen as the standard-technology providing energy for cordless power tools (CPT) their properties have been taken into account, when specifying the requirements of Table 4-1.

Table 4-1: Desired properties of energy sources for cordless power tools (CPT) [based on EPTA 2009b]

Technical properties	
Power discharge	600 W/kg
	900 W/l
	up to 40 A [Rentz et al. 2001] (corresponds to 720 W/18 V power pack)
Voltage	6 – 24 V or above power packs must be possible
Voltage stability over discharge	High voltage stability over discharge
Energy storage capacity/cycle	37 Wh/kg
	56 Wh/l
Number of recharging cycles	1,000
Energy storage capacity over life time	16,000 Wh/kg
Temperature range of operation	- 20 °C to + 50 °C
Self discharge	< 20 % / month
Operational life	5 years
Reliability, safety and effort for maintenance	Reliable, robust towards mechanical wear, resistant to abuse, sealed, leak proof, maintenance free, safe under accident conditions
Energy efficiency of discharging/charging	> 90 %
Duration of recharging	< 1 hour
Sensitivity with respect to overcharge and over-discharge	Not sensitive
Development of the properties over the recharging cycles	Stable energy storage capacity, no memory effect
Weight per 18 V power pack	< 1.1 kg
Volume per 18 V power pack	< 0.68 l
Environmental / system / economic properties	
Availability of materials	Low risk of material supply
Environment friendliness of materials	Low environmental and health impact of materials during their life-cycles
Hazardous substances' concentration	Low hazardous substance concentration
Suitability for recycling	Easy to collect, separate, treat and recycle
Risk at disposal	Low risk at disposal
Maturity of production process	High maturity
Risk level of production process	Low risk level
Material costs / price	Low
Total macro economic cost	Low

4.2 Identification of Alternatives for Energy Storage Systems for Cordless Power Tools

In principle 3 alternative types of energy storage systems which show some potential for being applied with cordless power tools (CPT) have been identified:

- State-of-the-art batteries
- Batteries in the pipeline
- Other portable energy storage systems

4.2.1 State-of-the-art batteries

Table 4-2 shows the most widely used state-of-the-art portable battery types and Table 4-3 their metal composition. Usually primary batteries are used for applications with an energy consumption of up to 0.01 Wh/day [Wikipedia 2009A]. Cordless power tools (CPT), however, consume up to 40 Wh/h [EPTA 2009b]. Thus primary batteries are not used for cordless power tools as they would have to be replaced even as multi-cell-powerpack virtually after every use of the CPT. From the macro economic point of view also the material consumption simply would be too high.

Table 4-2: Types of state-of-the-art portable battery types with highest market shares [BIPRO et al.2009]

Non rechargeable (primary)	Rechargeable (secondary)
• Alkaline-manganese (AlkMn) • Zinc-carbon (ZnC) • Lithium (Li) • Button cells (zinc air, silver oxide, manganese oxide, lithium)	• Nickel-cadmium (NiCd) • Nickel-metal-hydride (NiMH) • Lithium-ion (Li-ion) • Lead-acid

Table 4-3 gives an overview of metal composition of different portable batteries in % by mass. It enables among other to assess which and how much metals are needed for the production of a certain amount of a specific battery type.

Table 4-3: Overview of metal composition of different portable batteries in % by mass [European Commission2003] (Lithium-value from [ERM 2006])

Battery Type	Mercury (Hg)	Cadmium (Cd)	Lead (Pb)	Zinc (Zn)	Nickel (NI)	Manganes (Mn)	Iron (Fe)	Cobalt (Co)	Lithium (Li)
Zinc-carbon	0.0005	0.007	0.15 – 2	35		18	21		
Alkaline Manganese	0.0013	0.0074	0.04 – 2	35		28	28		
Portable NiCd		**15-20**		**0.06**	**15 - 20**	**0.083**	**29 – 40**	**0.6**	
Portable NiMH					25 - 46	0.81 – 3.0	20 – 25	1.0 – 4.5	
Portable Li-based					12 - 15	10 -15	4.7 - 25	12 - 20	3
Lead Acid batteries			65-70						

Table 4-4 shows a comparison of primary battery cells of AA type and the biggest button cell type with an AA type rechargeable NiCd-battery. It can be seen, that in order to provide the same amount of energy which can be provided by a rechargeable NiCd-battery between 185 and 574 times more material would be required with primary batteries. The comparison was done on the AA-type-level as no primary battery power packs for cordless power tools (CPT) are commercially available. The conclusion, that primary batteries would consume too much material when used as energy source for cordless power tools (CPT), is valid, also if primary power packs were developed.

A life-cycle analysis in which the environmental impact of primary batteries and of Nickel-cadmium- and Nickel-metalhydride batteries were compared, showed that primary batteries have environmental impacts 10 to 131 times bigger than NiCd batteries. The main factor was the energy consumption for the wholesale and retail of the many pieces of batteries necessary [Parsons 2007].

Furthermore, in spite of intensive literature research no hint was found that there is any activity to develop primary batteries for cordless power tools. Not even a proposal into this direction was found. Consequently, **rechargeability** is a technical requirement for batteries intended for the use in cordless power tools (CPT) and primary batteries are not further considered in the analyses of this report.

Table 4-4: Comparison of primary batteries with NiCd-secondary battery

		Secondary	Primary batteries			
Battery type		Nickel-Cadmium (NiCd)	Alkaline Zinc-Manganese Dioxide (Zn/MnO2)	Carbon-Zinc	Lithium-Iron Disulfide (Li/FeS2)	Zinc-Air (Zn-O2)
Example		Energizer No. CH 15 1.2 V AA	Energizer No. E91 1.5 V AA	Energizer Everyday 1215 1.5 V AA super heavy duty	Energizer No. EA 91 1.5 V AA	Energizer No. PP425 1.4 V prismatic
Property	Unit					
Nominal voltage	V	1.2	1.5	1.5	1.5	1.4
Mass/cell	kg	0.0227	0.023	0.015	0.0145	0.0117
Volume	l	0.0083	0.0081	0.008	0.008	0.004
Rated capacity	Ah	0.65	2.8	1.1	3	3.6
Capacity rating against voltage	V	1	0.8	0.8	1	1
Capacity rating at discharge rate	A	0.13	0.025	0.025	0.1	0.02
Source:		[Energizer 2009a]	[Energizer 2009c]	[Energizer 2009d]	[Energizer 2009e]	[Energizer 2009f]
Energy storage capacity/cycle	Wh	1.65	3.6	1.9	4	4.6
Assumed charging cycles [EPTA 2009b]		1,000	1	1	1	1
Life cycle energy storage capacity	Wh	1,650	3.6	1.9	4	4.6
Number of cells for storing 1,650 Wh over lifetime		1	458	868	413	359
Mass of cells for storing 1,650 Wh over life time	**kg**	**0.023**	**10.54**	**13.03**	**5.98**	**4.20**
	factor as compared to NiCd	**1**	**464**	**574**	**263**	**185**

From the state-of-the-art batteries shown in Table 4-2 also lead-acid batteries were not selected to be included in the scope of the technical assessment. The reason for leaving out lead-acid batteries from further consideration as energy source in cordless power tools (CPT) can be seen in Figure 4-1 through Figure 4-4.

These figures are from three different sources and they show slightly different details:

- Figure 4-1 through Figure 4-3 show the gravimetric power density (the watts of power discharge per **kilogram** of battey) versus the gravimetric energy density (the watthours of energy stored per kg battery), while Figure 4-4 shows the volumetric power density (the watts of power discharge per **liter** of battey) versus the volumetric energy density (the watthours of energy stored per liter of battery).

- In Figure 4-1, Figure 4-3 and Figure 4-4 only the y-axis is logarithmic, while in Figure 4-2 both axes are logarithmic.

However, all figures show, that lead-acid batteries do not provide enough gravimetric and volumetric energy density to drive cordless power tools (CPT) at 400 to 500 W for sufficiently long time.

From the state-of-the-art-batteries shown in Table 4-2 this leaves the NiCd-, the NiMH- and the Li-ion batteries for further analyses in the technical assessment.

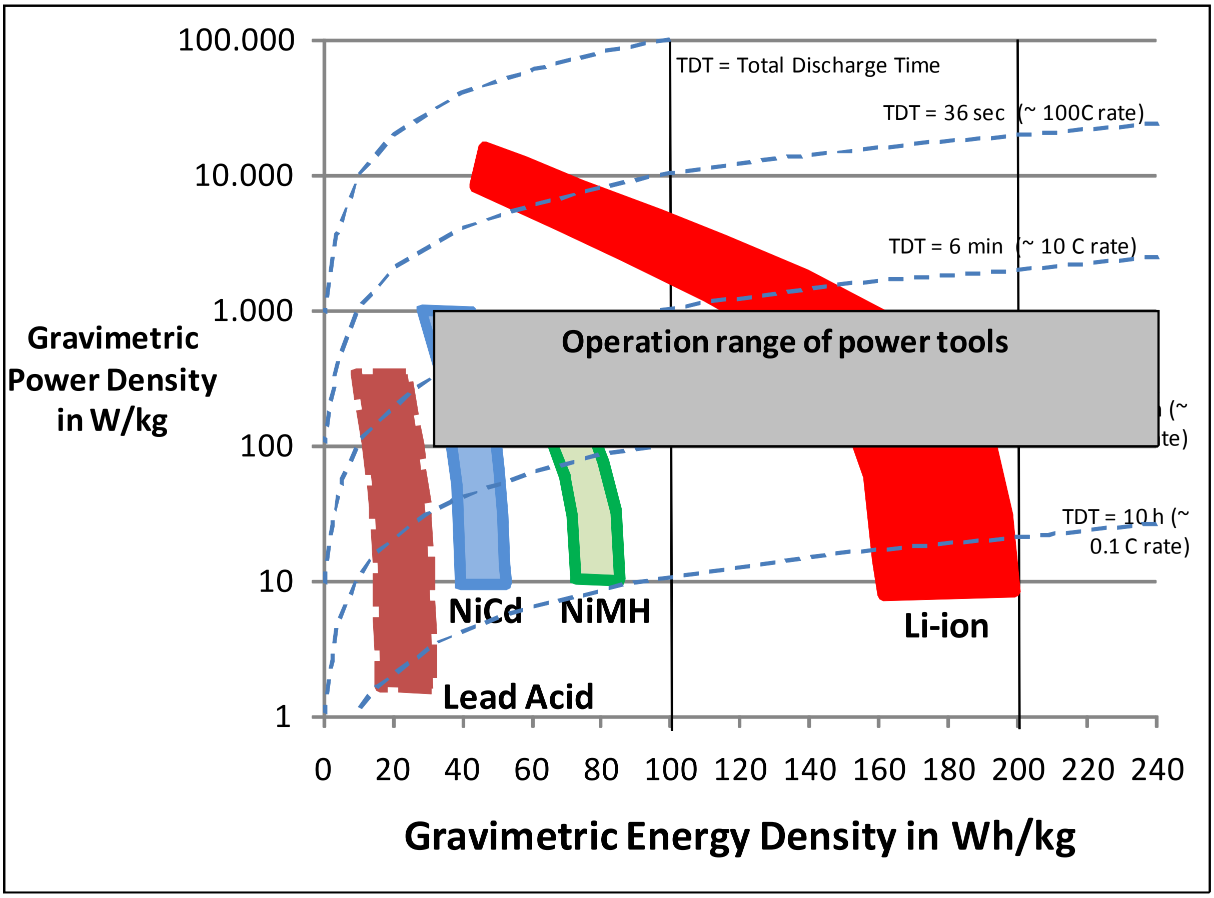


Figure 4-1 : **Gravimetric power density versus gravimetric energy density for 4 rechargeable battery types as reported by SAFT (Société des Accumulateurs Fixes et de Traction (Saft S.A.) [Vulcan 2008]**

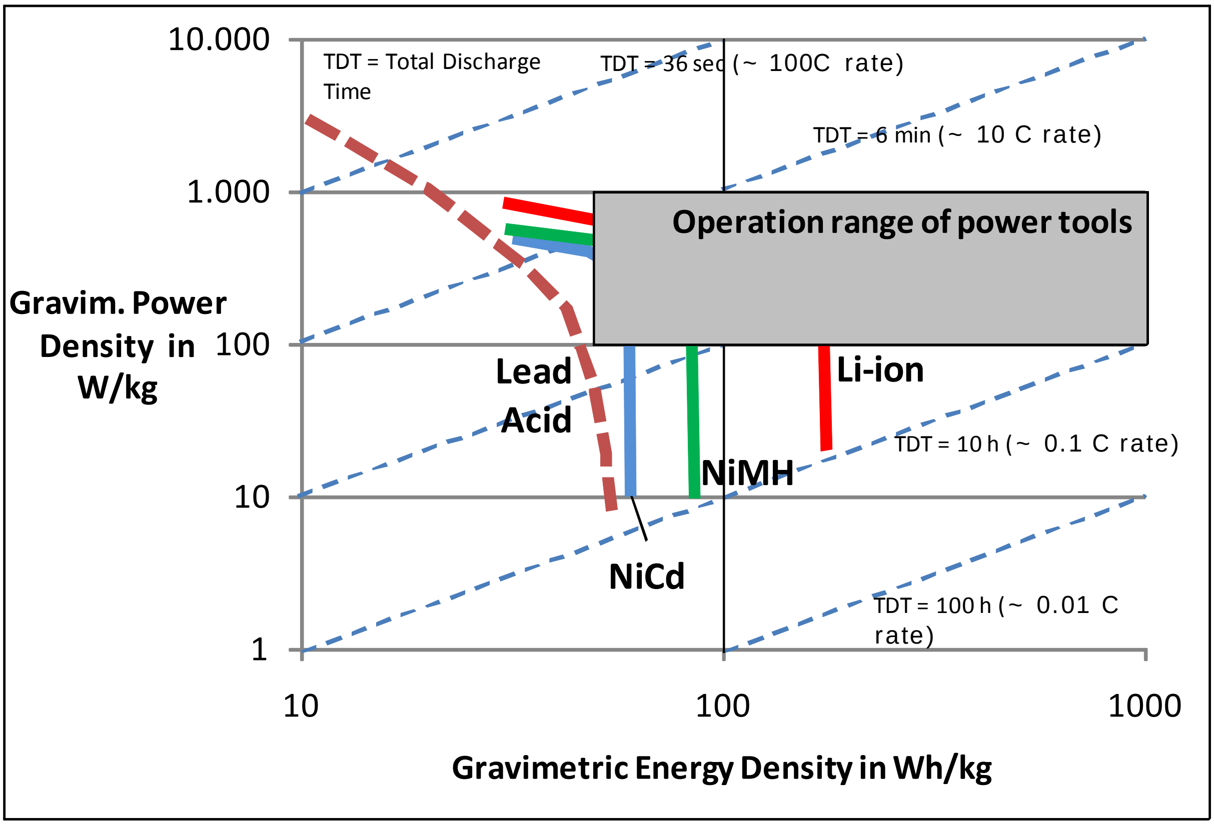


Figure 4-2 : Gravimetric power density versus gravimetric energy density for 4 rechargeable battery types as reported by Altairnano [Lecklider 2008]

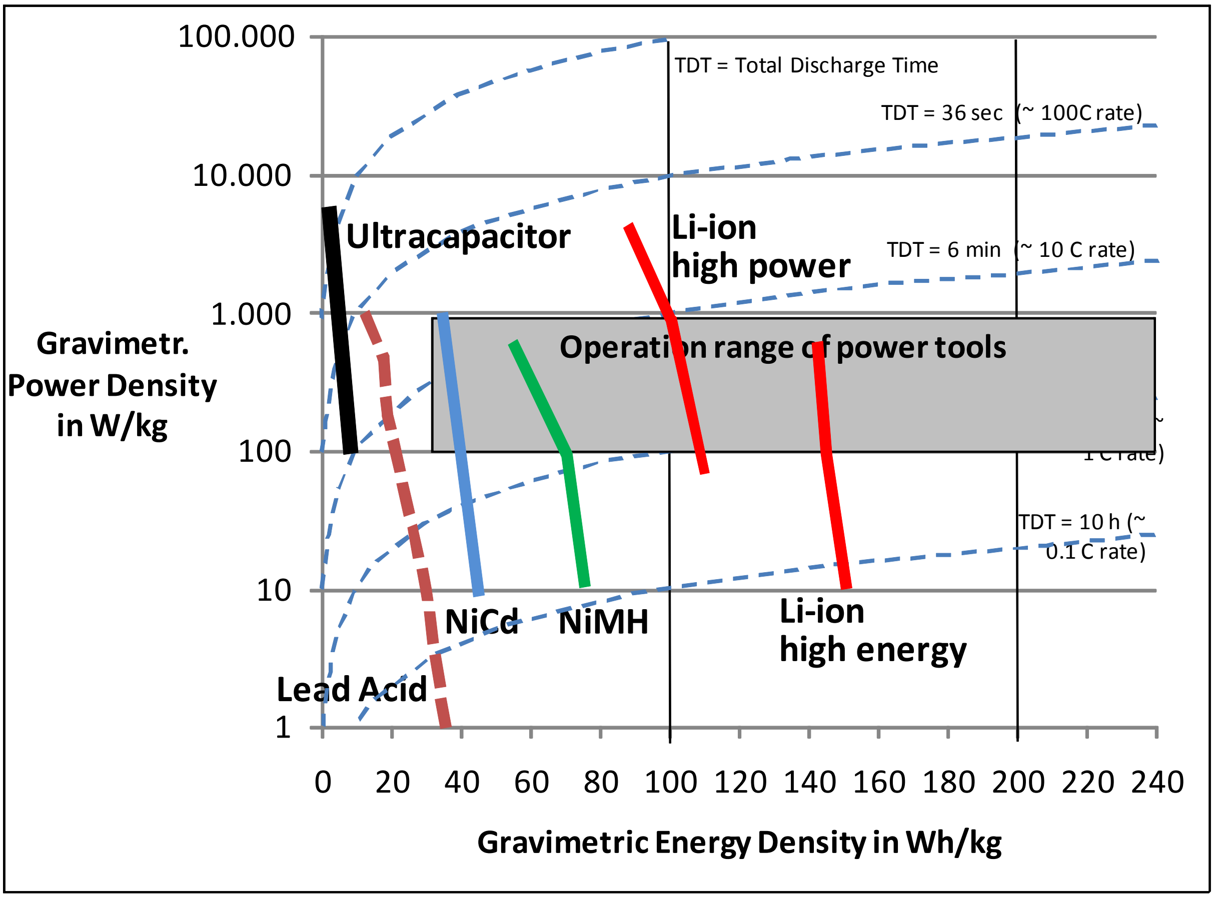


Figure 4-3 : Gravimetric power density versus gravimetric energy density for 5 rechargeable battery types and ultracapacitor as reported by Delphi Automotive Systems (source: [Recharge 2009])

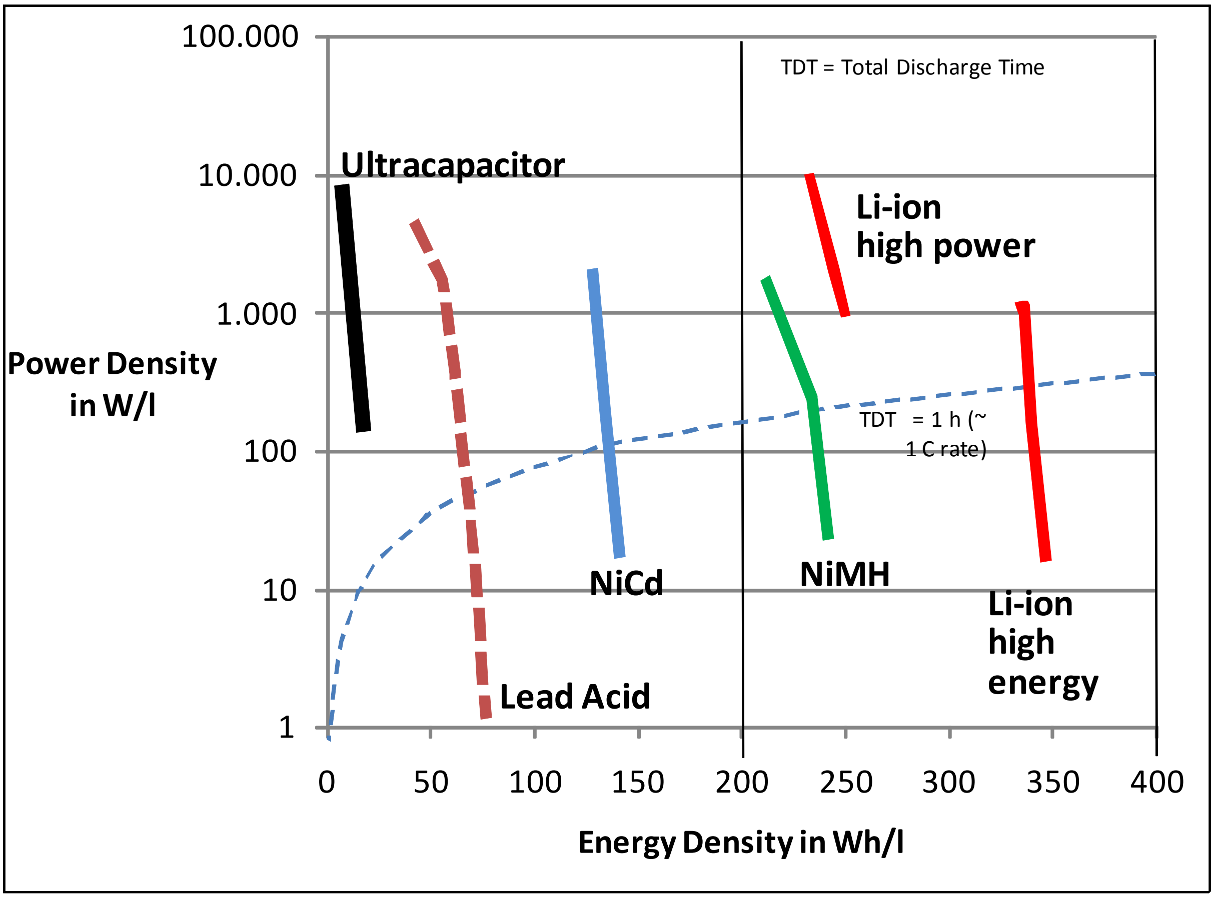


Figure 4-4 : Volumetric power density versus energy density for 5 rechargeable battery types and ultracapacitor as reported by Delphi Automotive Systems (source: [Recharge 2009])

4.2.2 Other rechargeable battery technologies

Table 4-5 gives an overview on specific properties of secondary (rechargeable) batteries which might be considered as an energy source for cordless power tools (CPT). From these the 2 high temperature battery types Sodium-sulfur (NaS) and Molten salt (ZEBRA) were not considered in the further technical assessment, as the former's development has been discontinued and the latter is suitable for large capacity batteries > 20KWh only [Woodbank Communications 2005a], while cordless power tolls (CPT) operate in the range of 40 Wh.

Table 4-5 : Overview on specific properties of secondary (rechargeable) battery types [Umweltbundesamt 2009, Woodbank Communications 2005b, Altair 2009, Wikipedia 2009A,B,C]

	Commercialisation	**Voltage**	**Energy density**		**Power density**	**Efficiency**	**Cylces**	**Life time**	**Self discharge**	**Temperature range**
Battery type		**V**	**Wh/kg**	**Wh/l**	**W/kg**	**%**		**years**	**%/month**	**°C**
State-of-the-art batteries for cordless power tools (CPT)										
Nickel-cadmium (NiCd)	1956	1.2	50	100	175	80	1,500	6-8	20	-20 / +50
Nickel-metalhydride (NiMH)	1990	1.2	65	220	130	80	1,000	6	20	-20 / +45
Li-ion - cobalt ($LiCoO_2$)	1992	3.6	125	285	600	95	1,200	5	1	-10 / +55
Li-ion - manganese ($LiMn_2O_4$)	1999	3.6	160	270			1,200		1	
Other secondary batteries										
Li-polymer	.	3.7	120	300		90	>1,000	2	5	+60 / +100
Lithium-iron-phosphate ($LiFePO_4$)	.	3.25	100	170	600	97	2,000	5	1	-20 / +60
Li-titanate (nano)	.	2.3	72	135	760	91	9,000			
Li-sulfur (Li_2S_8)	2003	2.1	400	350			100		< 5%	
Ni-iron (NiFe)	1901	1.2	50			65			30	
Ni-zinc (NiZn)	1920	1.7	60	170	900		300		20	
RAM (Rechargeable alkaline manganese)	.	1.5	85	250		99.9	60 (when discharged not more than 50 %)		<0.3	
Zinc-bromine (ZnBr)	.	1.8	80		90	90	1,000	2	5	-5 / + 45
Vanadium redox	.	1.35	30			80	14,000		20	
Sodium-sulfur (NaS)	1960	2.1	90		110	93	600	2	4	+280 / +330
Molten salt (NaNiCl) (ZEBRA)	1982	2.58	90	160	125	88	1,000	5	3.5	+250 / +370

4.2.3 Other portable energy storage systems

In literature following portable non-battery energy storage system, which might have potential for being used in cordless powert tools (CPT) are mentioned:

- Electric Double Layer Capacitors (EDLCs, also known as supercapacitors or ultracapacitors)
- Superconducting Magnetic Energy Storage (SMES)
- Flywheels and
- Portable fuel cells.

These technologies will also be considered in the following technical assessment.

4.2.4 Summary of alternative identification

Table 4-6 gives an overview of battery and non-battery energy storage technologies, their advantages and disadvantages, and if they were not selected for technical assessment the reasons for the decline.

Table 4-6 : First evaluation of battery types regarding the adequacy as energy source for CPTs

Battery type	Advantages	Disadvantages	Selected for technical assessment (Reason for decline)
Primary batteries		Too high material and life-cycle energy consumption	No (too little lifetime energy storage capacity)
Secondary batteries – state-of-the-art			
Nickel-cadmium (NiCd)	• High power density • Long lifetime • Many loading cycles • Wide temperature range • reliable • Relatively cheap	• Contains cadmium which is a very toxic and carcinogenic substance • Relatively high self discharge	Yes
Nickel-metalhydride (NiMH)	• High energy density	• Relatively high self discharge	Yes
Lithium-ion (Li-ion)	• High energy density • Low mass (light) • Low self discharge	• Loses capacity during storage	Yes
Lead-acid		Too heavy for application in power tools	No (too heavy)
Secondary batteries – in the pipeline			
Li-polymer	• Long storage life • Less vulnerable to problems caused by overcharge, damage or abuse	• Low power density	Yes
Lithium-iron-phosphate ($LiFePO_4$)	• More cycles as compared to standard Li-ion • Less sensitive with power peaks	• Lower energy density than Li-ion • Under development	Yes

Battery type	Advantages	Disadvantages	Selected for technical assessment (Reason for decline)
Li-titanate (nano)	• Many more cycles as compared to standard Li-ion • Wide temperature range	• Under development	Yes
Lithium-air	• Very high energy density	• Safety concerns • Under development	Yes
Air-fueled Lithium-ion	• Very high energy and power density	• Early in the development phase	Yes
Li-sulfur (Li_2S_8)	• High energy density • tolerant of over-voltages	• Lower voltage than Li-ion • Under development	Yes
Ni-iron (NiFe)	• Reliable • many cycles	• Low coulomb efficiency • High self discharge	Yes
Ni-zinc (NiZn)	• High power density	• Limited number of cycles	Yes
RAM (Rechargeable alkaline manganese)	• Can hold charge for up to 7 years, EnviroCell does not contain toxic material	• best suited for use in low-drain devices such as remote controls	Yes
Zinc-bromine (ZnBr)	• High energy density • No performance loss over cycles	• Low power density • Energy loss by moving parts • Large	Yes
Vanadium redox	• High power density 14,000 cycles	• Low energy density • Energy loss by moving parts • Large	Yes
Sodium-sulfur (NaS)	• High energy density No self discharge	• High temperature 350 °C, • damaged if temperature < 200 °C, discontinued	No (development discontinued)
Molten salt (NaNiCl) (ZEBRA)		• Suitable for large capacity batteries only (> 20KWh)	No (too big)
Non-battery energy storage systems which might be used in CPT			
EDLC = electro chemical double layer capacitors	• High power density • High voltage possible • Development potential for higher energy density	• Low energy density • Discharged after a few seconds	Yes
Superconducting Magnetic Energy Storage		• Large • Needs cooling • Low energy density	Yes
Flywheels	• Long life • Low mass	• huge gyroscopic forces • extreme material requirements	Yes
Portable fuel cells (DMFC)	• no time loss for recharging	• Low cell voltage • Complex system required	Yes

4.3 Technical Characterisation of NiCd batteries and its Alternatives

4.3.1 NiCd batteries

Nickel-cadmium batteries have been made for over 100 years, addressing a wide variety of professional and industrial applications, with capacities from 0.1 to 1,500 Ah. Several different electrode technologies can be used, with pocket-type, sintered plate, foam and SAFT's recent proprietary "PNE" (Plastic Nickel Electrode) anodes, and pocket-type, sintered plate or PBE cathodes (Plastic Bonded Electrodes) [SAFT 2007].

Nickel-cadmium cells have an anode (negative) in cadmium hydroxide and a cathode (positive) in nickel hydroxide, immersed in an alkaline solution (electrolyte) comprising potassium, sodium and lithium hydroxides.

The chemical reactions of the NiCd cell during discharge are as follows [Nilsson 2002] (see also Figure 4-5):

$$\text{Cd-anode:}\ \ Cd + 2\,OH^- \rightarrow Cd(OH)_2 + 2\,e^- \qquad (1)$$

$$\text{Ni-cathode:}\ \ NiO(OH) + H_2O + e^- \rightarrow Ni(OH)_2 + OH^- \qquad (2)$$

During discharge at the cadmium cathode metallic cadmium dissolves in the caustic hydroxide solution while releasing two electrones. At the anode nickel-3-oxid-hydroxide ($NiO(OH)$) takes up an electron to form nickel-2-hydroxide ($Ni(OH)_2$) and to release hydroxide (OH^-).

The total reaction for discharge/charge is:

$$Cd + 2\,NiO(OH) + 2\,H_2O \leftrightarrow Cd(OH)_2 + 2\,Ni(OH)_2 \qquad (3)$$

(charged) KOH (discharged)

The cells are rechargeable and deliver a voltage of 1.2 V during discharge.

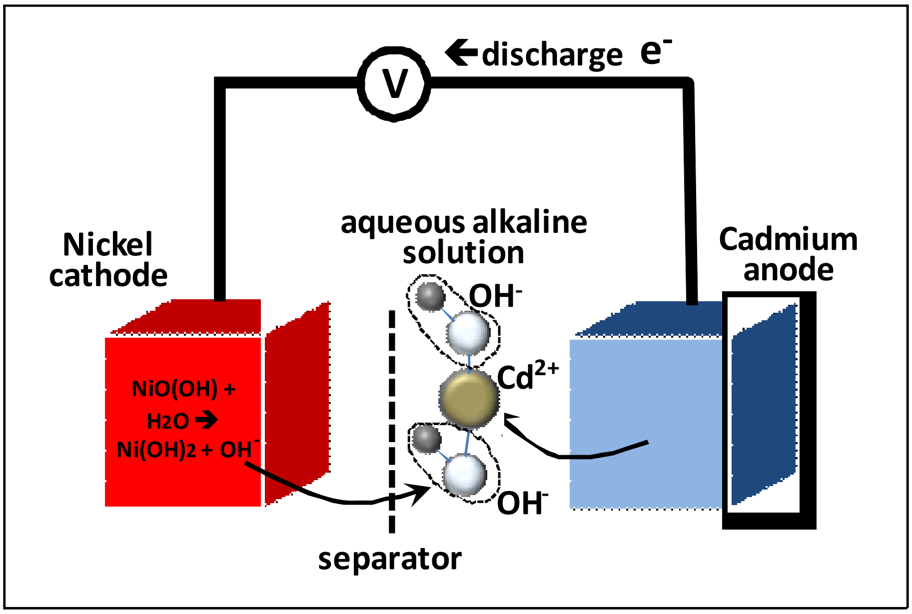


Figure 4-5 : NiCd cell schematic diagram

Power density and energy density

The power discharge and the energy density, both per kg, per liter, per cell of NiCd batteries are shown in Figure 4-1 through Figure 4-4 (above) and Table 4-18 (below).

Charging

NiCd batteries can charge at several different rates, depending on how the cell was manufactured. The charge rate is measured based on the percentage of the ampere-hour (Ah) capacity the battery is fed as a steady current over the duration of the charge. Regardless of the charge speed, more energy must be supplied to the battery than its actual capacity, to account for energy loss during charging, with faster charges being more efficient. For example, the typical overnight charge, called a C/10 charge, is accomplished by applying 10% of the battery's total capacity for a period of 14 hours; that is, a 100 mAh battery takes 140 mAh of energy to charge at this rate. At the fast-charge rate, done at 100% of the rated capacity, the battery holds roughly 80% of the charge, so a 100 mAh battery takes 120 mAh of energy to charge (that is, approximately 1 hour and fifteen minutes). The downside to faster charging is the higher risk of overcharging, which can damage the battery [Powerstream 2007a].

The safe temperature range for a NiCd battery in use is between −20°C and 45°C. During charging, the battery temperature typically stays low, around 0°C (the charging reaction absorbs heat), but as the battery nears full charge the temperature will rise to 45–50°C. Some battery chargers detect this temperature increase to cut off charging and prevent over-charging.

When not under load or charge, a NiCd battery will self-discharge approximately 10% per month at 20°C, ranging up to 20% per month at higher temperatures. It is possible to perform a trickle charge at current levels just high enough to offset this discharge rate; to keep a battery fully charged. However, if the battery is going to be stored unused for a long period of time, it should be discharged down to at most 40% of capacity (some manufacturers recommend fully discharging and even short-circuiting once fully discharged), and stored in a cool, dry environment [Wikipedia 2009D].

High quality NiCd's have a thermal cut-off so if the battery gets too hot the charger stops. If a NiCd is still warm from discharging and been put on charge, it will not get the full charge possible. A hot battery should be allowed to cool to room temperature before charging it [Wikipedia 2009D].

A NiCd battery requires a charger with an intelligent charge termination method if a fast charger is used. Often NiCd battery packs have a thermal cut-off inside that feeds back to the charger telling it to stop the charging once the battery has heated up and/or a voltage peaking sensing circuit. At room temperature during normal charge conditions the cell voltage increases from an initial 1.2V to an end-point of about 1.45V. The rate of rise increases markedly as the cell approaches full charge. The end-point voltage decreases slightly with increasing temperature [Wikipedia 2009D].

Overcharging

With NiCd batteries, there are two possible results of overcharging:

- If the anode is overcharged, hydrogen gas is produced.

$$\text{Cd-anode: } H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^- \quad (4)$$

- If the positive electrode is overcharged, oxygen gas is produced.

$$\text{Ni-cathode: } 2\,H_2O \rightarrow O_2 + 4\,H^+ + 4\,e^- \quad (5)$$

For this reason, the anode is always designed for a higher capacity than the cathode, to avoid releasing hydrogen gas. There is still the problem of eliminating oxygen gas, to avoid rupture of the cell casing.

NiCd power packs for cordless power tool (CPT) usually are of the sealed type. Cells of this type consist of a pressure vessel that is supposed to contain any generation of oxygen and hydrogen gasses until they can recombine back to water. Such generation typically occurs during rapid charge and discharge and exceedingly at overcharge condition. If the pressure exceeds the limit of the safety valve, water in the form of gas is lost. Since the vessel is designed to contain an exact amount of electrolyte this loss will rapidly affect the capacity of the cell and its ability to receive and deliver current. To detect all conditions of overcharge demands great sophistication from the charging circuit. A cheap charger will eventually damage even the best quality cells [Wikipedia 2009D].

Discharging

Figure 4-6 shows the discharge characteristics of a NiCd-cell used at the rating current of 0.65 A (1C). Within the first 10 minutes the peak voltage drops to the rated voltage of 1.2 V, stays for some time at that level, and then drops off to below 0.9 V at about 1 hour of use.

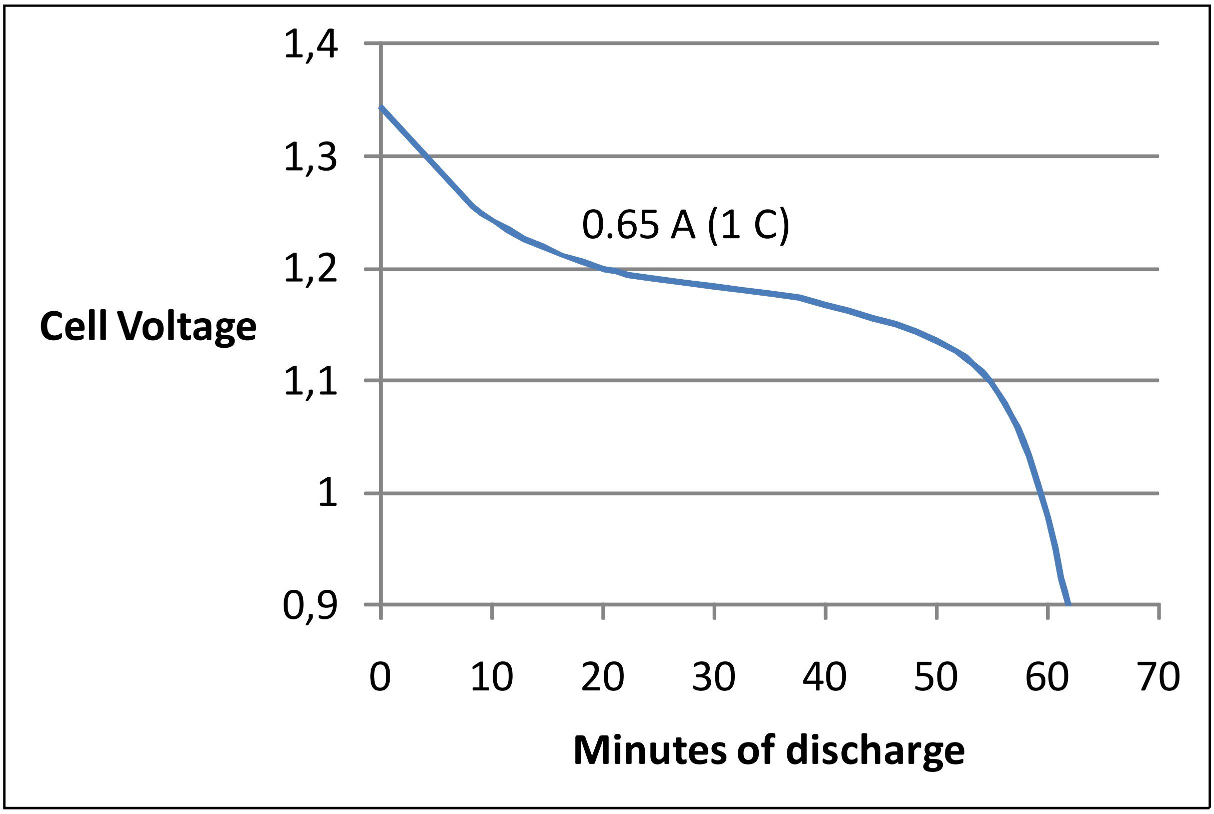


Figure 4-6: Typical discharge characteristics of 1.2 V NiCd-cell type AA (rechargeable) – Average performance at 21°C [Energizer 2009a]

Discharging to charging efficiency

[EPTA 2009b] reports that NiCd batteries have a discharging to charging of 67 to 91 % varying with temperature and current. This means that up to 50 % more energy has to be pumped into the NiCd cell, than comes out of it.

Cell reversal – Over discharge

A potential problem with NiCd power-packs is reverse charging. This can occur due to an error by the user, or more commonly, when a battery of several cells is fully discharged. Because there is a slight variation in the capacity of cells in a battery, one of the cells will usually be fully discharged before the others, at which point reverse charging begins seriously damaging that cell, reducing battery life. The first cell that reaches zero is pushed beyond to negative voltage and gasses generated open the seal and dry the cell. The by-product of reverse charging is hydrogen gas, which can be dangerous. Some commentators advise that **one should never discharge multi-cell NiCd batteries to zero voltage (V).**

In modern cells, an excess of *anti-polar material* (basically active material ballast at positive electrode) is inserted to allow for moderate negative charge without damage to the cell. This excess material slows down the start of oxygen generation at the negative plate. This means a cell can survive a negative voltage of about -0.2 to -0.4 volts. However if discharge is continued even further, this excess ballast is used up and both electrodes change polarity, causing destructive gassing (gas generation).

Battery packs with multiple cells in series should be operated well above 1 volt (V) per cell to avoid placing the lowest capacity cell in danger of going negative [Wikipedia 2009D].

Memory and lazy battery effects

NiCd batteries suffer from a "memory effect" if they are discharged and recharged to the same state of charge hundreds of times. The apparent symptom is that the battery "remembers" the point in its charge cycle where recharging began and during subsequent use suffers a sudden drop in voltage (V) at that point, as if the battery had been fully discharged.

Some electronics designed to be powered by NiCd batteries are able to withstand this reduced voltage long enough for the voltage to return to normal. However, if the device is unable to operate through this period of decreased voltage, the device will be unable to get as much energy out of the battery, and for all practical purposes, the battery has a reduced capacity.

There is controversy about whether the memory effect actually exists, or whether it is as serious a problem as is sometimes believed. [Nilsson 2002] states that the “memory effect” is mainly a phenomenon in sealed cells with sintered electrodes, which can be cured by deeply discharging the cell.

There is much evidence that the memory effect story originated from orbiting satellites, where they were typically charging for twelve hours out of twenty-four for several years [Goodman 1997]. After this time, it was found that the capacities of the batteries had declined significantly, but were still perfectly fit for use. It is unlikely that this precise repetitive charging (e.g., 1000 charges / discharges with less than 2% variability) could ever be reproduced by consumers using electrical goods.

[EPTA 2009b] states that in any case problems with the memory effect now have been solved by development of cells and charging system, which avoid the memory effect.

An effect with similar symptoms to the memory effect is the so-called “voltage depression” or “lazy battery effect”. This results from repeated overcharging; the symptom is that the battery appears to be fully charged but discharges quickly after only a brief period of operation. Larger cells may benefit from refilling with distilled water, or a complete electrolyte replacement. In rare cases, much of the lost capacity can be recovered by a few deep-discharge cycles, a function often provided by automatic NiCd battery chargers. However, this process may reduce the lifetime of the battery [Dan’s Data 2008]. If treated well, a NiCd battery can last for 1000 cycles or more before its capacity drops below half its original capacity [Wikipedia 2009D].

Dendritic shorting

NiCd batteries, when not used regularly, tend to develop dendrites which are thin, conductive crystals which may penetrate the separator membrane between electrodes. This leads to internal short circuits and premature failure, long before the 800–1000 charge/discharge cycle life claimed by most vendors. Sometimes, applying a brief, high-current charging pulse to individual cells can clear these dendrites, but they will typically reform within a few days or even hours. Cells in this state have reached the end of their useful life and should be replaced [Wikipedia 2009D].

Self-discharge

The self-discharge is highest immediately after charge, and then tapers off. The capacity loss of NiCd batteries is 10% in the first 24h, then declines to about 10% every 30 days thereafter. High temperature increases self-discharge [Buchmann 2006].

Temperature

The temperature range within which NiCd batteries may be operated lies between – 20 °C and + 45 °C [Wikipedia 2009D]. [Buchmann 2006] reports a wider temperature range for discharge of - 40 °C to + 60 °C. It has, however to be taken into account that the batterie's capacity is much lower at low and high temperatures than at room temperature (see Figure 4-7).

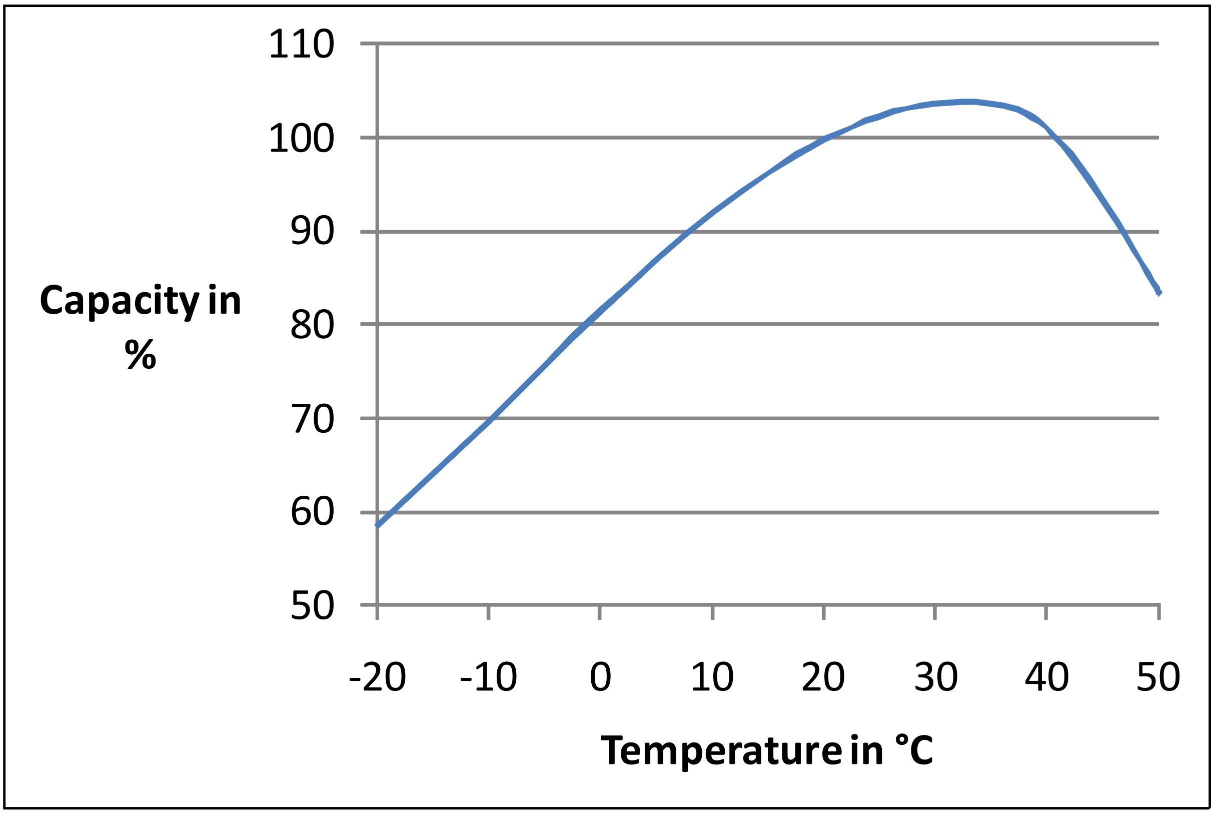


Figure 4-7: Capacity versus temperature characteristics of a 9 V NiCd battery (rechargeable) [Energizer 2009b]

Lifetime

Reported values for the number of charging cycles cover a wide range from 400 [Noreus 2000] to 3,000 [SAFT 2007]. Most frequently, however, a value of 1,000 charging cycles for NiCd batteries is reported [Bosch 2009a, Wikipedia 2009D]. This value is also confirmed by [EPTA 2009b].

The actual lifetime of a NiCd-battery very much depends on its use and maintenance. Usually an operational lifetime of 5 years and more is reported [EPTA 2009b].

Safety

NiCd power packs are very robust and have a sealed configuration with gas release vent. Nevertheless following safety regulations need be observed:

- Never short-circuit the battery because this may cause the battery to explode. (A short-circuit is a direct electrical connection between the + and – battery terminals, such as with a wire. Batteries should never be short circuited.)
- Never incinerate NiCd batteries; along with the possibility of an explosion, incinerating a NiCd battery will result in the release of a toxic gas containing cadmium. Recycle the battery instead.
- Avoid dropping, hitting, or denting the battery because this may cause internal damage including (internal) short-circuiting of the cell.
- Avoid rapid overcharging of the battery; this may cause leakage of the electrolyte, outgassing, or possibly an explosion [Wikipedia 2009D].
- In the event of a battery rupture, prevent skin contact and collect all released material in a plastic lined metal container.
- SkinandEyes: In the event that battery the ruptures, flush exposed skin with copious quantities of flowing lukewarm water for a minimum of 15 minutes. Get immediate medical attention for eyes. Wash skin with soap and water.
- Swallowing**:** Ingestion of a battery can be harmful.
- Storage: Store in a dry place. Storing unpackaged cells together could result in cell shorting and heatbuild-up [Rayovac 2007].

Table 4-7 sumarizes the technical properties of NiCd cells and 18 V NiCd power-packs, resepectivly. The table also shows a material cost estimate.

Table 4-7 : Properties of NiCd batteries [EPTA 2009b]

		Performance	
		NiCd	
Property	**Unit**	**Single cell**	**18V power pack**
Power discharge	**W/kg**		599
	W/l		900
	A		40
Voltage	**V**	1.2	18
Energy storage capacity/cycle[*1]	**Wh/kg**		37.4
	Wh/l		56.2
	Wh/cell,pack		38.0
Number of recharging cycles at full energy storage capacity			1,000
Energy storage capacity over lifetime[*1]	**Lifetime Wh/kg**		33,695
	Lifetime Wh/l		50,623
	Lifetime Wh/cell,pack		34,200
Temperature range of operation	**°C (from-to)**	-20°C to 60°C	
Self discharge	**%/month**	15 to 20%	
Operational life	**Years**		5+
Reliable, robust towards mechanical wear, resistant to abuse		Very abuse tolerant. Can use 100% of charge and tolerate deep discharge and fully recover	
Sealed, leak proof, maintenance free, safe under accident conditions		Sealed configuration with gas release vent	
Energy efficiency of discharge/charge	**% charge out to charge in (coulombic efficiency)**	67 to 91 % (varies with temperature and current)	
Duration of recharging	**h**	0.25 to 16	
Sensitivity with respect to overcharge		Superior durability; Designed to withstand overcharge and overdischarge	
Development of properties over the recharging cycles (e.g. no memory effect)		Memory effect now solved by development of cells and charging system	
Weight	**kg/cell,pack**	0.055	1.015
Volume	**l/cell,pack**	0.0179	0.676
Material cost	US$ $_{\text{of the year 2000}}$/Wh	0.22 [Noreus 2000]	1.0
Note [*1]: All energy values from 10 Ampere (A) discharge.			
General note: The range of properties varies over a wide range. The data shown in the table are single figures for each of the properties, but in practice the properties vary considerably depending on the source and specification of each individual cell on the market.			

Composition

Table 4-8 shows the composition of NiCd batteries. In addition to the electrode material cadmium and nickel, the main component of the NiCd batteries is iron/steel as structural material. The NiCd batteries contain also small amounts of cobalt, manganese and zinc. Further materials are the electrolyte (e.g. potassium hydroxide in water) and plastics (for the separator and the packaging).

Table 4-8 : Composition of rechargeable NiCd batteries - Share in %

Source	[EC 2003]	[ERM 2006]	[EPBA 2007]
Cadmium (Cd)	15-20	15	15
Cobalt (Co)	0.6		
Iron (Fe) and steel	29 – 40	35	40
Manganese (Mn)	0.083		
Nickel (Ni)	15 - 20	22	22
Zinc (Zn)	0.06		
Alkali		2	2
Plastics		10	5
Water		5	
Other non metals		11	16

Recycling

NiCd batteries can be treated by pyro-metallurgical processes to recover the cadmium, nickel and iron [EPBA 2007].

Advantages

NiCd batteries show robustness, reliability and a relatively long service life. This is the benchmark technology for difficult and demanding applications [SAFT 2007]. NiCd batteries have:

- Fast and simple charge, even after prolonged storage [Recharge 2009].
- A high tolerance for deep discharge for long periods (NiCd batteries in long-term storage are typically stored fully discharged);
- A broad operating temperature range from –20 °C to +50 °C [Energizer 2009a] ([SAFT 2007] reports -40 °C to + 60 °C); working below 0°C is possible as the electrolyte has a very low freezing point;
- A high cycling capability of 1,000 charge/discharge cycles on the average [ETPA 2009b];
- Long shelf life - five-year storage is possible. Some priming prior to use will be required [Recharge 2009];
- Simple storage and transportation - most airfreight companies accept NiCd batteries without special conditions [Recharge 2009];

- Low or zero maintenance [SAFT 2007].
- NiCd batteries are more difficult to damage than other batteries.

Because of the structural materials they use, NiCd batteries are robust, and exempt from risk of sudden failure. They can be made with very thin electrodes, for high-power units.

SAFT in France makes an increasing proportion of its NiCd batteries using cadmium from recycled batteries [SAFT 2007].

Disadvantages

- NiCd batteries store less energy by mass and volume than both NiMH and Li-ion batteries (see Figure 4-3 and Figure 4-4). Therefore NiCd batteries need to be charged more frequently. As compared to Li-ion power packs, NiCd power packs are also heavier.
- NiCd batteries have a lower discharge to charge efficiency than both NiMH and Li-ion batteries.
- Memory effect - nickel-cadmium batteries must periodically be exercised (discharge/charge) to prevent memory effects [Recharge 2009].
- Relatively high self-discharge - needs recharging after storage [Recharge 2009].

4.3.2 NiMH batteries

The basic chemistry of a NiMH cell is similar to the one of the NiCd cell (see Figure 4-8). However, instead of the cadmium anode there is a mischmetal anode which forms metalhydrids (MH). During discharge, these metalhydrids release hydrogen-ions (H^+) while releasing electrons:

$$\text{MH-anode: } MH \rightarrow M + H^+ + e^- \qquad (6)$$

The cathode reaction is the same as with the NiCd cell (see equation (2)).

The total reaction for NiMH cell discharge/charge is:

$$\underset{\text{(charged)}}{MH + NiO(OH) + 2\,H_2O} \underset{\text{KOH}}{\leftrightarrow} \underset{\text{(discharged)}}{M + Ni(OH)_2} \qquad (7)$$

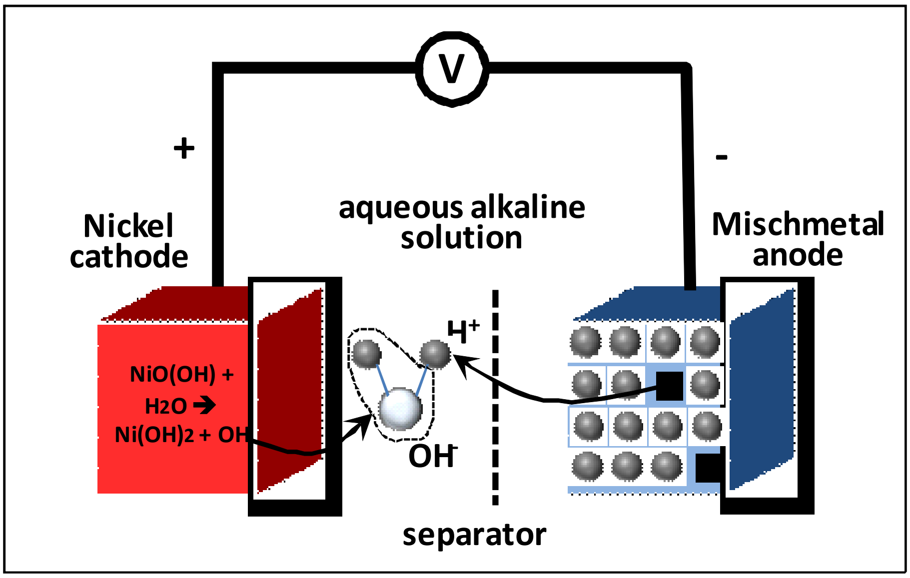


Figure 4-8 : NiMH cell schematic diagram – discharge reaction

Power density and energy density

According to [ECD Ovonic 2009] the gravimetric energy density of NiMH cells has doubled from 1991 to 2008 and the volumetric energy density has more than dobled to reach 110 Wh/kg and 435 Wh/l in 2008, respectively. As can be seen from Figure 4-1 through Figure 4-4 (above) and Table 4-18 (below) other sources report a considerably lower energy density for NiMH batteries. These figures and the table also show the power discharge per kg, per liter and per NiMH cell.

Charging

The charging voltage of a NiMH cell is in the range of 1.4–1.6 V. A fully charged cell measures 1.35–1.4 V, and supplies a nominal average 1.2 V/cell during discharge, down to about 1.0–1.1 V/cell (further discharge may cause permanent damage). In general, a constant-voltage charging method cannot be used for automatic charging. When fast-charging, it is advisable to charge the NiMH cells with a smart battery charger to avoid overcharging, which can damage cells and cause dangerous conditions. A NiCd charger should not be used as an automatic substitute for a NiMH charger [Wikipedia 2009E].

Smart battery chargers can apply one of the following methods:

- ΔV charging[27]: After the cell is fully charged, and as it begins to overcharge, the voltage polarity of the electrodes inside the battery will begin to reverse, and this will cause the battery voltage to decrease slightly. A "ΔV" type battery charger ends the charge cycle by switching off the charging current when it senses this drop in voltage.

---

[27] The symbol ″Δ″ stands for ″change″. ″ΔV″ stands for a change (here: drop) in voltage.

- Δ temperature charging: When the cell is fully charged, most of the charging power will then be converted to heat. This results in an increase in the rate of change of temperature, which can be detected by a sensor measuring the battery temperature.
- Trickle charging: Some equipment manufacturers consider that NiMH cells can be safely charged in simple fixed, low-current chargers with or without timers. The trickle charge rate should be limited to between $0.033 \times C$ per hour and $0.05 \times C$ per hour (with C being the nominal capacity of the battery in Ampere-hour) for a maximum of 20 hours to avoid damaging the batteries. For a slow charge, or "trickle charge" process, Duracell recommends "a maintenance charge of indefinite duration at C/300 rate". To maximize battery life, the preferred charge method of NiMH cells uses low duty cycle pulses of high current rather than continuous low current.

A safety feature of a custom-built charger is to use a resettable fuse in series with the cell, particularly of the bimetallic strip type. This fuse will open if either the current or the temperature goes too high [Wikipedia 2009E].

Overcharging

In principle, when being overcharged NiMH batteries are subject to the same chemical reactions as NiCd batteries (see equations 4 and 5 above). However, with NiMH-cells the buildup of hydrogen, may become a more serious problem. The hydrogen is adsorbed by the anode-material in an exothermic reaction [Nilsson 2002] causing the cell to heat up. Therefore, NiMH cells:

- either have a vent for releasing hydrogen in the event of serious overcharging (with the disadvantage that the cell loses some of its capacity [Nilsson 2002]),
- or contain catalysts to recombine the formed gases ($2\ H_2 + O_2$ ---catalyst → $2\ H_2O$). However, this only works with overcharging currents of up to $C/10$ h (nominal capacity divided by 10 hours). As a result of this reaction, the batteries will heat up considerably, marking the end of the charging process. Some quick chargers have a fan to keep the batteries cool [Wikipedia 2009E].

Discharging

Under a light load (0.5 ampere), the starting voltage of a freshly charged AA NiMH cell in good condition is about 1.4 volts; some measure almost 1.5 volts. Mid-discharge at a load of 1 ampere, the output is about 1.2 volts; at 2 amperes, about 1.15 volts; the total effective differential internal resistance is about 0.05 ohms [Wikipedia 2009E].

Discharging to charging efficiency

[EPTA 2009b] reports that NiMH batteries have a discharging to charging efficiency of 91 to 95 % reduced at high temperature.

Cell reversal – Over discharge

A complete discharge of a NiMH cell until it goes into polarity reversal can cause permanent damage to the cell. This situation can occur in the common arrangement of power packs, where one cell will be completely discharged before the others, due to small differences in capacity among the cells. When this happens, the "good" cells will start to "drive" the discharged cell in reverse, which can cause permanent damage to that cell [Wikipedia 2009E].

Irreversible damage from polarity reversal is a particular danger in systems, even when a low voltage threshold cutout is employed, where cells in the battery are of different temperatures. This is because the capacity of NiMH cells significantly declines as the cells are cooled. This results in a lower voltage under load of the colder cells [Wikipedia 2009E].

Memory effect

Memory effect may occur, but is reversible through repeated charging/discharging [Duracell 2009].

Self-discharge

NiMH cells historically had a somewhat higher self-discharge rate than NiCd cells. The self-discharge is 5–10% on the first day and stabilizes around 15 – 30 % per month at room temperature. The rate is strongly affected by the temperature at which the batteries are stored with cooler storage temperatures leading to slower discharge rate and longer battery life. The highest capacity batteries on the market (>8 Ah) are reported to have the highest self-discharge rates [Wikipedia 2009E].

A new type of NiMH cell was introduced in 2005 that reduces self-discharge and therefore lengthens shelf life. By using a new separator, manufacturers claim the cells retain 70–85% of their capacity after one year when stored at 20 °C. These cells are marketed as "ready-to-use" or "pre-charged" rechargeables.

Low self-discharge NiMH cells have lower capacity than standard NiMH cells. The highest capacity low-self-discharge cells have 2000-2450 mAh and 850 mAh capacities for AA and AAA cells, respectively, compared to 2800 mAh and 1000 mAh for standard AA and AAA cells. However, after only a few weeks of storage, the retained capacity of low-self-discharge NiMH batteries often exceeds that of traditional NiMH batteries of higher capacity [Vorkoetter 2008].

Temperature

[EPTA 2009b] reports a temperature range within which NiMH cells can operate of 0°C to 50 °C. [Buchmann 2006] reports a temperature range of -20 °C to +60 °C. Both sources, however, agree, that NiCd cells can operate at somewhat lower temperatures than NiMH cells.

Lifetime

[EPTA 2009b] for NiMH batteries reports a lifetime of 500 charging/discharging cycles or 3 to 5 years.

Safety

NiMH power packs are sealed, have a gas release vent and are not harmful, as long as they are used in compliance with the manufacturer instructions. The content of the battery housing does not create a hazard, as long as the integrity of the battery housing is not affected by abuse (mechanicel, thermal, electrical). Fire, explosion and severe, burn hazard in such abuse conditions may occur.

When the battery housing is damaged, small amounts of electrolyte may leak. Seal battery air tight in a plastic bag, adding some dry sand, chalk ($CaCO_3$) or lime (CaO) powder or Vermiculite. Electrolyte traces may be wiped off dryly using household paper. Rinse with water afterwards.

Following safety aspects need be considered for NiMH batteries:

- Never short circuit, puncture, deform, disassemble, heat above 85 ºC or incinerate NiMH batteries.
- Storage preferably in a cool (below 30 ºC), dry area that is subject to little temperature change.
- Do not place near heating equipment, nor expose to direct sunlight for long periods. Elevated temperatures can result in reduced battery service life.
- Upon contact to internal battery content:
  - Skin: Immediately flush with plenty of water for at least 15 minutes. If symptoms are present after flushing, get medical attention.
  - Eyes: Immediately flush with plenty of water for at least 15 minutes and get medical attention.
  - Respiratory system: Leave area immediately. With large quantities and irritation of the respiratory tract get medical attention.
  - Ingestion: Rinse mouth and sorrounding area with water. Seek for immediate medical attention [VARTA 2008].

Table 4-9 summarizes the technical properties of NiMH batteries.

Table 4-9 : Properties of NiMH batteries [EPTA 2009b]

Property	Unit	Performance	
		Single cell	18V power pack
Power discharge	W/kg		543
	W/l		836
	A		40
Voltage	V	1.2	18
Energy storage capacity/cycle [*1]	Wh/kg		41.1
	Wh/l		63.2
	Wh/cell,pack		42.7
Number of recharging cycles at full energy storage capacity			500
Energy storage capacity over lifetime [*1]	Lifetime Wh/kg		19,771
	Lifetime Wh/l		30,436
	Lifetime Wh/cell,pack		20,562
Temperature range of operation	oC (from-to)	0°C to 50°C	
Self discharge	%/month	15 to 20%	
Operational life	Years		3 to 5
Reliable, robust towards mechanical wear, resistant to abuse		Somewhat abuse tolerant	
Sealed, leak proof, maintenance free, safe under accident conditions		Sealed configuration with gas release vent	
Energy efficiency of discharge/charge	% charge out to charge in (coulombic efficiency)	91 to 95 % (reduced at high temperature)	
Duration of recharging	h	0.5 to 1	
Sensitivity with respect to overcharge		Moderate; recombination reaction slower.	
Sensitivity with respect to overdischarge		Sensitive	
Development of properties over the recharging cycles (e.g. no memory effect)		Cell Ah capacity imbalance	
Weight	kg/cell,pack	0.059	1.040
Volume	l/cell,pack	0.0179	0.676
Note [*1]: All energy values from 10 Ampere (A) discharge.			
General note: Wh from cells that are commercially available today were used. The data shown in the table are single figures for each of the properties, but in practice the properties vary considerably depending on the source and specification of each individual cell on the market.			

Composition

Table 4-10 shows the typical composition of NiMH batteries. The hydrogen storage mischmetal is a complex alloy from different metals which may vary from producer to producer. One patented mischmetal used in NiMH batteries has the composition $(Ti_{0.1-60}Zr_{0.1-40}V_{0-60}Ni_{0.1-57}Cr_{0-56})_{70.5-87}*Co_{0-7.5}*Mn_{13-17}*Fe_{0-3.5}Sn_{0-1.5}$ [Ovshinsky et al. 1996]. Thus its main component may be either titanium, zirconium, vanadium, nickel or chromium.

Table 4-10 : Composition of NiMH batteries - Share in %

Source	[EC 2003]	[ERM 2006]	[EPBA 2007]	[VARTA 2008]
Aluminium (Al)				< 2
Cobalt (Co)	1.0 – 4.5	4	3	2 - 8
Iron (Fe) and steel	20 – 25	20	30	15 - 57
Lithium (Li)				< 1.2
Manganese (Mn)	0.81 – 3.0	1	1	< 2
Nickel (Ni)	25 - 46	35	33	17 - 40
Zinc (Zn)		1	1	< 3
Other metals (hydrogen storage mischmetal alloy / **lanthanides**)		10	10	4 - 20
Alkali		4	2	3 - 15
Plastics		9	5	
Water		8	8	
Other non metals	.	8	7	

Recycling

NiMH batteries can be recycled together with NiCd batteries to recover ferro-nickel and cobalt [EPBA 2007].

Advantages

- NiMH batteries by mass and volume can store more energy than NiCd batteries. Consequently they can be used longer till they need to be recharged.
- NiMH batteries have a better discharging to charging efficiency than NiCd batteries
- Less prone to memory effect than NiCd batteries - fewer exercise cycles are required [Recharge 2009].
- Simple storage and transportation - transport is not subject to regulatory control [Recharge 2009].

Disadvantages

- With 3 to 5 years the operational life of NiMH batteries [EPTA 2009b] is somewhat shorter than the life of NiCd batteries.
- NiMH batteries can be recharged only 500 times as compared to the 1,000 times a NiCd cell can be recharged [EPTA 2009b].
- The temperature range within which NiMH batteries can be operated is narrower than with NiCd batteries [EPTA 2009b].
- Limited discharge current - although a NiMH battery is capable of delivering high discharge currents, heavy load reduces the battery's cycle life [Recharge 2009].
- More complex charge algorithm needed – a NiMH battery generates more heat during charge and requires slightly longer charge times than NiCd batteries. Trickle charge settings are critical because the NiMH battery cannot absorb overcharge [Recharge 2009].
- High self-discharge - typically 50% higher than NiCd batteries [Recharge 2009].
- Performance degrades if stored at elevated temperatures - NiMH batteries should be stored in a cool place at 40% state-of-charge [Recharge 2009].
- High maintenance - NiMH batteries require regular full discharge to prevent crystalline formation. NiCd batteries should be exercised once a month, NiMH batteries once in every 3 months [Recharge 2009].

4.3.3 Li-Ion batteries

When a Li-ion cell is charged, Li-ions move from the positive cathode to the negative anode. The ion travel direction is reversed during discharge. Figure 4-9 shows a Li-ion cell discharging and producing a voltage (V). The cathode is represented by the red cube with ions stored in spaces within the crystal structure. Typically the cathode material is either manganese spinel, cobalt oxide ($LiCoO_2$) or iron-phosphate (see Table 4-11).

Li ions are small but finite in size. Because of the large difference in the number of Li ions present in the cathode of a charged or discharged cell, manganese-based material slightly expands or contracts as the cell is cycled.

A graphite anode is represented by the layered purple structure shown in Figure 4-9. The process of storing Li-ions in a layered material is called “intercalation”; that is, the ions occupy the spaces between the layers of carbon making up the graphite [Lecklider 2008].

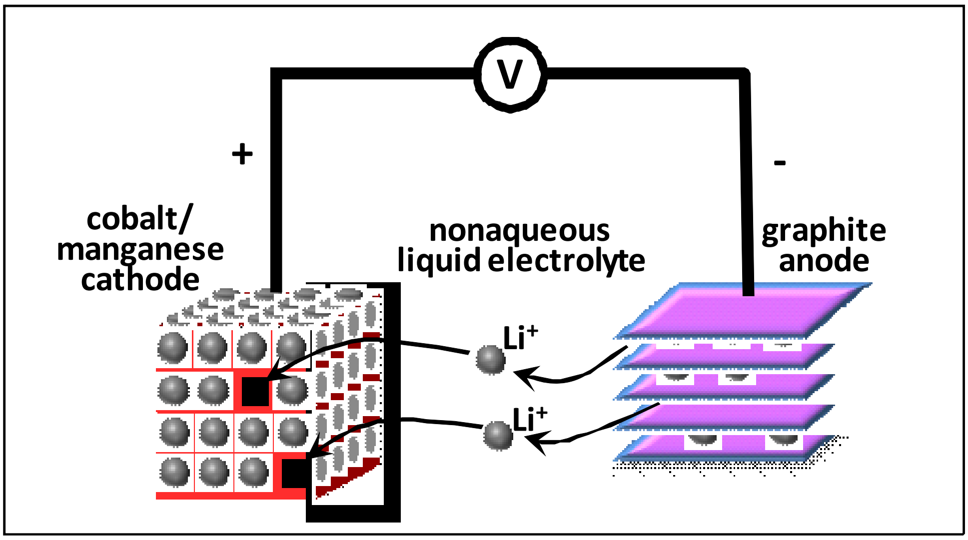


Figure 4-9 : **Li-ion cell schematic diagram – discharge reaction [Lecklider 2008]**

Table 4-11 : Properties of Li-ion-electrode materials [Wikipedia 2009F]

Material	Average Voltage in V	Gravimetric Capacity in Ah/kg	Gravimetric Energy in Wh/kg
Cathode			
$LiCoO_2$	3.7	140	518
$LiMn_2O_4$	4.0	100	400
$LiFePO_4$	3.3	150	495
Li_2FePO_4F	3.6	115	414
Anode			
Graphite (LiC_6)	0.1-0.2	372	37.2 - 74.4

The cell voltages given in Table 4-11 are larger than the potential at which aqueous solutions would electrolyze. Therefore, nonaqueous solutions are used as electrolyte for Li-ion cells.

Liquid electrolytes in Li-ion batteries consist of lithium salts, such as $LiPF_6$, $LiBF_4$ or $LiClO_4$ in an organic solvent, such as ethylene carbonate. A liquid electrolyte conducts Li-ions, acting as a carrier between the cathode and the anode when a battery passes an electric current through an external circuit. Typical conductivities of liquid electrolyte at room temperature (20 ^{o}C) are in the range of 10 mS/cm, increasing by approximately 30-40% at 40 ^{o}C and decreasing by a slightly smaller amount at 0 ^{o}C [Wenige et al.].

Unfortunately, organic solvents are easily decomposed on anodes during charging. However, when appropriate organic solvents are used as the electrolyte, the solvent is decomposed on initial charging and forms a solid layer called the “solid electrolyte interphase” (SEI) [Balbuena & Wang 2004], which is electrically insulating yet sufficiently conductive to lithium ions. The interphase prevents decomposition of the electrolyte after the second charge. For example, ethylene carbonate is decomposed at a relatively high voltage, 0.7 V vs. Li, and forms a dense and stable interface [Wikipedia 2009F].

Power density and energy density

The power discharge and the energy density, both per kg, per liter, per cell of Li-ion batteries are shown in Figure 4-1 through Figure 4-4 (above) and Table 4-18 (below).

Charging

Figure 4-10 shows the charging characteristics of a Li-ion power pack. It can be seen that 80 % of the charging is completed after 25 minutes, while the whole charging takes 50 minutes [Bosch 2009b].

[Bosch 2009a] claims that in contrast to NiCd cells, which should be recharged only after full discharge in order to avoid permanent capacity losses, Li-ion cells maybe recharged from any part charge level without negative consequences.

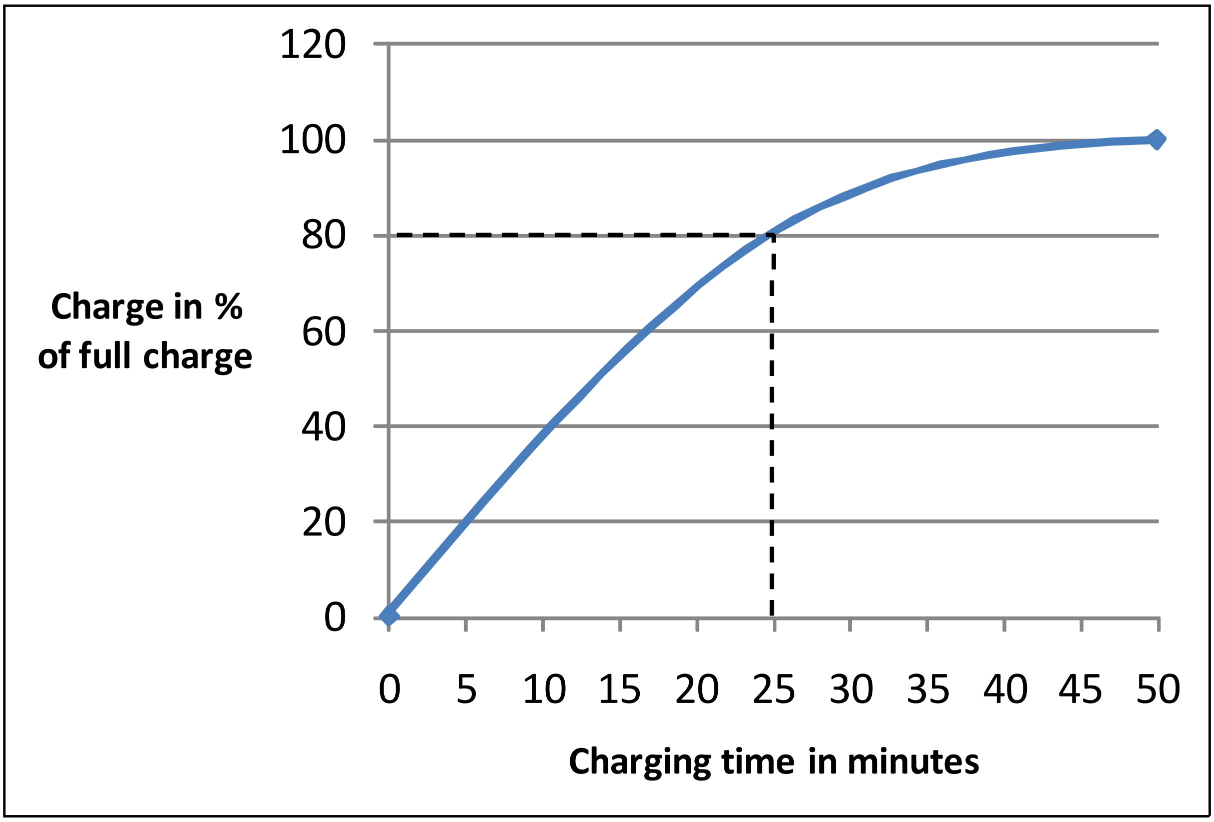


Figure 4-10: Charging characteristics of a Li-ion power pack [Bosch 2009b]

Overcharging – Over discharge

Upon every (re)charge, deposits are generated inside the electrolyte. These deposits inhibit the transport of Li ions. As a result the capacity of the cell diminishes. The increase in internal resistance affects the cell's ability to deliver current, thus the problem is more pronounced in high-current applications.

Also, high charge levels and elevated temperatures (whether resulting from charging or being ambient) hasten permanent capacity loss for lithium-ion batteries. The heat generated during a charge cycle is caused by the traditional carbon anode. Experiments have shown, replacing carbon with lithium titanate as anode material drastically reduces the degenerative effects associated with charging, including expansion and other factors [Wikipedia 2009F].

Li-ion batteries may explode if overheated or if charged to an excessively high voltage. Furthermore, they may be irreversibly damaged if discharged *below* a certain voltage. To reduce these risks, lithium-ion batteries generally contain a small circuit that shuts down the battery when it is discharged below about 3 V or charged above about 4.2 V. In normal use, the battery is therefore prevented from being deeply discharged. When stored for long periods, however, the small current drawn by the protection circuitry may drain the battery below the protection circuit's lower limit, in which case normal chargers are unable to recharge the battery. More sophisticated battery analyzers can recharge deeply discharged cells by slow-charging them [Wikipedia 2009F].

Other safety features are also required for commercial lithium-ion batteries:

- shut-down separator (for overtemperature),
- tear-away tab (for internal pressure),
- vent (pressure relief), and
- thermal interrupt (overcurrent/overcharging).

These devices occupy useful space inside the cells, and reduce their reliability; typically, they permanently and irreversibly disable the cell when activated. They are required because the anode produces heat during use, while the cathode may produce oxygen. Safety devices and recent and improved electrode designs greatly reduce or eliminate the risk of fire or explosion [Wikipedia 2009F].

Discharging to charging efficiency

[EPTA 2009b] reports that Li-ion batteries have a discharging to charging efficiency of 100 %.

Memory and lazy battery effects

Li-ion batteries show no memory effect. But they irreversibly lose capacity, 3 %/per year when charge 40 to 60 % of their maximum capacity and 20 % per year when fully charged [Wikipedia 2009F].

Self-discharge

Self-discharge is less than 0.1 % per month. Internal protection circuits typically consume 3 % of the stored energy per month [Buchmann 2006].

Temperature

As the cathode materials have a relatively weak metal-oxygen bond, if the cell is overheated, oxygen can be released and react with the electrolyte, causing further heating leading to thermal runaway.

In Li-ion cells that use a carbon anode a solid electrolyte interface (SEI) layer is formed on the surface of the anode when the cell is first charged. The SEI provides a safety layer between the highly reactive carbon anode and the electrolyte. At temperatures above 120°C, the SEI breaks down, and the anode can react violently.

The SEI also figures prominently in low temperature operation. Rather than pass a small current below 0°C, the SEI becomes virtually nonconductive. This means that efforts to charge a cell at low temperatures cause Li ions to plate onto the SEI rather than to pass through it to the anode. This condition also can lead to thermal runaway. Consequently Li-ion batteries can not be charged at temperatures below 0°C or above 120°C [Wikipedia 2009F].

Also discharge is not possible when the cell core temperature goes below – 10 °C [Bosch 2009a].

Lifetime

[Lecklider 2008] reports Li-ion batteries to have a life time of 500 charge/discharge cycles. [Bosch 2009a], however, states that Li-ion batteries have 1,000 charge/discharge cycles as compared to 800 – 1,000 charge/discharge cycles of the NiCd-power packs they also sell together with their cordless power tools (CPT). [EPTA 2009b] reports that the averge number of charging cycles of Li-ion batteries is 700.

[Bosch 2009a] states that Li-ion batteries have the same life expectancy as Ni-Cd-batteries. [EPTA 2009b], however, reports, that the actual lifetime of the Li-ion batteries still needs to be confirmed.

At a 100% charge level, a typical Li-ion laptop battery that is full most of the time at 25 °C will irreversibly lose approximately 20% capacity per year. However, a battery in a poorly ventilated laptop may be subject to a prolonged exposure to much higher temperatures, which will significantly shorten its life. Different storage temperatures produce different loss results: 6% loss at 0 °C, 20% at 25 °C, and 35% at 40 °C. When stored at 40%–60% charge level, the capacity loss is reduced to 2%, **4%**, 15% at 0, 25 and 40 °C respectively [Wikipedia 2009F].

Safety

[EPTA 2009b] reports that Li-ion-cells are not as abuse tolerant as NiCd batteries with respect to overcharging, overdischarging and mechanical wear, and therefore require electronic controls and proper pack construction. Li-ion power packs are supplied in sealed configuration with one-time gas release vent.

Table 4-18 summarizes the technical properties of Li-ion cells and 18 V Li-ion-power-packs.

Table 4-12 : Technical properties of Li-ion batteries [EPTA 2009b]

Property	Unit	Performance	
		Single cell	18V power pack
Power discharge	**W/kg**		851
	W/l		869
	A		40
Voltage	**V**	3.6	18
Energy storage capacity/cycle[*1]	**Wh/kg**		61.0
	Wh/l		62.2
	Wh/cell,pack		43.0
Number of recharging cycles at full energy storage capacity			700
Energy storage capacity over life time[*1]	**Lifetime Wh/kg**		30,129
	Lifetime Wh/l		30,750
	Lifetime Wh/cell,pack		21,241
Temperature range of operation	**oC (from-to)**	0°C to 60°C	
Self discharge	**%/month**	<5% (depends on electronic protection circuit)	
Operational life	**Years**		to be determined
Reliable, robust towards mechanical wear, resistant to abuse		Not abuse tolerant; requires electronic controls and proper pack construction	
Sealed, leak proof, maintenance free, safe under accident conditions		Sealed configuration with one-time gas release vent.	
Energy efficiency of discharge/charge	**% charge out to charge in (coulombic efficiency)**	100%	
Duration of recharging	**h**	0.5 to 1	
Sensitivity with respect to overcharge		Very sensitive; requires precise voltage control system.	
Sensitivity with respect to overdischarge		Sensitive	
Development of properties over the recharging cycles (e.g. no memory effect)		Impedance increase	
Weight	**kg/cell,pack**	0.0452	0.705
Volume	**l/cell,pack**	0.0165	0.691
Note [*1]: All energy values from 10 Ampere discharge.			
General note: Wh from cells that are commercially available today were used.There are higher Wh Li-Ion cells being sampled and also claimed but not yet widely in use. The range of properties varies over a wide range. The data shown in the table are single figures for each of the properties, but in practice the properties vary considerably depending on the source and specification of each individual cell on the market.			

Composition

Lithium batteries in which the anode is made from metallic lithium would pose severe safety issues. As a result, lithium-ion batteries were developed in which the anode, like the cathode, is made of a material containing lithium ions. In 1981, Bell Labs developed a workable graphite anode. The first commercial lithium-ion battery was released by Sony in 1991. The cells used layered oxide chemistry, specifically lithium cobalt oxide.

In 1983, Michael Thackeray, John Goodenough, and coworkers identified manganese spinel as a cathode material. Spinel showed great promise, since it is a low-cost material, has good electronic and lithium ion conductivity, and possesses a three-dimensional structure which gives it good structural stability. Although pure manganese spinel fades with cycling, this can be overcome with additional chemical modification of the material.

In 1989 it was shown that cathodes containing polyanions, eg. sulfates, produce higher voltage than oxides due to the inductive effect of the polyanion.

In 1996 lithium iron phosphate ($LiFePO_4$) and other phospho-olivines (lithium metal phosphates with olivine structure) were identified as cathode materials for lithium ion batteries.

In 2002 it was shown that improvements can be achieved by doping the $LiFePO_4$ with aluminum, niobium and zirconium. In 2004 the performance was further improved by utilizing iron-phosphate particles of less than 100 nm in diameter. This miniaturized the particle density by almost a hundredfold, increased the surface area of the cathode and improved the battery's capacity and performance [Wikipedia 2009F].

The three primary functional components of a lithium-ion battery are the anode, cathode, and electrolyte, for which a variety of materials may be used. Commercially, the most popular material for the anode is graphite. The cathode is generally one of three materials:

- a layered oxide (such as lithium cobalt oxide),
- a spinel (such as lithium manganese oxide ($LiFePO_4$)),
- or a material based on a polyanion (such as lithium iron phosphate) [Wikipedia 2009F].

In literature there is disagreement on which is the type of cathode used for cordless power tools (CPT). While [Buchmann 2006] states that spinel is mostly used in this application, [Wikipedia 2009F] reports that $LiFePO_4$ “*is used for most lithium-ion batteries powering portable devices such as laptop computers and power tools*” and [BOSCH 2009] communicates that they currently only use lithium cobalt oxide in their cordless power tools (CPT).

As electrolyte

- either a salt, such as $LiPF_6$ (lithium hexafluorophosphate) dissolved in an aprotic solvent (that is a liquid which cannot release protons (H^+-ions) such as ethylene carbonat (EC) or diethylene carbonat (DC)

- or a polymer such as poly-(vinylidene fluoride) (PVDF) or Poly-(vinylidene fluoride – hexafluorpropene) (PVDF-HFP)

is used [Wikipedia 2009G].

Table 4-13 shows the composition of Li-ion batteries as reported by different sources. As the Li-ion battery technology underwent rapid development through recent years, and as no standard composition has yet been set, the composition of Li-ion batteries varies over a wide range.

While lithium-ions carry the main function of the battery, the actual lithium content is with 3 % relatively low. The main mass of the Li-ion battery is contributed by the electrode materials (cobalt or manganese and graphite) and the materials which protect the battery from the environment and connect it to the environment (aluminium, copper, iron). Additionally a mix of organic substances provides the electrolytic function.

Table 4-13 : Composition of rechargeable Li-ion batteries - Share in %

	Manganese cathode	Cobalt cathode		
Source	[European Commission 2003]	[European Commission 2003]	[ERM 2006]	[EPBA 2007]
Aluminium (Al)			5	15 - 25
Cobalt (Co)		12.0 - 20.0	18	14.5 - 27.1
Copper (Cu)				5 -15
Iron (Fe) and steel	4.7 - 25	4.7 - 25	22	balance
Lithium (Li)			3	1.75 - 3.88
Manganese (Mn)	10.0 - 15.0			
Nickel (Ni)	12.0 - 15.0	12.0 - 15.0		balance
Other metals			11	
Carbon			13	0.1 - 1
Graphite powder				10 - 30
Dietyhl carbonate (DEC)				1 - 10
Ethylene carbonate (EC)				1 - 10
Methyl ethyl carbonate (MEC)				1 - 10
Lithium hexafluorophosphate (LiPF6)				1 - 15
Poly(vinylidene fluoride) (PVDF)				1 - 2
Other non metals			28	balance

Recycling

Li-ion batteries can be treated in specialised treatment plants with the primary objective to recover the metals contained [EPBA 2007].

Advantages

Rechargeable lithium-ion batteries are common in portable applications because of their:

- high energy-to-weight ratios,
- high power discharge,
- lack of memory effect, and
- slow self-discharge when not in use. The self-discharge rate is approximately 0.1% per month (when not taking into account the consumption of 3 % /month for the internal protection circuits [Buchmann 2006]).
- Lithium-ion batteries are lighter than other energy-equivalent secondary batteries. A key advantage of using lithium-ion chemistry is also the high cell voltage of 3.6 V, thus even more powerful applications may be possible than with NiCd cells.
- With 100 % discharging to charging efficiency [EPTA 2009b] the Li-ion-battery is the most energy efficient energy storage technology in use. In use it needs the least amount of energy per service provided.
- Lithium-ion batteries can be formed into a wide variety of shapes and sizes so as to efficiently fill available space in the devices they power [Wikipedia 2009F].
- Does not need prolonged priming when new. One regular charge is all that's needed.
- Low Maintenance - no periodic discharge is needed; there is no memory.
- Specialty cells can provide very high current to applications such as power tools [Recharge 2009].

Disadvantages

- Li-ion batteries can not be charged at temperatures below 0°C or above 120°C.
- Li-ion batteries cannot discharge below – 10 °C inner cell temperature.
- Li-ion batteries irreversibly lose capacity, 3 %/per year when charge 40 to 60 % of their maximum capacity and 20 % per year when fully charged. This limits their lifetime [Wikipedia 2009F].
- Requiresprotection circuit to maintain voltage and current within safe limits.
- Transportation restrictions - shipment of larger quantities may be subject to regulatory control. This restriction does not apply to personal carry-on batteries [Recharge 2009].

Li-ion battery development is a widely studied topic with hundreds of materials under scrutiny. The most prominent examples are described in the next subchapters.

4.3.4 Lithium-polymer (Li-poly) batteries

Lithium-ion polymer batteries use liquid Lithium-ion electrochemistry in a matrix of ion conductive polymers that eliminate free electrolyte within the cell. The electrolyte thus plasticises the polymer, producing a solid electrolyte that is safe and leak resistant. Lithium polymer cells are often called Solid State cells.

Because there's no liquid, the solid polymer cell does not require the heavy protective cases of conventional batteries. The cells can be formed into flat sheets or prismatic (rectangular) packages or they can be made in odd shapes to fit whatever space is available. As a result, manufacturing is simplified and batteries can be packaged in a foil. This provides added cost and weight benefits and design flexibility. Additionally, the absence of free liquid makes Lithium-ion polymer batteries more stable and less vulnerable to problems caused by overcharge, damage or abuse.

Solid electrolyte cells have long storage lives, but low discharge rates.

There are some limitations on the cell construction imposed by the thicker solid electrolyte separator which limits the effective surface area of the electrodes and hence the current carrying capacity of the cell, but at the same time the added volume of electrolyte provides increased energy storage. This makes them ideal for use in high capacity low power applications [Woodbank Communications 2005c].

4.3.5 Lithium-iron-phosphate batteries

One cell variant to have resulted from recent development work replaced the typical cobalt oxide ($LiCoO_2$) or manganese spinel cathode of a Li-ion battery with an iron-phosphate one ($LiFePO_4$). In this approach, the cell uses a graphite anode but one with special additives according to the battery manufacturer A123 Systems [Lecklider 2008].

Compared to conventional Co- or Mn-based cathodes, $LiFePO_4$ maintains its size regardless of a cell's state of charge. This means that cells with $LiFePO_4$ cathodes benefit from having one less built-in wear-out mechanism. Indeed, these cells typically remain useful after at least twice as many charge/discharge cycles as cobalt- or manganese-based cells.

The original work on $LiFePO_4$ cathodes done at the University of Texas was improved upon by Yet-Ming Chiang and others at MIT by doping the material with aluminium, niobium, and zirconium. These changes improved characteristics significantly, especially the cathode's electrical conductivity.

A123 Systems has developed a line of Li-ion batteries based on $LiFePO_4$ technology and applied them to the portable power tool industry. Cordless power tools (CPT) manufacturer DeWalt tools use these batteries in a 36-V pack, which delivers much greater torque than earlier 18-V battery packs [Lecklider 2008].

Another approach to increasing conductivity is being commercialized by Phostech Lithium in cooperation with Hydro-Quebec and Université de Montréal, owners or co-owners of several patents on $LiFePO_4$. In the process used by Phostech Lithium, nanoparticles of $LiFePO_4$ are coated with carbon. A high energy density results, and the process retains the economic and safety benefits of the basic phosphate material [Lecklider 2008].

4.3.6 Lithium-titanate batteries

Most of the Li-ion battery improvements reported to date involve changes to the cathode material. An exception is the lithium titanate development undertaken by Altairnano that replaces the traditional carbon anode.

As shown in Figure 4-9, during charge/discharge cycling, Li ions are added to or removed from the carbon anode. Intercalation causes a carbon anode to change size slightly because of the presence or absence of Li ions. In contrast, nanostructured lithium titanate oxide ($Li_4Ti_5O_{12}$) spinel behaves structurally like $LiFePO_4$ to the extent that both are low- or zero-strain materials in this application: Their structures do not change size as Li ions are added or removed.

Cells using lithium titanate oxide anodes can be charged to 90% of room-temperature capacity at -30°C in 30 minutes. The new material increases charge/discharge cycles by at least a factor of 10 while improving both high- and low-temperature operation. In addition, the 2.0-V to 4.2-V window within which conventional Li-ion cells must operate has been extended from 0 V to about 5 V over a temperature range from -50°C to +260°C. For futher features of the Lithium titanate-cell see Table 4-14.

Both Phostech Lithium and Altairnano are running pilot production plants for lithium titanate oxide based batteries and sell their nanomaterials to interested battery companies [Lecklider 2008].

Table 4-14 : Cell specifications of Altair-Nano Lithium-titanate-cell [Altair 2009]

Property	Unit	Performance				
Operating temperature range	in °C	– 40 / +55				
Recommended storage temperature	in °C	– 40 / +55				
Nominal voltage	in V	2.3				
Nominal capacity	in Ah	50				
Recommended standard charge/discharge	in A	50				
Recommended fast charge	in A	300				
Cell weight	in kg	1.6				
Cell volume	in l	0.86				
Typical power	in W/cell	1,250	in W/kg	760	in W/l	1,450
Typical energy	in Wh/cell	116	in Wh/kg	72	in Wh/l	135
Expected calendar life	in years	20				
Cycle life at 25 A charge/discharge, 100 % discharge, 25 °C	in number of cycles	>12,000				
Cycle life at 50 A charge/discharge, 100 % discharge, 55 °C	in number of cycles	>4,000				

4.3.7 Lithium-air-battery and air-fueled-Lithium-ion battery

Originally conceived as primary cells, lithium-air -cells offer a very high energy density. Rechargeable versions are now under development.

A **lithium-air battery** consists of **metallic lithium anodes** electrochemically coupled to atmospheric oxygen through porous carbon which serves as air cathode. The Li/oxygen battery is rechargeable when the carbon cathode contains catalysts derived from complexes or oxides of metals such as cobalt. A gel polymer electrolyte membrane (made from poly(acrylonitrile)(PAN) or poly(vinylidene fluoride) (PVdF)) serves as both the separator and ion-transporting medium. The electrolyte can also be organic liquid, dry organic polymer or inorganic solid electrolytes.

Air fueled rechargeable batteries with metal anodes can be the most energy batteries. The Li-air battery, with a cell discharge reaction between Li and oxygen to yield Li_2O, according to $4Li + O_2 \rightarrow 2Li_2O$, has an open circuit voltage of 2.91 V and a theoretical specific energy of 5,200 Wh/kg . In practice, oxygen is not stored in the battery, and the theoretical specific energy excluding oxygen is 11,140 Wh/kg.

The non-aqueous metal-air batteries represent a class of potentially ultrahigh energy density power sources useful for a variety of applications. When fully developed these batteries could exhibit practical specific energies of 1,000-3,000 Wh/kg [Wikipedia 2009H].

There are potential safety concerns with the metallic lithium anodes [Woodbank Communications 2005c].

The **air-fueled Lithium-ion battery** combines the air soaked carbon cathode of the Lithium-air-battery with the lithiom-ion soaked graphite anode of the Lithium- ion battery.

The air-fueled Lithium-ion battery has been invented by researchers at the University of St Andrews with partners at Strathclyde and Newcastle in the year 2009.

This new type of battery has a much higher energy density than the currently existing lithium ion batteries, due to the fact that it does not contain dense lithium cobalt oxide. Instead, the positive electrode is made from lightweight porous carbon, and the lithium ions are packed into the electrolyte, which streams into the porous material. Therefore the air-fueled Lithium-ion battery has the potential to increase the capacity up to 10 times for the same volume and mass as compared to Li-ion batteries [Wikipedia 2009I].

4.3.8 Lithium-sulfur battery

Lithium sulfur (Li_2S_8) contains high energy density chemistry, significantly higher than Lithium-ion metal oxide chemistries. This chemistry is under joint development by several companies but it is not yet commercially available [Woodbank Communications 2005c].

The lithium sulfur battery (Li-S battery) is a rechargeable galvanic cell with a very high energy density (400-600 Wh/kg and 350 Wh/l). By virtue of the low atomic weight of lithium and moderate weight of sulfur, Li-S batteries are relatively light; about the density of water. Lithium Sulfur batteries might have the potential to replace lithium-ion cells.

The chemical processes in the Li-S cell include lithium dissolution from the anode surface (and incorporation into polysulfides) during discharge, and lithium plating back on to the nominal anode while charging. This contrasts with conventional lithium-ion cells, where the lithium ions are intercalated in the anode and cathodes, and consequently Li-S allows for a much higher lithium storage density. Polysulfides are reduced on the anode surface in sequence while the cell is discharging:

S8 → Li2S8 → Li2S6 → Li2S4 → Li2S3

Across a porous diffusion separator, the polymers of sulfur are formed at the nominal cathode as the cell charges:

Li2S → Li2S2 → Li2S3 → Li2S4 → Li2S6 → Li2S8 → S8

For experimentational purposes most batteries are constructed with a carbon and sulfur cathode and a lithium anode. Sulfur lacks electroconductivity. Therefore the sulphur is coated by carbon nanofibers to provide the required electroconductivity

Advantages

- Higher energy density than Li-ion-cells.
- Low cost of sulfur
- Lithium sulfur cells are tolerant of over-voltages.

Shortcomings

- The cell voltage is 2.1 Volts and thus lower as with Li-ion-cells.
- S and Li_2S are relatively insoluble in most electrolytes used, many of the intermediary polysulfides are. The disolving of LiS_n into electrolytes causes irreversible loss of active sulfur material. The majority of research on Lithium-sulfur batteries at the moment is to improve the choice of electrolytes to minimize this side reaction.
- Nonlinear discharge and charging response of the cell.

Because of the high potential energy density and the nonlinear discharge and charging response of the cell, a microcontroller and other safety circuitry is sometimes used along with voltage regulators to control cell operation and prevent rapid discharge.

Recent advances

Lithium sulfur batteries have been demonstrated on the longest and highest-altitude solar powered airplane flight in August, 2008.

Research conducted at the University of Waterloo has produced Li-S cells with 84% of the theoretical maximum energy density for Li-S that suffer minimal degradation during charge cycling, and thus potentially offer four times the gravimetric energy density of lithium-ion [Wikipedia 2009J].

4.3.9 Nickel-iron battery

The nickel-iron battery (NiFe battery) is a storage battery having a nickel(III) oxide-hydroxide cathode and an iron anode, with an electrolyte of potassium hydroxide. The active materials are held in nickel-plated steel tubes or perforated pockets. The nominal cell voltage is 1.2V. It is a very robust battery which is tolerant of abuse, (overcharge, overdischarge, short-circuiting and thermal shock) and can have very long life even if so treated. It is used in backup situations where it can be continuously charged and can last for more than 20 years. Its use has declined, due to low specific energy, poor charge retention (similar to nickel-metal hydride), and poor low-temperature performance.

The ability of these batteries to survive frequent cycling is due to the low solubility of the reactants in the electrolyte. The formation of metallic iron during charge is slow because of the low solubility of the Fe_3O_4. While the slow formation of iron crystals preserves the electrodes, it also limits the high rate performance: these cells charge slowly, and are only able to discharge slowly.

Advantages

- Very robust, tolerant of abuse, (overcharge, overdischarge, short-circuiting and thermal shock)
- Can have very long life (more than 20 years)
- Can be continuously charged

Shortcomings

- low energy density
- low power density
- poor charge retention
- poor low-temperature performance.
- Slow charge

Nickel-iron batteries have long been used in European mining operations because of their ability to withstand vibrations, high temperatures and other physical stress. They are being examined again for use in wind and solar power systems and for modern electric vehicle applications.

Currently no nickel-iron batteries are being manufactured in the Western world, but they are still manufactured in China [Wikipedia 2009K].

4.3.10 Nickel-zinc-battery

While nickel-zinc battery (NiZn battery) systems have been around for over 100 years, recent technological breakthroughs have created the potential to replace NiCd as energy source of cordless power tools (CPT).

The charge/discharge reaction of the NiZn-battery is:

$$2\ Ni(OH)_{2(solid)} + Zn(OH)_{2(solid)} \leftrightarrow 2\ Ni(OH)_{3(solid)} + Zn_{(solid)}$$

The discharge reaction is:

The electrochemical open circuit voltage potential is ~1.73V. NiZn technology is suited for fast recharge cycling. The maximum charge time is 2.5 hours.

The affinity for the zinc electrode to dissolve into solution and not fully migrate back to the cathode has, in the past resulted in limited battery recharge cycles.

Recent technological steps have allowed PowerGenix to patent a commercially viable battery system. These technology breakthroughs include: improved electrode separators materials, zinc material stabilizers, and electrolyte improvements. The resulting PowerGenix NiZn battery has realized battery cycle life comparable to both NiCd and NiMH battery systems.

Advantages

- Low internal impedance (typical 5 milliohm) provides for high battery discharge rates capability of 900 W/kg.
- 1.6V cell voltage vs. 1.2V for NiCd and NiMH rechargeable cells; thus Fewer cells are required compared to NiCd and NiMH to achieve battery pack voltage reducing pack weight, size and improving pack reliability.
- No use of metal hydrides (rare-earth metals) that are difficult to recycle.
- No flammable active material or organic electrolyte.
- Simple recycling process, similar to the one in use for primary alkaline batteries (Zinc and nickel can be fully recycled)
- Both nickel and zinc are commonly occurring elements in nature and are not hazardous.

Shortcomings

- Dentrite growth causes short cycle life (at least with traditional NiZn-cells)
- High self discharge rate

Following companies are NiZn-battery producers:

- Evercel (Hingham, MA): ceased NiZn operations in 2004 which included it wholly owned subsidiary Xiamen Evercel Battery Co. in China. Evercel produced a flooded rechargeable prismatic large format battery. Evercel issued an exclusive, worldwide license for its rechargeable nickel-zinc battery technology to CM Partner of Kyungkido, Korea in 2006.
- Xellerion, Inc./eVionyx, Inc. (Hawthorne, NY): large format rechargeable prismatic battery.
- PowerGenix (San Diego, CA): cylindrical rechargeable battery cells.
- Optimum Battery CO. (Shenzhen China): cylindrical rechargeable battery cells.
- Toshiba Battery Co. (Tokyo Japan): Giga Energy, cylindrical primary cells [Wikipedia 2009C].

4.3.11 Rechargeable alkali-manganese (RAM) batteries

The Rechargeable Alkaline Manganese (RAM) battery is a type of alkaline battery that is rechargeable. The first generation rechargeable alkaline technology was developed by Battery Technologies Inc in Canada and licensed to Pure Energy, EnviroCell, Rayovac and Grandcell. Subsequent patent and advancements in technology have been introduced. The shapes include AAA, AA, C, D and snap-on 9-volt batteries. Rechargeable alkaline batteries have the ability to carry their charge for years.

The main difference in composition between rechargeable and regular alkaline is that the blend of materials and formula used to make the batteries has been altered to allow for the batteries to recharge. Without this modification in chemical composition, the batteries would not hold multiple charges. The batteries are also designed to resist leakage.

RAMs are formulated to last longest in periodical use items. **This type of battery is best suited for use in low-drain devices such as remote controls,** or for devices that are used periodically such as flashlights, television remotes, portable radios, etc. [Wikipedia 2009L].

Advantages

RAMs are relatively cheap, contain a high charge-capacity and store their energy for up to 7 years

Disadvantages

- RAMs can easily lose charge capacity if discharged by more than 50 %:
    - If they are discharged by less than 25%, they can be recharged for hundreds of cycles to about 1.42V.
    - If they are discharged by less than 50%, they can be almost-fully recharged for a few dozen cycles, to about 1.32V.
    - After a 'Deep Discharge', they can be brought to their original high-capacity charge only after a few charge-discharge cycles [Wikipedia 2009L].

- [Wikipedia 2009B] reports a power drain capacity of only 50 W/kg, which is less than 10 % of the capacity of a NiCd battery.

EnviroCell Alkaline Rechargeable Batteries

Launched in February 2009, EnviroCell batteries are a new product designed for use in everyday low-drain devices such as wireless keyboards, flashlights and radios. Featuring a patented technology, EnviroCell batteries can be recharged safely up to 60 times with no memory effect. Unlike other rechargeable batteries like lithium ions, EnviroCells contain no toxic metals and can be safely disposed [LePage's 2009].

Other Brands

Rayovac produced a variety of RAMs called "Renewal". Rayovac discontinued these products, possibly due to corporate strategy and superior profit from single use batteries. Similar rechargeable alkaline batteries are still available from other vendors.

Yet another Rechargeable Alkaline batteries producer brand is "PureEnergy". PUREENERGY's website state: "Rechargeable Alkaline is the only rechargeable battery that can be used in any application that uses disposable alkaline batteries. It also offers several performance and cost saving advantages over other Rechargeable batteries." [Wikipedia 2009L].

Use in cordless power tools (CPT)

Due to the high sensitivity of the energy storage capacity on the discharge-level, the low number of charging/discharging cycles and the low power drain it is not believed, that RAMs will have the potential for being an efficient energy source for cordless power tools (CPT) in the foreseable future.

4.3.12 Flow-battery, Zinc-bromine-battery and Vanadium-redox-flow battery

Modern flow batteries are generally two electrolyte systems in which the two electrolytes, acting as liquid energy carriers, are pumped simultaneously through the two half-cells of the reaction cell separated by a membrane (see Figure 4-11). On charging, the electrical energy supplied causes a chemical reduction reaction in one electrolyte and an oxidation reaction in the other. The thin ion exchange membrane between the half-cells prevents the electrolytes from mixing but allows selected ions to pass through to complete the redox reaction. On discharge the chemical energy contained in the electrolyte is released in the reverse reaction and electrical energy can be drawn from the electrodes. When in use the electrolytes are continuously pumped in a circuit between reactor and storage tanks [Woodbank Communications 2005d].

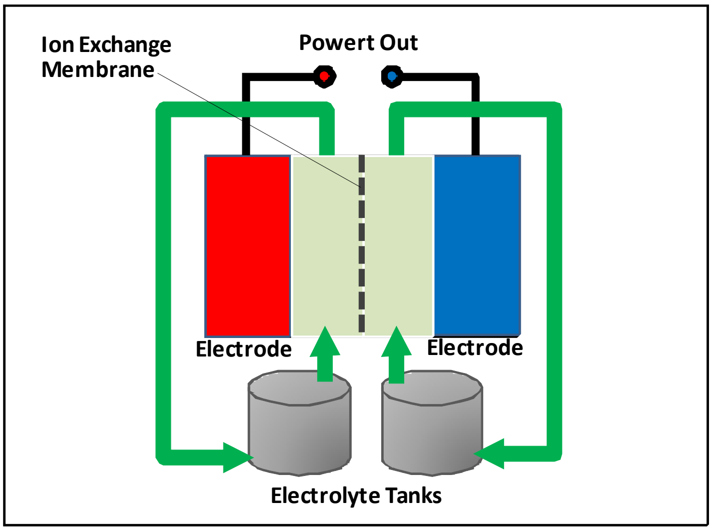


Figure 4-11 : Scheme of a flow battery [Woodbank Communications 2005d]

High power batteries are constructed using a multiple stack of cells in a bipolar arrangement. The power rating of the system is fixed and determined by the size and number of electrodes in the cell stacks, however the great advantage of this system is that it provides almost unlimited electrical storage capacity, the limitation being only the capacity of the electrolyte storage reservoirs. Opportunities for thermal management are also facilitated by using the electrolytes as the thermal working fluids as they are pumped through the cells.

For the same power, flow batteries are typically dimensioned to store five times the energy stored in conventional cells. However, for the same storage capacity, conventional cells will provide five times the power of flow batteries and in addition they have no moving parts or energy consuming pumps.

The **Zinc-bromine battery** is a modern example of a flow battery. It is based on the reaction between two commonly available chemicals, Zinc and Bromine. The battery consists of a Zinc negative electrode and a Bromine positive electrode separated by a microporous separator. An aqueous solution of Zinc Bromide is circulated through the two compartments of the cell from two separate reservoirs. The other electrolyte stream in contact with the positive electrode contains Bromine. The Bromine storage medium is immiscible with the aqueous solution containing Zinc Bromide.

The battery uses electrodes that cannot and do not take part in the reactions but merely serve as substrates for the reactions. There is therefore no loss of performance, as in most rechargeable batteries, from repeated cycling causing electrode material deterioration. When the Zinc-Bromine battery is completely discharged, all the metal Zinc plated on the negative electrodes is dissolved in the electrolyte. The Zinc is deposited again when the battery is charged. In the fully discharged state the Zinc-Bromine battery can be left indefinitely.

Energy densities better than NiCd batteries are claimed however the Coulombic (round trip) efficiency is typically only around 75% [Woodbank Communications 2005d].

The **Vanadium-redox-flow battery** is an example of both a flow battery and a two electrolyte system. In this case, it depends on two different active aqueous electrolytes of vanadium dissolved in sulfuric acid separated by a membrane at which ionic interchange takes place. The chemical reactions take place on inert graphite electrodes stacked in a bipolar configuration. The electrolytes are stored externally from the battery and must be pumped through the cell for the chemical action to take place [Woodbank Communications 2005e].

Advantages of Vanadium-redox battery

- Very high power output (Tens of kiloWatts)
- Fast recharge by replacing spent electrolyte
- Capable of long life due to replacement of electrolyte.
- Can be fully discharged

Shortcomings of Vanadium-redox battery

- Complex.
- Low energy density
- Little commercial take up to date
- High costs since little progress from experimental systems to high volume applications.

Applications

Suitable for high power rechargeable storage systems in applications such as load levelling [Woodbank Communications 2005e].

It is difficult to imagine that all functionalities of a flow battery (including electrolyte tanks and pumps) can be stored in the limited volume of a power pack for cordless power tools (CPT).

4.3.13 Non-battery portable energy storage overview

Figure 4-12 gives an overview of portable non-battery energy storage technologies with their range of power density and energy density. Also shown is the area of batteries and area required for the operation of cordless power tools (CPT).

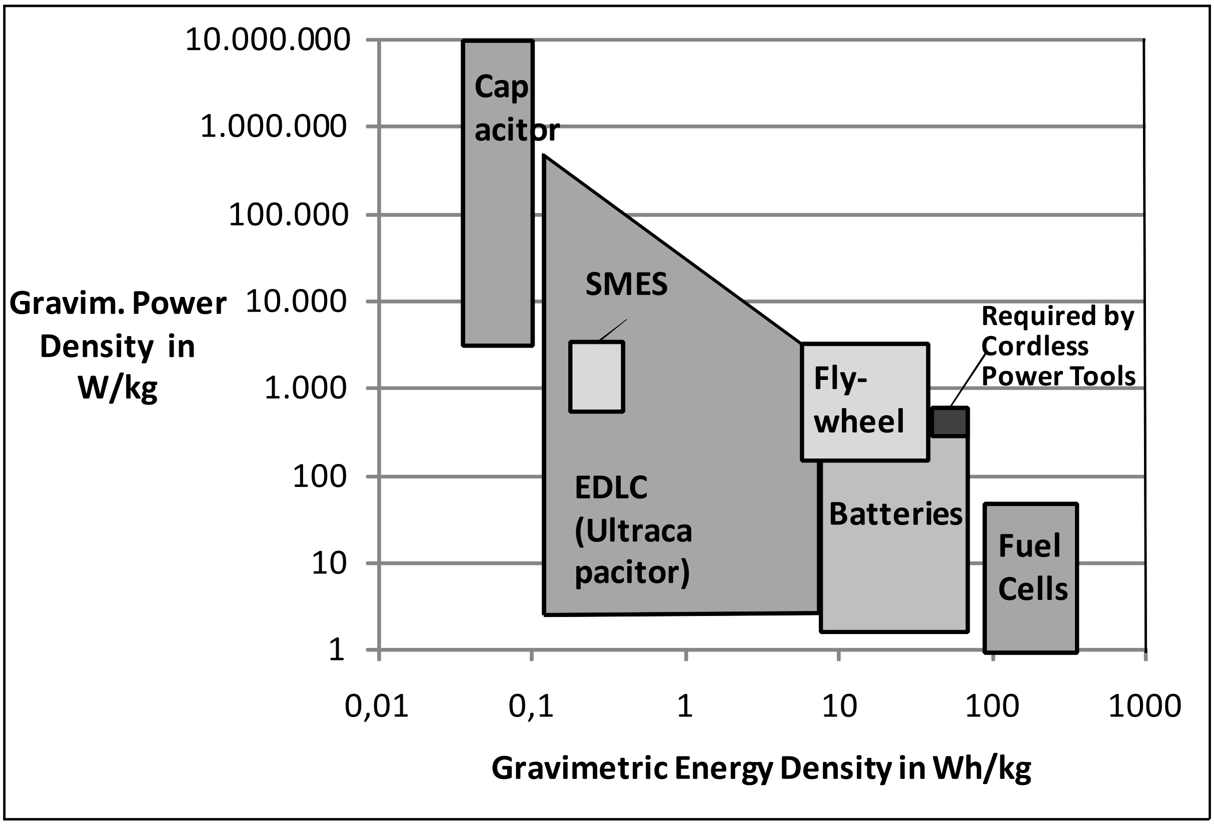


Figure 4-12 : Gravimetric power density versus gravimetric energy density for non-battery portable energy storage technologies as compared to batteries [Woodbank Communications 2005f]

4.3.14 *Capacitors - The Electrostatic Battery*

The use of capacitors for storing electrical energy predates the invention of the battery. Eighteenth century experimenters used Leyden jars as the source of their electrical power.

Capacitors store their energy in an electrostatic field rather than in chemical form. They consist of two electrodes (plates) of opposite polarity separated by a dielectric or electrolyte. The capacitor is charged by applying a voltage across the terminals which causes positive and negative charges to migrate to the surface of the electrode of opposite polarity.

Since capacitors store charge only on the surface of the electrode, rather than within the entire electrode, they tend to have lower energy storage capability and lower energy densities. The charge/discharge reaction is not limited by ionic conduction into the electrode bulk, so capacitors can be run at high rates and provide very high specific powers but only for a very short period [Woodbank Communications 2005f] (see Figure 4-12 and Table 4-15).

Table 4-15 : Typical performance values of batteries and capacitors – a comparison [Woodbank Communications 2005f]

Device	Energy density in Wh/l	Power density in W/l	Cycle life Cycles	Discharge time in Seconds
Batteries	50-250	150	1 - 103	> 1000
Capacitors	0.05 - 5	105 - 108	105 - 106	<1

Since there is no chemical reactions involved, the charge/discharge reactions can typically be cycled many more times than batteries. For the same reason, capacitors don't require any special charging circuits. For high voltage applications such as electric vehicles, a series chain of capacitors must be used to avoid exceeding the working voltage of individual capacitors and this reduces the effective capacity of the chain.

Capacitors are suitable for applications which require a short duration power boosts such as Uninterruptable Power Supply (UPS) systems which need fast take over of substantial electrical loads for a short period until back up power units, such as rotary generators or fuel cells, have switched on and reached their full output. Similarly they can be used to provide an instantaneous power boost in Electric and Hybrid vehicles.

Capacitors are now used extensively as power back up for memory circuits and in conjunction with batteries to provide a power boost when needed.

4.3.15 EDLC = electro chemical double layer capacitors

Supercapacitors, **Ultracapacitors** or **EDLC (Electric Double Layer Capacitors)** as they are also called, look very much like batteries. They have double layer construction consisting of two carbon electrodes immersed in an organic electrolyte (see Figure 4-13).

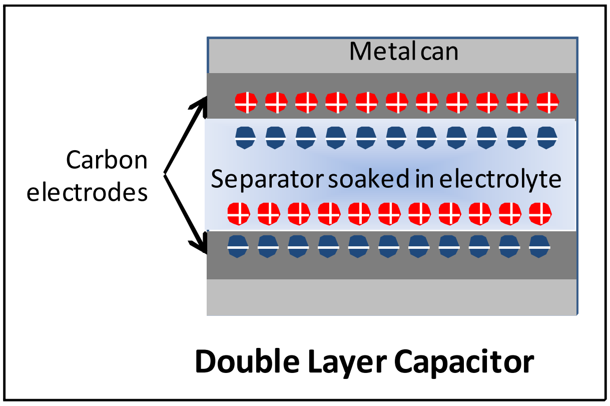


Figure 4-13 : Scheme of Electric Double Layor Capacitor [Woodbank Communications 2005g]

During charging, the electrically charged ions in the electrolyte migrate towards the electrodes of opposite polariity due to the electric field between the charged electrodes created by the applied voltage. Thus two separate charged layers are produced. Although similar to a battery, the double layer capacitor depends on electrostatic action. Since no chemical action is involved the effect is easily reversible and the typical cycle life is hundreds of thousands of cycles.

They have a low energy density of less than 15 Wh/kg but a very high power density of 4,000 W/Kg. Although the power density is very high the cell voltage is limited to about 2.3 Volts to avoid electrolysis of the electrolyte with the consequent emission of gas [Woodbank Communications

2005g]. Voltage equalisation to spread the available charge evenly between the capacitors in a series chain may also be needed for many applications.

Advantages of EDLCs

- Cell voltage determined by the circuit application, not limited by the cell chemistry.
- Very high cell voltages possible (but there is a trade-off with capacity)
- High power available.
- High power density.
- Simple charging methods. No special charging or voltage detection circuits required.
- Very fast charge and discharge. Can be charged and discharged in seconds.
- Can not be overcharged.
- Long cycle life of more than 500,000 cycles at 100% discharge.
- No chemical actions.
- 10 to12 year life

Shortcomings of EDLCs

- Linear discharge voltage characteristic prevents use of all the available energy in some applications.
- Power only available for a very short duration.
- Low capacity.
- Low energy density (6Wh/Kg)
- Cell balancing required for series chains.
- High self discharge rate. Much higher than batteries.

High power applications

The shortcomings above render supercapacitors unsuitable as primary power source for EV and HEV applications, however, their advantages make them ideal for temporary energy storage for capturing and storing the energy from regenerative braking and for providing a booster charge in response to sudden power demands.

Since the capacitor is normally connected in parallel with the battery in these applications, it can only be charged up to the battery upper voltage level and it can only be discharged down to the battery lower discharge level, leaving considerable unusable charge in the capacitor, thus limiting its effective or useful energy storage capacity.

Using EDLCs in EVs and HEVs to facilitate regenerative braking can add 15% to 25% to the range of the vehicle.

At the same time, supercapacitors can provide an effective short duration peak power boost allowing the prime battery to be downsized.

It should be noted however that while supercapacitors can be used to to provide the increased range and short term power, it is at the cost of considerable added weight and bulk of the system, and this should be weighed against the advantages of using higher capacity batteries.

EDLCs are also used to provide fast acting short term power back up for UPS applications. By combining a capacitor with a battery-based uninterruptible power supply system, the life of the batteries can be extended. The batteries provide power only during the longer interruptions, reducing the peak loads on the battery and permitting the use of smaller batteries.

Carbon Nanotube Enhanced Supercapacitors

Recent developments at MIT have shown that the performance of supercapacitors can be significantly improved by using nanomaterials. The energy storage capability of a capacitor is directly proportional to its capacitance which in turn is proportional to the area of the plates or electrodes. Likewise the current carrying capability is directly proportional to the area of the electrodes. By using vertically aligned, single-wall carbon nanotubes which are only several atomic diameters in width instead of the porous, amorphous carbon normally employed, the effective area of the electrodes can be dramatically increased. **While the achievable energy density of 60Wh/Kg still can not match the level obtainable in Lithium Ion batteries (120Wh/kg), the power densities achieved of 100kW/kg are three orders of magnitude better than batteries** [Woodbank Communications 2005g]. Nevertheless these features would allow Carbon Nanotube Enhanced Supercapacitors to be used as energy source for cordless power tools (CPT).

Commercial products are not yet available but should be within 5 years [PESWiki 2009].

Similar advances are promised by the use of new very high permittivity dielectrics such as Barium titanate.

4.3.16 Superconducting Magnetic Energy Storage (SMES) - The Magnetic Battery

Superconducting magnetic energy storage systems store energy in the field of a large magnetic coil with direct current flowing. It can be converted back to AC electric current as needed. Low temperature SMES cooled by liquid helium is commercially available. High temperature SMES cooled by liquid nitrogen is still in the development stage and may become a viable commercial energy storage source in the future.

SMES systems are large and generally used for short durations, such as utility switching events [Woodbank Communications 2005f].

According to Figure 4-12 the gravimetric energy density of SMEs lie well below 1 Wh/kg and thus are not capable of storing enough energy for a cordless power tool (CPT).

4.3.17 Flywheels - The Kinetic Battery

Slow speed flywheels, combined with opportunity charging at bus stops have been used since the 1950s for public transport applications, however they are very bulky and very heavy and this has limited their adoption.

Modern super flywheels store kinetic energy in a high speed rotating drum which forms the rotor of a motor generator. When surplus electrical energy is available it is used to speed up the drum. When the energy is needed the drum provides it by driving the generator. Modern high energy flywheels use composite rotors made with carbon-fiber materials. The rotors have a very high strength-to-density ratio, and rotate at speeds up to 100,000 rpm in a vacuum chamber to minimize aerodynamic losses. The use of superconducting electromagnetic bearings can virtually eliminate energy losses through friction.

The magnitude of the engineering challenge should not be underestimated. A 30 cm diameter flywheel, one 30 cm in length, weighing 10 kg spinning at 100,000 rpm will store 3 kWh of energy. However at this rotational speed the surface speed at the rim of the flywheel will be 5,700 km/h and the centrifugal force on particles at the rim is equivalent to 1.7 million G. The tensile strength of material used for the flywheel rim must be over 34,500 bar to stop the rotor from flying apart [Woodbank Communications 2005f].

Flywheels are preferred over conventional batteries in many aerospace applications because of the benefits shown in Table 4-16.

Table 4-16 : Advantages of Flywheel over Battery Energy Storage [Woodbank Communications 2005f]

Energy Storage Characteristic	Resulting Benefits
5 to 10+ times greater specific energy	Lower mass
Long life (15 yr.) Unaffected by number of charge/discharge cycles	Reduced logistics, maintenance, life cycle costs and enhanced vehicle integration
85-95% round-trip efficiency	More usable power, lower thermal loads, compared with <70-80% for NiCd battery system
High charge/discharge rates & no taper charge required	Peak load capability, 5-10% smaller solar array
Deterministic state-of-charge	Improved operability
Inherent bus regulation and power shunt capability	Fewer regulators needed

Advanced flywheels are used for protecting against interruptions to the national electricity grid. The flywheel provides power during period between the loss of utility supplied power and either the return of utility power or the start of a sufficient back-up power system (i.e., diesel generator). Flywheels can discharge at 100 kilowatts (kW) for 15 seconds and recharge immediately at the same rate, providing 1-30 seconds of ride-through time. Back-up generators are typically online within 5-20 seconds.

Flywheels have also been proposed as a power booster for electric vehicles. Speeds of 100,000 rpm have been used to achieve very high power densities, however containment of the high speed rotor in case of accident or mechanical failure would require a massive enclosure negating any power density advantages. The huge gyroscopic forces of these high speed flywheels are an added complication. **Practicalities have so far prevented the large scale adoption of flywheels for portable applications** [Woodbank Communications 2005f]**.**

4.3.18 Portable fuel cells

Fuel cells in their simplest forms generate electricity from the reaction of hydrogen with oxygen to form water in a process which is the reverse of electrolysis (see Figure 4-14).

The potential power generated by a fuel cell stack depends on the surface area, the number and size of the individual fuel cells that comprise the stack [Woodbank Communications 2005h].

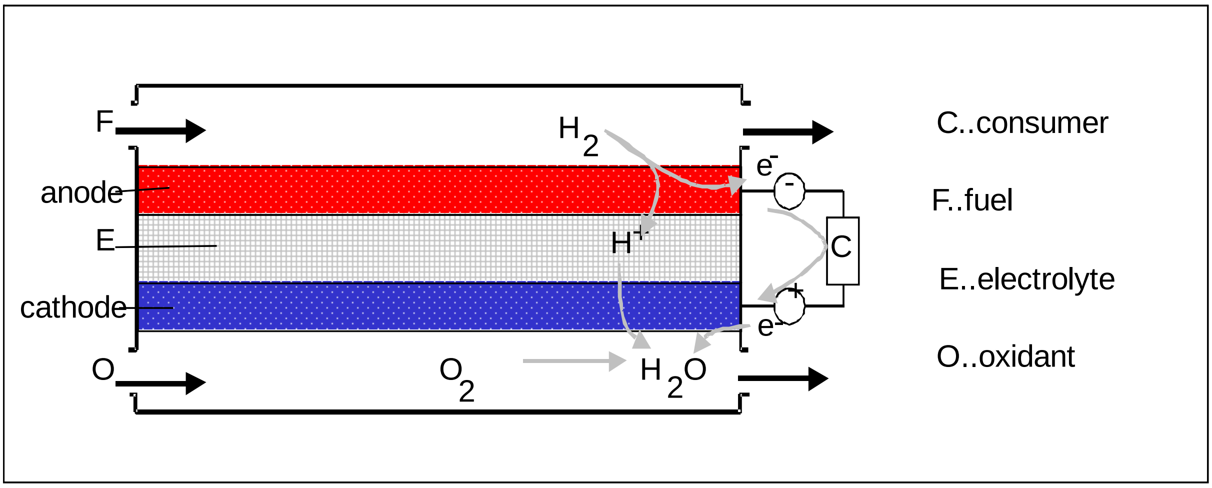


Figure 4-14 : Scheme of a fuel cell

The fuel cell relies on a basic oxidation/reduction reaction, as with a battery, but the reaction takes place on the fuel rather than the electrodes. The fuel cell produces electricity as long as the cell receives a supply of fuel and can dispose of the oxidized old fuel. In a fuel cell, the anode usually is bathed in the fuel; the cathode collects and makes available the oxidant (often atmospheric oxygen). An ion-conducting membrane separates the two, allowing the reaction to take place without affecting the electrodes [Woodbank Communications 2005h].

Six major fuel cell technologies are currently being pursued for different applications each with its own characteristics. Some operate at high temperatures, some use exotic electrode materials or catalysts, all are very complex:

- Alkali
- Phosphoric Acid

- Solid Oxide
- Molten Carbonate
- Proton Exchange Membrane (PEM)
- Direct Methanol Fuel Cells (DMFC)

They have been proposed for a wide range of applications from powering laptop computers, through automotive traction to high power load levelling. The most active developments are currently in the automotive sector where the favoured technology is PEM. This promises a high conversion efficiency of over 60% and an energy density of 120 W/kg. DMFCs do not use hydrogen fuel with its associated supply problems, but the more convenient liquid methanol. They are less efficient but offer compact and convenient designs suitable for future consumer electronics applications [Woodbank Communications 2005h].

DMFCs use a methanol in water solution to carry the reactant into the cell. Currently, platinum is used as a catalyst for both half- reactions.

Anode:

$$\mathrm{CH_3OH + H_2O \rightarrow 6\ H^+ + 6\ e^- + CO_2}$$

Cathode:

$$\frac{3}{2}\mathrm{O_2 + 6\ H^+ + 6\ e^- \rightarrow 3\ H_2O}$$

Because of the methanol cross-over, a phenomenon by which methanol diffuses through the membrane without reacting, methanol is fed as a weak solution: this actually improves efficiency significantly, since crossed-over methanol, after reaching the air side (the cathode), immediately reacts with air. The end result is a reduction of the cell voltage. Cross-over remains a major factor in inefficiencies, and often half of the methanol is lost to cross-over.

A direct methanol fuel cell is usually part of a larger system including all the ancillary units that permit its operation. The main reasons for its complexity are:

- providing water along with methanol would make the fuel supply more cumbersome, so water has to be recycled in a loop;
- CO2 has to be removed from the solution flow exiting the fuel cell;
- water in the anodic loop is slowly consumed by reaction and drag; it is necessary to recover water from the cathodic side to maintain steady operation.

Common operating temperatures are in the range 50–120 °C, where high temperatures are usually pressurised. Atmospheric-pressure configurations, however, are preferred.

The main advantages of DMFCs are the ease of transport of methanol, an energy-dense yet reasonably stable liquid at all environmental conditions, and the lack of complex steam reforming operations. Efficiency is quite low for these cells, so they are targeted especially to portable applications, where energy and power density are more important than efficiency.

Current DMFCs are limited in the power they can produce, but can still store a high energy content in a small space. This makes them ideal but ideal for consumer goods such as mobile phones, digital cameras or laptops. Power packs are currently available with power outputs between 25 and 250 Watts with durations up to 100 hours between refuelings.

If another catalyst could be found for the reduction of oxygen, the problem of methanol crossover would likely be significantly lessened. Furthermore, platinum is very expensive and contributes to the high cost per kilowatt of these cells. During the methanol oxidation reaction carbon monoxide (CO) is formed, which strongly adsorbs onto the platinum catalyst, reducing the surface area and thus the performance of the cell. The addition of another components, such as ruthenium or gold, to the catalyst tends to ameliorate this problem [Wikipedia 2009M].

Advantages

- No recharging is necessary.
- No time lost through recharging (acts like a perpetual primary cell).
- So long as fuel provided, the cells can provide constant power in remote locations.

Shortcomings

- Low cell voltage of 0.6 - 0.7 Volts.
- Fuel cells have a low dynamic range and slow transient response which causes an unacceptable lag in responding to calls for power by the user. In a car a power boost from a battery or from supercapacitors is therefore needed to achieve the desired system performance.
- Most designs need to work at high temperatures in order to achieve reasonable operating efficiencies. To generate the same efficiencies at lower temperatures requires large quantities of expensive catalysts such as platinum.
- Low temperature freeze-up of the electrolyte.
- Electrodes are prone to contamination.
- Due to the need to use scarce materials and complex system designs the system are still very expensive [Woodbank Communications 2005h].

Applications

For automotive applications fuel cells are only suited to hybrid applications for providing the base power load with the demand peaks and troughs, and regenerative braking, being accommodated by batteries or booster capacitors. The fuel cell can therefore be dimensioned to work at its optimum working point, providing the average power rather than the peak power requirement permitting significant cost savings.

Fuel cells have been used successfully in aerospace applications.

Perhaps the best applications for fuel cells will be for high power load levelling.

Prototypes of Direct Methanol Fuel cells (DMFC) are currently being trialled for mobile phone and laptop computer applications [Woodbank Communications 2005h]**.** The properties of this type of fuel cell are shown in Table 4-17.

Table 4-17 : Properties of DMFC (Direct Methanol Fuel Cell) [Woodbank Communications 2005h].

Common Electrolyte	Operating Temperature	System Output	Electrical Efficiency	Applications	Advantages	Disadvantages
Solid organic polymer, poly-perfluoro-sulfonic acid	50 - 100°C	Up to 1.5kW	20 - 25%	• Consumer goods • Laptops • Mobile phones	• High energy storage • No reforming needed • Easy storage and transport	• Low power output • Methanol is toxic and flammable

4.4 Conclusions from Technical Assessment – Consequences of NiCd-ban

In accordance with the objective of this study, the technical assessment will first have a look on the short term replacement alternatives to NiCd batteries, these are NiMH batteries and Li-ion batteries, and then look at medium to long term replacement options, these are the technologies under development

4.4.1 NiMH and Li-ion as replacement for NiCd in cordless power tools (CPTs)

Table 4-18 summarises and directly compares the properties of NiCd-, NiMH- and Li-ion batteries as reported by [EPTA 2009b]. It has to be noted, that providers of cordless power tools such as [Bosch 2009a] claim that their youngest generation of Li-ion power packs they distribute together with their power tools have the same number of charging cycles and life time as NiCd batteries. We conclude that the 700 recharching cycles of Li-ion batteries shown in Table 4-18 are a conservative estimate.

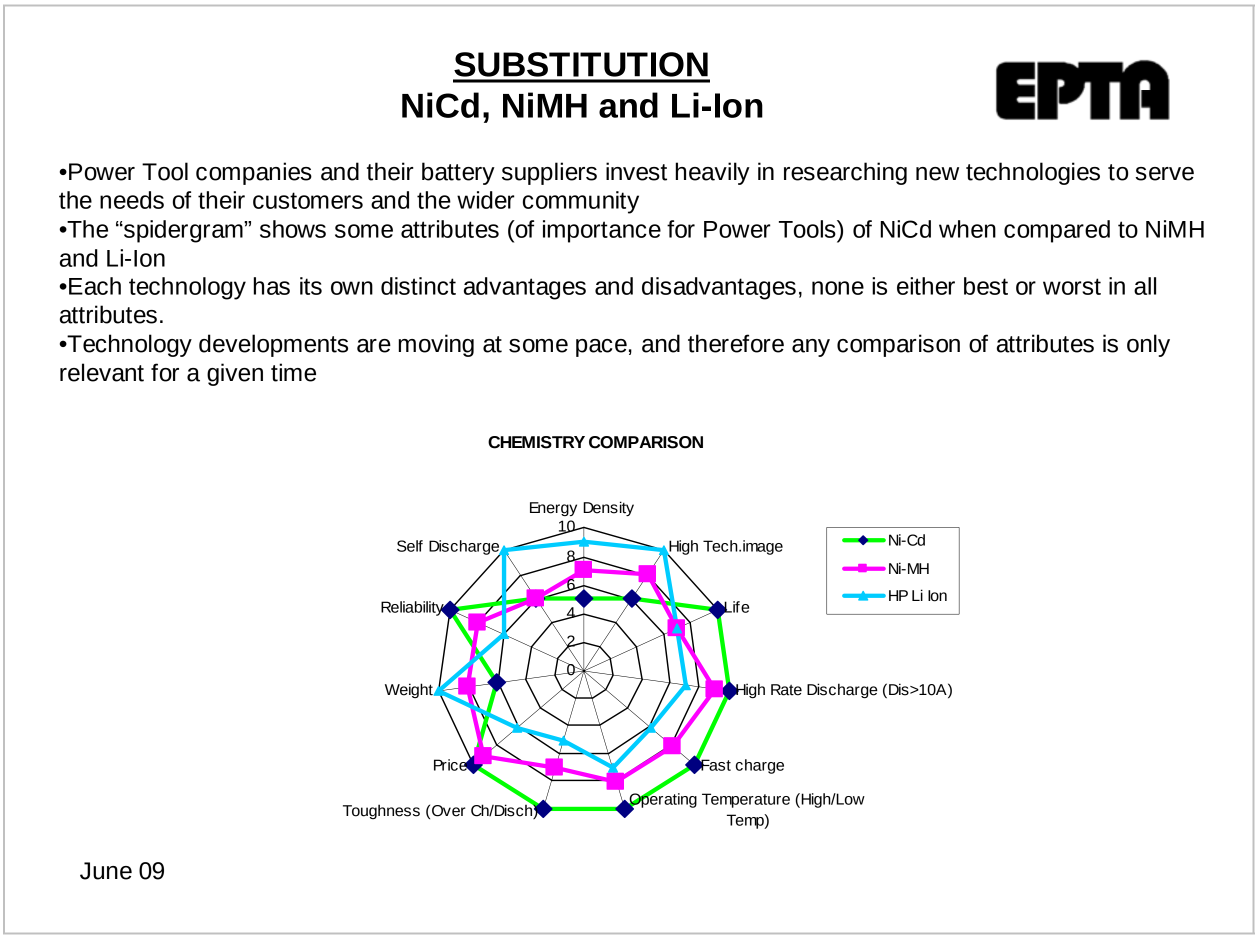
Table 4-18: Technical properties and cost ratio according to [EPTA 2009b]

		Performance of rechargeable battery					
		NiCd		NiMH		Li Ion	
Property	Unit	Single cell	18V power pack	Single cell	18V power pack	Single cell	18V power pack
Power discharge	W/kg		599		543		851
	W/l		900		836		869
	A		40		40		40
Voltage	V	1.2	18	1.2	18	3.6	18
Energy storage capacity/cycle [*1]	Wh/kg		37.4		41.1		61.0
	Wh/l		56.2		63.2		62.2
	Wh/cell,pack		38.0		42.7		43.0
Number of recharging cycles at full energy storage capacity			1,000		500		700
Energy storage capacity over life time [*1]	Lifetime Wh/kg		33,695		19,771		30,129
	Lifetime Wh/l		50,623		30,436		30,750
	Lifetime Wh/cell,pack		34,200		20,562		21,241
Temperature range of operation	oC (from-to)	-20°C to 60°C		0°C to 50°C		0°C to 60°C	
Self discharge	%/month	15 to 20%		15 to 20%		<5% (depends on electronic protection circuit)	
Operational life	Years		5+		3 to 5		to be determined
Reliability (robust towards mechanical wear, resistant to abuse)		Very abuse tolerant. Can use 100% of charge and tolerate deep discharge and fully recover		Somewhat abuse tolerant		Not abuse tolerant; requires electronic controls and proper pack construction	
Safety aspects (Sealed, leak proof, maintenance free, safe under accident conditions)		Sealed configuration with gas release vent		Sealed configuration with gas release vent		Sealed configuration with one-time gas release vent.	
Energy efficiency of discharge/charge	% charge out to charge in (coulombic efficiency)	67 to 91 % (varies with temperature and current)		91 to 95 % (reduced at high temperature)		100%	
Duration of recharging	h	0.25 to 16		0.5 to 1		0.5 to 1	
Sensitivity with respect to overcharge		Superior durability; Designed to withstand overcharge and overdischarge		Moderate; recombination reaction slower.		Very sensitive; requires precise voltage control system.	
Sensitivity with respect to overdischarge				Sensitive		Sensitive	
Development of		Memory effect now		Cell Ah capacity		Impedance increase	

		Performance of rechargeable battery					
		NiCd		NiMH		Li Ion	
Property	Unit	Single cell	18V power pack	Single cell	18V power pack	Single cell	18V power pack
properties over the recharging cycles (e.g. no memory effect)		solved by development of cells and charging system		imbalance			
Weight	**kg/cell,pack**	0.055	1.015	0.059	1.040	0.0452	0.705
Volume	**l/cell,pack**	0.0179	0.676	0.0179	0.676	0.0165	0.691
Market Price	**cost ratio^{*2}**		1.0		1.3		2.0
Note ^{*1}: All energy values from 10 Amp discharge.							
Note ^{*2}: Cell Ah and costs that are commercially available today were used. There are higher Ah Li Ion cells being sampled and also claimed but not widely in use.							
General note: The range of properties vary over a wide range within each battery type. Indeed, this is not only true for Li-Ion, but for the Ni technologies also. The data shown in the matrix are single figures for each of the properties, but in practice the properties vary considerably depending on the source and specification of each individual cell on the market.							

EPTA was also asked whether there are any (technical or economic) obstacles or reasons according to which the use of NiCd batteries is still required in cordless power tools (CPT)? The answer to this question (source: [EPTA 2009a]) was the following:

There is no “ideal” battery technology which suits the requirement of all customers and applications. EPTA have constructed the attached diagram to indicate the relative strengths and weaknesses of NiCd, NiMH and Li-Ion:



SUBSTITUTION

NiCd, NiMH and Li-Ion

- Power Tool companies and their battery suppliers invest heavily in researching new technologies to serve the needs of their customers and the wider community
- The “spidergram” shows some attributes (of importance for Power Tools) of NiCd when compared to NiMH and Li-Ion
- Each technology has its own distinct advantages and disadvantages, none is either best or worst in all attributes.
- Technology developments are moving at some pace, and therefore any comparison of attributes is only relevant for a given time

June 09

Figure 4-15 : Result of an EPTA technical assessment of NiCd, NiMH and Li-ion batteries intended for the use in cordless power tools [source: EPTA 2009a]

Probably EPTA today with respect to high rate discharge and fast charge would rate Li-ion batteries, somewhat better than in June 2009 (compare Table 4-18 from October 2009 to Figure 4-15 from June 2009). EPTA’s conclusion from June 2009, however, is still valid: no one technology is best or worst in all attributes.

Comparing the values in Table 4-18 with elder literature [Noreus 2000, Rentz et al. 2001, Nilsson 2002, Buchmann 2006] it can be concluded that all 3 technologies (NiCd, NiMH and Li-ion) have improved during the last years. Li-ion, however, more so than the others.

While in 2004 the NiMH-battery was seen as the most promising alternative to NiCd as energy source for CPTs [Pillot 2004], today Li-ion seems to be the most competitive technology [Pillot 2009].

(1) Power density and energy density (per weight and volume)

Earlier studies questioned if the NiMH- and the Li-ion batteries provided enough power drain to meet the requirements of cordless power tools (CPT), if they can provide a gravimetric power density of **400/500 W/kg over some period of time with peak powers up to 900 W/kg** [Noreus 2000].

With respect to NiMH the different sources are not conclusive. While Figure 4-1, Figure 4-3 and Table 4-18 give a somewhat smaller peak power density of NiMH as compared to NiCd, Figure 4-2 shows a somewhat higher peak power density of NiMH as compared to NiCd. All sources, however, show that NiMH has a higher energy density than NiCd.

With respect to Li-ion Figure 4-1 through Figure 4-4 show that Li-ion batteries can have both higher power density and higher energy density than NiCd batteries. According to [EPTA 2009b] (see Table 4-18, line "power discharge") this, however, is only true for the gravimetric power density (inW/kg), where the Li-ion batteries are superior by 42 % but not for the volumetric power density (in W/l), where Li-ion batteries slightly lag behind the NiCd batteries by 3 %.

Figure 4-1 to Figure 4-3 imply that at the same power drain a 1kg Li-ion-powerpack can provide energy 3 times as long as 1 kg NiCd-power pack. Figure 4-4 implies that Li-ion can store 100 % more energy in the same volume as NiCd. According to Table 4-18 this is only 10 % more. This underlines, that the values shown for Li-ion batteries as compared to NiCd batteries are estimated rather conservatively.

But even when only considering the values of Table 4-18 (line "power discharge") it can be concluded that from the point of view of power density and energy density Li-ion is an excellent alternative to NiCd batteries.

With respect to energy storage by mass and by volume per cycle NiMH batteries and Li-ion batteries are superior to NiCd batteries (see Table 4-18 values on energy storage capacity per cycle). However, with respect to energy storage by mass over the lifetime NiCd batteries and Li-ion batteries are much better than NiMH batteries, and with volumetric lifetime energy storage capacity NiCd batteries are still superior to the other two (see Table 4-18 values on energy storage capacity over life time). As compared to other sources (e.g. [Bosch 2009a]) the life time expectation of Li-ion batteries shown in Table 4-18 is very conservative. Thus it may be that Li-ion in reality shows better of lifetime-features than shown in Table 4-18.

Table 4-19 : Conclusion from the technical assessment – (1) Power density and energy density (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(1) Power density and energy density	NiCd	High lifetime energy density	-	4	3 technologies are more or less equal
	NiMH	High per cycle energy density	Low lifetime energy density	4	
	Li-ion	High per cycle energy density	Low volumetric lifetime energy density	4	

(2) Temperature range

For NiCd batteries an operation temperature range of -20°C to 60°C, for NiMH a range of 0°C to 50°C and for Li-ion an operation temperature range of 0°C to 60°C is reported [EPTA 2009b]. Thus a ban of

NiCd batteries would require that cordless power tools (CPT) are kept at core temperatures above 0°C.

A cordless power tool producer [Bosch 2009a] states that Li-ion batteries can operate also at lower temperatures, as it produces heat as long as it is in use. Even if its core temperature goes below – 10 °C no irreversible damage would occur with Li-ion batteries. Also professionals operating cordless power tools (CPT) by Li-ion batteries in the cold region of northern Sweden have no problems with this battery type [SE EPA 2009].

It also needs to be mentioned that below 0°C NiCd batteries show a much lowered energy storage capacity (see Figure 4-7).

Table 4-20 : Conclusion from the technical assessment – (2) Temperature range (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(2) Temperature range	NiCd	Can be operated below 0 °C (however, also with NiCd performance is reduced below 0 °C: At -20 °C less than 60 % of the stored energy is released (see Figure 4-7)	-	4	Limits below 0 °C for all, more so for NiMH and Li-ion
	NiMH	-	Much reduced performance below 0 °C	3	
	Li-ion	-	Much reduced performance below 0 °C	3	

(3) Charging cycles and life time

NiCd still seems to have the edge with respect to charging cycles and life time. According to [EPTA 2009b] (see Table 4-18, line “energy storage capacity over lifetime”) NiMh has 40 % and Li-ion has 38 % less lifetime energy storage capacity than NiCd. [Bosch 2009a], however, states that Li-ion batteries hold as long and can be recharged as frequently as NiCd batteries. In any case, with all 3 battery types the lifetime strongly depends on the mode of operation, the frequency and severeness of use and the temperature and charge of storage. While the optimal operation mode maybe different, a careful operation and storage may extend the lifetime with all 3 types. For example the 20 %/a loss of energy storage capacity of Li-ion batteries when stored 100 % charged can be lowered to 3 %/a when stored only 40 % charged. In comparison, NiCd need to be discharged/charged regularly and stored uncharged, so that they need to be charged before use.

Table 4-21 : Conclusion from the technical assessment – (3) Charging cycles and lifetime (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(3) Charging cycles and lifetime	NiCd	Life time 7 years	-	5	NiCd seem to have the longest lifetime, NiMH the shortest, the lifetime of Li-ion needs to be confirmed, but seems to be between NiMH and NiCd
	NiMH	-	Life time approx. 4 years	3	
	Li-ion	Life time maybe 7 years	Life time maybe 4 years	4	

(4) Overcharge and over-discharge

All 3 types should not be overcharged and over-discharged. With all 3 types, the chargers supplied with the power packs and the power packs themselves contain equipment which prohibits overcharge, over-discharge and overheating guaranteeing a safe operation.

Table 4-22 : Conclusion from the technical assessment – (4) Overcharge and over-discharge (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(4) Overcharge and over-discharge	NiCd	Equipment for avoiding overcharge/overdischarge included	May be destroyed by overcharge or overdischarge	4	No differentiation because charging equipment ensures safe operation
	NiMH	Equipment for avoiding overcharge/overdischarge included	May be destroyed by overcharge or overdischarge	4	
	Li-ion	Equipment for avoiding overcharge/overdischarge included	May be destroyed by overcharge or overdischarge	4	

(5) Energy efficiency of discharge/charge

According to [EPTA 2009b] (see Table 4-18) the discharge/charge efficiency of NiCd is 67 to 91 %, of NiMH is 91 to 95 % and of Li-ion is 100%. That means for providing 100 Wh of energy to the cordless power tool NiCd needs to be charged with about 127 Wh, NiMH with about 108 Wh and Li-ion with only 100 Wh. Thus from the point of view of energy efficiency a ban of NiCd batteries would be beneficial.

Table 4-23 : Conclusion from the technical assessment – (5) Energy efficiency of discharge/charge (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(5) Energy efficiency of discharge/charge	NiCd	-	67 to 91 % effieciency	3	Li-ion is most efficient with respect to energy utilisation
	NiMH	-	91 to 95 % effieciency	4	

	Li-ion	Almost 100 % efficiency	-	5	

(6) Fast charge

In the past NiCd had a strong advantage with respect to fast charge rates. Today this advantage has vanished, as the charging time for all 3 battery types are in the same range (see Table 4-18, line "duration of recharging").

Table 4-24 : Conclusion from the technical assessment – (6) Fast charge (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(6) Fast charge	NiCd	Fast charge possible	Better performance when charged at lower rate	4	All 3 more or less equal
	NiMH	Fast charge possible	Better performance when charged at lower rate	4	
	Li-ion	Fast charge possible	Better performance when charged at lower rate	4	

(7) Low self discharge

NiCd and NiMH lose 15 to 20 % of the stored charge per month, Li-ion less than 5 % (see Table 4-18, line "self discharge").

Table 4-25 : Conclusion from the technical assessment – (7) Low self discharge (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(7) Low self discharge	NiCd	-	15 to 20% self discharge/month	3	Li-ion can keep the stored energy over the longest time and needs to be recharged less frequently during "shelf live"
	NiMH	-	15 to 20% self discharge/month	3	
	Li-ion	<5% self discharge/month	Loses energy storage capacity when stored fully charged	4	

(8) Reliability

The 3 battery types exhibit different abuse tolerance. However, all 3 battery types are completely sealed with safety gas release vent and electronic equipment for prevention overcharge and overdischarge (see Table 4-18, lines "Reliability" and "Safety aspects")While the chemistry of the Li-ion cell is the most sensitive, the electronic safety equipment enables the Li-ion-power pack to be considered a fully reliable energy source. Considering the corresponding charging equipment ensures safe operation of all 3 battery types. They can therefore be considered equally reliable.

Table 4-26 : Conclusion from the technical assessment – (8) Reliability (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(8) Reliability	NiCd	Very reliable	-	5	Only small differentiation because charging equipment ensures safe operation
	NiMH	Reliable	-	4	
	Li-ion	Reliable	-	4	

(9) Maturity and potential for further improvement

Obviously there is much longer experience with NiCd. But the use of all 3 battery types in millions of applications around the world proves that all 3 battery types are mature technologies. With respect to further improvements Li-ion and other lithium based technologies have the biggest potential.

Table 4-27 : Conclusion from the technical assessment – (9) Maturity (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(9) Maturity and development potential	NiCd	Highest degree of maturity	(Nearly) no further development potential	5	Longer experience for NiCd is outweighed by future potential of Li technologies
	NiMH	-	-	4	
	Li-ion	Highest development potential	Maturity may be further improved	5	

In total, from technical point of view Li-ion batteries are not as good as NiCd in very low temperatures, but need to be charged less frequently, can drive even more powerful tools and are lighter. Thus Li-ion cannot beat NiCd in every technical respect, but in many respects. Also NiMH can be used to replace NiCd batteries, but has somewhat more limitations.

Table 4-28 summarises the results of the technical assessment.

Table 4-28 : Conclusions from the technical assessment of commercially available technical substitutes (Ranking: 5 is very good, 1 is insufficient)

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
(1) Power density and energy density	NiCd	High lifetime energy density	-	4	3 technologies are more or less equal
	NiMH	High per cycle energy density	Low lifetime energy density	4	
	Li-ion	High per cycle energy density	Low volumetric lifetime energy density	4	
(2) Temperature range	NiCd	Can be operated below 0 °C	Reduced performance	4	Limits below °C for all,

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
			below 0 °C		more so for NiMH and Li-ion
	NiMH	-	Much reduced performance below 0 °C	3	
	Li-ion	-	Much reduced performance below 0 °C	3	
(3) Charging cycles and lifetime	NiCd	Life time 7 years	-	5	NiCd seem to have the longest lifetime, NiMH the shortest, the lifetime of Li-ion needs to be confirmed, but seems to be between NiMH and NiCd
	NiMH	-	Life time approx. 4 years	3	
	Li-ion	Life time maybe 7 years	Life time maybe 4 years	4	
(4) Overcharge and over-discharge	NiCd	Equipment for avoiding overcharge/overdischarge included	May be destroyed by overcharge or overdischarge	4	No differentiation because charging equipment ensures safe operation
	NiMH	Equipment for avoiding overcharge/overdischarge included	May be destroyed by overcharge or overdischarge	4	
	Li-ion	Equipment for avoiding overcharge/overdischarge included	May be destroyed by overcharge or overdischarge	4	
(5) Energy efficiency of discharge/charge	NiCd	-	67 to 91 % effieciency	3	Li-ion is most efficient with respect to energy utilisation
	NiMH	-	91 to 95 % effieciency	4	
	Li-ion	Almost 100 % efficiency	-	5	
(6) Fast charge	NiCd	Fast charge possible	Better performance when charged at lower rate	4	All 3 more or less equal
	NiMH	Fast charge possible	Better performance when charged at lower rate	4	
	Li-ion	Fast charge possible	Better performance when charged at lower rate	4	
(7) Low self discharge	NiCd	-	15 to 20% self discharge/month	3	Li-ion can keep the

Criterion	Technology	Advantages	Disadvantages	Ranking (1 to 5)	Conclusion and justification
	NiMH	-	15 to 20% self discharge/month	3	stored energy over the longest time and needs to be recharged less frequently during “shelf live”
	Li-ion	<5% self discharge/month	Loses energy storage capacity when stored fully charged	4	
(8) Reliability	NiCd	Very reliable	-	5	Only small differentiation because charging equipment ensures safe operation
	NiMH	Reliable	-	4	
	Li-ion	Reliable	-	4	
(9) Maturity and development potential	NiCd	Highest degree of maturity	(Nearly) no further development potential	5	Longer experience for NiCd is outweighed by future potential of Li technologies
	NiMH	-	-	4	
	Li-ion	Highest development potential	Maturity may be further improved	5	
Average of ranking points	**NiCd**			**4.1**	
	NiMH			**3.7**	
	Li-ion			**4.1**	

Recent market developments (see chapter 3), advertisement strategies of cordless power tool producers [Bosch 2009a], and the technical properties lead to following conclusions on what will happen when NiCd batteries are banned from application in cordless power tools (CPT):

1. Replacement batteries for existing NiCd-battery-driven cordless power tools will be NiMH batteries.
2. All new cordless power tools that are currently based on NiCd technology will be covered mainly by Li-ion batteries.

In that event the still existing disadvantageous properties of Li-ion batteries in relation to NiCd batteries can to a big extend be balanced by adaptations in the handling of the battery.

The best prove that a NiCd ban will not have dramatic consequences from the technical point of view is, that leading CPT producers sell for standard tools all three types of, while developing their most advanced tools in line with Li-ion batteries only [Bosch 2009b,c].

As Li-ion batteries are already on the market for many other applications and already today need to be separately collected and treated as waste, also no negative effects from the supply logistics and the waste management logistics are to be expected. When the NiCd batteries disappear from the market in most of their applications, even simplifications in the supply logistics and the waste management modes may be possible.

4.4.2 Technologies in the pipeline

From the technologies which are currently under development following technologies seem to have the biggest potential to be used as efficient energy source for cordless power tools (CPT) in the foreseeable future:

- Different types of advances Lithium-ion- and the Lithium-air-battery
- The Nickel-zinc-battery
- Carbon Nanotube Enhanced Supercapacitors (which might be commercially available by 2014)

Other technologies such as Direct Methanol Fuel Cells or Redox-Flow-Batteries may also have the potential to become an efficient energy source for CPTs, but still have to overcome severe technical problems, before they can used in this application.

5 Environmental, Economic and Social Impacts of Cadmium-Batteries and their Alternatives

The main policy objective of a prohibition of cadmium in batteries and accumulators intended for use in CPTs is to avoid negative environmental impacts that are related to this use. The most important objective of an assessment of the impacts related to a prohibition is to assess the impacts which will be caused by technical substitutes, i.e. by a possible increased use of NiMH and particularly Li-ion technologies. The previous studies performed are to a certain extent outdated due to the technological development of substitutes which took place the elaboration of the mentioned studies (i.e. after the years 2000 to 2004).

Therefore, the previous studies (mainly from the period 2000 to 2004) could particularly not appropriately consider the availability and maturity of Li-ion technologies as these were not significantly represented in specific market segments, including the market of cordless power tools (CPT) before. According to [EPTA 2009a], in 2008 the European share of battery chemistries in the cordless power tool (CPT) market were 55% for NiCd, 36% for Li-ion and 9% for NiMH technologies. The trend for NiCd batteries is decreasing whereas it is increasing for Li-ion batteries and more or less stable for NiMH batteries. The impact assessment of the present study takes the current state-of-the-art in battery development into account.

As a consequence several impacts have to be reconsidered in the light of the current state-of-the-art in battery development.

The impact assessment consists of following parts:

- Nature of the problem
- Identification of possible impacts from NiCd batteries and technical substitutes, stakeholders and affected resources
- Environmental impacts:
  - Hazardousness of materials used
  - Impacts during mining, processing, manufacturing, transport, distribution, use, storage, waste collection, waste treatment (recycling and re-use) waste disposal
- Economic impacts
- Social impacts
- Synopsis of impact assessment
  - measures for impact abatement

5.1 Nature of the problem

Currently the use of cadmium in portable batteries and accumulators is restricted to 0,002% of cadmium by weight. However, according to Article 4(3) of the Batteries Directive (2006/66/EC) portable batteries and accumulators intended for use in cordless power tools (CPT) are exempted from this prohibition.

The objective of the impact assessment is to assess the environmental, economic and social impacts of the use of cadmium in portable batteries intended for the use in CPT and of possible technical substitutes.

Most relevant technical substitutes are NiMH and Li-ion technologies which have already penetrated the market of cordless power tools (CPT). These are currently operated with rechargeable portable NiCd, Li-ion or NiMH batteries. According to different information sources, in 2008 the worldwide shares of these battery chemistries in the cordless power tool (CPT) market were in the ranges of 48 to 56% for NiCd, 30 to 37% for Li-ion and 7 to 22% for NiMH technologies. In 2008 the European share of battery chemistries in the cordless power tool (CPT) market were 55% for NiCd, 36% for Li-ion and 9% for NiMH technologies. The trend for NiCd batteries is decreasing whereas it is increasing for Li-ion batteries and more or less stable for NiMH batteries.

5.2 Identification of possible Actors, Impacts, and affected Resources

Actors

Figure 5-1 illustrates the causal relations in the supply, recycling and disposal chain of all batteries used in CPT and of CPT themselves. The dotted lines shall illustrate that relevant shares of waste batteries and waste CPTs are directly disposed instead of being collected and recycled.

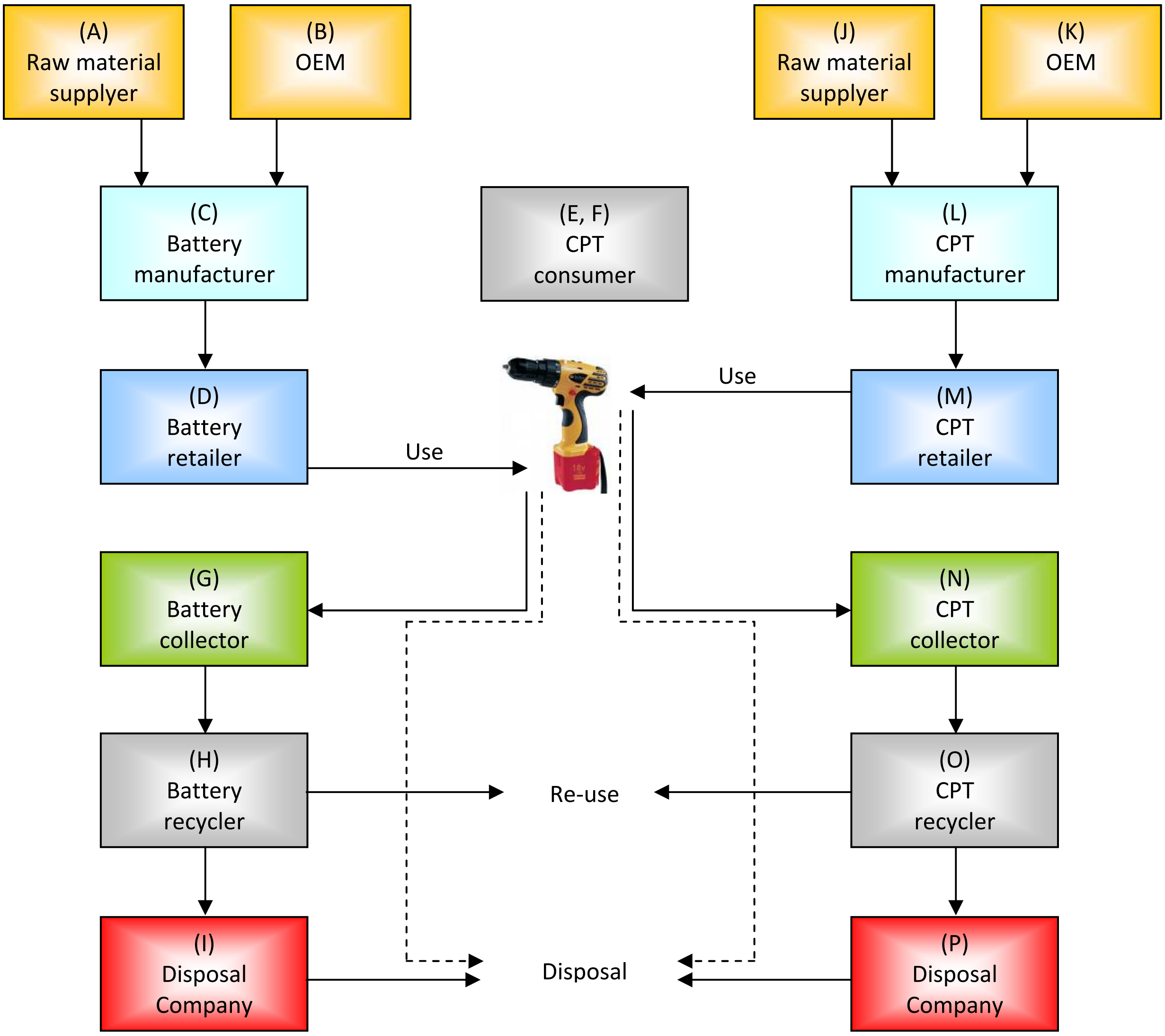


Figure 5-1 : **Causal relations in the supply, recycling and disposal chain of batteries used in CPT and of CPT**

Along the chain of raw material supply, manufacturing, collection, recycling and disposal all relevant actors and all relevant impacts can be systematically identified. Battery manufacturers are manufacturers of NiCd, NiMH, Li-ion batteries and manufacturers of all possible technical substitutes.

In addition to the actors illustrated in Figure 5-1 the environment and the society as a whole and public authorities have to be considered. The state of the environment may change due to altered releases of pollutants to air, water and soil. Also, altered loss of scarce resources and the society may be concerned due to impacts on life quality and external costs. Public authorities may be concerned due to different administrative burden.

Impacts

Economic impacts are possible in the form of increased or reduced turnover of the concerned actors, increased or reduced retail prices for cordless power tools (CPT) due to the use of CPTs.

Social impacts are closely related to the economic impacts. They are possible in terms of job gains or losses.

Environmental impacts are possible due to the hazardousness of materials used and due to environmental impacts that occur during mining, processing, manufacturing, transport, distribution, use, storage, waste collection, waste treatment (recycling and re-use), waste disposal e.g. as a consequence of releases of hazardous substances to the environment.

Table 5-1 lists all involved actors and generally possible impacts of a cadmium ban in PBA for CPT. However, it is expected that only some of them will be affected by relevant impacts. However, the systematic listing of all possible involved actors supports the systematic identification of relevant impacts. Most important stakeholders are (A) raw material suppliers for battery manufacturers, (C) battery manufacturers, (E) DIY consumers, (H) battery recyclers, (L) CPT manufacturers and (Q) the society and environment as a whole.

Table 5-1: Concerned actors and possible relevant impacts related to a ban of cadmium in batteries for CPT

Actors		Possible impacts		
		Economic	Social	Environmental
(A)	Raw material supplier for battery manufacturers (in particular Ni, Cd, Li, Co and Mn industry)	Change of turnover	Job gains or losses	Environmental impacts from mining and processing of battery raw materials (releases of pollutants to air, water and soil, use of scarce resources)
(B)	Operational equipment manufacturer (OEM) for battery manufacturers	Change of turnover	Job gains or losses	Environmental impacts from provision of operational equipment for battery manufacturing (releases of pollutants to air, water and soil)
(C)	Battery manufacturer of portable NiCd, NiMH, Li-ion and other technical substitutes (including manufacturer of battery packs for CPTs)	Change of turnover	Job gains or losses	Environmental impacts from manufacturing of batteries (releases of pollutants to air, water and soil, use of scarce resources, use of hazardous materials)
(D)	Battery retailer	Change of turnover	Job gains or losses	Environmental impacts from retailing of batteries for CPT (releases of pollutants to air, water and soil, use of scarce resources)
(E)	DIY consumers of CPTs	Change of the price for CPTs		Environmental impacts from the DIY use of CPT (releases of pollutants to air, water and soil)
(F)	Professional consumers of CPTs	Change of turnover	Job gains or losses; Job quality	Environmental impacts from the professional use of CPT (releases of pollutants to air, water and soil)
(G)	Battery collector	Change of turnover	Job gains or losses	Environmental impacts from the collection of batteries used in CPT (releases of pollutants to air, water and soil)
(H)	Battery recycler	Change of turnover	Job gains or losses	Environmental impacts from recycling of batteries (releases of pollutants to air, water and soil, provision of resources for re-use)
(I)	Disposal company that disposes of waste from battery recycling	Change of turnover	Job gains or losses	Environmental impacts from treatment and disposal of waste from battery recycling (releases of pollutants to air, water and soil)

Actors	Possible impacts		
	Economic	Social	Environmental
(J) Raw material supplier for CPT manufacturers	Change of turnover	Job gains or losses	Environmental impacts from mining and processing of CPT raw materials (releases of pollutants to air, water and soil, use of scarce resources)
(K) Operational equipment manufacturer (OEM) for CPT manufacturers	Change of turnover	Job gains or losses	Environmental impacts from provision of operational equipment for CPT manufacturing (releases of pollutants to air, water and soil)
(L) CPT manufacturers (including importer, assembler, battery incorporator)	Change of turnover	Job gains or losses	Environmental impacts from manufacturing of CPT (releases of pollutants to air, water and soil, use of scarce resources)
(M) CPT retailer	Change of turnover	Job gains or losses	Environmental impacts from transport emissions and very rare cases of breaking batteries during handling
(N) CPT collector	Change of turnover	Job gains or losses	Environmental impacts from collection of CPTs (releases of pollutants to air, water and soil)
(O) CPT recycler	Change of turnover	Job gains or losses	Environmental impacts from recycling of CPT (releases of pollutants to air, water and soil)
(P) Disposal company that disposes of waste from CPT recycling	Change of turnover	Job gains or losses	Environmental impacts from treatment and disposal of waste from CPT recycling (releases of pollutants to air, water and soil)
(Q) Society and Environment	Change of external costs	Impact on life quality	Environmental impacts from direct disposal of waste batteries and CPT that are not collected and recycled (releases of pollutants to air, water and soil; loss of resources)
(R) Public authorities	Change of administrative burden	Job gains or losses	Small environmental impacts e.g. from additional traffic caused by additional inspections.

The environmental concerns related to batteries and accumulators are linked to the materials they contain. This is particularly the case for mercury, lead and cadmium.

Commission Decision 2000/532/EC has established two categories of batteries: non-hazardous and hazardous batteries. Hazardous batteries are lead batteries, NiCd batteries and mercury-containing batteries. Mercury, various compounds of cadmium and lead are classified under Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances [EC 2003].

Other metals used in batteries, such as zinc, copper, manganese, lithium and nickel may also pose an environmental risk when they accumulate in the environment after disposal operations (landfill or incineration). Batteries and accumulators may also contain strong acids or bases and many are considered corrosive [EC 2003].

The following environmental impact assessment focuses on NiCd batteries and their likely alternatives NiMH batteries and Li-ion batteries. Table 4-3 gives an overview of metal composition of different portable batteries in % by mass. It enables among other to assess which and how much metals are needed for the production of a certain amount of a specific battery type.

According to Table 4-3 these battery types contain various amounts of following metals:

- Cadmium
- Cobalt
- Lithium
- Manganese
- Nickel.

The environmental impacts of these metals are assessed in detail, before analyzing the environmental impact of the battery types, taking into account also the other materials contained in these battery types.

5.3 Environmental Impacts of Materials used in Batteries

The environmental impact assessment takes to show the consequences of a ban of NiCd ban for use in CPTs from the environmental point of view. As the likely consequence of a ban is the replacement of NiCd by Li-ion batteries and in a transition phase by NiMH batteries, this impact assessment concentrates on these 3 technologies and their materials.

At the start of the environmental impact assessment we investigate the properties, health and environmental effects, the exploitation and the recycling of the materials contained in the NiCd, NiMH and Li-ion batteries (chapter 5.3).

In the second step the NiCd, NiMH and Li-ion batteries themselves are assessed (chapter 5.4).

The materials assessed are:

- The electrode materials:
    - Cadmium (anode of NiCd)
    - Cobalt (cathode of Li-ion)
    - Lithium (electrodes of Li-ion)
    - Manganese (cathode of Li-ion)
    - Nickel (Cathode of NiCd and NiMH)
    - Rare-earth-metals (Lanthanides) (as representative material for the NiMH anode)
    - Carbon/Graphite (anode of Li-ion)
- And the electrolyte materials:
    - Alkali (in NiCd and NiMH)
    - Aprotic salts and solvents, such as $LiPF_6$ and di-etyhl carbonate (in Li-ion)

The materials enveloping the cells and power packs are neglected in this assessment, as they are not technology specific and can be expected to be materials of much less environmental impact as the electrode/electrolyte materials.

The next subchapters show the properties, health effects, the occurrence, the exploitation techniques and the status of recycling of the battery materials. For the metals and the industrial minerals fluorspar and graphite further more detailed descriptions including reserve, economic and market aspect can be found in Appendix A (chapter 8.1).

5.3.1 Cadmium

Cadmium is used in NiCd batteries (see Table 4-8).

Cadmium is a relatively rare, soft, bluish-white, transition metal. Cadmium is a soft, malleable, ductile, toxic, bluish-white bivalent metal. It is similar in many respects to zinc but reacts to form more complex compounds. The most common oxidation state of cadmium is +2, though rare examples of +1 can be found. Physical and chemical properties as well as risk and safety classification are shown in Table 5-2.

Table 5-2: Physical and chemical characterization, labelling requirements and limit values for non-pyrophoric Cadmium [JRC 2009, Wikipedia 2009N, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name			Cadmium
Symbol			Cd
Atomic Number			48
Element category			transition metals
Appearance			silvery grey metallic
Standard atomic weight in g/mol			112.41
Density (at room temperature) in g/cm³			8.65
Melting point in °C			321
Boiling point in °C			767
Mohs hardness			2
Standard voltage at pH=0 in V			-0.402
Mass share of earth crust in %			0.00003
CAS registry number			7440-43-9
Labelling requirements according to Directive 1967/548/EEC	Labels		N, T+
	R-phrases		R:26-45-48/23/25-50/53-62-63-68
	S-phrases		S: 7/8-43-45-53-60-61
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H332 H312 H302 H400 H410
OSHA permissible exposure limits (PEL)	acceptable ceiling concentration in mg/m³		0.3
	8-hour average in mg/m³	total particulate	0.2
		respirable particulate	0.1
Austrian Grenzwerteverordnung	TRK-value	Daily average in mg/m³	0.015 (respirable particulate)
		15 min average in mg/m³	0.06 (respirable particulate)
	List of carcinogenic substances	A2 Substances which cause tumors with animals	cadmium and its compounds

Note:
CAS registry number = Chemical Abstracts Services Registry Number
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;

For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration TRK-value = technical compliance concentration.

Health Effects

Cadmium is a toxic and carcinogenic substance. The International Agency for Research on Cancer has identified Cd as a known human carcinogen. Epidemiologic studies of Cd-exposed workers show excess lung cancer. The main non-cancer endpoint of concern is kidney damage. Bone and hematologic disorders have also occurred at high level exposure. A wider range of organ toxicity has been demonstrated in animals.

Even doses of as little as 50 mg of cadmium compounds are toxic to humans as cadmium is easily resorbed and suppresses the intracellular zinc supply.

Cadmium can be taken up via the breathing air, via food or via drinking water. Cadmium accumulates in the liver and especially in the kidneys. Heavy organ damage may be caused. Cadmium vapour may irritate the eyes and especially the respiratory tract. Inhalation may cause headache and oedemata of the lungs.

Chronic cadmium poisoning may lead to the loss of smelling capacity, yellow coloured teeth and anemia. Cadmium may cause osteoporosis and sever damage of the skeleton (Itai-Itai-disease in Japan).

Cadmium is an occupational hazard associated with industrial processes such as metal plating and the production of nickel-cadmium batteries, pigments, plastics and other synthetics. The primary route of exposure in industrial settings is inhalation. Inhalation of cadmium-containing fumes can result initially in metal fume fever but may progress to chemical pneumonitis, pulmonary edema, and death [Wikipedia 2009N].

Cadmium and several cadmium-containing compounds are known carcinogens and can induce many types of cancer [Wikipedia 2009N]. At high chronic exposure cadmium may cause prostate cancer [Parzefall 2001]. In addition Cadmium is suspected to be mutagenic for germ cells [DFG 2004]. Cadmium affects the repair mechanisms of DNA-damage and thus favours the formation of cancer.

Under [DIR 67/548/EEC], non-pyrophoric cadmium is classified as:

- Carcinogenic Category 2, R45 - May cause cancer
- Mutagenic Category, R68 - Possible risk of irreversible effects
- Reproduction Category 3; R62-63 - Possible risk of impaired fertility and possible risk of harm to the unborn child
- T; R48/23/25 - Toxic: danger of serious damage to health by prolonged exposure through inhalation and if swallowed
- T+; R26 - Very toxic by inhalation
- N; R50-53 - Very toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment [JRC 2009].

According to [Regulation (EC) No 1272/2008] cadmium compounds are categorised as:

- H332 - Acute toxicity (inhalation), Hazard Category 4 | Harmful if inhaled.
- H302 - Acute toxicity (oral), Hazard Category 4 | Harmful if swallowed.
- H312 - Acute toxicity (dermal), Hazard Category 4 | Harmful in contact with skin.
- H400 - Hazardous to the aquatic environment — Acute Hazard, Category 1 | **Very toxic to aquatic life**.
- H410 - Hazardous to the aquatic environment — Chronic Hazard, Category 1 | **Very toxic to aquatic life with long lasting effects.**

Environmental effects

Cadmium emissions accumulate in the environment and are a potential environmental hazard. Human exposures to environmental cadmium are primarily the result of the burning of fossil fuels and municipal wastes. However, there have been notable instances of toxicity as the result of long-term exposure to cadmium in contaminated food and water [Wikipedia 2009N].

According to [Regulation (EC) No 1272/2008] cadmium poses an acute and a chronic hazard being very toxic to aquatic life in the short and in the long term.

With a melting point of 321 °C and a boiling point of 767 °C cadmium is volatile during incineration. Cadmium is soluble in water, most of its salts are highly soluble. Consequently cadmium easily dissipates into the environment. As can be seen in Table 5-3 cadmium gets about 20 times easier into the environment than lead.

Table 5-3 : Share of the cadmium and lead input, respectively, into the Austrian economy 2005 which was emitted into the air and into water, respectively [Umweltbundesamt & TU-Wien 2009]

	Share in % of input	
	Cadmium	Lead
Emissions into air	0.81	0.03
Emissions into water (without erosion)	0.20	0.009

Exploitation

Cadmium occurs in zinc ores in a proportion between 1:27 and 1:7,000 [Fleischer et al. 1974] and has an average crustal abundance by mass of 0.1 mg/kg [Alloway 1995]. Its availability in soils is dependent on the bio-geochemical parameters of soils.

Cadmium is a common impurity in zinc, and it is most often isolated during the production of zinc. Zinc sulfide ores are roasted in the presence of oxygen converting the zinc sulfide to the oxide. Zinc metal is produced either by smelting the oxide with carbon or by electrolysis in sulfuric acid.

Cadmium is isolated from the zinc metal by vacuum distillation if the zinc is smelted, or cadmium sulfate is precipitated out of the electrolysis solution [Wikipedia 2009N].

Cadmium-containing ores are rare and when found they occur in small quantities. Greenockite (CdS), the only cadmium mineral of importance, is nearly always associated with sphalerite (ZnS). Consequently, cadmium is produced mainly as a by-product from mining, smelting, and refining sulfide ores of zinc, and to a lesser degree, lead and copper. Zinc-to-cadmium ratios in typical zinc ores range from 200:1 to 400:1 [Wikipedia 2009N].

Concern over cadmium's toxicity has spurred various recent legislative efforts, especially in the European Union, to restrict the use of cadmium in most of its end-use applications. The final effect of this legislation on global cadmium consumption has yet to be seen. If recent legislation involving cadmium dramatically reduces long-term demand, a situation could arise, such as has been recently seen with mercury, where an accumulating oversupply of by-product cadmium will need to be permanently stockpiled [USGS 2009].

Most of the world's primary cadmium (approximately 51%) was being produced in Asia and the Pacific—specifically China, Japan, and the Republic of Korea—followed by North America (22%), Central Europe and Eurasia (18%), and Western Europe (6%).

Estimated worldwide identified resources of cadmium were about 6 million tonnes, based on identified zinc resources of 1.9 billion tonnes containing about 0.3% cadmium. Zinc-bearing coals of the Central United States and Carboniferous age coals of other countries also contain large subeconomic resources of cadmium [USGS 2009].

Recycling

About 10% of the cadmium needed worldwide is produced from secondary sources. Cadmium is mainly recovered from spent consumer and industrial NiCd batteries. Other waste and scrap from which cadmium can be recovered includes copper-cadmium alloy scrap, some complex non-ferrous alloy scrap, and cadmium-containing dust from electric arc furnaces [USGS 2009].

Worldwide secondary cadmium production accounted for approximately 20% of all cadmium metal production, and this percentage was expected to increase in the future [USGS 2009].

5.3.2 Cobalt

Cobalt is used in one type of Li-ion batteries, but also in NiMH and to much smaller extend in NiCd batteries.

Cobalt is a hard, lustrous, grey metal. Cobalt is found in various metallic-lustred ores for example cobaltite (CoAsS), but it is produced as a by-product of copper and nickel mining. The copper belt in the Democratic Republic of the Congo and Zambia yields most of the worldwide mined cobalt.

Physical and chemical properties as well as risk and safety classification are shown in Table 5-4.

Table 5-4: **Physical and chemical characterisation, labelling requirements and limit values for Cobalt [JRC 2009, Wikipedia 2009o, NIOSH 2009, MinEcon AT 2003, Seel 1973]**

Name			Cobalt
Symbol			Co
Atomic Number			27
Element category			tranistion metals
Appearance			hard lustrous gray metal
Standard atomic weight in g/mol			58.9332
Density (at room temperature) in g/cm^3			8.9
Melting point in °C			1,495
Boiling point in °C			2,928
Mohs hardness			5
Standard voltage at pH=0 in V			-0.277
Mass share of earth crust in %			0.003
CAS registry number			7440-48-4
Labelling requirements according to Directive 1967/548/EEC	Labels		Xn
	R-phrases		R: 42/43-53
	S-phrases		S: (2)-22-24-37-61
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H334 H317 H413
OSHA permissible exposure limits (PEL)	8-hour average in mg/m^3	total particulate	0.1
Austrian Grenzwerteverordnung	TRK-value	Daily average in mg/m^3	0.1 (respirable particulate)
		15 min average in mg/m^3	0.4 (respirable particulate)
	List of carcinogenic substances	A2 Substances which cause tumors with animals	cobalt and its compounds

Note:
CAS registry number = Chemical Abstracts Services Registry Number
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;

For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration; TRK-value = technical compliance concentration.

Health Effects

Pulmonary disease has been reported frequently in workers exposed to cobalt in the manufacture of cemented tungsten carbide. The adverse effect of exposure is generally chronic interstitial pneumonitis. Fatalities have been reported occasionally from exposures to cobalt at concentrations of 1 to 2 mg/m^3 or less. An increase in serum A-2 globulin fraction was reported in the case of a welder exposed to fumes containing cobalt; the welder had a history of exertional dyspnea and an abnormal chest X-ray. Allergic dermatitis has been caused by contact with cobalt and its compounds [NIOSH 2009].

Under [DIR 67/548/EEC], cobalt is classified as

- Xn - harmful
- R 42/43 - May cause sensitization by inhalation and skin contact
- R 53 - May cause long-term adverse effects in the aquatic environment [JRC 2009].

According to Regulation (EC) No 1272/2008 cobalt is classified as

- H317 | 3.4— Sensitisation — Skin, Hazard Category 1 | May cause an allergic skin reaction. |
- H334 | 3.4— Sensitisation — Respiratory, Hazard Category 1 | May cause allergy or asthma symptoms or breathing difficulties if inhaled. |
- H413 | 4.1— Hazardous to the aquatic environment — Chronic Hazard, Category 4 | May cause long lasting harmful effects to aquatic life. |

Environmental effects

Cobalt may cause long-term adverse effects in the aquatic environment [JRC 2009].

Exploitation

Pure cobalt is not found in nature, but compounds of cobalt are common. Small amounts of it are found in most rocks, soil, plants, and animals. In nature, it is frequently associated with nickel.

Cobalt occurs in copper and nickel minerals and in combination with sulfur and arsenic in the sulfidic cobaltite ($CoAsS$), safflorite ($CoAs_2$) and skutterudite ($CoAs_3$) minerals. The mineral cattierite is similar to pyrite and occurs in the copper deposits in the Katanga Province [Wikipedia 2009o].

Recycling

Cobalt is expensive and scarce. Cobalt recovery from scrap and catalysts are state-of-the-art. More difficult and expensive is the recovery of cobalt from batteries. Here substantial recycling capacities need to be developed in future [Angerer et al. 2009].

5.3.3 Lithium

Lithium is used in Li-ion batteries (see Table 4-13).

Lithium is a soft alkali metal with a silver-white color. Under standard conditions, it is the lightest metal and the least dense solid element. Like all alkali metals, lithium is highly reactive, corroding quickly in moist air to form a black tarnish. Lithium metal is also highly flammable [Wikipedia 2009P].

Physical and chemical properties as well as risk and safety classification are shown in Table 5-5.

Table 5-5: Physical and chemical characterisation, labelling requirements and limit values for Lithium [JRC 2009, Wikipedia 2009P, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name		Lithium
Symbol		Li
Atomic Number		3
Element category		alkali metals
Appearance		silvery white
Standard atomic weight in g/mol		6.941
Density (at room temperature) in g/cm³		0.53
Melting point in °C		181
Boiling point in °C		1,342
Mohs hardness		0.6
Standard voltage at pH=0 in V		-3.02
Mass share of earth crust in %		0.006
CAS registry number		7439-93-2
Labelling requirements according to Directive 1967/548/EEC	Labels	C, F+
	R-phrases	R: 14/15-34
	S-phrases	S: (1/2)-8-43-45
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	H260 H314

Note:
Labels: C = corrosive, E = explosive, F+ = highly flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant.
For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively

Health Effects

Under [DIR 67/548/EEC] metallic lithium is classified as

- F+ – higly flammable: R14/15 - Reacts violently with water, liberating extremely flammable gases
- C – corrosive: R 34 - Causes burns [JRC 2009].

According to [Regulation (EC) No 1272/2008] metallic lithium is classified as

- H260 | 2.12 —Substances and Mixtures which, in contact with water, emit flammable gases, Hazard Category 1 | In contact with water releases flammable gases which may ignite spontaneously. |
- H314 | 3.2— Skin corrosion/irritation, Hazard Category 1A, 1B, 1C | Causes severe skin burns and eye damage. |

Exploitation

Lithium is widely distributed on earth, however, it does not naturally occur in elemental form due to its high reactivity. Estimates for crustal content range from 20 to 70 ppm by weight.

There are a fairly large number of both lithium mineral and brine deposits but only comparatively a few of them are of actual or potential commercial value. The most important deposit of lithium is in the Salar de Uyuni area of Bolivia, which holds half of the world's reserves. Subsurface brines have become the dominant raw material for lithium carbonate production worldwide because of lower production costs as compared with the mining and processing costs for hard-rock ores.

On a commercial scale, lithium metal is isolated electrolytically from a mixture of lithium chloride and potassium chloride

Chile is the leading lithium chemical producer in the world; Argentina, China, and the United States also are major producers. Australia, Canada, Portugal, and Zimbabwe are major producers of lithium ore concentrates [Wikipedia 2009P, USGS 2009].

Recycling

Up to now recycling is insignificant, but increasing through the recycling of lithium batteries [USGS 2009]. Within the EU Li-ion batteries are currently recycled by Belgium and French recyclers (see [BiPRO et. al 2009] p. 48).

5.3.4 Manganese

Manganese is used in one type of Li-ion batteries, but also in NiMH and to a small extent in NiCd batteries.

Manganese is a gray-white metal, resembling iron. It is a hard metal and is very brittle, fusible with difficulty, but easily oxidized.

Manganese is found as a free element in nature (often in combination with iron), and in many minerals. As a free element, manganese is a metal with important industrial metal alloy uses, particularly in stainless steels.

Manganese ions have various colors, depending on their oxidation state, and are used industrially as pigments. The permanganates of sodium, potassium and barium are powerful oxidisers. Manganese dioxide is used as the cathode (electron acceptor) material in standard and alkaline disposable dry cells and batteries [Wikipedia 2009Q].

Physical and chemical properties as well as risk and safety classification are shown in **Table 5-6**.

Table 5-6: Physical and chemical characterisation, labelling requirements and limit values for Manganese [JRC 2009, Wikipedia 2009Q, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name			Manganese
Symbol			Mn
Atomic Number			25
Element category			tranistion metals
Appearance			silvery metallic
Standard atomic weight in g/mol			54.938
Density (at room temperature) in g/cm³			7.43
Melting point in °C			1,536
Boiling point in °C			2,062
Mohs hardness			6
Standard voltage at pH=0 in V			-1.05
Mass share of earth crust in %			0.09
CAS registry number			7439-96-5
Labelling requirements according to Directive 1967/548/EEC	Labels		F (powder)
	R-phrases		R: 11 (powder**)**
	S-phrases		S: 7-33-43-60(powder)
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H332 H302
OSHA permissible exposure limits (PEL)	8-hour average in mg/m³	total particulate	5
Austrian Grenzwerteverordnung	MAK-value	Daily average in mg/m³	0.5 (respirable particulate)
		Limit for short term exposure in mg/m³	2 (respirable particulate)
		Duration of short term exposure in min	15
		Frequency of short term exposure per shift	4

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;

For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration; TRK-value = technical compliance concentration.

Health Effects

Manganese(II) ions function as cofactors for a number of enzymes in higher organisms, where they are essential in detoxification of superoxide free radicals. The element is a required trace mineral for all known living organisms. In larger amounts, and apparently with far greater activity by inhalation, manganese can cause a poisoning syndrome in mammals, with neurological damage which is sometimes irreversible [Wikipedia 2009Q].

Symptoms of manganese poisoning range from sleepiness and weakness in the legs to difficulty in walking and uncontrolled laughter. Health surveys of employees exposed to manganese fume have demonstrated a high incidence of pneumonia in these workers [NIOSH 2009].

Under [DIR 67/548/EEC] only the powder of the manganese metal is classified as:

- F – flammable: R11 - Highly flammable [Wikipedia 2009R].

According to [Regulation (EC) No 1272/2008] manganese is classified as:

- H302 | 3.1— Acute toxicity (oral), Hazard Category 4 | Harmful if swallowed. |
- H332 | 3.1— Acute toxicity (inhalation), Hazard Category 4 | Harmful if inhaled. |

Recycling

Manganese is recycled incidentally as a minor constituent of ferrous and non-ferrous scrap; however, scrap recovery specifically for manganese was negligible. Manganese is recovered along with iron from steel slag [USGS 2009].

5.3.5 Nickel

Nickel is used in all 3 battery types, most in NiMH, somewhat less in NiCd and least in Li-ion batteries.

Nickel is a silvery-white lustrous metal with a slight golden tinge. The metal is hard and ductile, as well as corrosion-resistant, finding many uses in alloys, as a plating, in the manufacture of coins, magnets and common household utensils, as a catalyst for hydrogenation, and in a variety of other applications. Enzymes of certain life-forms contain nickel as an active center making the metal essential for them [Wikipedia 2009S].

Physical and chemical properties as well as risk and safety classification are shown in Table 5-7.

Table 5-7: Physical and chemical characterisation, labelling requirements and limit values for Nickel [JRC 2009, Wikipedia 2009S, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name		Nickel
Symbol		Ni
Atomic Number		28
Element category		tranistion metals
Appearance		lustrous, metallic and silvery with a gold tinge
Standard atomic weight in g/mol		58.7
Density (at room temperature) in g/cm³		8.9
Melting point in °C		1,453
Boiling point in °C		2,914
Mohs hardness		3.8
Standard voltage at pH=0 in V		-0.250
Mass share of earth crust in %		0.01
CAS registry number		7440-02-0
Labelling requirements according to Directive 1967/548/EEC	Labels	T (powder)
	R-phrases	R: 40-43-48/23-52/53
	S-phrases	S: (2)-36/37/39-45-61
Labelling requirements according to Regulation	H-codes	H351-H317

(EC) No 1272/2008			
OSHA permissible exposure limits (PEL)	8-hour average in mg/m^3	total particulate	1
Austrian Grenzwerteverordnung	TRK-value	Daily average in mg/m^3	0.5 (respirable particulate)
		15 min average in mg/m^3	2 (respirable particulate)
	List of carcinogenic substances	A1 - Substances which cause tumors with humans	Nickel
		A2 Substances which cause tumors with animals	Nickeltetracarbonyl

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;

For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration; TRK-value = technical compliance concentration.

Health Effects

Nickel is an essential substance for many organisms. It is unclear if this applies also for the human body. In high doses nickel may cause different diseases.

A variety of toxic effects results from exposure to nickel compounds. Soluble nickel salts cause contact dermatitis in sensitized individuals and eye irritation. Cases of asthmatic lung disease have been reported among nickel-plating workers [DFG 2004].

Exposure to soluble nickel at low levels and for relatively short durations causes pathological changes in the lungs of experimental animals. The results of animal studies suggest that some soluble nickel compounds are potentially carcinogenic [NIOSH 2009]. Especially highly soluble nickel compounds such as nickel acetate and nickel sulfids are suspected to be carcinogenic.

Under [DIR 67/548/EEC] nickel is classified as:

- Carcinigenic category 3: R40 - Limited evidence of a carcinogenic effect
- Toxic: R48/23 - Toxic: danger of serious damage to health by prolonged exposure through inhalation;
- R43 - May cause sensitisation by skin contact [JRC 2009].

According to [Regulation (EC) No 1272/2008] nickel is classified as:

- H317 | 3.4— Sensitisation — Skin, Hazard Category 1 | May cause an allergic skin reaction. |
- H351 | 3.6— Carcinogenicity, Hazard Category 2 | Suspected of causing cancer. |

Exploitation

The bulk of the nickel mined comes from two types of ore deposits. The first are laterites where the principal ore minerals are nickeliferous limonite: (Fe, Ni)O(OH) and garnierite (a hydrous nickel silicate): $(Ni, Mg)_3Si_2O_5(OH)$. The second are magmatic sulfide deposits where the principal ore mineral is pentlandite: $(Ni, Fe)_9S_8$.

In terms of supply, the Sudbury region of Ontario, Canada, produces about 30 % of the world's supply of nickel. Russia contains about 40% of the world's known resources at the Norilsk deposit in Siberia. The Russian mining company MMC Norilsk Nickel obtains the nickel and the associated palladium for world distribution. Other major deposits of nickel are found in New Caledonia, France, Australia, Cuba, and Indonesia. Recently, a nickel deposit in western Turkey had been exploited, with this location being especially convenient for European smelters, steelmakers and factories [Wikipedia 2009S].

Recycling

About 77,300 tonnes of nickel was recovered in the US from purchased scrap in 2008. This represented about 38% of reported secondary plus apparent primary consumption for the year [USGS 2009].

5.3.6 Rare Earth Metals - Lanthanoides

Rare-earth metals are used in form of “mischmetal” in NiMH batteries (see Table 4-10).

According to IUPAC[28], rare-earth elements or rare earth metals are a collection of seventeen chemical elements in the periodic table, namely scandium, yttrium, and the fifteen lanthanoids. Cerium is the most abundant of the rare-earth elements and with 68 ppm in Earth’s crust is even more abundant than lead. Cerium is a silvery metal. It resembles iron in color and luster, but is soft, and both malleable and ductile. Cerium has the longest liquid range of any non-radioactive element: 2648 C° (795 °C to 3443 °C) [Wikipedia 2009T].

Physical and chemical properties as well as risk and safety classification of cerium are shown in Table 5-8.

Table 5-8: Physical and chemical characterisation and labelling requirements for Cerium [Wikipedia 2009T,U, NIOSH 2009]

Name	Cerium
Symbol	Ce
Atomic Number	58
Element category	lanthanides
Appearance	silvery white
Standard atomic weight in g/mol	140.12
Density (at room temperature) in g/cm³	6.78
Melting point in °C	798
Boiling point in °C	3,426

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[28] IUAPC = International Union of Pure and Applied Chemistry

Mohs hardness		2.5
Mass share of earth crust in %		0.0046
CAS registry number		7440-45-1
Labelling requirements according to Directive 1967/548/EEC	Labels	F
	R-phrases	R: 11
	S-phrases	S: 17
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	cerium oxide isostearate: H413
Note: Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant; For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively.		

Health Effects

Cerium, like all rare-earth metals, is of low to moderate toxicity. Cerium is a strong reducing agent and ignites spontaneously in air at 65 to 80 °C. Fumes from cerium fires are toxic. Water should not be used to stop cerium fires, as cerium reacts with water to produce hydrogen gas. Workers exposed to cerium have experienced itching, sensitivity to heat, and skin lesions. Animals injected with large doses of cerium have died due to cardiovascular collapse.

Solid cerium can ignite already at 65 °C and therefore under [DIR 67/548/EEC] is classified as:

- F: R11 - Highly flammable [Wikipedia 2009U]

According to [Regulation (EC) No 1272/2008] cerium oxide isostearate is classified as

- H413 | 4.1— Hazardous to the aquatic environment — Chronic Hazard, Category 4 | May cause long lasting harmful effects to aquatic life. |

Exploitation

Rare earths are relatively abundant in the Earth’s crust, but discovered minable concentrations are less common than for most other ores. U.S. and world resources are contained primarily in bastnäsite and monazite. Bastnäsite deposits in China and the United States constitute the largest percentage of the world’s rare-earth economic resources, while monazite deposits in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the United States constitute the second largest segment [USGS 2009].

A few sites are under development outside of China, the most significant of which are the Nolans Project in Central Australia, the remote Hoidas Lake project in northern Canada and the Mt. Weld project in Australia. The Hoidas Lake project has the potential to supply about 10% of the $1 billion of rare earth consumption that occurs in North America every year

Large deposits of monazite, allanite, and bastnäsite will supply cerium, thorium, and other rare-earth metals for many years to come [Wikipedia 2009U].

Neodyme seems to be the metal which controlled the mining of rare earth minerals (bastnäsite). The concentrations of the rare earths in bastnäsite, however, do not comply with their commercial demand. Thus 25 % of the rare earths produced remain unused [Angerer et al. 2009].

Recycling

Small quantities of rare-earth metals, mostly from permanent magnet scrap, are recycled [USGS 2009].

5.3.7 Carbon/Graphite

Carbon/graphite is used in Li-ion batteries (see Table 4-13).

The mineral graphite is one of the allotropes of carbon. HOPG (Highly Ordered Pyrolytic Graphite) is an artificial form used in research. Thin graphite flakes are flexible but inelastic, the mineral can leave black marks on hands and paper, it conducts electricity, and displays superlubricity. Its best field indicators are softness, luster, density and streak [Wikipedia 2009V].

Physical and chemical properties as well as risk and safety classification of carbon and graphite are shown in Table 5-9.

Table 5-9: Physical and chemical characterisation, labelling requirements and limit values for Carbon and Graphite [Wikipedia 2009V, NIOSH 2009, Grenzwerteverordnung]

Name			Carbon	Graphite
Symbol			C	
Atomic Number			6	
Element category			nonmetals	nonmetals
Appearance			Black (Graphite), Clear (Diamond	black
Standard atomic weight in g/mol			12.011	
Density (at room temperature) in g/cm^3			2.62	2.2
Melting point in °C			3,827	
Boiling point in °C			4,197	
Mohs hardness			0.5-10	1-2
Mass share of earth crust in %			0.09	
CAS registry number			7440-44-0	7782-42-5
OSHA permissible exposure limits (PEL)	8-hour average in mg/m^3	total particulate		15
		respirable particulate		5
Note: OSHA = U.S. Occupational Safety and Health Administration.				

Health Effects

Early reports established that graphite deposited in the lungs of occupationally exposed workers caused pneumoconiosis. Subsequent research described the condition produced by exposure to graphite as anthracosilicosis, a pulmonary condition similar to that seen in coal miners, based on radiographic and histologic examinations in exposed individuals. The fibrotic changes seen in graphite workers appear to be related to the silica content of the graphite [Niosh 2009].

Carbon and graphite are not classified in [DIR 67/548/EEC][29].

Environmental Effects

Environmental impacts from graphite mills consist of air pollution including fine particulate exposure of workers and also soil contamination from powder spillages leading to heavy metals contaminations of soil. Dust masks are normally worn by workers during the production process to avoid worker exposure to the fine airborne graphite and zircon silicate [Wikipedia 2009V].

Exploitation

China is usually the top producer of graphite, followed by India and Brazil.

Graphite is mined around the world by both open pit and underground methods. While flake graphite and amorphous graphite are both mined open pit and underground, lump (vein) graphite is only mined underground in Sri Lanka. The open pit mines usually employ equipment (i.e. bulldozers) to scoop up the ore, which is usually put in trucks and moved to the plant. Since the original rock is usually lateritized or weathered, this amounts to moving dirt with flecks or pieces of graphite in it from the pit (blasting is seldom required). The underground graphite mines employ drilling and blasting to break up the hard rock (ore), which is then moved by mine cars pulled by a locomotive, or moved by automotive vehicles, to the surface and then to the plant. In less-developed areas of the world, the ore can be mined by pick and shovel and transported by mine cars pushed by a laborer or by women carrying baskets of ore on their heads [Wikipedia 2009V].

Recycling

Refractory brick and linings, alumina-graphite refractories for continuous metal castings, magnesia graphite refractory brick for basic oxygen and electric arc furnaces, and insulation brick led the way in recycling of graphite products. The market for recycled refractory graphite material is growing with material being recycled into products such as brake linings and thermal insulation.

Recovering high-quality flake graphite from steelmaking kish is technically feasible, but not practiced at the present time. The abundance of graphite in the world market inhibits increased recycling efforts. Information on the quantity and value of recycled graphite is not available (USGS 2009).

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[29] Carbon and graphite are not classified as being hazardous.

5.3.8 Alkali

In NiCd- and NiMH batteries aqueous alkali solutions are used as electrolyte. Potassium-hydroxide (KOH) is a representative alkali-material. Its properties of shall be shown hear. Physical and chemical properties as well as risk and safety classification of potassium-hydroxide are shown in Table 5-10.

Table 5-10: Physical and chemical characterisation and labelling requirements for potassium-hydroxide [Wikipedia 2009W]

Name		Potassium hydroxide
Symbol		KOH
Standard atomic weight in g/mol		56.11
Density (at room temperature) in g/cm^3		2.044
Melting point in °C		420
Boiling point in °C		1327
Solubility in water in g/100 ml (25 °C)		110
Acidity – pKa of 0.1 molar solution		13.5
CAS registry number		1310-58-3
Labelling requirements according to Directive 1967/548/EEC	Labels	C, Xn
	R-phrases	R22, R35
	S-phrases	(S1/2), S26, S36/37/39, S45
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	H302, H314
Note: Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant; For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively.		

Health Effects

Under [DIR 67/548/EEC] potassium hydroxide is classified as

- Xn: R22 - Harmful if swallowed
- C – corrosive: R35 - Causes severe burns

According to [Regulation (EC) No 1272/2008] potassium hydroxide is classified as

- H302 | 3.1— Acute toxicity (oral), Hazard Category 4 | Harmful if swallowed. |
- H314 | 3.2— Skin corrosion/irritation, Hazard Category 1A, 1B, 1C | Causes severe skin burns and eye damage. |

Exploitation

Potassium-hydroxide (KOH) is produced by the electrolysis of potassium chloride solutions:

$$2\,\mathrm{KCl} + 2\,\mathrm{H_2O} \rightarrow 2\,\mathrm{KOH} + \mathrm{Cl_2} + \mathrm{H_2}$$

Potassium-chloride occurs naturally as sylvite, and it can be extracted from sylvinite. It is also extracted from salt water and can be manufactured by crystallization from solution, flotation or electrostatic separation from suitable minerals. It is a by-product of the making of nitric acid from potassium nitrate and hydrochloric acid [Wikipedia 2009W].

5.3.9 Lithium hexafluorophospate

Lithium hexafluorophosphate is used as electrolyte in Li-ion batteries (see Table 4-13).

Lithium hexafluorophosphate ($LiPF_6$) is an inorganic chemical compound. It is a white crystalline powder that hydrolyzes readily in contact with water or moisture and then can form hydrofluoric acid (HF).

Lithium hexafluorophosphate can be dissolved in some organic solvents, eg. propylene carbonate with dimethoxyethane, for use as an electrolyte in lithium batteries [Wikipedia 2009X].

Physical and chemical properties as well as risk and safety classification of $LiPF_6$ are shown in Table 5-11.

Table 5-11: Physical and chemical characterisation and labelling requirements for $LiPF_6$ [Wikipedia 2009X]

Name		Lithium hexafluorophosphate
Symbol		$LiPF_6$
Standard atomic weight in g/mol		151.9
Density (at room temperature) in g/cm³		1.5
Melting point in °C		200
Boiling point in °C		Not applicable
Solubility in water in g/100 ml (25 °C)		soluble
CAS registry number		21324-40-3
Labelling requirements according to Directive 1967/548/EEC	Labels	C
	R-phrases	R20/R21/R22, R34
	S-phrases	?
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	Not listed
Note: Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant; For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively.		

Health Effects

Lithium hexafluorophosphate is very destructive to mucous membranes. Harmful if swallowed, inhaled, or absorbed through skin [Wikipedia 2009X].

Lithium hexfluorophosphate is classified by [DIR 1967/548/EEC] as:

- C - corrosive: R20/R21/R22 Harmful by inhalation, in contact with skin and if swallowed; R34 Causes burns - Very destructive of mucous membranes [Lebensministerium 2007].

Lithium-hexfluorophosphate seems not to be classified under [Regulation (EC) No 1272/2008]. Following classifications of chemically similar compounds, however, may give an impression of its potential health impacts:

- sodium fluoride:
  - H301 | 3.1 —Acute toxicity (oral), Hazard Category 3 | Toxic if swallowed. |
  - H315 | 3.2— Skin corrosion/irritation, Hazard Category 2 | Causes skin irritation. |
  - H319 | 3.3— Serious eye damage/eye irritation, Hazard Category 2 | Causes serious eye irritation. |
- alkali fluorosilicates:
  - H301 | 3.1 —Acute toxicity (oral), Hazard Category 3 | Toxic if swallowed. |
  - H311 | 3.1— Acute toxicity (dermal), Hazard Category 3 | Toxic in contact with skin. |
  - H331 | 3.1— Acute toxicity (inhalation), Hazard Category 3 | Toxic if inhaled. |
- (η-cyclopentadienyl)(η-cumenyl)iron(1+)hexafluorophosphate(1-):
  - H412 | 4.1— Hazardous to the aquatic environment — Chronic Hazard, Category 3 | Harmful to aquatic life with long lasting effects. |

5.3.10 Fluorine and Fluorides

The assessment of lithium hexafluorophosphate ($LiPF_6$) would be incomplete without an assessment of its major component fluorine. Lithium hexafluorophosphate is by 75 % made of fluorine (F) or fluoride (F^-).

Fluorine is a supremely reactive, poisonous, pale, yellowish brown gas. Elemental fluorine is the most chemically reactive and electronegative of all the elements. In moist air fluorine reacts with water to form the also dangerous hydrofluoric acid.

Hydrogen fluoride is a weak acid when dissolved in water, but is still very corrosive and attacks glass. Consequently, fluorides of alkali metals produce basic solutions. For example, a 1 M solution of NaF in water has a pH of 8.59 [Wikipedia 2009W].

Fluorides are compounds that combine fluorine with some positively charged counterpart. They often consist of crystalline ionic salts. Fluorine compounds with metals are among the most stable of salts. Fluorine-containing compounds range from potent toxins such as sarin to life-saving pharmaceuticals such as efavirenz and from refractory materials such as calcium fluoride to the highly reactive sulfur tetrafluoride. The range of fluorine-containing compounds is considerable as fluorine is capable of forming compounds with all the elements except helium and neon [Wikipedia 2009Z].

Lithium fluoride is a chemical compound of lithium and fluorine. It is a white, inorganic, crystalline, ionic, solid salt under standard conditions [Wikipedia 2009z1].

Physico-chemical properties and classifications of fluorine, hydrogen fluoride and lithium fluoride are shown in Table 5-12.

Table 5-12: Physical and chemical characterisation, labelling requirements and limit values for Lithium Fluoride [Wikipedia 2009Y, Z, z1,z2, NIOSH 2009, Grenzwerteverordnung 2006]

Name			Fluorine	Hydrogen Fluoride	Lithium Fluoride
Symbol			F, F_2	HF	LiF
Atomic Number			9		
Element category			halogen		salt
Appearance			yellowish brown gas	Colourless gas	colourless to white solid
Standard atomic weight in g/mol			18.998	20.006	25.94
Density (at room temperature) in g/cm^3			0.0017	0.00115	2.64
Melting point in °C			-219.62	-83	870
Boiling point in °C			-188.12	19.5	1676
Solubility in water in g/l at 20 °C				miscible	2.7
CAS registry number			7782-41-4	7664-39-3	7789-24-4
Labelling requirements according to Directive 1967/548/EEC	Labels		O, C, T+	T+, C	T
	R-phrases		R8, R26, R35	R26/27/28-R35	R25-R36/37/38
	S-phrases		S1/S2-S9-S26-S28-S36/37/39-S45	S1/S2-S7/9-S26-S36/37/39-S45	S20-S26-S36/37-S45
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H270 H330 H314	H330 H310 H300 H314	
OSHA permissible exposure limits (PEL)		in mg/m^3	0.1	3 (8-hour average)	Not defined
Austrian Grenzwerteverordnung	MAK-value	Daily average in mg/m^3	0.2	1.5	2.5 (breathable fraction)
		Limit for short term exposure in mg/m^3	0.4	2.5	12.5 (breathable fraction)
		Duration of short term exposure in min	5	15	30
		Frequency of short term exposure per shift	8	4	2

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;
For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively
OSHA = U.S. Occupational Safety and Health Administration, MAK-value = maximum working place concentration TRK-value = technical compliance concentration.

Health Effects

Though F_2 (fluorine gas) is too reactive to have any natural biological role, fluorine is incorporated into compounds with biological activity. Naturally occurring organofluorine compounds are rare, the most notable example is fluoroacetate, which functions as a plant defence against herbivores in at least 40 plants

Fluorine is not an essential nutrient, but its importance in preventing tooth decay is well-recognized [Wikipedia 2009Y].

Elemental fluorine (fluorine gas) is a highly toxic, corrosive oxidant, which can cause ignition of organic material. Fluorine gas has a characteristic pungent odor that is detectable in concentrations as low as 20 µg/kg [Wikipedia 2009Y].

Upon contact with moisture, including tissue, hydrogen fluoride immediately converts to hydrofluoric acid, which is highly corrosive and toxic, and requires immediate medical attention. Hydrogen fluoride and hydrofluoric acid are dangerous, because undissociated molecular HF penetrates the skin and biological membranes, causing deep and painless burns. The free fluoride, once released from HF in dissociation, also is capable of chelating calcium ion to the point of causing death by cardiac dysrhythmia. Burns with areas larger than 160 cm^2 have the potential to cause serious systemic toxicity [Wikipedia 2009Z,z2].

In high concentrations, soluble fluoride salts are toxic and skin or eye contact with high concentrations of many fluoride salts is dangerous. Referring to a common salt of fluoride, sodium fluoride (NaF), the lethal dose for most adult humans is estimated at 1–10 grams (5 mg of fluoride per kg of bodyweight). Ingestion of fluoride can produce gastrointestinal discomfort at doses at least 15 to 20 times lower (0.2–0.3 mg/kg) than lethal doses.

Like most soluble materials, fluoride compounds are readily absorbed by the intestines and excreted through the urine. Trace amounts are incorporated in bone. Ingested fluoride initially acts locally on the intestinal mucosa, where it forms hydrofluoric acid in the stomach. Thereafter it binds calcium and interferes with various enzymes [Nochimson 2008].

The mechanism of toxicity involves the combination of the fluoride anion with the calcium ions in the blood to form insoluble calcium fluoride, resulting in hypocalcemia; calcium is indispensable for the function of the nervous system, and the condition can be fatal.

Consumption of fluoride for a long period of time causes skeletal fluorosis. In some areas, particularly the Asian subcontinent, skeletal fluorosis is endemic. It is known to cause irritable-bowel symptoms and joint pain [Wikipedia 2009Z].

A few organofluorine compounds are extremely toxic, such as organophosphates like sarin and diisopropylfluorophosphate that react with the cholinesterase enzyme at neuromuscular junctions and thus block the transmission of nerve impulses to the muscles. Here, a reactive fluorine-phosphorus bond in the inhibitor is the site of nucleophilic attack by a serine residue in the enzyme's active site, causing the loss of a F^- ion and alkylation and inactivation of the enzyme [Wikipedia 2009Z].

Fluorine under {DIR 67/548/EEC] is classified as:

- O – oxidising: R8 - Contact with combustible material may cause fire
- T+ -very toxic: R26 – Very toxic by inhalation
- C – corrosive: R35 - Causes severe burns [JRC 2009]

According to [Regulation (EC) No 1272/2008] fluorine is classified as

- H270 | 2.4 —Oxidising Gases, Hazard Category 1 | May cause or intensify fire; oxidiser.
- H314 | 3.2— Skin corrosion/irritation, Hazard Category 1A, 1B, 1C | Causes severe skin burns and eye damage. |
- H330 | 3.1— Acute toxicity (inhalation), Hazard Category 1, 2 | Fatal if inhaled. |

Hydrogen fluoride under [DIR 67/548/EEC] is classified as:

- T+ -very toxic: R26/27/28: Very toxic by inhalation, in contact with skin and if swallowed
- C – corrosive: R35 - Causes severe burns [JRC 2009]

According to [Regulation (EC) No 1272/2008] hydrogen fluoride is classified as

- H330 | 3.1— Acute toxicity (inhalation), Hazard Category 1, 2 | Fatal if inhaled. |
- H310 | 3.1— Acute toxicity (dermal), Hazard Category 1, 2 | Fatal in contact with skin. |
- H300 | 3.1 —Acute toxicity (oral), Hazard Category 1, 2 | Fatal if swallowed. |
- H314 | 3.2— Skin corrosion/irritation, Hazard Category 1A, 1B, 1C | Causes severe skin burns and eye damage. |

Lithium fluoride under {DIR 67/548/EEC] is classified as:

- T - toxic: R25: Toxic if swallowed;
- R36/37/38: Irritating to eyes, respiratory system and skin [Wikipedia 2009z1].

Environmental Effects

Historically, most cases of fluoride poisoning have been caused by accidental ingestion of insecticides or rodenticides (e.g. sodium fluoroacetate[30]) containing fluoride. Currently most cases are due to the ingestion of toothpaste. Other sources include glass-etching or chrome-cleaning agents like ammonium bifluoride, industrial exposure to fluxes used to promote the flow of a molten metal on a

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[30] See http://en.wikipedia.org/wiki/Fluoride_poisoning - cite_note-5

solid surface, volcanic ejecta, for example in cattle grazing after a 1845–1846 eruption of Hekla, and the 1783–1784 flood basalt eruption of Laki, and metal cleaners. Malfunction of water fluoridation equipment has happened several times, including a notable incident in Alaska.

Exploitation

Industrial production of fluorine entails the electrolysis of hydrogen fluoride (HF) in the presence of potassium fluoride. The HF required for the electrolysis is obtained as a by-product of the production of phosphoric acid. Phosphate-containing minerals contain significant amounts of calcium fluorides, such as fluorite (see chapter 8.8 in Annex A). Upon treatment with sulfuric acid, these minerals release hydrogen fluoride:

$$CaF_2 + H_2SO_4 \rightarrow 2\ HF + CaSO_4$$

5.3.11 Poly(vinylidene fluoride) (PVDF)

Poly(vinylidene fluoride) is used in Li-ion batteries as polymere-electrolyte (see Table 4-13.

Poly(vinylidene fluoride) or PVDF is a highly non-reactive and pure thermoplastic fluoropolymer. Its CAS-number is 24937-79-9. It is a whitish or translucent solid with the molecular formular $-(C_2H_2F_2)_n-$. It is not soluble in water.

PVDF is a specialty plastic material in the fluoropolymer family; it is used generally in applications requiring the highest purity, strength, and resistance to solvents, acids, bases and heat and low smoke generation during a fire event. Compared to other fluoropolymers, it has an easier melt process because of its relatively low melting point of around 177°C.

It has a low density (1.78) and low cost compared to the other fluoropolymers. It is available as piping products, sheet, tubing, films, plate and an insulator for premium wire. It can be injected, molded or welded and is commonly used in the chemical, semiconductor, medical and defense industries, as well as in Li-ion batteries [Wikipedia 2009z3].

Processing

PVDF may be synthesized from the gaseous vinylidene fluoride monomer via a free radical (or controlled radical) polymerization process. This may be followed by processes such as melt casting, or processing from a solution (e.g. solution casting, spin coating, and film casting).

In the case of solution-based processing, typical solvents used include dimethylformamide as well as the more volatile methyl-ethyl-ketone. In aqueous emulsion polymerization, the fluorosurfactant perfluorononanoic acid is used in anion form as a processing aid by solubilizing monomers [Wikipedia 2009z3].

5.3.12 *Carbonate esters*

Carbonate esters are used as solvents in Li-ion batteries (see Table 4-13).

The aprotic solvents dietyhl carbonate (DEC), ethylene carbonate (EC) and methyl ethyl carbonate (MEC) used in Li-ion batteries belong to the chemical group of Carbonate esters. Figure 5-2 shows the chemical structure of this type of compounds.

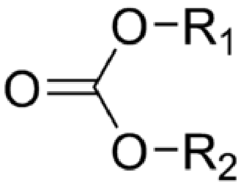

Figure 5-2 : Chemical structure of the carbonate ester group [Wikipedia 2009z4].

The simplest carbonate ester is dimethyl carbonate (DMC). It is a flammable clear liquid boiling at 90 °C. It has recently found use as a methylating reagent. Its main benefit over other methylating reagents such as iodomethane and dimethyl sulfate is its lesser toxicity and its biodegradability [Wikipedia 2009z4]. The physical-chemical properties and labeling requirements of dimethyl carbonate are shown in Table 5-13.

Table 5-13: Physical and chemical characterisation and labelling requirements for dimethyl carbonate [Wikipedia 2009z4, JRC 2009]

Name		Dimethyl carbonate
Symbol		CH_3-O-CO-O-CH_3
Standard atomic weight in g/mol		90.08
Appearance		Clear liquid
Density (at room temperature) in g/cm³		1.07
Melting point in °C		3
Boiling point in °C		90
Solubility in water in g/100 ml (25 °C)		13.9
CAS registry number		616-38-6
Labelling requirements according to Directive 1967/548/EEC	Labels	F+
	R-phrases	R11
	S-phrases	S2-S9-S16
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	H225
Note: Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant; For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively.		

A solvent actually used in Li-ion batteries is ethylene carbonate. Its structure is shown in Figure 5-3.

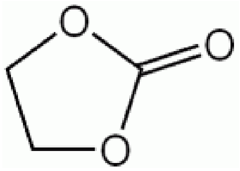

Figure 5-3 : Chemical structure of ethylene carbonate [Wikipedia 2009z5].

Ethylene carbonate at room temperature is a solid. It is watersoluble, has a flashpoint of 150 °C and an autoignition point of 465 °C [Wikipedia 2009z5]. Therefore it is not as flammable as other carbonate esters.

The physical-chemical properties and labeling requirements of ethylene carbonate are shown in Table 5-14.

Table 5-14: Physical and chemical characterisation and labelling requirements for ethylene carbonate [Wikipedia 2009z5]

Name		Ethylene carbonate
Symbol		-(O-CO-O-CH_2-CH_2)-
Standard atomic weight in g/mol		88.06
Appearance		White to yellow solid
Density (at room temperature) in g/cm³		1.321
Melting point in °C		34-37
Boiling point in °C		260.7
Solubility in water in g/100 ml (25 °C)		soluble
CAS registry number		96-49-1
Labelling requirements according to directive 1967/548/EEC	Labels	Xi
	R-phrases	R41
	S-phrases	S26-S39
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	Not established
Note: Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant; For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively.		

Health Effects

Dimethyl carbonate in Germany is classified as Water Pollutant Class Germany 1 [Lebensministerium 2007] andunder [DIR 67/548/EEC] as:

- F - flammable: R11 - Highly flammable [JRC 2009].

According to [Regulation (EC) No 1272/2008] dimethyl carbonate is classified as:

- H225 | 2.6 —Flammable liquids, Hazard Category 2 | Highly flammable liquid and vapour. |

Ethylene carbonate (1,3-Dioxolan-2-one: CAS 96-49-1) is hazardous in case of skin contact (irritant), slightly hazardous in case of ingestion, of inhalation (lung irritant), non-hazardous in case of inhalation.

Ethylene carbonate under Directive 67/548/EEC is classified as:

- Xi - irritant: R41 - Risk of serious damage to eyes [Wikipedia 2009z5] and R 36/37/38 - Irritating to eyes, respiratory system and skin [Lebensministerium 2007].

Propylene Carbonate (synonyms: carbonic acid cyclic methylethylene ester, carbonic acid propylene ester, cyclic 1,2-propylene carbonate - CAS No: 108-32-7) is classified as:

- Xi, Irritant. May be harmful by inhalation, ingestion or skin contact. Risk phrases - R36 (limit for irritant: 20%) [Lebensministerium 2007].

Production and Environmental Effects

Dimethyl carbonate is now prepared from catalytic oxidative carbonylation of methanol with carbon monoxide and oxygen, instead of from phosgene making its production non-toxic and environmentally friendly [Wikipedia 2009z4].

5.4 Environmental Impacts related to the relevant Battery Technologies

5.4.1 NiCd batteries

As shown in Table 3-8 it is estimated that 240 million NiCd cells were sold in Europe for cordless power tool applications in the year 2008. With a mass of 55 g/cell [EPTA 2009] this gives a total mass of 13,200 tonnes of NiCd cells sold in 2008 for application in cordless power tools (CPT) in Europe.

Table 5-15 shows an estimation of the substance-flows caused by the total of all NiCd-cells sold for CPTs in 2008 in Europe and the effect on production and reserve depletion for the contained metals. It can be seen, that 10.6 % of the world 2008 cadmium production can be refered to the NiCd batteries for cordless power tools (CPT) in Europe. About 0.45 % of the world cadmium reserves were used for that end.

Smaller shares of 0.11 % and 0.16% of the world cobalt and the world nickel production respectively were also required. The effect of the NiCd batteries on world iron, manganese and zinc production and reserves is really small.

Table 5-15 : Materials contained in rechargeable NiCd batteries sold in Europe for CPTs in 2008 and effect on world metal production (Sources: composition = average from [EC 2003] and [ERM 2006]; production and reserves [USGS 2009])

	Assumed share in cell in %	Mass for all 2008 NiCd cells in t	% of year 2008 worldwide metal production	% of worldwide reserves
Cadmium (Cd)	16.7	2,200	10.6	0.45
Cobalt (Co)	0.6	79	0.11	0.0011
Iron (Fe) and steel	34.7	4,576	0.0004	0.00002
Manganese (Mn)	0.1	11	0.0001	0.000002
Nickel (Ni)	19.0	2,508	0.16	0.0036
Zinc (Zn)	0.1	8	0.0001	0.000004
Alkali (KOH)	2.0	264		
Plastics	10.0	1,320		
Water	5.0	660		
Other non metals	11.9	1,574		
Total	**100**	**13,200**		

Health Effects & Environmental Effects

From the materials contained in NiCd batteries the highest health and environmental risk emanates from cadmium as this metal

- is carcinogenic,

- mutagenic
- carries a possible risk of impaired fertility and possible risk of harm to the unborn child
- is very toxic by inhalation
- carries danger of serious damage to health by prolonged exposure through inhalation and if swallowed
- is very toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment [JRC 2009].

Due to its relatively low melting and boiling point, respectively, it can be easily released into the environment and may accumulate there.

The next most hazardous substance in is nickel:

- for carrying limited evidence of a carcinogenic effect
- and for being toxic showing danger of serious damage to health by prolonged exposure through inhalation [JRC 2009].

Other substances contained in NiCd batteries are hazardous to some degree:

- Cobalt is classified as harmful, it may cause sensitization by inhalation and skin contact, and it may cause long-term adverse effects in the aquatic environment [JRC 2009].
- Manganese is classified as being harmful when swallowed or inhaled [Regulation (EC) No 1272/2008].
- Alkali is corrosive, harmful if swallowed, and may cause severe burns [JRC 2009].

As NiCd-power packs are well protected, closed systems, in the use phase health and environmental risks occur only very rarely, that is when the power pack ruptures due to extreme mechanical wear, heat or an explosion of the gases produced during overcharge.

From the life-cycle perspective the phases with the highest health and environmental risks are:

- The mining phase (especially the mining of cadmium)
- The treatment of ores and production of metals phase
- The phase of waste collection
- The phase of waste treatment and recycling.

Separate collection of batteries

[DIR 2006/66/EC] requires from EU-Member States to introduce schemes for the separate collection of batteries. In Germany such schemes have been implemented since 1998. Figure 5-4 shows the tonnes of batteries which were sold in each year in Germany by NiCd-, NiMH- and Li-ion battery type for the period 2001 to 2008. While in recent years in Europe the NiCd batteries are almost exclusively used in CPTs, the sold NiMH and Li-ion batteries are used in many different applications. Figure 5-5 shows the tonnes of NiCd batteries collected each year in the German separate battery collection systems. When comparing Figure 5-5 with Figure 5-4 we have to take into account the residence time of NiCd batteries in the use phase. In Japan the average age of NiCd batteries returned to recycling plants is 7.3 years [Recharge 2009]. This very well corresponds to the 7 years of average life-time of NiCd cells estimated by [EPTA 2009 b]. Thus, when comparing the NiCd collection masses of 2007 and 2008 with the sales masses of 2001 and 2002 we get recycling rates of 38 to 44 %.

In 2002 [EC 2003] reported that 45.5% of the portable batteries sold in the EU-15 that year went to final disposal (incineration or landfill), instead of being collected and recycled.

It has to be concluded, that in spite of very well established and montiored separate collection systems such as in Germany, the majority of NiCd batteries and thus of the contained cadmium is collected with residual household waste and possibly other waste streams, and either incinerated in municipally solid waste incineration plants, mechanical-biological treatment plants, in plants of treating non-ferrous metals separated from residual waste or directly landfilled. Thus there is some likelihood that cadmium can dissipate uncontrolled into the environment during the waste-phase of NiCd batteries.

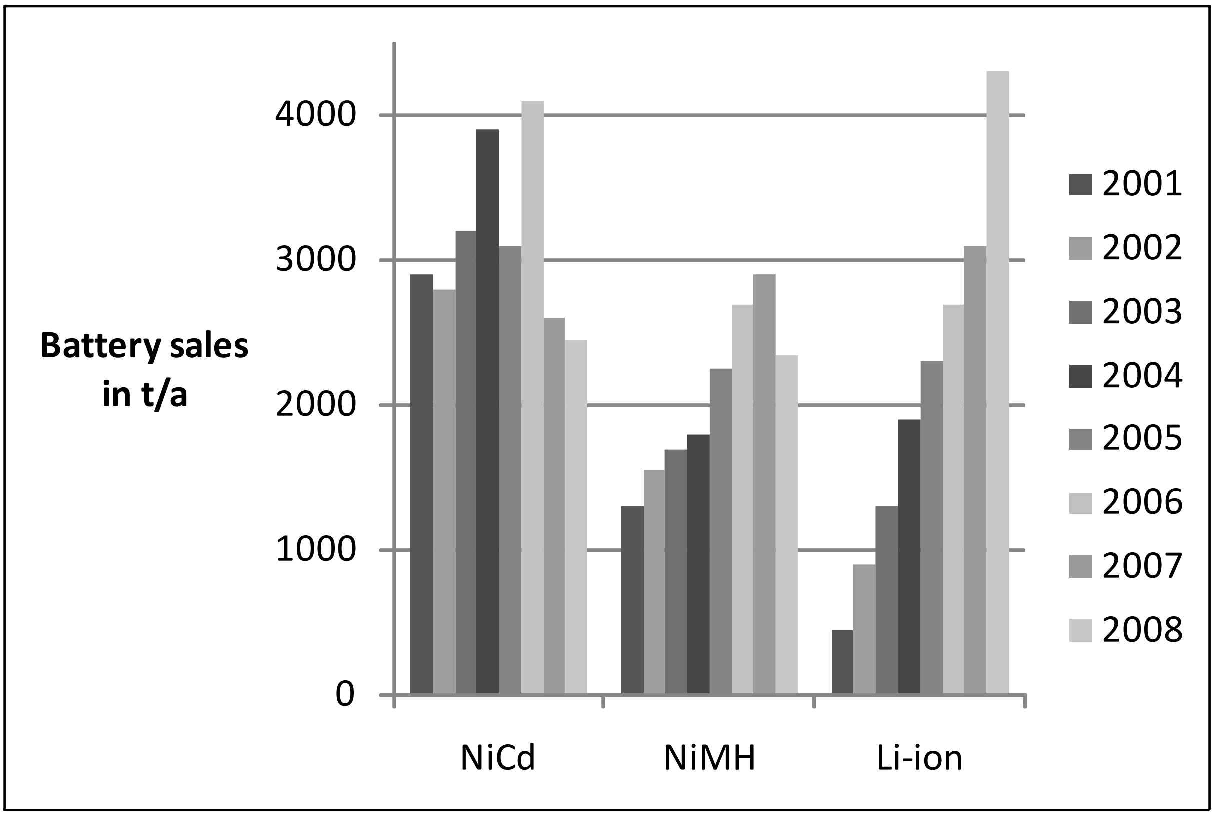

Figure 5-4 : Battery sales in Germany in tonnes/year [Recharge 2009]

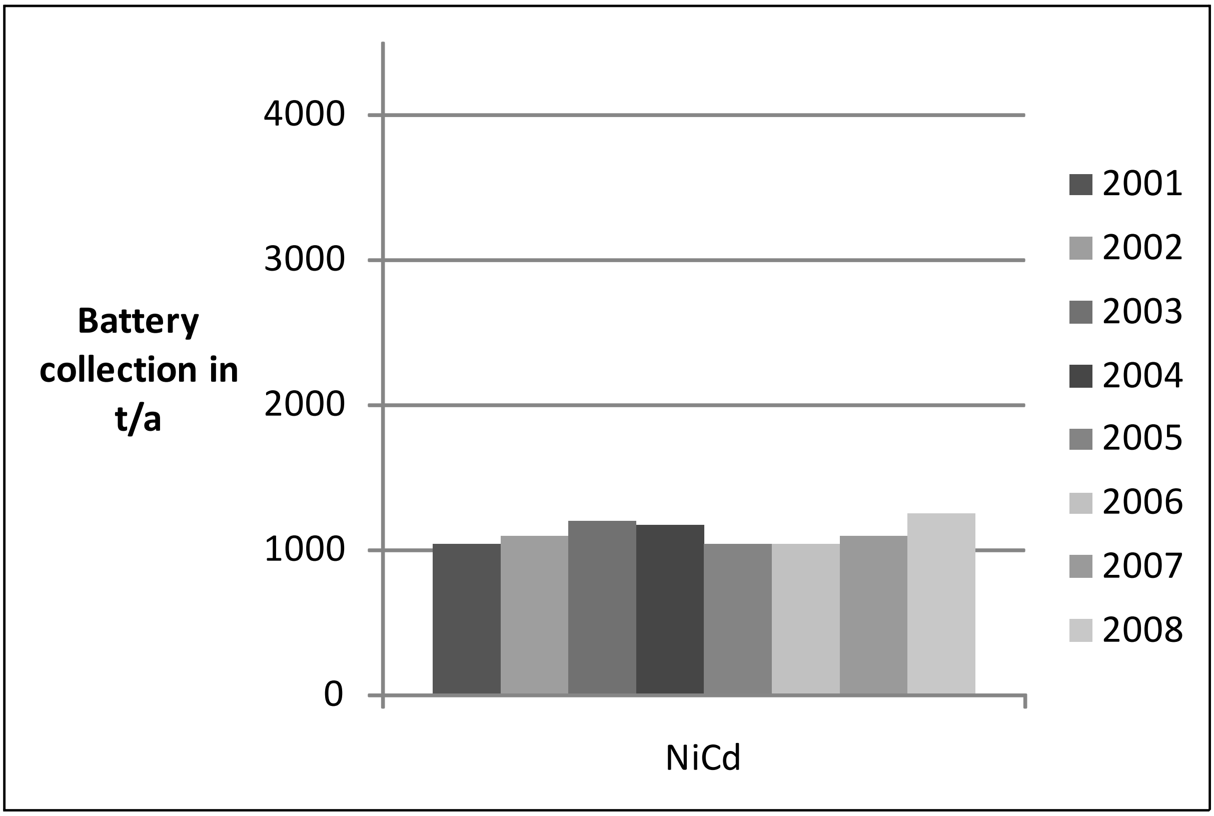

Figure 5-5 : Separate collection of NiCd batteries in Germany in tonnes/year [Recharge 2009]

NiCd-battery recycling

Ni-Cd batteries have been recycled for many years in Europe. The economics of the recycling (separate collection, treatment for recycling and selling the recovered materials) are known to vary between a net cost of € **minus** 500 / tonne, when the price of Nickel is in the range of € 10 /kg and a net revenue of € **plus** 500 / tonne, when the price of Nickel is of € 20 / kg. These net costs or revenues include the value of the recovered cadmium (0.5 to 2.0 €/kg) which is re-used in the production of new batteries [Recharge 2009b]. This means that the treatment costs[31] for NiCd-batteries amount to approximately € 3,000 / tonne[32].

Currently three European Companies (Accurec GmbH, DE; SAFT Group, FR; SNAM, FR) are recycling NiCd batteries (see [BiPRO et. al 2009] p. 48 and p. 172 and following).

One example the "Societe Nouvelle d' Affinage des Metaux" (SNAM) is a European company which treats NiCd and NiMH batteries for recycling. SNAM is a recycling company with facilities based in

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[31] The calculation is based on the information contained in [Recharge 2009b]. In the information source it is not specified what is exactly included in the calculation. The assumption of the project team is that the whole chain of recycling, i.e. collection, pre-treatment and the recycling process are included.

[32] The information given by [Recharge 2009b] significates that at a nickel price of 15 €/kg and a cadmium price of 1.25 €/kg the revenues from the sales of nickel and cadmium just cover the costs. With an average nickel contents of the NiCd-batteries of 190 kg per tonne of batteries (see Table 5-15) and an average cadmium content of 167 kg the revenues would be 15*190 + 1.25*167 = 3,058.78 € per tonne of battery. As a consequence this should be the costs for recycling one tonne of NiCd batteries.

Lyon and Viviez, France. The company processes portable and industrial NiCd and NiMH batteries, cadmium-containing waste (powders, slag, etc.) and other streams containing cadmium. The SNAM process is high temperature pyrometallurgical process [ERM 2006].

The SNAM pyrometallurgical process for the treatment of NiCd- and NiMH batteries

The SNAM process used to recycle NiCd and NiMH batteries are shown diagrammatically in Figure 5-6. Firstly, power packs are dismantled, separating the cells from the plastic cover. The cells are, together with other portable rechargeable batteries, transferred into a static pyrolysis reactor. At a temperature of 500˚C (at this temperature, no cadmium is released) the waste batteries are held in the reactor for 16 hours.

Traces of mercury, present as a consequence of incomplete sorting of the battery feedstock, evaporate in the pyrolysis reactor. Active carbon is used for its removal, and is the only additive to the process.

The treatment of NiMH batteries ends at this stage; the residues of ferronickel that are yielded are used in steel production.

The treatment of NiCd batteries involves an additional step. After pyrolysis, residues are placed in steel distillation ovens, which are tightly sealed off.

Each batch is electrically heated at 900˚C for 16 hours and is subsequently cooled for eight hours. At these temperatures, a combination of distillation of metallic cadmium and sublimation of cadmium-oxides and –hydroxides takes place. Cadmium is condensed from the gaseous phase and is further purified, by means of continuous distillation [ERM 2006].

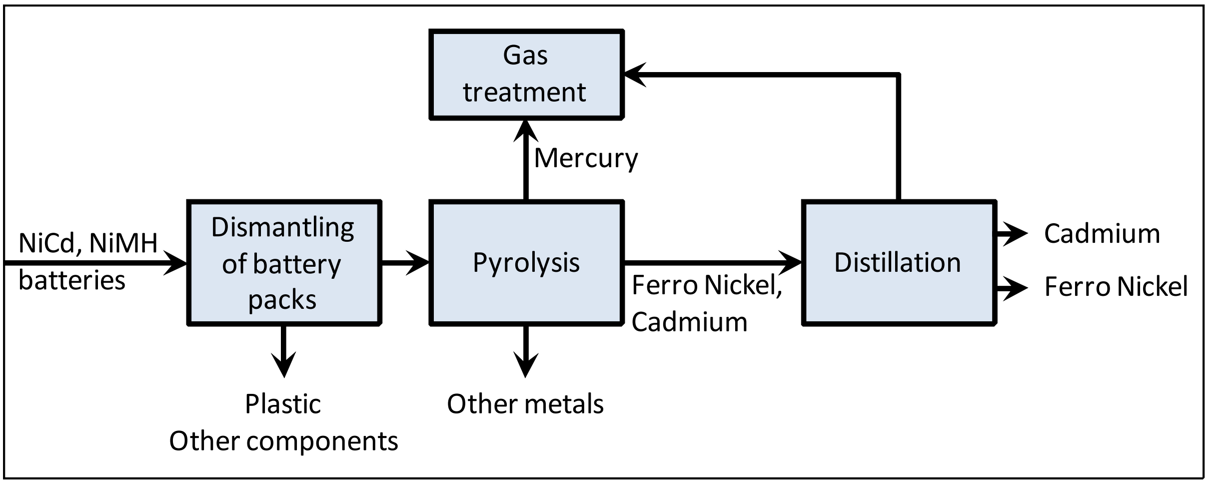

Figure 5-6 : SNAM Process for Recycling of NiCd and NiMH Batteries [ERM 2006]

A life-cycle analysis by [ERM 2006] for the waste collection, treatment and recycling phase of portable consumer batteries in the UK, stresses the potential of environmental impact reduction by proper waste treatment for recycling. Table 5-16 shows the environmental benefits (the reduced environmental impact) of the separate collection and treatment of portable consumer batteries over disposal/incineration of batteries as part of residual household waste. The value of the reduced environmental impact was estimated to be 84€ per tonne of battery waste.

It can be seen, that keeping batteries from becoming part of the residual household waste leads to substantial environmental benefits. These results, however, do not provide information if a high collection and recycling rate of NiCd batteries or a ban of NiCd batteries is the more efficient and effective instrument. Experience with existing battery recycling schemes [Recharge 2009] tells us, that in order to achieve the benefits shown in Table 5-16 both are necessary:

- A ban of the most hazardous substances and
- High battery collection and recycling rates.

Table 5-16 : Environmental benefits of separate battery collection and treatment as compared to 90 % landfilling and 10 % incineration of portable batteries [ERM 2006]

	Abiotic depletion in kg $Sb_{equivalent}$ / t battery waste arisings	Worldwide warming potential in kg $CO_{2,equivalent}$ / t battery waste arisings	Ozon layer depletion in kg CFC-$11_{equivalent}$ / t battery waste arisings	Human toxicity in kg 1,4-$Dichlorobenzene_{equivalent}$ / t battery waste arisings	Fresh water aquatic toxicity in kg 1,4-$Dichlorobenzene_{equivalent}$ / t battery waste arisings	Terrestrial toxicity in kg 1,4-$Dichlorobenzene_{equivalent}$ / t battery waste arisings	Acidification in kg $SO_{2,equivalent}$ / t battery waste arisings	Eutrophication in kg $PO_{4,equivalent}$ / t battery waste
Scenario: Separate kerbside collection of batteries + treatment for recycling	-3	-248	-0.04	-3,088	-3,588	-43	-3	-0.50

5.4.2 *NiMH batteries*

Table 5-17 gives an estimation of the mass of NiMH batteries which would be required to provide the same amount of lifetime energy as the 13,200 tonnes of NiCd batteries sold in Europe in 2008. It shows that 22,500 t of NiMH batteries would be required.

Table 5-17 : Estimation of the mass of NiMH- and Li-ion batteries, respectively which would be required to provide the same amount of lifetime-energy as the 13,200 tonnes of NiCd batteries sold in Europe for CPTs in 2008 (based on data from [EPTA 2009b])

Battery type	Total mass in t	kg/pack (18 V)	Number of packs	Lifetime Wh/pack	Lifetime GWh of all packs	Lifetime Wh/pack	Number of packs	kg/pack (18 V)	Total mass in t
NiCd	13,200	1.015	13,000,000	34,200	951				
NiMH					951	20600	21,600,000	1.040	22,500
Li-ion					951	21200	21,000,000	0.705	14,800

Table 5-18 shows the material streams which would be required to replace the NiCd batteries sold in 2008 in Europe for CPTs by NiMH batteries to give the same lifetime energy. It can be seen that in absolute terms considerable amounts of nickel, iron and mischmetall (lantanides or rare-earths) would be required. Relative to the world metal production, however, the mischmetalls, cobalt and lithium are the most critical metals. Here it has to be noted that only one information source specifically mentions lithium as being a component of NiMH batteries, too [VARTA 2008]. So the real lithium demand caused by NiMH batteries may be considerably lower than estimated in Table 5-18.

Table 5-18 : Materials contained in the NiMH batteries which would be required to deliver the same lifetime energy as the NiCd batteries sold for CPTs in 2008 in Europe and effect on world metal production (composition = average from [EC 2003, ERM 2006, EPBA 2007, VARTA 2008], production and reserves from [USGS 2009])

	Assumed share in cell in %	Mass for all NiMH cells necessary to replace NiCd in t	% of year 2008 worldwide metal production	% of worldwide reserves
Aluminium (Al)	1.0	225	0.001	<<
Cobalt (Co)	3.7	830	1.156	0.012
Iron (Fe) and steel	27.1	6,103	0.001	0.000
Lithium (Li)	1.0	225	0.821	0.005
Manganese (Mn)	1.5	332	0.002	0.000
Nickel (Ni)	33.0	7,425	0.461	0.011
Zinc (Zn)	1.7	375	0.003	0.000
Mischmetal alloy / lanthanides (calculated as rare earth oxides)	10.7	2,400	1.935	0.003
Alkali	5.0	1,125		
Plastics	7.0	1,575		
Water	8.0	1,800		
Other non metals	0.4	85		
Total	**100.0**	**22,500**		

Health & Environmental Effects

NiMH batteries do not contain cadmium.Thus the highest health and environmental risks of NiMH batteries emanate from nickel.

In addition to the hazardous substances contained in NiCd batteries, NiMH batteries contain:

- Lithium which is only dangerous in its reactive metallic form (but not as lithium salt)
- Mischmetall alloy which is of low to moderate toxicity.

Some experts claim that NiMH batteries are somewhat less abuse tolerant than NiCd batteries [EPTA 2009b], so that the likelihood of rupture may be somewhat higher with NiMH batteries but still low. [It's difficult to understand what is meant here. Could you please clarify what is the context of this sentence?]

The critical life-cycle phases during which the highest health or environmental impacts may occur are the same as with NiCd.

NiMH battery recycling

For the treatment of NiMH batteries the same SNAM-process can be used as for NiCd batteries (see above).

Other processes used for the recycling of NiMH processes are listed in [BiPRO et al. 2009] page 48.

Due to its nickel content, the collection and recycling of nickel-metal hydride batteries leads to a positive market value that is estimated to range from 2,000 to 4,000 € / tonne when the nickel price varies between respectively 10 to 20 € / kg. The recovered nickel is used in iron-nickel alloys metallurgy. Today, it is not recycled for being used in batteries. This could only be achieved with much less favourable economic conditions [Recharge 2009b, Accurec 2009].

5.4.3 Li-Ion Batteries

Table 5-17 (above) shows the estimation of which mass of Li-ion batteries would be required to deliver the same lifetime energy as all NiCd batteries sold in Europe in 2008; this would be 14,800 t.

Table 5-19 shows the material streams which would be required to replace the NiCd batteries sold in 2008 in Europe for CPTs by Li-ion batteries to give the same lifetime energy. The share of lithium is relatively low. However, when compared to the world production of each material, a ban of NiCd batteries in cordless power tools (CPT) would have its biggest impact on cobalt- and on lithium-production. A corresponding ban would increase the world cobalt-demand by 3.75 % and the world lithium demand by 1.57 %.

At the bottom of Table 5-19 it can be seen, that the fluorine contained in the $LiPF_6$-electrolyte and in the PVDF-membrane on the average may constitute some 5 % of the Li-ion-battery material. According to [EPBA 2007] the share of $LiPF_6$ on the total Li-ion cell material may lie between 1 and 15 %, the share of PVDF between 1 and 2 %, this gives a range for the fluorine share of 1.3 to 12.4 % with an average of 5.1 %. The total amount of fluorine needed to replace all NiCd batteries in CPTs in Europe thus lies at about 758 t per year.

Table 5-19 : Materials contained in the Li-ion batteries which would be required to deliver the same lifetime energy as the NiCd batteries sold for CPTs in Europe in 2008 and effect on world metal production (composition = average from [EC 2003, ERM 2006, EPBA 2007], production and reserves from [USGS 2009])

Material	Assumed share in cell in %	Mass for all Li-ion cells necessary to replace NiCd in t	% of year 2008 worldwide metal production	% of worldwide reserves
Aluminium (Al)	12.5	1,845	0.005	<<
Cobalt (Co)	**18.3**	2,697	**3.75**	0.038
Copper (Cu)	10.0	1,476	0.009	0.000
Iron (Fe) and steel	18.4	2,720	0.000	0.000

Lithium (Li)	**2.9**	429	**1.57**	0.010
Nickel (Ni)	**13.5**	1,993	0.124	0.003
Carbon/Graphite	13.5	1,993	0.180	0.002
Carbonate ester	4.1	612		
Lithium hexafluorophosphate (LiPF6)	5.7	835		
Poly(vinylidene fluoride) (PVDF)	1.5	221		
Total (due to doublecounting of Li > 100 %)	100.3			
Total without doublecounting of Li	**100**	**14,800**		
Fluorine	**5.1**	758	0.027	0.001
Manganese (Mn) (in manganese-Li-ion cell instead of cobalt)	*12.5*	*1,845*	*0.013*	*0.000*

Health and environmental Effects

The contents of an opened Li-ion battery can cause serious chemical burns; N-methyl pyrrolidinone, ethylene carbonate, ethyl methyl carbonate, dimethyl carbonate, and biphenyl may be absorbed through the skin causing localized inflammation.

Li-ion batteries do not contain cadmium. Thus similar to the situation with NiMH, also with Li-ion batteries the most dangerous metal is nickel. However, Li-ion batteries with Lithium hexfluorophosphate ($LiPF_6$) contain an additional substance of major concern. Lithium hexafluorophosphate ($LiPF_6$) is very destructive to mucous membranes. Harmful if swallowed, inhaled, or absorbed through skin [Wikipedia 2009x, Lebensministerium 2007].

Lithium-hexfluorophosphate forms fluoric acid in contact with water which in turn:

- Is very toxic by inhalation, in contact with skin and if swallowed
- Causes severe burns [JRC 2009].

In addition to the substances discussed heretofore, Li-ion batteries may also contain following chemical compounds:

- Lithium cobalte oxide : CAS-Nr. 12190-79-3; Xn; R: 42/43
- Acetylene black is listed as possible carcinogens by the International Agency for Research on Cancer (IARC) [Lebensministerium 2007].
- Manganese dioxide MnO_2: CAS-Nr. 1313-13-9; Xn; R20/22 - harmful by inhalation or ingestion – (limit: 25 % - Xn, sum of harmful substances)
- Lithium tetrafluoroborate $LiBF_4$: CAS-Nr 14283-07-9; C corrosive - causes burns; R20 R21 R22 R31 R34 - harmful, if swallowed or inhaled, and in contact with skin; very destructive of mucous membranes. Toxicology not fully investigated. UN No 3260. Packing group II. Major hazard class 8
- Lithium trifluoromethanesulfonate: CAS-Nr 33454-82-9; Xi – irritant; R 36/37/38 Irritating to eyes, respiratory system and skin.

- Lithium perchlorate $LiClO_4$: CAS-Nr 7791-03-9; strong oxidizer - contact with combustible material may cause fire; incompatible with organic materials, combustible materials, strong reducing agents; R 36/37/38 Irritating to eyes, respiratory system and skin.
- Biphenyl: CAS-Nr 92-52-4, R36/37/38-50/53; Xi, N (irritant – limit 20%); German Water Pollution Class 2
- N-Methyl-2-pyrrolidinone: CAS-Nr 872-50-4; Xi; R 36/38 [Lebensministerium 2007]

In spite of having extensive protection equipment [EPTA 2009b] classifies Li-ion power packs as not being abuse tolerant. Nevertheless, also with Li-ion batteries the highest health and environmental risks likely occur during the mining and recovery phase as well as during the waste collection and the waste treatment phase.

Li-ion battery recycling

Recycling of significant quantities of Li-ion at industrial level is currently not done in Europe (sources: [Recharge 2009b], [Accurec 2009]).

[Recharge 2009b] expects that the treatment costs of the Li-$FePO_4$ technology used in CPT, in absence of valuable materials to be recovered from these batteries, will probably be superior to € 1000 / tonne. Therefore, the additional impact on recycling costs would be between € 500 to € 1500 / tonne compared to the current situation for Ni-Cd batteries.

The other two commonly used Li-ion battery types (using a cobalt cathode ($LiCoO_2$) or a manganese cathode ($LiMn_2O_4$)) contain nearly as much nickel as NiCd batteries. In addition the Li-ion battery type with the cobalt cathode contains substantial amounts of the even more precious cobalt (compare Table 4-13, Table 5-20, Table 8-12 and Table 8-6). On the average over the Li-ion battery types the authors of this study expect the same economics of battery recycling as with NiCd batteries that is, in dependence of the metal prices ranging between net costs of 500 €/tonne and net revenues of 500 €/tonne. Consequently a NiCd ban for use in CPTs would have no consequence of the recycling economics.

It needs to be mentioned here, that regardless of the NiCd-ban, in any case the rapid market penetration of Li-ion-batteries in the many different portable applications, requires substantial adaptations of the recycling industry[33]. A relevant question in this context is, whether Li-ion batteries shall be collected separately from other battery types. If so, an own Li-ion battery collection system has to be established. If the Li-ion batteries are collected together with other battery types, it may be necessary to introduce technologies for separating Li-ion batteries from the other battery types after collection. Another question is whether the Li-ion batteries are treated in few central plants for

---

[33] In the scenario of the future quantities of NiCd batteries (see chaper 5.5.6.) it is assumed that the decision on the ban is in 2010, the transposition in the Member States' Laws is finished in 2012 and the ban is fully effective by 01.01.2015. The project team is of opinion that if the ban will be effective from 2015 this would provide sufficient time for the relevant stakeholders to take corresponding adjustment measures and to develop appropriate management strategies.

Europe or in many smaller plants. This has to take into account transport costs and economy of scales. The optimum solution being subject to still changing compositions of the Li-ion batteries and changing world market prices for contained materials. In any case investments may be necessary which go beyond the capacity of Small and Medium Sized enterprises [Accurec 2009], so that the organisation of the Li-ion battery recycling market will like require big company and government involvement.

Li-ion batteries may be treated either pyrometallurgically or hydrometallurgically.

- Pyrometallurgy uses high temperatures to transform metals.
- Hydrometallurgy refers to the aqueous processing of metals. Hydrometallurgical processing of waste batteries involves a mechanical step and a chemical step. In the mechanical phase, the batteries are shredded in order to separate the metals, paper, plastic and the black mass. The black mass is further chemically processed to produce a solution, which undergoes electrolysis, or other treatment, in order to separate out the dissolved metals [ERM 2006].

"Batrec" (Switzerland) carries out a pyrometallurgic process that can treat Li-ion batteries. "Recupyl" (France), "Eurodieuze" (France) and "Revatech" (Belgium) have each developed a process that can treat Li-ion batteries hydrometallurgically [ERM 2006]. Further information on recycling of Li-ion batteries in Europe is available in [BiPRO et al. 2009].

"Batrec" pyrometallurgic process for the treatment of Li-ion batteries

The main safety concern with *pyrometallurgical* Li-ion battery treatment processes is to render the highly flammable batteries inert. The BATREC™ process is shown diagrammatically in Figure 5-7.

The Li-ion batteries are fed to a crushing unit, where they are crushed in a controlled atmosphere. The released lithium is neutralised and other products (chrome-nickel steel, cobalt, non-ferrous metals, manganese oxide and plastic) are separated in a multistage separating plant [ERM 2006].

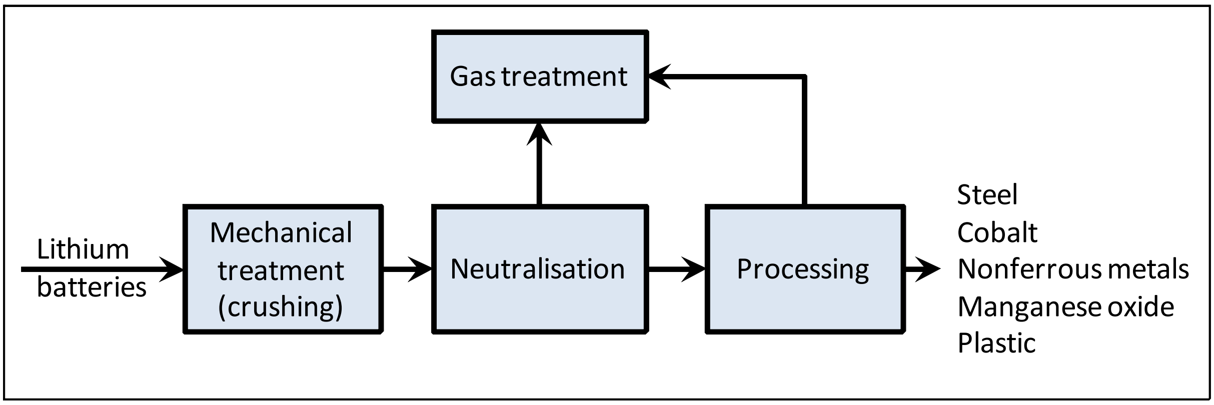

Figure 5-7 : Batrec's recycling process for Li-ion batteries [ERM 2006]

"Recupyl Valibat" process

"Recupyl" is a development process company located outside Grenoble, France.

The RECUPYL™ process uses hydrometallurgy for processing batches of mixed batteries.

Initially, batteries are sorted by size and shredded. The mechanical treatment step that follows sifts and magnetically separates steel, paper and plastics from the shredded batteries, leaving a "black mass". The "black mass" is subsequently treated with acid, resulting in the separation of mercury and other (non ferrous) metals. Using either a traditional electrolysis step or another, newly developed, purification step enables the separation of metal salts.

A variant of the RECUPYL™process, called "Valibat", is used to recycle Li-ion batteries. This process includes treating the batteries with inert gas once they are shredded. The products obtained include lithium salts and a number of metals. The process flow sheet is shown in Figure 5-8 [ERM 2006].

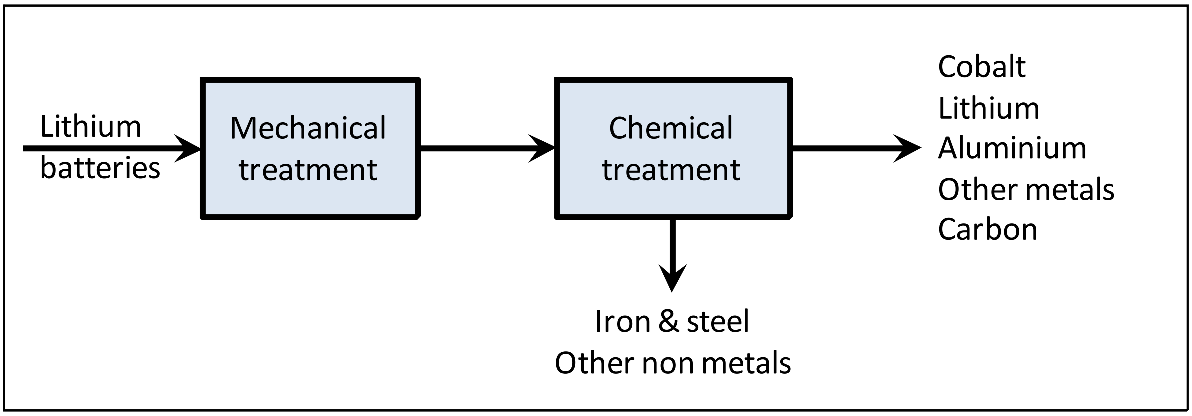

Figure 5-8 : RECUPYL™ Valibat process for recycling of Li-ion batteries [ERM 2006]

5.4.4 *Consequences of a ban NiCd batteries for use in CPTs for health and environment*

Table 5-20 directly compares the materials necessary for providing the same amount of life-time energy by either NiCd, NiMH or Li-ion batteries as can be provided by the NiCd batteries sold in Europe for CPTs in 2008.

Table 5-20 : Materials contained in the 13,200 tonnes of NiCd batteries sold in Europe in 2008 for use in CPTs and materials which would be necessary to replace NiCd batteries either by 22,500 tonnes of NiMH batteries or by 14,800 tonnes of Li-ion batteries [EC 2003, ERM 2006, EPBA 2007, VARTA 2008, USGS 2009]

	NiCd		NiMH		Li-ion	
Material	Mass of all 2008 NiCd cells in t	% of year 2008 global metal production	Mass of all NiMH cells necessary to replace NiCd in t/a	% of year 2008 global metal production	Mass of all Li-ion cells necessary to replace NiCd in t/a	% of year 2008 global metal production
Aluminium (Al)	.		225	0.00	1,845	0.00
Cadmium (Cd)	**2,200**	**10.58**				
Cobalt (Co)	79	0.11	830	1.16	**2,697**	3.76
Copper (Cu)	.				1,476	0.01
Iron (Fe) and steel	4,576	0.00	6,103	0.00	2,720	0.00

Lithium (Li)	.		225	0.82	**429**	1.57
Manganese (Mn)	11	0.00	332	0.00		
Nickel (Ni)	2,508	0.16	**7,425**	0.46	1,993	0.12
Zinc (Zn)	8	0.00	375	0.00		
Mischmetal alloy / lanthanides (calculated as rare-earth oxides)	.		**2,400**	1.94		
Carbon/Graphite	.				1,993	0.18
Carbonate ester	.				612	
Lithium hexafluorophosphate ($LiPF_6$)	.				**835**	
Poly(vinylidene fluoride) (PVDF)	.				221	
Alkali (KOH)	264		1,125			
Plastics	1,320		1,575			
Water	660		1,800			
Other non metals	1,574		85			
Total (rounded)	**13,200**		**22,500**		**14,800**	
of which Fluorine	.				758	0.06

The numbers of Table 5-20 show:

- When only NiMH batteries replaced the NiCd batteries in European Cordless Power Tools,
  - 2,200 t/year of very toxic (also and especially to aquatic organisms), accumulating and category 2 carcinogenic cadmium

  would be replaced by roughly:

  - 4,900 t/year [34] of toxic and category 3 carcinogenic nickel
  - 750 t/year[35] of harmful cobalt and
  - 2,400 t/year of low to moderate toxic mischmetal alloy.
- When only Li-ion batteries replaced the NiCd batteries,
  - 2,200 t/year of very toxic (also and especially to aquatic organisms), accumulating and category 2 carcinogenic cadmium

  would be replaced by roughly:

  - 835 t/year of very toxic lithium hexafluorophosphate (or 1,600 t of fluorine) and
  - 2,600 t/year[36] of harmful cobalt.

---

[34] 4,900 t is the difference of 7,425 t in NiMH batteries and 2,508 t in NiCd batteries

[35] 750 t is the difference of 830 t in NiMH batteries and 79 t in NiCd batteries

[36] 2,600 t is the difference of 2,697 t in Li-ion batteries and 79 t in NiCd batteries

All three technologies, NiCd batteries, NiMH batteries and Li-ion batteries contain hazardous substances. By far the most hazardous substance to health and environment, however, is the cadmium contained only in the NiCd batteries.

In 2003 a “Targeted Risk Assessment Report (TRAR) on the use of cadmium oxide in batteries” was circulated, showing the results of life cycle analysis on cadmium emissions in EU-15. Table 5-21 shows that the emissions related to NiCd batteries would be small compared to the emissions from oil/coal combustion, iron and steel production or phosphate fertilizers. Thus NiCd batteries would only be responsible for 1.35 % of the atmospheric cadmium emissions, 1.51 % of the cadmium emissions into water and 0.65 % of the total emissions ([EC 2003b] cited in [Recharge 2004]).

Lacking the publication of the underlying assumptions it is not possible to evaluate the results of the TRAR shown in Table 5-21. It, for example, would be necessary to know, how the different behaviour of cadmium in fertilizers (release of cadmium immediately after distributing the fertiliser on the field) and in landfills (release over decades and possibly even centuries) was modelled.

In any case the picture drawn by Table 5-21 would very likely change dramatically:

- when taking into account also the new EU - Member States (in which the landfilling of untreated residual household waste is still common practice and thus the rate of cadmium emissions from landfills much higher) and
- when taking into account also the first steps of the NiCd-batteries’ life cycles which occur outside Europe, that is during the mining and processing of cadmium and during the preparation of the NiCd-cells in countries which do not have the environmental protection standards of the EU.

Based on the fact that 1 % of the cadmium which is brought into Austria is emitted over its lifetime, it can be estimated that the total cadmium emissions connected to NiCd batteries for CPTs over its total lifetime is also some 1 % of the cadmium contained in these batteries. This results in an amount of cadmium emissions of 22 tonnes connected to the 2,200 tonnes of cadmium brought into the European Union in 2008 by NiCd batteries for CPTs. A big share of these emissions occurs outside the European Union e.g. during processes related to mining, processing, manufacturing and transport of the cadmium.

Irrespective of these considerations, **NiCd batteries used in Europe in CPTs are responsible for 10.5 % of the total cadmium which is brought into the economy worldwide intentionally**. A ban of NiCd batteries in cordless power tools (CPT) would substantially reduce the amount of cadmium brought into the European economy and used in everyday products and the corresponding risk of cadmium releases to the environment.

Table 5-21: Annual cadmium emissions in EU-15 by source ([EC 2003b] cited in [Recharge 2004])

	Emission per sector/process/technology	NiCd Battery contribution	
	Tonnes per year	Tonnes per year	% of total
Atmospheric emissions			
Cd alloys	0,82		
Cd/CdO Production	3,90		
Non-ferous metals	9,70		
Iron & steel	31,00		
Oil/coal combustion	54,00		
Phosphate process	0,70		
Municipal solid waste incineration	**3,20**	**1,62**	**1,31**
Wood/peat combustion	1,70		
Others	19,00		
NiCd batteries production and recycling	**0,05**	**0,05**	**0,04**
Total atmospheric emissions	**124,07**	**1,67**	**1,35**
Emissions into water			
Cd plating	0,20		
Cd/CdO Production	1,20		
Non-ferous metals	9,70		
Iron & steel	15,60		
Oil/coal combustion	0,10		
Phosphate process	9,10		
Municipal solid waste incineration	**0,35**	**0,18**	**0,46**
Metal mining	1,10		
Others (chemical industry, waste treatment)	1,20		
Landfill leaching	**0,55**	**0,34**	**0,87**
NiCd batteries production and recycling	**0,07**	**0,07**	**0,18**
Total emissions into water	**39,17**	**0,59**	**1,51**
Agricultural soil emissions			
Phosphate fertilizers	231,00		
Sludge from municipal sewage treatment plants	**13,60**	**0,38**	**0,16**
NiCd batteries production and recycling	**Not relevant**		
Total Agricultural soil	**244,60**	**0,38**	**0,16**
Total cadmium emissions	**407,84**	**2,64**	**0,65**

Current market developments let expect that the NiCd batteries would be replaced by NiMH batteries in existing cordless power tools and by Li-ion batteries in new cordless power tools. This would for some years increase the nickel- and mischmetal-alloy (rare-earth) turnover and on the long term the cobalt, lithium and fluorine turnover.

The high chemical reactivity of the Li-ion system in general and of lithium hexafluorophosphat in special is a matter of concern especially for the collection and treatment of power packs and power pack containing waste. As Li-ion cells, however, are ubiquitous due to use in information and communication technology, appropriate waste treatment systems have to be introduced anyway.

Weighing the benefits of reduced cadmium turnover against the impacts from temporarily increased nickel, mischmetal alloy, and long term cobalt, lithium and fluorine turnover, it can be concluded that **a ban of NiCd batteries intended for use in cordless power tools (CPT) will be beneficial for the environment and human health**.

5.5 Economic Impacts

5.5.1 *Markets for raw materials*

Table 5-20 shows that a replacement of all NiCd batteries used in CPTs worldwide by NiMH batteries world wide would increase:

- The cobalt market by 2.5 %
- The lithium market by 1.8 %
- The nickel market by 1.0 % and
- The rare-earth market by 4.1 %.

Table 5-20 also shows that a replacement of all NiCd batteries used in CPTs worldwide by Li-ion batteries world wide would increase:

- The cobalt market by 8 % and
- The lithium market by 3.4 %.

The following sections shall reveal, if these materials will be available on the world market without major supply problems.

The cobalt market

Cobalt is used in many different applications (see Table 5-22), most of which are high-tech applications. In 2006 the worldwide cobalt demand was caused 30 % by Europe, 29 % by the Americas, 20 % by Japan and 20 % by China. Cobalt demand is expected to further grow in future [Angerer et al. 2009] (see also chapter 8.3.2 in Annex A).

Table 5-22: Applications of cobalt [Angerer et al. 2009]

Application segment	Share in %	Technology and product examples
Batteries	22	Lithium-ion- and nickel-metal-hydride (NiMH) accumulators
Super-alloys	22	Gas-turbine-blades, medical implantates for hips and knees
Catalysts	11	Fischer-Tropsch-synthesis for gas- and biomass-to-liquid fuels
Hard-metals	11	Cutting tools (cementing material for tungsten-, titanium- and tantalum-carbide)
Pigments	9	Glass, ceramics
High-temperature steels, surface layers	8	Turbine-blades, wear-resistant engine parts
Chemicals	8	Tire additives, cobalt soaps, ink-siccative
Magnetic alloys	7	Electro-engines, -generators, permanent magnets
Other	2	Magnetic tabes, medicaments, food additive

In 2008, 71,800 tonnes of cobalt were mined, which was 122 % more than in the year 2000. In the year 2008 45 % of cobalt was mined in the Democratic Republic of Congo, 12 % in Canada and 11 % in Zambia. Cobalt reserves to 48 % are situated in the Democratic Republic of Congo and to 21 % in Australia. Currently accessible reserves amount to 7.1 million tonnes of cobalt [USGS 2009], providing a reserve range of 99 years at current consumption rates, which is relatively long in comparison to other years.

China was the world's leading producer of refined cobalt, and much of its production was from cobalt-rich ore and partially refined cobalt imported from Congo (Kinshasa). As a result of restrictions on exports of unprocessed cobalt from Congo (Kinshasa), the Chinese cobalt industry was expected to develop more domestic and foreign sources of cobalt supply, to invest in African cobalt projects, to increase the recycling of cobalt scrap, to continue to shift its consumption towards more downstream materials, and to consolidate into fewer larger companies [USGS 2009].

Cobalt prices increased from 34,000 US $/t in the year 2000 to 89,000 US $/t in 2008 [USGS 2009] that is by 161 %. As of September 2009 the cobalt price was at about 40,000 US $/t, but due to increased demand from China rose again to 63,000 US $/t in mid October 2009 [Metal Bulletin 2009].

<u>Conclusion on the availability of cobalt:</u>

Due to concentration of reserves in the Democratic Republic of Congo and of refining in China, there is some reason for concern that prices also will be volatile in the future. On the other hand, however, a base of economic reserves of an estimated 13 million tonnes [USGS 2009], should allow to increase the cobalt production by 2,700 tonnes/year, as would be required to replace the NiCd batteries in the EU in CPTs (see Table 5-20) without major disturbances.

The lithium market

Lithium and its compounds have several commercial applications, including heat-resistant glass and ceramics, high strength-to-weight alloys used in aircraft, and lithium batteries [Wikipedia 2009P].

Worldwide end-use markets for lithium are estimated as follows (source [USGS 2009]):

- batteries, 25%;
- ceramics and glass, 18%;
- lubricating greases, 12%;
- pharmaceuticals and polymers, 7%;
- air conditioning, 6%;
- primary aluminium production, 4%;
- continuous casting, 3%;
- chemical processing 3%;
- and other uses, 22%.

While Li-ion batteries already have the major share of the rechargeable battery market for portable electronic devices, they have yet to be used commercially in either hybrid electric vehicles (HEVs) or electric vehicles (EVs). With the advantages that lithium ion technology appears to offer, however, it's nearly certain that Li-ion batteries will win out in HEVs and EVs over the currently used NiMH batteries. As yet, though, no single Li-ion battery technology has proved itself superior to any of the others for use in this market segment [Vulcan 2008].

Lithium demand grew by nearly 20% in 2007 and is expected to grow in the medium term future by some 10% per annum [Vulcan 2008].

In 2008, 27,400 tonnes of lithium were mined globally, which was 111 % more than in the year 2000. In the year 2008 44 % of lithium was mined in Chile, 25 % in Australia and 13 % in China.

4.1 million tonnes of lithium lie in currently accessible reserves, which at year 2008 consumption rates would last for 150 years. 73 % of these reserves, however, are in Chile and 13 % in China [USGS 2009].

The world's largest lithium producers, who, together, constitute 75% of global production are:

- Rockwood Holdings - 30%,
- Sociedad Quimica y Minera de Chile SA (SQM) - 35% and
- FMC Corporation - 5-10%.

For each, however, it should be noted that lithium production is just one of a number of business activities.

Of the remaining quarter of the world's 50-80,000 tonnes of lithium production (expressed in terms of lithium carbonate production), the majority comes from a number of smaller producers located in China.

While most of the world's lithium comes from South America, with the three big producers extracting the metal from salt flats located in the "lithium triangle" along the borders of Argentina, Bolivia and Chile, other producers are already looking to exploit reserves elsewhere in the world.

To take the example of just two:

In 2008 Nordic Mining ASA acquired a 68% stake in Finnish mining company Keliber Oy. Keliber, which plans to open a lithium plant in Finland's Österbotten region in 2010, claims to be Europe's first lithium producer.

At the end of October 2008, Canadian company Black Pearl Minerals, having already "initiated lithium brine exploration in the Great Basin (including parts of California, Nevada and Utah) of the United States in April 2008," bought the largest-known lithium spodumene pegmatite deposit in Canada [Vulcan 2008].

Lithium prices grew relatively moderately from 23,800 USD/t in the year 2000 to 32,000 USD/t in 2008 [USGS 2001, 2009].

Conclusion on the availability of lithium:

Due to concentration of reserves in Chile and of production by 3 companies only, there is some reason for concern that a monopolistic lithium market may develop in the future. On the other hand, however, a base of economic reserves of an estimated 11 million tonnes [USGS 2009], should allow to increase the lithium production by 429 tonnes/year (see Table 5-20), as would be required by Li-ion batteries to replace the NiCd batteries in CPTs in the EU without major disturbances.

The nickel market

Nickel is used in many industrial and consumer products, including stainless steel, magnets, coinage, rechargeable batteries, electric guitar strings and special alloys. The amounts of nickel used for various applications are:

- 60% used for making nickel steels,
- 14% used in nickel-copper alloys and nickel silver,
- 9% used to make malleable nickel, nickel clad, Inconel and other superalloys,
- 6% used in plating,
- 3% use for nickel cast irons,
- 3% in heat and electric resistance alloys, such as Nichrome,
- 2% used for nickel brasses and bronzes
- with the remaining 3% of the nickel consumption in all other applications combined [Wikipedia 2009S].

World nickel mining is relatively evenly distributed over the major producing countries, with Russia having a share of 17 %, Canada of 16 % and Indonesia of 13 %. World nickel production increased from 1.2 million tonnes in 2000 to 1.6 million tonnes in 2008. 37 % of the currently accessible reserves are found in Australia, 10 % in New Caledonia.

Prices increased from 8,600 USD/t in 2000 to 21,400 USD/t in 2008, and were at 19,450 USD/t on 22 October 2009 [London Metal Exchange 2009].

Conclusion on the availability of Nickel:

The 7,425 tonnes (see Table 5-20) of nickel per year which additionally would be required by NiMH batteries to replace all NiCd batteries in CPTs within the EU should be suppliable without disturbing the world nickel market. If NiCd batteries are replaced by Li-ion batteries the nickel demand will decrease.

The rare-earths market

Rare-earth elements are incorporated into many modern technological devices, including superconductors, miniaturized magnets, electronic polishers, refining catalysts and hybrid car components. Rare-earth ions are used as the active ions in luminescent materials used in optoelectronics applications. Phosphors with rare-earth dopants are also widely used in cathode ray tube technology such as television sets.

The use of rare earth elements in modern technology has increased dramatically over the past years. For example, dysprosium has gained significant importance for its use in the construction of hybrid car motors. Unfortunately, this new demand has strained supply, and there is growing concern that the world may soon face a shortage of the materials. All of the world's heavy rare-earths (such as dysprosium) are sourced from Chinese Rare-Earth sources such as the polymetallic Bayan Obo deposit. High Rare-Earth prices have wreaked havoc on many rural Chinese villages, as many illegal rare-earth mines have been spewing toxic waste into the general water supply [Wikipedia 2009T].

Rare-earths are relatively abundant in the Earth’s crust, but discovered minable concentrations are less common than for most other ores.

In 2008, 124,000 tonnes of rare earth oxides were mined, which was 53 % more than in the year 2000. In the year 2008 97 % of rare-earth oxides was mined in China. Rare-earth oxide reserves to 31 % are situated in China and to 15 % in the USA. Currently accessible reserves amount to 88 million tonnes of rare-earth oxides [USGS 2009], providing a reserve range of 710 years at current consumption rates.

Rare-earth oxides prices increased from 2,870 USD/t in the year 2000 to 8,820 USD/t in 2008 [USGS 2009] that is by 207 %.

Conclusion on the availability of the rare-earth elements:

Due to the concentration of rare-earth production in China, there is reason for concern that prices also will be volatile in the future. On the other hand, however, a base of economic reserves of an estimated 150 million tonnes [USGS 2009], should allow to increase the production of rare earth mischmetal alloy by 2,400 tonnes/year (seeTable 5-20), as would be required by NiMH batteries to replace the NiCd batteries in CPTs within the EU without major disturbances.

Conclusions from raw material market analysis

A ban of NiCd batteries for use in cordless power tools (CPT) would have an effect primarily on the markets of cobalt and lithium (when Li-ion batteries replace the NiCd batteries) and of nickel and rare-earth-oxides (when NiMH batteries replace the NiCd batteries). For all 4 materials the reserves are large enough to guarantee enough supply for the decades to come. Due to the concentration of the exploitable and production ores in few countries (cobalt in the Democratic Republic of Congo and

China, lithium in Chile, and rare-earth oxides in China), however, high future price volatilities for cobalt, lithium and rare-earth oxides need to be expected.

5.5.2 Economic Impact on miners

Primary cadmium is generally not mined on its own but recovered as a by-product from zinc concentrates [USGS 2009]. Therefore no effects on miners are to be expected.

Only a small part of the primary metals used in rechargeable batteries originate from Europe. Thus the impact will be mostly outside Europe. A ban of NiCd batteries for CPT would cause a shift from cadmium refinement to the mining of other metals. As cadmium is mined only as by-product of zinc-mining the effect on raw material suppliers will be small. With respect to cobalt and lithium (contained in Li-ion batteries) primary reserves are concentrated in few countries. Therefore high price volatilities are to be expected. However, there are also mature Li-ion technologies without cobalt.

Also in a telephone conversation of the Swedish Environmental Protection Agency with the professional association of the mining industry a statement was made by the latter that *“the mining industry was a secondary stakeholder and consequently will not be significantly affected by a ban on cadmium in batteries for power tools*” (telephone interview with mining industry association, 8 September 2008 cited in [SE EPA 2009]).

5.5.3 Economic Impact on battery manufacturers

At the beginning of the decade, SAFT produced primarily NiCd batteries (more than 85% of its yearly sales according to industry sources). In the year 2003 SAFT had been the last European producer, with two plants producing both portable and industrial NiCd batteries, one in France and one in Sweden, and plants producing industrial NiCd batteries in Spain and Germany [Bio 2003].

Currently SAFT is the last European producer of NiCd cells. SAFT does not produce anymore NiCd cells for batteries intended for the use in CPTs. All NiCd batteries used in CPTs are imported to the EU, mainly from Asia.

Economic or social impacts on the EU batteries industry due to a ban of NiCd batteries for CPTs are therefore not expected.

In any case the rechargeable NiCd-market is shrinking, leading to shrinking profit margins (see Figure 3-2). Thus, on the medium to long term, NiCd for cordless power tools (CPT) has no good business perspectives even if it is not banned. The ban of NiCd batteries for CPT would only accelerate an existing development.

If the European battery industry wants to stay competitive it has to develop efficient Li-ion-production capacity. A NiCd-ban for cordless power tools (CPT) would rather support than hamper such an establishment.

Like all other relevant competitors also SAFT currently offers among its products NiMH and Li-ion batteries and it can therefore be concluded that SAFT is also engaged in the corresponding market[37] and will be able to develop strategies to appropriately participate in the future market of portable batteries.

If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) it can be expected that a ban of NiCd batteries for CPTs may contribute to the creation of new jobs in the manufacturing of current and future substitutes.

Generally it can be stated that European production of NiMH and Li-ion should take efforts to get a sustainable market share. A ban of NiCd batteries in CPTs might be of help for the market development.

5.5.4 Economic Impact on manufacturers and retailers of cordless power tools (CPT)

There could be a relevant economic impact on manufacturers of appliances that include batteries (e.g. CPT manufacturers) if the use of substitutes of NiCd batteries would make the appliances less attractive to potential purchasers. However, as the technical performance of NiMH or Li-ion batteries is usually equal or better compared to NiCd batteries and the expected price increase for CPTs is low to moderate (Li-ion driven CPT system is 10 to 49% more expensive compared to a NiCd system; see chapter 5.5.5), it is not expected that CPT appliances will become significantly less attractive if NiCd batteries will be banned.

On the other hand the increasing prices will lead to increased turnover of due to the sales of more powerful and expensive CPTs.

According to industry information CPT manufacturers would have to technically adapt assembly lines in Europe due to changing from NiCd battery technology to Li-ion systems. EPTA argues that although new product development is mainly based on Li-ion batteries, some equipment for producing NiCd battery based CPTs can return their investment only by 2016 [EPTA 2009e]. [Recharge 2009b] estimates the total cost for all EU-based CPT producers for replacing existing production lines for NiCd-based CPTs by production lines for Li-ion-based CPTs to be 60 million €.

In addition Recharge and EPTA expect negative economic impacts on CPT manufacturers because existing stocks of CPT equipped with NiCd batteries will get lost. Recharge expects one-time costs amounting up to 7.5 million € [Recharge 2009b, EPTA 2009e]. Such impacts can not be excluded. However the CPT industry already takes appropriate actions to significantly reduce the relevant costs. The NiCd battery-based CPTs of Bosch, for example, can be operated by both NiCd and NiMH batteries as well. Accordingly the project team does not expect relevant economic impacts due to stock losses.

Li-ion driven cordless power tools (CPT) are manufactured by European companies. A ban of NiCd batteries for CPTs may contribute to their competitiveness and may thus have a positive economic

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impact. Correspondingly, selected producers of cordless power tools (CPT) see Li-ion-technology as chance.

In total the market is a dynamic and an increasing market (with respect to numbers cordless power tools and value). **The NiCd batteries ban would have either no effect or even support the transition of the European industry towards more profitable products**.

In 2008 the Swedish Environmental Protection Agency contacted manufacturers and agents of power tools with questionnaires and interviews and summarised: *"Several cordless power tool manufacturers said that a ban on Cadmium would be positive for them, partially because a ban would speed up the development of other types of batteries, especially the Li-Ion, partially because goodwill is enhanced when cadmium is removed from their product range. Arguments given for future sales of NiCd are primarily concerned with the need to replace batteries in older machines run on NiCd and that NiCd manages extreme temperatures better."* [SE EPA 2009].

It is noteworthy, that the lower performance at cold temperatures is however not considered a disadvantage by users of CPTs [SE EPA 2009]. NiCd batteries in older machines can be replaced without difficulties by NiMH batteries together with the corresponding charging equipment. However, additional costs for the charging equipment and a faster replacement of existing CPTs may occur. [Recharge 2009b] estimates the corresponding costs to be 6.4 million € / year till the existing equipment is replaced by production lines for NiMH-based CPTs.

EPTA reports on possible impacts on EU battery pack assemblers that assemble battery packs for CPTs. According to EPTA, *"the portable NiCd technology allows EU companies to play an important role in the commercial chain. Li-ion cells include an electronic component which is very sensitive and is only done by Asian companies. The dominant Li-Ion producer is the company "A123" in China. A forced change in CPT battery technologies will hurt the EU pack assemblers and may lead to their disappearance as the complete Li-ion batteries charging module will be manufactured in Asia by the companies producing the cells. This will have employment consequences"* [source: EPTA 2009e]. There is no further information available if and to what extent such impacts are relevant or not. A quantification of corresponding impacts is not available.

5.5.5 Economic Impact on the final consumer

Table 5-23 shows the parameters of a type of cordless power tool (CPT) which is offered in two versions, one which may be driven by a NiCd- or a NiMH- power pack, the other which is driven by Li-ion batteries. The price of the base tool and of the complete equipment in the Li-ion version is 22 % higher than the NiCd version. For the additional price the final consumer gets a lighter and more powerful tool.

Table 5-23 : Parameters of alternative percussion drill screwdrivers [Bosch 2009c,d]

Type		GSB 18 VE-2		GSB 18 VE-2-Li
Voltage in V		18		18
Torque in Nm		75		80
Weight in kg		3		2.5
Charging time in min		30		30
Power source		NiCd (2*2.4 Ah)	NiMH (2*2.6 Ah)	Li-ion (2*2.6 Ah)
Prices in € 2009	Base tool	246.00	246.00	298.80

(including tax)	Tool with charger and power pack	413.30 (estimated)	430.80	502.80

Table 5-24 shows the prices of Bosch for the 14.4 V replacement power packs of their cordless power tools (CPT) in the do-it-yourself (DIY) category. In this segment the Li-ion-battery is some 20 % more expensive than the NiCd battery.

It is interesting to note that "Bosch" does not offer any NiMH batteries for the do-it-yourself category. Thus earlier expectations, that the NiMH battery would replace the NiCd battery in the low price segment, if the NiCd batteries are banned, seem not to be true anymore. In fact, "Bosch" strongly promotes the Li-ion-technologies also for the low price do-it-yourself (DIY) segment.

Table 5-24 : Capacity and price of 14.4 V power packs for the Do-It-Yourself segment [Bosch 2009b]

Application	Cell type	Capacity in Ah	Capacity in Wh	Price per piece in € 2009	Price per capacity in €/Wh
Do-It- Yourself (DIY)	NiCd	1.2	17.3	46.01	2.66
	Li-ion	1.3	18.7	59.00	3.15

Table 5-25 shows the prices of "Bosch" for the 18 V replacement power packs of their cordless power tools (CPT) for 3 different application categories:

- Do-It-Yourself
- Standard Duty
- Heavy Duty.

When only comparing the “Heavy Duty” power packs with the highest capacity, the NiCd power pack per piece is 20 % cheaper than either the NiMH power pack or the Li-ion power pack. However, the NiCd power pack is the most expensive per Wh stored energy.

Table 5-25 : Capacity and price of 18 V power packs [Bosch 2009c]

Application	Cell type	Capacity in Ah	Capacity in Wh	Price in € 2009	Price per capacity in €/Wh
Do It Yourself	Li-ion	1.3	23.4	69.00	2.95
Standard Duty	NiCd	1.5	27	75.01	2.78
	NiCd	2	36	151.00	4.19
	Li-ion	1.3	23.4	99.60	4.26
Heavy Duty	NiCd	2.4	43.2	153.00	3.54
	NiMH	2.6	46.8	169.00	3.61
	NiMH	3	54	184.00	3.41
	Li-ion	2.6	46.8	138.99	2.97
	Li-ion	3	54	183.00	3.39

Looking at the lifetime energy storage capacity, however, gives a different picture. The data given by [EPTA 2009b] (see Table 4-18) reveal, that 1 NiCd power pack, 1.66 NiMH power packs or 1.61 Li-Ion power packs are needed to provide 34,200 Wh of lifetime energy.

Table 5-26 shows the assumption and results of the life-time cost calculation for providing the services of a cordless percussion drill screw driver by either NiCd-, NiMH- or Li-ion-technology. The technical assumptions are based on [EPTA 2009b], the price assumptions on [Bosch 2009 b, c, d]. In order to determine the life-time costs, the costs for charging electricity the discharging/charging efficiency, the different life-time expectations are taken into account. The applied methodology is dynamic cost accounting with a discount rate of 5 % per year.

The two bottom lines of Table 5-26 show the total discounted life-time costs of the 3 options and the cost ratio. NiCd is the cheapest option, NiMH 57 % more expensive and Li-ion 49 % more expensive.

Table 5-26 : Estimating the life-time costs of the services of a percussion drill screw driver (the micro economic point of view)

	NiCd	NiMH	Li-ion	Source
Cordless Power Tool (Bosch percussion drill screw driver)	GSB 18 VE-2		GSB 18 VE-2-Li	[Bosch 2009b,c,d]
Power source	2*2.4 Ah, 18 V NiCd	2*2.6 Ah, 18 V NiMH	2*2.6 Ah, 18 V Li-ion	[Bosch 2009b,c,d]
Energy per double-pack in Wh	86.4	93.6	93.6	[Bosch 2009b,c,d]
Lifetime energy per double pack in Wh	68,400	41,124	42,482	[EPTA 2009b]
Assumed lifetime of CPT in years	14	14	14	
Assumed lifetime of powerpack in years	7	4.2	4.3	NiCd: [EPTA 2009b]
Price cordless power tool incl. Charger and base doublepack in €	413.3	430.8	502.8	[Bosch 2009b,c,d]
Price per doublepack in €	306.00	338.00	277.98	[Bosch 2009b,c,d]
Required discharging energy in Wh/a	9,771	9,771	9,771	
Discharge/charge efficiency	0.79	0.93	1.00	[EPTA 2009b]
Required charging energy in Wh/a	12,369	10,507	9,771	
Price per kWh electricity in €cents (incl. Tax)	19.24	19.24	19.24	[e-control 2009]
Discount rate in %/a	5	5	5	
Total discounted life-time costs	**656**	**1,029**	**977**	
Cost ratio	**1.00**	**1.57**	**1.49**	

Table 5-27 shows a sensitivity analysis of the result with respect to discount rate. The result is not really sensitive to the discount rate. Even at 10 % discount rate the NiMH option and the Li-ion-option are some 45 % more expensive than the NiCd-option.

Table 5-27 : Sensitivity analysis 1 – effect of discount rate on relative life-time costs for providing the services of a percussion drill screw driver

Discount rate in %	Cost ratio of		
	NiCd	NiMH	Li-ion
0	1	1.69	1.57
5	1	1.57	1.49

10	1	1.47	1.44

As already mentioned above, [Bosch 2009a] claims that the Li-ion power packs they sell together with their CPTs hold as long as NiCd batteries. When this should prove to be true, the Li-ion option (that is the Li-ion-cordless-power toll, together with the charging equipment and the necessary replacement power packs to operate the power tool for 14 years) would be only 10 % (see Table 5-28 and Figure 5-9).

Table 5-28 : Sensitivity analysis 2 – effect of life-time of Li-ion power pack on relative life-time costs for providing the services of a percussion drill screw driver compared to NiCd

Li-ion lifetime in years	Costs Li-ion/Ni-Cd
4	1.55
6	1.19
7	1.10
Note: all other parameters see Table 5-26	

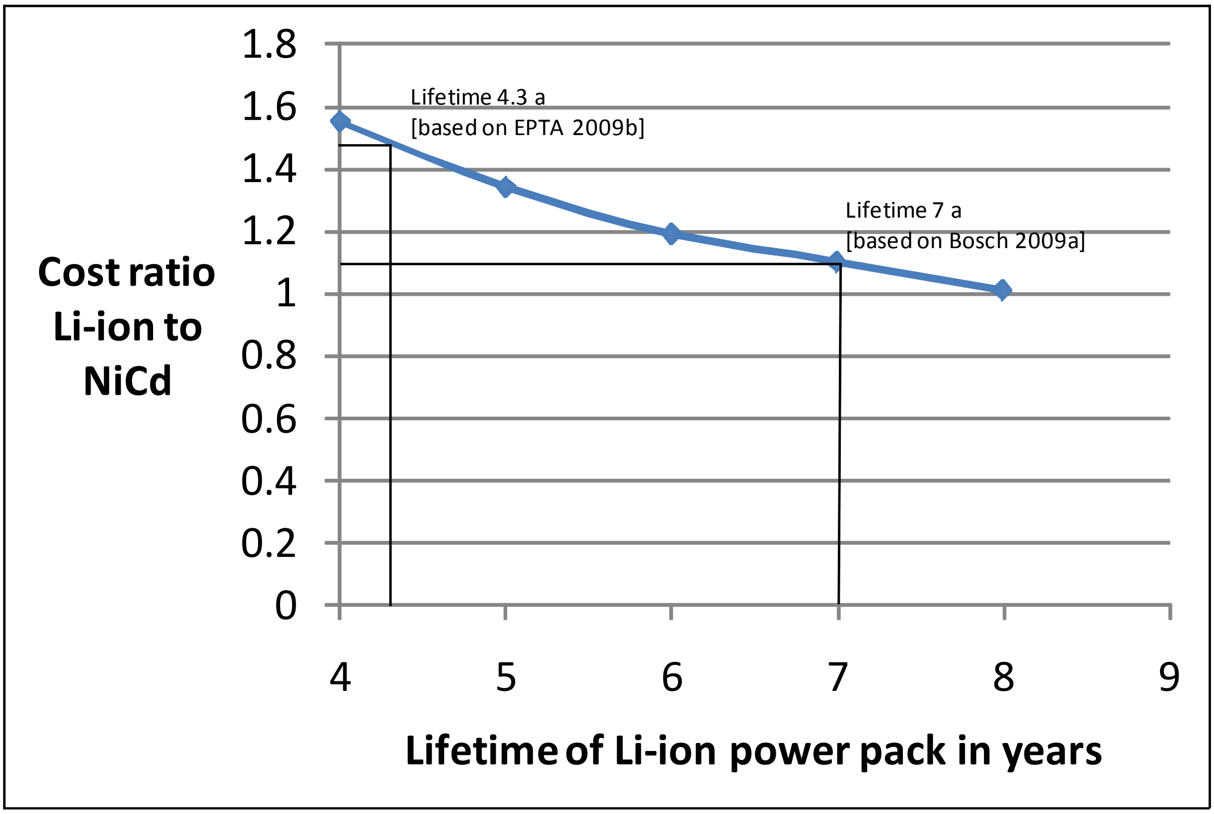

Figure 5-9 : Sensitivity analysis 2 – effect of life-time of Li-ion power pack on relative life-time costs for providing the services of a percussion drill screw driver compared to NiCd (assumed life time for NiCd-battery = 7 years)

Summarising these results it can be concluded that the final consumer over the life-time of the Cordless Power Tool has to pay 57 % more with NiMH than with NiCd systems, and 49 % more with Li-ion than with NiCd-systems, when assuming that the life-time of the NiMH and of the Li-Ion power packs are 4.2 and 4.3 years, respectively. When, however, the actual life-time of the Li-ion power packs after regular use is 7 years, the final consumer has to pay only 10 % more with Li-ion than with NiCd, while having a lighter tool and, at least in the beginning, power packs which need to be recharged less frequently.

The costs for all CPTs (together with one power pack and charging equipment) sold in Europe in 2008 was 1.5 billion € (see Table 3-1). When considering that 54 % of the cheaper Do-it-yourself (DIY) CPTs and 42 % of the more expensive professional CPTs were NiCd based, and when assuming that on the average the NiCd-based CPTs were 30 % cheaper than the Li-ion based CPTs and 5 % cheaper than NiMH based CPTs, then the market volume of NiCd-based CPTs in 2008 can be estimated to be 653 million €. When further assuming that the additional costs for replacing the NiCd-based CPT-system by a comparable Li-ion-battery-based CPT-system are 10 to 50 %, the additional costs for final consumers caused by a ban of NiCd-batteries in cordless power tools (CPT) lie between 65 and 326 million €/year.

It, however, needs to be stressed, that:

- that part of the additional costs is caused by the necessary system changes (such as product development and waste management) and will become smaller over the years and,
- that part of the additional costs for final consumers is for the benefit of cordless power tool-producers in Europe.

5.5.6 Economic impact on waste management system

As stated above, the market penetration of rechargeable Li-ion batteries in the information and communication technology segment requires high separate collection rates for batteries and an adaptation of the whole spent-battery treatment system in any case. A ban of NiCd batteries for CPT would simplify this task, as the most hazardous substance would be taken out of the system to a big extent, but would not completely eliminate this task.

Waste amounts resulting from the use of NiCd batteries and Li-ion batteries in CPTs depend on the life-time of the Li-ion technology. When the lifetime is 4.3 years (as assumed by [EPTA 2009b], this would lead to a mass increase of 12 % as compared to NiCd. If the life-time is the same as NiCd (= 7 years), the mass of the Li-ion batteries would be 30 % less than the mass of NiCd batteries. As also the revenues from recovered metals should be about the same with Li-ion batteries as with NiCd batteries (see chapter 5.4.3), **relevant economic impacts due to the market penetration of Li-ion-batteries are not expected.**

This does not mean that Li-ion-battery recycling occurs without costs. However, the revenues from recovered nickel and cobalt could more or less cover the costs of Li-ion battery recycling. Recharge estimates that these costs range from 500 to 2000 €/tonne [Recharge 2009b].

In Europe there are three companies who recycle NiCd batteries (SNAM in France, SAFT in France and ACCUREC in Germany [BiPRO et al 2009]). These recycle not only NiCd batteries for cordless power tools (CPT) but also industrial batteries [CEU 2004]. In addition these facilities are also capable to recycle NiMH batteries. The aim of recycling is primarily to remove the nickel that is found in both types of battery [SE EPA 2009].

In a telephone conversation of the Swedish Environmental Protection Agency with NiCd recyclers it was stated “that the NiCd recyclers do not regard a possible ban as a problem” (telephone interview with NiCd and NiMH recycling company, 13 October 2008; source; [SE EPA 2009]).

The situation for NiCd battery recyclers in France and Germany appears to be different. The following summarises information provided by the German NiCd battery recycler Accurec GmbH:

Company	Current annual turnover (million €)	Number of workplaces	Current annual turnover directly related to the recycling of portable NiCd batteries (million €)	Number of workplaces directly related to the recycling of portable NiCd batteries
Accurec GmbH, Germany	3 to 4	20	2.1 to 2.8	14
SNAM S.A., France*	~ 12	~ 50	~ 8.4	35

* Figures related to SNAM are indicative only and are to be confirmed by SNAM.

The annual turnover which is directly related to the recycling of portable NiCd batteries is based on the statement that the turnover of both enterprises is due to the recycling of portable NiCd batteries contributing 70% to the turnover. The recycling of industrial batteries is of low relevance. The use of industrial NiCd batteries is since a long time constantly decreasing [Accurec 2009].

According to Accurec, NiMH batteries cannot replace the recycling of NiCd batteries (in case of a NiCd batteries ban for CPTs) in dedicated battery recycling plants. This is due to the fact that NiMH batteries have a positive market value[38] and are directly recycled in steel recycling plants. Dedicated battery recycling plants can only obtain small amounts of NiMH batteries. **As a consequence the capacities of the dedicated recycling plants of Accurec and SNAM will by far not be exhausted and these plants would have to shut down in case of a ban for NiCd batteries in CPTs** [Accurec 2009].

A thinkable strategy to change the recycling technology and to recycle e.g. Li-ion batteries is not feasible for SMEs such as Accurec and SNAM due technological uncertainties and high investment costs for the corresponding technology. Appropriate recycling technology for Li-ion batteries is still under development and not yet established at industrial scale. In addition it will be difficult to make profit with the recycling of Li-ion batteries due to related costs which are estimated above 2000 € / tonne Li-ion batteries [Accurec 2009].

On the basis of the information provided by Accurec it can be estimated that the direct economic impacts of a ban of NiCd batteries for CPTs on Accurec and SNAM range from 10.5 to 11.2 million € (related to 49 workplaces). If these two SMEs will have to shut down as a consequence of the ban the economic impacts would range from 15 to 16 million € (related to approximately 70 workplaces).

Recharge has provided information concerning the corresponding impacts on NiCd recycling plants covering the whole European perspective. The estimates range from 20 to 30 million €/year loss of turnover (associated with losses of workplaces in the range of 70 to 90 people) [Recharge 2009b].

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[38] note: 2000 to 4000 €/t; source [Recharge 2009b]

The information given by [Recharge 2009b], however, is not conclusive. From the data given it can be derived that the cost for treating 1 tonne of NiCd batteries lies with 3,000 €. That means the costs for treating NiCd batteries are as high as the costs for treating Li-ion batteries. When also taking into account that the world market price of 1 tonne of cobalt is 4 times as high as the world market price of nickel (and this was the case in the year 2000 and in the year 2008, as well [USGS 2001, 2009]) the recycling economics of Li-ion batteries should be better than of NiCd batteries, as long as the average cobalt content across all Li-ion-battery types is higher than 5 %. Only if the Li-ion batteries would contain no material of value at all a turnover loss in the recycling sector of 20 to 30 million €/year would have to be expected. **Only one time costs for closing down the existing NiCd recycling infrastructure and for establishing new Li-ion recycling infrastructure seem to be much more realistic.**

It has to be noted that a ban of NiCd batteries for CPTs would cause a slow disappearance of **waste NiCd batteries** from the recycling market as a consequence of the life-time of the NiCd batteries and the hoarding effect. Accordingly the recycling of NiCd batteries would have to continue for several years for decreasing amounts of NiCd batteries.

A scenario of the future quantities of NiCd batteries waste after a NiCd battery ban in CPTs can be developed based on the following assumptions:

1. It is assumed that the decision on the ban is in 2010, the transposition in the Member States' Laws is finished in 2012 and the ban is fully effective by 1.1.2015.
2. Immediately after the decision on the ban in 2010 NiCd-based CPT sales go down rapidly, while the sales of NiCd batteries will shrink smoothly from 12,300 tonnes in 2010 to zero tones in 2015.
3. It is assumed that the average residence time of NiCd batteries in the European economy and households is 8 years and that all NiCd batteries sold by 2014 have become waste by the year 2030.

The resulting scenario of NiCd battery waste arisings in Europe after a NiCd ban in CPTs is shown in Table 5-29. The NiCd battery waste would go down continuousely after 2010 and almost become 0 in the year 2026.

It has to be noted, that

- The NiCd battery waste arisings in 2010 is higher than the sales of NiCd batteries for CPTs in 2008 in Europe, as the sales had been higher the years before.[39]
- Only part of the battery waste arisings is collected separately and treated for recycling.

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[39] In accordance with Figure 3-2 and Table 3-8, it is estimated that the number of NiCd cells sold for Cordless Power Tools (CPTs) in Europe fell from 349 million cells in 1994 to 240 million cells in the year 2008. With a mass of 0.055 kg/cell, the total mass of NiCd batteries sold for CPTs in Europe fell from the 19,200 tonnes in 1994 to 13,200 tonnes in 2008. The NiCd batteries waste arising in the EU was approximately 16,500 tonnes in the year 2008 and is estimated to amount to approximately 16,000 tonnes in the year 2010.

Table 5-29 : Scenario of NiCd battery waste arisings from CPTs in Europe after a NiCd ban in CPTs in 2010

Year	2010	2015	2020	2025	2030
Amount of NiCd-battery waste in tones/year	15,986	10,272	5,210	817	0

Recharge estimates that in case of a ban of NiCd batteries for CPTs it would be necessary to consider **landfill costs** for the disposal of waste NiCd batteries: *"In case of a marketing restriction, it will also be necessary to take into consideration landfill costs for spent NiCd batteries. When 2'000 tonnes will be collected and landfilled in hazardous waste landfills, at a unit cost of € 1,000 / tonne, this will represent an additional cost of € 2'000'000 / year over a period of ten years. Indeed it is anticipated that a significant return of NiCd batteries will last for at least another ten years in case of a marketing restriction."* [Recharge 2009b]. In the opinion of the project team, if corresponding costs will indeed appear they will be considerably lower as expected by Recharge. Disposal costs for hazardous waste currently range from 260 to 400 € per tonne[40] and the assumed amount of 2,000 tonnes / year will only occur in the beginning of the mentioned period of 10 years and will continuously decrease within this period. On average the annual amount could therefore be about 1,000 tonnes. Accordingly the expected average annual costs could be about 0.26 and 0.4 million € over a period of 10 years.

In the medium term the waste management sector may profit from the elimination of one of the most hazardous substances they have to deal with and possibly from reduced costs for landfilling fly ash from waste incineration in underground disposals for hazardous waste.

5.5.7 Economic Impact from the macro economic point of view

The ban of NiCd batteries could be related to additional administrative burden for controlling whether the ban will be implemented. According to EPTA it would be vital that a ban is accompanied by measures to guarantee that no NiCd CPTs are entering the EU market [EPTA 2009e]. According to the opinion of the authors random sampling that can be done by the competent Member State authorities in the frame of other product control activities is appropriate and would be possible at neglectible additional costs (no quantification available). It is expected that the players on the market of CPTs will control one another if a ban will be implemented. To conclude, additional administrative costs for the monitoring of a ban are considered irrelevant.

The prices for NiMH- and Li-ion systems are higher than for NiCd systems. The NiCd systems, however, are much longer on the market than the other two. According to micro economic theory, profit margins, due to market competition get smaller the longer a technology is on the market. Therefore it can be assumed that the prices of NiCd-systems contain only a small profit margin, so that the prices are not much higher than the material and production costs. On the other hand, the prices of NiMH and Li-ion systems as relatively new technologies should contain a considerable profit margin, so that their material and production costs should be much lower than their market prices.

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[40] Personal communication underground disposal Herfa Neurode

Consequently, the difference in material and production costs between NiCd on the one hand and NiMH or Li-ion on the other hand should be considerably smaller than the price differences.

When also the external costs of environmental and health impacts are taken into account, it is very likely, that NiCd-systems are related to higher costs than either NiMH or Li-ion systems.

5.6 Social Impacts

In the early years of this decade, industry claimed that 3,500 people are directly employed by NiCd battery producers in the EU-15 [EC 2003]. This statement concerns the whole sector including all portable and industrial NiCd batteries.

NiCd batteries for CPTs are not produced in within the EU (see chapter 5.5.3). Impacts on workplaces in the batteries industry are therefore not expected in case of a ban of NiCd batteries intended for the use in CPTs

If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) there is a chance that new workplaces will be created in other battery manufacturing sectors.

It is probable that between 70 and 90 workplaces will be lost at EU recyclers of NiCd batteries (see chapter 5.5.6).

However, it can be expected that possible job losses in NiCd recycling sector will be outweighed or surpassed by new jobs related to the recycling of NiMH batteries and particularly Li-ion batteries.

EPTA reports on possible workplace losses at EU battery pack assemblers (see chapter 5.5.4). There is no information available if and to what extent such impacts are relevant or not. A quantification concerning workplaces is not available).

Li-ion driven cordless power tools (CPT) are manufactured by European companies. A ban of NiCd batteries in CPTs may contribute to their competitiveness and the creation of jobs. There is no information available if and to what extent such impacts are relevant or not. A quantification concerning workplaces is not available).

The Swedish Environmental Protection Agency [SE EPA 2009] has asked professional users about their experience and use of NiCd batteries. As cold has been stated as a competitive advantage for NiCd batteries – they are not affected in the same way as other batteries – the agency has primarily interviewed professional users in the north of Sweden where temperatures are amongst the lowest in Europe.

"These interviews show that the use of batteries in power tools varies, but that the professional users surveyed currently use NiMH and Li-Ion. None of them select a tool based on the type of battery in them; the battery is something that is included in the purchase. The factors that influence the purchase or selection of tools are the brand name, its performance or capacity and the weight of the hand tool. They have previously worked with a certain tool and the experience they gained from that tool affects their further choices.

Whether the price is higher or lower depending on battery type does not make a great deal of difference according to those interviewed. Quality is decisive and what is important is whether the tools last well. However price is of importance if a private person is buying the tool. Interviews of professional users proved that they do not consider the specific battery that the machine contains when they buy it.

Professional users are unanimous about the fact that NiCd are heavy to work with which is a disadvantage. In addition, NiCd has problems with its memory effect: if they are not totally empty they do not give optimal effect when next charged. One professional user indicated that Li-Ion can be difficult to charge when it is cold but that NiMH are just as easy to charge as NiCd when it is cold." [SE EPA 2009].

5.7 Impacts on Management of Risks

Globally NiCd batteries account for nearly 25 % of all cadmium consumed. Residual waste analyses and material flow analyses allow to draw the conclusion, that NiCd batteries is the most important source of cadmium at least in Austrian municipal solid waste [Umweltbundesamt 2006, Umweltbundesamt & TU-Wien 2009]. [CEU 2004] estimates that even 75 % of the cadmium found in residual household waste can be related to NiCd batteries. [EC 2003b] assumes that 50 % of the cadmium emission from municipal solid waste (MSW) into air in the EU-15 is caused by NiCd batteries (see Table 5-21). As a consequence of a ban of NiCd batteries in CPTs the cadmium contents in municipal solid waste, and thus in all off-streams of municipal solid waste treatment installations should substantially recede in the long term.

However, also the alternatives to NiCd batteries contain hazardous substances. In addition to the heavy metals nickel, cobalt and rare-earth metals the fluorine containing electrolytes of the Li-ion battery are of concern.

Li-ion batteries are more and more in use in the segment of entertainment and information technology. Therefore a ban of NiCd batteries for CPTs would only strengthen a trend towards more Li-ion batteries which develops anyway. Risk management has to acknowledge this trend and to care for high safety standards in the production, retail, use, collection and treatment after use of batteries. A high separate collection rate of spent batteries is an important contribution of keeping the risks connected to these technologies at bay.

In total it can be concluded, that a ban of the application of NiCd batteries in cordless power tools (CPT) is an important and efficient measure to reduce the environmental and health risks connected to the use of cordless power tools (CPT). The risk will be substantially lowered, but not to zero.

5.8 Comparison with the Findings of other Reports

In this subchapter, the results of this study are compared to the conclusions of four other NiCd impact assessment studies:

- The study “Impact Assessment on selected Policy Options for Revision of the Battery Directive“ from Bio Intelligence Services published in 2003 [Bio 2003],
- The Extended Impact Assessment of the Batteries Directive published by the European Commission in 2003 [EC 2003]
- The “Impact assessment of key Council amendments to the Commission proposal for a Batteries Directive” from Council of the European Union published in 2004 [CEU 2004]
- The report “Cadmium in power tool batteries - The possibility and consequences of a ban” from the Swedish Environmental Protection Agency, published in 2009 [SE EPA 2009].

The comparison is shown in Table 5-30. Based on this comparison, the impacts of a NiCd-battery ban in cordless power tools (CPT) on the different concerned actors is shown in Table 5-31.

Table 5-30 : Impacts related to a ban of NiCd batteries in cordless power tools (CPT) expected by different sources

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
Environmental Impacts					
- NiCd batteries are an important source of cadmium circulating in the economy - Impact of NiCd ban - Total environmental impact of NiCd ban for cordless power tools (CPT)	A ban has no relevant impact on general human cadmium exposure. Portable NiCd batteries may pose relevant environmental risks, these may be reduced due to a partial ban: (a) possible risk due to air emissions; (b) Cd concentration levels in sediment already cause adverse effects; (c) non-EU-conform landfills pose risk for groundwater.	The amount of total cadmium releases during the life-cycle of NiCd batteries is 607 to 2,566 kg per year (in EU-15) The replacement of NiCd batteries by NiMH and Li-ion batteries would result in decreased environmental impacts.	NiCd batteries account for 75% of the total use of refined cadmium in products on the market within the Community. Refined cadmium accounts for a small proportion of total discharges of cadmium to the environment, with the application of fertilizer being the main source. Batteries create a risk of releases of cadmium to the environment during production and, more significantly, disposal of NiCd, particularly via incineration residues and inputs to groundwater from landfill sites. Estimate for 2002 indicate that 2000 tonnes of portable NiCd batteries end up in the MSW stream and cause the input of 13 to 66 kg cadmium to groundwater.		[EC 2003] figures may not include emission during mining and processing in foreign countries. European NiCd batteries in cordless power tools (CPT) are responsible for 10.5 % of the total cadmium which is brought into the economy worldwide intentionally. Thus it is expected that a ban has a relevant impact on human cadmium exposure. When NiCd batteries would be replaced in European Cordless Power Tools, 2,200 t/year of very toxic accumulating and category 2 carcinogenic cadmium would be replaced by other, generally less hazardous substances. NiCd batteries create a risk of releases of cadmium to the environment during production and, more significantly, disposal of NiCd batteries. It is estimated that from 2,200 tonnes of cadmium imported to the EU in NiCd batteries for CPTs 22 tonnes are released to the environment during the life cycle The replacement of NiCd

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					batteries by NiMH and Li-ion batteries would result in decreased health and environmental impacts. The monetarisation of the environmental and health benefits of a ban of NiCd batteries is related to high uncertainties. However it is estimated that the benefits are 1 to 2 orders of magnitude higher than the corresponding costs.
Recycling instead of a ban for NiCd batteries in CPTs			The Commission's proposal (a specific collection target for portable NiCd batteries of 80% of the amount of such batteries collected and disposed of) implies that up to 20% of NiCd batteries - or more than 400 tonnes based on the estimate mentioned above - would continue to be disposed of with MSW year on year. A partial ban would stop several hundred tonnes of NiCd batteries ending in MSW each year.	A considerable amount of cadmium is used in batteries for cordless power tools (CPT). Even if the collection of spent batteries lives up to the requirements of the Battery Directive which is 45 % collected by 2016, this means that more than half of all the cadmium in portable batteries will not be collected and dealt with in a secure fashion. The consequence of a ban would be that the cadmium leakage into the environment from spent batteries would decrease and would, in the long term, cease.	An 80 % recycling target seems to be rather optimistic when compared to recycling rates of established systems and is no substitute for a NiCd-ban.

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
Economic impacts					
Risks for mining industry				The mining industry considers itself as a secondary stakeholder and will not be significantly affected by a ban on cadmium in batteries for cordless power tools	Cadmium is produced only as by-product. Therefore the mining industry will not be significantly affected.
Risks for producers of NiCd batteries	There is a risk of side effects for the NiCd batteries industry on other segments of the NiCd batteries	Industry estimates that a turnover of approximately € 1 billion is generated by the NiCd battery production activities. However, since the policy option is only limited to a small part of the NiCd battery market, the economic impacts for the manufacturers are expected to be less than this.	It is unclear whether there is any significant economic impact on EU producers of nickel and cadmium. SAFT is the last European producer of NiCd batteries with plants in DE, FR, ES, SE. Production of NiCd batteries in the EU concerns mainly industrial NiCd batteries. A ban on portable batteries should therefore not have a large direct impact on EU battery manufacturers.	A ban on NiCd batteries for use in CPTs in Europe will probably mean that NiCd batteries, which are currently produced to a certain extent in Europe, will be replaced by Li-Ion batteries produced in Japan.	The last European producer SAFT does not produce portable NiCd batteries for use in CPTs anymore. If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) this may contribute to the creation of new jobs in the manufacturing of current and future substitutes.
Risks for producers of cordless power tools (CPT) and other suppliers	There is a risk of domino effect for importers, assemblers and incorporators		There could be a relevant economic impact on manufacturers of appliances that include batteries (e.g. CPT manufacturers) if the use of substitutes would make the appliances less attractive to potential	Manufacturers and retailers of CPT expect partly positive impacts (speed up of the development of other battery types, especially Li-ion) and partly negative impacts (problems due to the	In total the market is a dynamic and an increasing market (with respect to numbers of cells and value). A ban of NiCd batteries for CPTs could: • Cause costs to technically adapt assembly lines due to

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
			purchasers.	replacement of batteries in older machines).	changing from Ni-Cd battery technology to Li-ion systems (approximately 60 million € one time costs) • reduce turnover of CPT manufacturers due to a shortened natural product life cycle for some NiCd based CPTs (not quantified) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for more powerful and expensive CPTs (ranging from 65 to 326 million €/year and including all costs for required system changes; these costs will decrease over the years) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for the replacement of charging equipment for existing tools (approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced) The NiCd batteries ban could support the transition of the European industry towards more

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					profitable products. Producers of cordless power tools (CPT) see Li-ion-technology as chance.
Risk for professional users				Professional users will not be affected by a ban of NiCd batteries in CPT. Interviews with professional users in northern Sweden indicate that the battery type is not relevant for them. Important are factors such as brand name, performance, capacity and the weight of the CPT	Professional users will not be affected
Risks for waste management sector and recyclers			A ban on portable NiCd batteries could affect the European recyclers of NiCd batteries. However, the factories concerned do not process only portable NiCd batteries, but also industrial NiCd batteries and other types of Nickel batteries.	Recyclers of NiCd batteries do not regard a possible ban of NiCd batteries for CPT as a problem. Management of surplus cadmium may be necessary.	The three European NiCd recycling companies (Accurec, Germany; SAFT, France; SNAM, France) would be affected. The estimates range from 20 to 30 million €/year loss of turnover. A ban of NiCd batteries for CPTs would cause a slow disappearance of waste NiCd batteries from the recycling market. The recycling of NiCd batteries would have to continue for several years for decreasing amounts of NiCd batteries. Part of the market share of NiCd recyclers would shift to recyclers

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					of other battery-types. In the medium term the waste management sector may profit from the elimination of one of the most hazardous substances they have to deal with.
Market distortion	Risk of market distortion if NiCd batteries are e.g. imported with equipment due to deficient control				May exist for no-name products. Not expected to be relevant.
Costs due to higher prices of substitutes	Yes	Substitutes for NiCd batteries in household appliances are more expensive than the NiCd batteries and have a shorter life-time, so this policy option could result in a price increase for rechargeable batteries used in household appliances for consumers. Estimates for additional costs for consumers range from 825 to 1,995 million € per year. The additional costs related to the fact that more waste is to be treated are estimated between 0 and 1.3 million €.	The principal reason why NiCd batteries retain a large market share for cordless power tools (CPT) for DIY users is their lower purchase price. The EIA (Environmental Impact assessment) quotes, in relation to the policy option of a complete cadmium ban, a Bio Intelligence estimate of additional annual costs for consumers of between € 825 and 1,995 million, equivalent to a rough additional cost per year per head of population of somewhere between € 2 and € 5. These figures are based on the dual assumption that portable NiCd batteries are cheaper	The price of a CPT is important for private persons buying a CPT	10 to 50 % higher life-cycle costs of Li-ion systems as compared to NiCd systems Additional costs for final consumers for more powerful and expensive CPTs range from 65 to 326 million €/year. This includes all costs for required system changes. These costs will decrease over the years) Additional costs for final consumers for the replacement of charging equipment for existing tools (costs amount to approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced).
Cost due to more frequent replacement of equipment					

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
			than those using substitute technologies and that they have a longer lifespan. However, these assumptions are open to challenge. The higher capacity of NiMH batteries compared to NiCd combined with equal charging cycles more than compensates the initial sales price. This means that the mentioned additional costs would not actually occur. Additional costs may arise due to the necessary replacement of chargers. Consumers often buy new appliances before they need to replace their batteries. In this case extra costs will not occur.		
Costs for waste treatment due to higher amounts of waste to be treated	Yes				Waste amounts resulting from the use of NiCd batteries and Li-ion batteries in CPTs depend on the lifetime of the Li-ion technology. When the lifetime is 4.3 years (as assumed by [EPTA 2009b]), this would lead to a mass increase of 12 % as compared to NiCd, if the lifetime is the same as NiCd (= 7 years), the mass of the Li-ion batteries

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					would be 30 % less than the mass of NiCd. Relevant economic impacts due to altered amounts of waste to be treated are therefore not expected. Additional costs may arise for the disposal of NiCd batteries as hazardous waste (in a range from 0.26 to 0.4 million €/year on average over a period of 10 years).
Costs to implement and monitor a control system	Yes				Monitoring and control costs for the NiCd ban in addition to the monitoring and control costs of the other Battery-Directive-requirements are expected to be irrelevant.
Social impacts					
Job creation	Job creation for production of substitutes and control system	Job creation for production of substitutes and control system			If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) this may contribute to the creation of new jobs in battery manufacturing (not quantified). The CPT industry will profit from the increased costs for consumers. This may be used for the creation of new workplaces (not quantified). Li-ion driven cordless power tools

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
					(CPT) are manufactured by European companies and may create jobs (not quantified). Job creation is possible in the recycling of technical substitutes particularly in the case of Li-ion batteries (could be in the range of job losses in NiCd recycling, i.e. between 70 and 90 workplaces).
Job losses	Job losses at production, assembling, incorporation, distribution Impacts on indirect jobs. Risk of outsourcing of production outside the EU	The EU produces approximately one third of the global cadmium production and exports 40% of it. Industry estimates a job loss of 10,000 jobs in the zinc and cadmium production industry if a general cadmium ban in all battery applications were to be implemented. Furthermore, industry claims that 3,500 people are directly employed by NiCd battery producers in the EU. However, as all producers also produce the substitutes to the portable NiCd batteries in household appliances (such as NiMH and Li- ion batteries), this policy	Social impacts depend on whether the direct or indirect impacts will lead to job losses.		Europe in 2008 covered only 4.7 % of the world cadmium refinement (USGS 2009). Cadmium is produced as by-product and not on its own. A number of 70 to 90 workplaces will be lost at EU recyclers of NiCd batteries. It can be expected that job losses in the NiCd recycling sector will be balanced by new jobs related to the recycling of NiCd battery substitutes. NiCd batteries for CPTs are not produced within the EU. Impacts on workplaces in the EU batteries industry are not expected. No job effect is expected in the mining sector.

Expected Impact	[Bio 2003]	[EC 2003]	[CEU 2004]	[SE EPA 2009]	Findings of this study
		option might eventually have limited negative effects on employment.			

Table 5-31 : Concerned actors and identified relevant impacts related to a ban of cadmium in batteries (n.r. = not relevant)

Actors	Expected impacts
(A) Raw material supplier for battery manufacturers (in particular Ni, Cd, Li, Co and Mn industry)	Only a small part of the primary metals used in rechargeable batteries originate from Europe. Thus the impact will be mostly outside Europe. A ban would cause a shift from cadmium refinement to the mining of other metals. As cadmium is mined only as by-product of zinc-mining the effect on raw material suppliers will be small. With respect to cobalt and lithium (contained in Li-ion batteries) primary reserves are concentrated in few countries. Therefore high price volatilities are to be expected. However, there are also mature Li-ion technologies without cobalt.
(B) Operational equipment manufacturer (OEM) for battery manufacturers	n.r.
(C) Battery manufacturer of portable NiCd, NiMH, Li-ion and other technical substitutes (including manufacturer of battery packs for CPTs)	All NiCd batteries used in CPTs are imported to the EU, mainly from Asia. Economic or social impacts on the EU batteries industry are not expected. If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) this may contribute to the creation of new jobs in the manufacturing of current and future substitutes. European production of NiMH and Li-ion must take efforts to get a sustainable market share. A ban of NiCd might be of help for the market development.
(D) Battery retailer	n.r.
(E) DIY consumers of CPTs	Dependent on the actual lifetime of the Li-ion batteries, Li-ion-based cordless power tool systems are 10 to 50 % more expensive than the NiCd-based systems. Additional costs for final consumers for more powerful and expensive CPTs range from 65 to 326 million €/year. This includes all costs for required system changes. These costs will decrease over the years) Additional costs for final consumers for the replacement of charging equipment for existing tools (costs amount to approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced). However, the Li-ion may prove to be more comfortable for the user (lighter, no full discharge required, less frequent charging, more powerful tools).
(F) Professional consumers of CPTs	
(G) Battery collector	n.r.
(H) Battery recycler	The three European NiCd recycling companies (Accurec, Germany; SAFT, France; SNAM, France) would be affected. Estimates range from 20 to 30 million €/year loss of turnover related to 70 to 90 workplaces. A ban of NiCd batteries for CPTs would cause a slow disappearance of waste NiCd batteries from the recycling market. The recycling of NiCd batteries would have to continue for several years for decreasing amounts of NiCd batteries. It can be expected that job losses in the NiCd recycling sector will be

		balanced by new jobs related to the recycling of NiCd battery substitutes.
(I)	Disposal company that disposes of waste from battery recycling	Treatment of landfill leachate for cadmium may be eliminated. However, additional efforts for fluoride monitoring and control may be necessary.
(J)	Raw material supplier for CPT manufacturers	n.r.
(K)	Operational equipment manufacturer (OEM) for CPT manufacturers	n.r.
(L)	CPT manufacturer (including importer, assembler, battery incorporator)	In total the market is a dynamic and an increasing market (with respect to numbers cordless power tools (CPT) and value). A ban of NiCd batteries for CPTs could: • cause costs to technically adapt assembly lines due to changing from Ni-Cd battery technology to Li-ion systems (approximately 60 million € one time costs) • reduce turnover of CPT manufacturers due to a shortened natural product life cycle for several CPTs (not quantified) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for more powerful and expensive CPTs (ranging from 65 to 326 million €/year and including all costs for required system changes such as product development and waste management; these costs will decrease over the years) • increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for the replacement of charging equipment for existing tools (approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced) The NiCd batteries ban could support the transition of the European industry towards more profitable products. Selected producers of cordless power tools (CPT) see Li-ion-technology as chance. Industry expects non quantified economic and social impacts on EU battery pack assemblers.
(M)	CPT retailer	Depends from impacts on CPT manufacturer
(N)	CPT collector	n.r.
(O)	CPT recycler	n.r.
(P)	Disposal company that disposes of waste from CPT recycling	n.r.
(Q)	Society and Environment	The replacement of NiCd batteries by NiMH and Li-ion batteries would result in decreased health and environmental impacts. The monetarisation of the environmental and health benefits of a ban of NiCd batteries is related to high uncertainties. However it is estimated that the benefits are 1 to 2 orders of magnitude higher than the corresponding costs. In total the NiCd ban will have either no effect on the jobs in Europe or a positive effect by supporting more innovative and profitable products (batteries and cordless power tools). The additional costs for the consumers are only partly caused by

	material costs. It can be assumed that parts of the additional costs create opportunities, profit and jobs for cordless power tool producers and battery producers. From the environmental point of view the NiCd ban is seen as the most efficient instrument to take one of the most hazardous substances out of the economic cycles in substantial quantities. This will not only be of benefit for health and environment but also make waste management to some extent less complex.
(R) Public authorities	Monitoring and control costs for the NiCd ban in addition to the monitoring and control costs of the other Battery-Directive-requirements are expected to be irrelevant.

On the 6th of November 2009 the results of the "Study Cadmium in power tool batteries - The possibility and consequences of a ban" by the Swedish Environmental Protection Agency were presented in Brussels [Ängerheim 2009].

The task that formed the basis of the report [SE EPA 2009] *"was to study whether it was possible, and what the consequences would be, of removing the derogation at EU level concerning permitting cadmium in batteries for power tools. The consequences of banning cadmium in these batteries can be divided up into consequences for professional users and consequences for other actors. For professional users the primary task is to study if power tools are perceived as performing less well as the result of a ban. The other actor group consists mainly of actors in the battery and power tool markets.*

The conclusion of this project is that the consequences for both professional users and other actors will be limited in scope and temporary in nature.

An examination of consequences for actors on the battery market shows that all actors, with the exception of battery producers, regard themselves as secondary stakeholders. Consequences for battery producers should be regarded in a broader perspective. Companies who wish to survive in the long term must follow developments and adopt new technologies as they appear. A ban on cadmium in batteries for power tools probably means that the three or four producers in Europe will be forced make new investments in order to adapt production or will have to close down their operations. Retaining cadmium in a product because it affects a handful of producers in the short term can, however, not be a reasonable point of departure for modern, European environmental legislation. As the EC Council, UN and WHO have all stated that cadmium may cause major health and environmental damage then the focus should instead be on these consequences and the consequences for the end users of the power tools.

The list of advantages and disadvantages of the different types of batteries shows that they all have both. However the conclusion must be that Li-Ion and NiMH are today fully competitive alternatives to NiCd, both as concerns price and performance.

Experience of Swedish environmental charges has proved that there are fully competitive alternatives to NiCd batteries on the market today with just as high performance rates. The decrease in sales experienced by NiCd in Sweden during the years after the environmental charge was introduced in 1997 prove that, given sufficient financial incentives, NiCd batteries could have already been replaced then."

The study [SE EPA] came to the following main conclusions:

- *"The EC Council, UN and WHO all state that cadmium is a problem for health and the environment.*
- *In connection with the preparation of the Battery Directive it was observed that as soon as there were fully acceptable alternatives, cadmium would be banned for these products.*
- *Batteries are responsible for a considerable part of cadmium use in the world.*
- *There are currently competitive alternatives to NiCd batteries for power tools, both as concerns price and performance.*

- *Swedish experience of levying an environmental charge proves that it is possible to replace NiCd in power tools.*
- *The development of the Li-Ion has progressed extremely rapidly over the last few years. These batteries possess low weight and a high level of capacity.*
- *Professional users want light tools that are strong and lie well in the hand. Many users are not aware of the type of batteries they have in their tools.*
- *There are a handfull manufacturers of NiCd batteries intended for power tools in Europe. Other stakeholders consider themselves to be secondary stakeholders only."*

The European Power Tool Association (EPTA) and RECHARGE[41] submitted comments on the study of the Swedish EPA. The European Commission asked the authors of the present study to reflect on these comments.

EPTA critizised the Swedish study in 3 respects:

1. The report only covers Sweden and Norway while drawing conclusions for the EU
2. A statement "Li-ion is the cheapest battery chemistry per kWh" is derived from Japanese date which are not representative for Europe.
3. That the study interprets the EU wrongly by "The EU has stated in connection with the review of the Battery Directive that if there are **any** alternatives to cadmium for batteries available, the substance **should be** banned in this context." [EPTA 2009c].

Our reflections to comment 1 are: In spite of the focus on information from Sweden and Norway, many of the conclusions seem to be valid for the EU.

Our reflections to comment 2 are: According to our own calculations the system cordless power tool – Li-ion-battery is some 10 to 50 % more expensive than the system cordless power tool – NiCd battery. On the other hand Li-ion batteries provide some additional comfort and show lower environmental impact than the NiCd batteries.

Our reflections to comment 3 are: For us the question is, do the environmental benefits from taking NiCd from the cordless power tool market outweigh the negative consequences of a NiCd ban? The results of the present study show, that the answer to this question is, yes.

The main conclusion of RECHARGE can be summarized as follows:

1. Today NiCd dominate the cost sensitive market segment and Li-ion the high end market segment
2. Even when the cost per Wh is considered the Li-ion remains the more expensive technology.
3. The efficiency of the collection of spent NiCd batteries used in cordless power tools (CPT) will be the critical factor to maintain the control of the flow of these batteries in the economy.

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[41] "RECHARGE aisbl" is the international association for the promotion and management of portable rechargeable batteries through their life cycle.

4. Any policy aiming at the protection of the environment and at the optimisation of the use of raw materials should consider high collection rates as a sustainable policy option for the placing on the market of batteries in the future independent of the battery technology [Recharge 2009].

Our reflections to these comments are: While all these statements are true, we do not agree to the possible interpretation that the EU could abstain from a ban of NiCd batteries in cordless power tools (CPT). A high recycling rate is very important (see next paragraph) but it is not an alternative for a ban of a substance which should be kept from the economy as far as possible.

The use of recycled metals in battery production instead of virgin metals has positive environmental impacts through reduced energy use and reduced pollution related to the mining of the virgin source. As an example, using recycled nickel require 75% less primary energy compared with the extraction and refining of virgin metal. For zinc, the relation between the energy needed for recycling and the energy needed for extraction from primary resources is 2.2 to 8. These figures are particularly important given the fact that the primary production of metals is the source of approximately 10% of global CO_2 emissions [EC 2003].

Nevertheless it has to be accepted that it is extremely difficult to achieve recycling rates of as high as 80 % as discussed in [CEU 2004]. Even in Germany with a long tradition in the establishment of consumer friendly collection systems the recycling rate for NiCd batteries does not exceed 44 % (see chapter 5.4).

Therefore, recycling cannot be a substitute for banning the most hazardous substances, such as cadmium, from the economic material flows. Such a ban of NiCd batteries for CPT also makes the recycling of the other materials more efficient, as the technical effort for recycling decreases when the waste to be treated is not contaminated with cadmium.

5.9 Synopsis of Impact Assessment – Cost Benefit Quantification

Table 5-32 gives an overview of the most important costs of a ban of NiCd batteries in cordless power tools (CPTs) compared to its benefits. As far as available cost and benefit quantifications are given. Details related to the quantification of economic impacts are given in chapter 5.5.

Table 5-32 : Semi-quantitative cost-benefit analysis based on expert judgement

Stakeholder	Cost Items	Quantification	Benefits	Quantification
Public health	No costs		Reduced adverse **health** impacts due to reduced cadmium emissions throughout the life cycle (from 2,200 t/year of less cadmium extracted from ores)	Up to 25 billion €/year (note: the quantification is related to high uncertainty)
Environment	No costs		Reduced adverse **environmental** impacts due to reduced cadmium emissions throughout the life cycle (from 2,200 t/year of less cadmium extracted from ores)	No quantification available
Final consumers	Additional costs for **final consumers** (including the costs for the necessary changes in the battery and recycling industry)	10 to 50% cost increase i.e. 65 to 326 million €/year (the annual costs will decrease over the years)		
	Additional costs for **final consumers** for replacement of charging equipment in existing CPTs	6.4 million €/year until the existing equipment is replaced		
	More difficult operation for **final consumer** at temperatures below 0°C	No quantification available; no relevant economic impact expected	More comfort/service for **final consumer** due to lighter/more powerful equipment which has to be recharged less frequently	No quantification available

Stakeholder	Cost Items	Quantification	Benefits	Quantification
Batteries industry			Possible benefits for EU **batteries industry** due to additional markets for technical substitutes	No quantification available
EU CPT manufacturers	Costs to technically adapt assembly lines due to changing from Ni-Cd battery technology to Li-ion systems Turnover losses for EU **CPT battery pack assemblers**	One time costs of 60 million € No quantification available	Increased turnover corresponding to the additional costs that have to be paid by the final consumer (related to possible creation of workplaces) Increased turnover for EU **CPT manufacturers** for replacement of charging equipment in existing CPTs	65 to 326 million €/year[42] (the annual amount will decrease over the years) 6.4 million €/year until the existing equipment is replaced
Waste management system	Additional costs for the **waste management system** for the disposal of waste NiCd batteries	0.26 to 0.4 million €/year for 10 years	Benefits due to the fact that the waste management sector has to deal with less hazardous substances	No quantification available
Battery recyclers	Economic impact on NiCd recyclers	Losses of turnover from 20 to 30 million €/year (related to loss of 70 to 90 workplaces)	Economic impact on Li-ion recyclers	Increased turnover from 20 to 30 million €/year (related to creation of 70 to 90 workplaces)
	Investment costs for shift from NiCd-recycling to Li-ion recycling (including sunk costs for existing equipment and tools)	One time costs (not quantified)		
Public administration	**Administrative costs** for monitoring the ban	No quantification available (small in comparison of existing monitoring obligations of batteries directive)		

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[42] A part of these additional costs will be used to cover the one time adaptation costs for final consumers, CPT manufacturers, waste management and recycling ranging from 107 to 128 million €.

The most significant costs are the additional costs for final consumers. The costs for all NiCd-based CPTs (together with one power pack and charging equipment) sold in Europe in 2008 is estimated to be some 653 million €. When assuming that the additional costs for Li-ion-battery systems are 10 to 50 %, the additional costs for final consumers caused by a ban of NiCd-batteries in cordless power tools (CPT) lie between 65 and 326 million €/year (see chapter 5.5.5).

A ban of NiCd batteries in CPTs would cause one time costs for financing the necessary adaptations in the battery and CPT supply and waste management industry and for the adaptation of existing CPT systems of final consumers. These comprise:

- For the final consumers during the first 7 to 10 years after the ban has become effective there are additional costs for buying NiMH battery chargers and NiMH batteries for those existing NiCd-battery-based CPTs for which no NiCd batteries will be available any more. These costs are estimated to be 6.4 million €/year during this period;
- One time costs of 60 million € for shifting the CPT production from NiCd based systems to Li-ion based systems;
- Costs of 2,6 to 4 million € for disposing the NiCd-batteries which are still in the system but cannot be recycled anymore;
- One time costs (not quantified) for shifting the recycling system from NiCd to Li-ion (see chapter 5.5.6).

Table 5-33 summarises these system adaptation costs. The table shows that the ban of NiCd batteries in CPTs will cause one time costs ranging from 107 to 128 million €. These costs will be covered by the final consumers, either directly or indirectly by a part of the above mentioned higher costs of the Li-ion-battery systems.

Table 5-33 : Summary of the one-time cost of a NiCd ban in CPTs for the required system adaptations

	Adaptation costs in million €	
	Minimum	Maximum
For final consumers	44,8	64
For CPT manufacturers	60	60
For waste management system*	2,6	4
Total adaptation costs	**107,4**	**128**

* Not considering the one time costs (not quantified) for shifting the recycling system from NiCd to Li-ion systems

The authors' estimates of annual costs of the NiCd-ban for cordless power tools in the range of 65 and 326 million €/year, is in line with estimates of Recharge. [Recharge 2009b] estimated the total costs of the NiCd-battery ban for cordless power tools (CPT) for consumers, the battery and CPT supply industry and the waste management industry combined to be 110 to 190 million €/year.

It, however, needs to be stressed that part of the additional costs for final consumers are spent for additional profits and jobs in Europe due to the sales of more powerful and expensive CPTs..

The most important benefit of the NiCd-battery-ban in cordless power tools (CPTs) - that is the reduced health and environmental impact due to reduced mobilisation of cadmium is much more difficult to monetarise. No life-cycle assessment was found in literature which gives concise numbers on the costs of cadmium to environment and health.

Only very rough estimates can be given to show the order of magnitude of the health impacts.

According to [Recharge 2009b] 64 % of a European smoker's cadmium exposition can be related to smoking while only 0,12 % (or 0.8 tonnes of Cd per year) is related to the cadmium emissions from the incineration of NiCd-batteries in residual household waste. According to [ENSP 2009] smoking is still the biggest cause of preventable death in the EU, with 650.000 smoking-related deaths each year. Though cadmium is not the only substance which causes the death of these people, cadmium contributes to the death of these people. When assuming the worst case that the cadmium from the incineration of NiCd batteries in residual household waste emitted into air by mass has the same health impact as the cadmium from smoking, it can be concluded that the 0.8 t/year of cadmium from the incineration of NiCd-batteries in residual household waste contribute to the premature death of approximately 1,200 persons per year. But this is the effect of the cadmium from NiCd-batteries in the household waste only. The cadmium emissions during ore processing and manufacture of batteries should be much higher.

As shown in Table 5-20, the NiCd-batteries sold in Europe for cordless power tools (CPTs) per year contain about 2,200 t cadmium. As shown in Table 5-3 about 1 % of the cadmium brought into the Austrian economy is emitted into water and air. If we assume that 1 % is a representative emission rate of cadmium over its lifetime, the cadmium emissions connected to the cadmium in the NiCd-batteries would be 22 t/year. In a worst case assumption, this could contribute to the premature death of approximately 33,500 persons per year.

[EC 2009] estimates the value of a statistical life year[43] to be 75.000 €. If the cadmium on the average reduces the life span of the affected person by only 1 year the total health effect costs would be 2,5 billion €/year. If the cadmium on the average reduces the life span of the affected person by 10 years the total health effect costs would be 25 billion €/year.

When assuming that the ban of NiCd batteries in cordless-power-tools (CPT) increases the life time of 33,500 persons per year for 1 year, the health benefit would be 2,5 billion €/year. When assuming that the ban of NiCd batteries in cordless-power-tools (CPT) increases the life time of 33,500 persons per year for 10 years, the health benefit would be 25 billion €/year.

In addition, there are the benefits for the reduced effects on the environment, which could be in a similar order of magnitude.

Environmental impacts from cadmium emissions during the whole life cycle of NiCd batteries are even more difficult to quantify and are therefore not included in the quantified cost estimates. However, it has to be noted:

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[43] The 'value of a statistical life year' is an standard expression used in health statistics. It denotes the value of the extension of one average person's life time expectancy by one year.

- that a considerable amount of the cadmium brought into Europe by NiCd batteries for CPTs, dissipates via the leachate of the landfills into the environment over many decades (and not just in one year);
- that cadmium is, inter alia, very toxic to aquatic life with long lasting effects;
- that therefore there is a high probability that the release of cadmium to air, water and soil/sediment actually causes and will cause significant adverse environmental impacts. These could be in the same order of magnitude as the health impacts.

The identified quantifiable costs for final consumers are additional annual costs of 65 to 326 million €/year for the more expensive Li-ion-battery based CPT systems. A part of these additional costs will be used to cover the one time adaptation costs for final consumers, CPT manufacturers, waste management and recycling ranging from 107 to 128 million €. The corresponding quantifiable one time benefits sum up to a range from approximately 45 to 64 million €/year.

The health benefits are estimated to amount up to 25 billion €/year. The environmental benefits could be in a comparable range.

Without taking account of health and environmental benefits the expected one time cost benefit ratio ranges from approximately 1 to 2. The annual cost benefit ratio is approximately 1.

Taking also the expected health and environmental benefits into account, it can however be assumed that the overall cost benefit ratio lies significantly below 1 because health and environmental benefits related to a ban of cadmium in batteries for the use in CPTs are expected being significantly higher than the corresponding costs.

6 Conclusions

Market data

The task of the market analyses was to provide an overview on the EU and worldwide market of portable batteries intended for the use in cordless power tools (CPT) as a basis for the technical and impact assessment of a possible ban of NiCd batteries intended for the use in CPTs.

The 2008 world market for portable rechargeable batteries (9,200 million US $) is dominated by Japan (5,100 million US $), China (2,300 million US $) and Korea (1,800 million US $). Sales in the rest of the world are below 100 million US $. The market of portable rechargeable batteries used for CPTs is increasing and was in 2008 13% of the world market value.

In the dynamic and growing CPT sector, the trend for NiCd batteries is decreasing whereas it is increasing for Li-ion batteries and more or less stable for NiMH batteries. Other battery technologies are currently not used in CPTs.

In total a number of around 1060 million cells (of all relevant types) have been used in cordless power tools (CPT) worldwide in 2008. This corresponds to a value of about 1400 million US $.

The number of cells used in CPTs in Europe in 2008 is about 41 % of the world market and estimated to amount to 436 million cells. These were used in about 12.9 million CPT units related to a market value of 1440 million US $.

The following table summarises shares of battery technologies currently applied in Europe in cordless power tools (CPT):

Table 6-1 : Shares of battery technologies applied in cordless power tools in Europe in 2008

NiCd	Li-ion	NiMH	Information and source
55%	36%	9%	Current share [EPTA 2009a]

A recent EPTA survey has shown that for 9 EPTA member companies (which represent a significant proportion of the market), the total share of battery technologies was NiCd 49% (professional CPTs 42%, DIY CPTs 54%), NiMH 11% (professional CPTs 19%, DIY CPTs 6%), Li-Ion 40% (professional CPTs 39%, DIY CPTs 40%) [EPTA 2009d]. These data indicate that the share of NiCd may actually be lower and that of Li-ion be higher than shown in Table 3-7 and that the penetration of Li-ion is higher in the segment of professional CPTs compared to DIY CPTs.

The number of NiCd cells used in CPTs in 2008 was about 515 million cells worldwide and 240 million cells within the EU. This corresponds to a world market share of 47%.

The average mass of a NiCd cell used in CPTs is 55 g resulting in a total mass of 13,200 tonnes of NiCd cells used in CPTs in Europe in 2008.

SAFT is the last European producer of NiCd cells. The production of NiCd cells by SAFT has decreased to 8% of the world market in 2008 i.e. to approximately 56 million dollars or about 84 million cells. SAFT does not produce any more NiCd cells for batteries intended for the use in CPTs. All NiCd batteries used in CPTs are imported to the EU.

Technical and impact assessment

The task of the technical and the impact assessment was to elaborate what would be the consequence of a ban of NiCd batteries for their application in cordless power tools (CPT) or more exactly what would be the consequence of limiting the cadmium concentration in the energy storage system of cordless power tools (CPT) at 0,002% by weight.

Current market trends and the technical assessment let expect that:

- For existing NiCd-driven cordless power tools[44] NiMH-power packs would be used as replacement (today power tools are sold which can be driven by either NiCd or NiMH batteries, only a different charging equipment may be necessary);
- New cordless power tools[45] would be driven by Li-ion-power packs;
- In the medium to long term, improved Lithium or Lithium-ion-batteries, Nickel-zinc-batteries, Carbon Nanotube Enhanced Supercapacitors may substitute the Li-ion-battery of today;
- In the long term possibly portable fuel cells or redox flow batteries may substitute the Li-ion battery of today.

However, already today's Li-ion-battery is a more than good substitute for NiCd batteries in cordless power tools (CPT). Li-ion batteries are:

- lighter,
- lose less energy during storage,
- have a better energy efficiency,
- store more energy per volume and
- Li-ion batteries having three times the cell voltage of NiCd batteries, will allow to design much more powerful CPTs in future.

Shortcomings of Li-ion batteries in comparison to NiCd batteries are the limitation in operations below 0 °C and a yet uncertain life-time.

The poor sub-zero °C performance of Li-ion batteries, however, does not keep professionals from preferring Li-ion batteries over NiCd batteries even in cold areas such as Northern Sweden.

The uncertain life-time is less a technical as an economic restriction. Even the most conservative estimate [EPTA 2009b] reports Li-ion of having 62 % of the NiCd's life-time-energy storage capacity. Other sources [Bosch 2009a] attest Li-ion batteries to have the same life-time-energy storage capacity as NiCd. Consequently the life-time system costs of Li-ion are

- 49 % higher than NiCd-system costs (when assuming as [EPTA 2009b] an average lifetime of 4.3 years for the Li-ion power packs)

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[44] Existing CPTs means CPTs manufactured and placed on the market prior to a ban of NiCd batteries for CPTs

[45] New CPTs means CPTs manufactured and placed on the market after a ban of NiCd batteries for CPTs

- or only 10 % higher (when assuming as [Bosch 2009a] an average lifetime of 7 years for the Li-ion power packs).

In practice the Li-ion batteries (and to a minor extend the NiMH batteries) already have replaced the NiCd batteries in the segment of professional cordless power tools (CPT). Here the technical advantages of Li-ion batteries are more important than the additional price.

Particularly in the low-price DIY segment the NiCd still keeps a hold.

Economic Impacts

Miners would be little affected by a NiCd-ban, as the cadmium is recovered from zinc-mining.

SAFT is the last European **battery producer** of NiCd cells. SAFT does not produce any more NiCd cells for batteries intended for the use in CPTs . All NiCd batteries used in CPTs are imported to the EU, mainly from Asia.

In any case the rechargeable NiCd-market is shrinking, leading to shrinking profit margins. Thus, on the medium to long term, NiCd batteries for cordless power tools (CPT) has no good business perspectives even if it is not banned. A ban of NiCd batteries for CPT would only accelerate an existing development.

If the EU battery industry will be able to compete in the market of future battery technologies (such as Li-ion) it can be expected that a ban of NiCd batteries for CPTs may contribute to the creation of new jobs in the manufacturing of current and future substitutes. A ban might support the market development.

There could be a relevant economic impact on **CPT manufacturers** if the use of substitutes would make the appliances less attractive to potential purchasers. However, as the technical performance of NiMH or Li-ion batteries is usually equal or better compared to NiCd batteries and the expected cost increase for CPTs is low to moderate[46] it is not expected that CPT appliances will become significantly less attractive if NiCd batteries for CPTs will be banned.

However a ban of NiCd batteries for CPTs could:

- cause costs for CPT manufacturers to technically adapt assembly lines due to changing from NiCd battery technology to Li-ion systems (approximately 60 million € one time costs);
- reduce turnover of CPT manufacturers due to a shortened natural product life cycle for several CPTs (not quantified);
- increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for more powerful and expensive CPTs (ranging from 65 to 326 million €/year and including all costs for required system changes; these costs will decrease over the years);

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[46] Li-ion driven CPT systems are 10 to 49% more expensive compared to NiCd systems.

- increase turnover of CPT manufacturers corresponding to the additional costs for final consumers for the replacement of charging equipment for existing tools (approximately 6.4 million €/year for the replacement of charging equipment until the existing equipment is replaced).

The NiCd batteries ban could support the transition of the European CPT industry towards the Li-ion technology and (due to the properties of Li-ion batteries) allow CPT producers to develop new, more powerful applications, to develop new markets, to generate more revenue and to create new jobs.

Industry expects non-quantified economic and social impacts on EU CPT battery pack assemblers because their business would be taken over by Asian companies if NiCd batteries would be banned for CPTs.

In the **waste management sector**, the three European companies which today recycle NiCd batteries (Accurec from Germany, SAFT and SNAM from France) would be most affected. The estimates range from 20 to 30 million €/year loss of turnover and loss of 70 to 90 workplaces.

Additional costs may have to be considered for the disposal of NiCd batteries as hazardous waste (cost are estimated in a range from 0.26 to 0.4 million €/year on average over a period of 10 years).

A ban of NiCd batteries for CPTs would cause a slow disappearance of waste NiCd batteries from the recycling market. It is estimated that by a NiCd battery ban for CPTs decided in the year 2010, the arisings of NiCd batteries in Europe would gradually go down to almost 0 by the year 2026. Without such a ban, it is expected that the European NiCd battery waste arisings would stabilize at a level of 12,000 tonnes per year and continue at this level for the foreseeable future.[47] The recycling of NiCd batteries would have to continue for several years for decreasing amounts of NiCd batteries. Part of the market share of NiCd recyclers would shift to recyclers of other battery-types.

In the medium term the waste management sector may profit from the elimination of one of the most hazardous substances they have to deal with.

Environmental impacts

- When only NiMH batteries replaced the NiCd batteries in European Cordless Power Tools,
  - 2,200 t/year of very toxic (also and especially to aquatic organisms), accumulating and category 2 carcinogenic cadmium

  would be replaced by roughly:

  - 4,900 t/year of toxic and category 3 carcinogenic nickel
  - 750 t/year of harmful cobalt and
  - 2,400 t/year of low to moderate toxic mischmetal alloy.
- When only Li-ion batteries replaced the NiCd batteries,

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[47] The current situation (e.g. a ban of NiCd batteries for CPTs) is an annual waste arising of ~ 16 000 tonnes/ year.

- 2,200 t/year of very toxic (also and especially to aquatic organisms), accumulating and category 2 carcinogenic cadmium

would be replaced by roughly:

- 835 t/year of very toxic lithium hexafluorophosphate(or 1,600 t of fluorine) and
- 2,600 t/year of harmful cobalt.

All three technologies, NiCd batteries, NiMH batteries and Li-ion batteries contain hazardous substances. By far the most hazardous substance to health and environment, however, is the cadmium contained only in the NiCd batteries.

Based on the fact that 1 % of the cadmium which is brought into Austria is emitted over its lifetime, it can be estimated that the total cadmium emissions connected to NiCd-batteries for CPTs over its total lifetime is also approximately 1 % of the cadmium contained in these batteries. This results in an amount of cadmium emissions of 22 tonnes connected to the 2,200 tonnes of cadmium brought into the European Union in 2008 by NiCd-batteries for CPTs. A big share of these emissions occurs outside the European Union e.g. during processes related to mining, processing, manufacturing and transport of the cadmium.

Irrespective of these considerations, **NiCd batteries used in Europe in CPTs are responsible for 10.5 % of the total cadmium which is brought into the economy worldwide intentionally**. A ban of NiCd batteries in cordless power tools (CPT) would substantially reduce the amount of cadmium annually brought into the European economy and used in everyday products and the corresponding risk of cadmium releases to the environment.

From the point of view of the environment, a NiCd ban would eliminate cadmium as the most hazardous substance from the portable battery segment and to a large extent (between 50 % (according to [EC 2003b]) and 75 % (according to CEU [2004]) reduce the concentration of the very toxic cadmium in waste streams which contain battery wastes, such as the residual fraction of municipal solid waste.

The cadmium would be replaced by less toxic, but partially still harmful substances such as nickel, cobalt, rare-earths or fluorine containing compounds. These (besides nickel) new substances require adaptations by the waste management sector. Due to the fast market penetration of Li-ion batteries in information- communication and entertainment technologies, these adaptations are required in any case (that is with or without NiCd ban).

From primary resources and the security of supply perspective a NiCd ban would primarily have an effect on the markets of cobalt and lithium (when Li-ion batteries replace the NiCd batteries) and of nickel and rare-earth-oxides (when NiMH batteries replace the NiCd batteries). For all mentioned materials the reserves are large enough to guarantee enough supply for the decades to come. Due to the concentration of the exploitable and production ores in few countries (cobalt in the Democratic Republic of Congo and China, lithium in Chile, and rate-earth oxides in China), however, high future price volatilities for cobalt, lithium and rare-earth oxides need to be expected.

The efficiency of the collection of spent NiCd batteries used in cordless power tools (CPT) is a critical factor to maintain the control of the flow of these batteries in the economy and to avoid high environmental impacts. With currently achieved collection rates (estimation for NiCd battery collection rates in Germany lie between 38 and 44%, see chapter 5.4.1) the majority of the very toxic cadmium contained in NiCd batteries is not treated in specialised battery treatment plants. The only long-term efficient measure to limit the cadmium release from NiCd batteries into the environment is a ban of NiCd batteries also in its use in cordless power tools.

In total the authors conclude that a ban of the application of NiCd batteries in cordless power tools (CPT):

- could be of substantial benefit for European health and environment;
- would not be related to substantial technical problems (only in applications where the temperature lies below 0°C additional equipment to warming the Li-ion batteries before start up might be necessary);
- would not cause inacceptable economic[48] and social impacts[49];
- could support the economy to be more competitive and to gain higher profit margins[50].

In total the identified benefits from a ban of NiCd batteries for application in cordless power tools (CPT) exceed its costs.

In order to achieve all environmental benefits from keeping batteries out of the household waste streams both are necessary:

- A ban of the most hazardous substances and
- High battery collection and recycling rates.

This is also in line with the waste hierarchy as specified in the Waste Frame Directive (2008/98/EC).

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[48] The identified quantifiable costs for final consumers are additional annual costs of 65 to 326 million €/year for the more expensive Li-ion-battery based CPT systems. A part of these additional costs will be used to cover the one time adaptation costs for final consumers, CPT manufacturers, waste management and recycling ranging from 107 to 128 million €. The corresponding quantifiable one time benefits sum up to a range from approximately 45 to 64 million €. The health benefits are estimated to amount up to 25 billion €/year. The environmental benefits could be in a comparable range. Without taking account of any health and environmental benefits the expected one time cost benefit ratio ranges from approximately 1 to 2. Taking also the expected health and environmental benefits into account, it can however be assumed that the overall cost benefit ratio lies significantly below 1 because health and environmental benefits related to a ban of cadmium in batteries for the use in CPTs are expected being significantly higher than the corresponding costs.

[49] It is expected that job losses will be balanced out by the creation of new jobs.

[50] The EU CPT could profit from the additional costs for final consumers ranging from 65 to 326 million €/year. A NiCd battery ban for CPTs could accelarate the transition to the Li-ion technology.

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8 Annexes

8.1 Appendix A – Fact sheets on metals used in portable rechargeable batteries

The following fact sheets provide an overview of the properties, health effects, use, occurrence, current market issues, primary production, prices, reserves, recyclability and substitutability of the most critical materials of portable rechargeable batteries.

8.2 Cadmium (Cd)

8.2.1 Properties, Environmental/Health Impacts

Cadmium is a relatively rare, soft, bluish-white, transition metal. Cadmium is a soft, malleable, ductile, toxic, bluish-white bivalent metal. It is similar in many respects to zinc but reacts to form more complex compounds. The most common oxidation state of cadmium is +2, though rare examples of +1 can be found.

Cadmium is known to cause cancer and occurs with zinc ores. Cadmium is used largely in batteries and pigments, for example in plastic products [Wikipedia 2009N].

Table 8-1: Physical and chemical characterization, labeling requirements and limit values for Cadmium [JRC 2009, Wikipedia 2009N, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name			Cadmium
Symbol			Cd
Atomic Number			48
Element category			transition metals
Appearance			silvery grey metallic
Standard atomic weight in g/mol			112.41
Density (at room temperature) in g/cm^3			8.65
Melting point in °C			321
Boiling point in °C			767
Mohs hardness			2
Standard voltage at pH=0 in V			-0.402
Mass share of earth crust in %			0.00003
CAS registry number			7440-43-9
Labelling requirements according to Directive 1967/548/EEC	Labels		F, N, T+
	R-phrases		R:17-26-45-48/23/25-50/53-62-63-68
	S-phrases		S: 7/8-43-45-53-60-61
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H332 H312 H302 H400 H410
OSHA permissible exposure limits (PEL)	acceptable ceiling concentration in mg/m^3		0.3
	8-hour average in mg/m^3	total particulate	0.2
		respirable particulate	0.1
Austrian Grenzwerteverordnung	TRK-value	Daily average in mg/m^3	0.015 (respirable particulate)
		15 min average in mg/m^3	0.06 (respirable particulate)
	List of carcinogenic	A2 Substances which cause tumors with	cadmium and its compounds

	substances	animals

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;
For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration; TRK-value = technical compliance concentration.

Health effects

Even doses of as little as 50 milligrams of cadmium compounds are toxic to humans as cadmium is easily resorbed and interacts with the zinc metabolism. Current research has found that cadmium toxicity may be carried into the body by zinc binding proteins; in particular, proteins that contain zinc finger protein structures. Zinc and cadmium are in the same period on the periodic table, contain the same common oxidation state (+2), and when ionized are almost the same size. Due to these similarities, cadmium can replace zinc in many biological systems, in particular, systems that contain softer ligands such as sulfur. Cadmium can bind up to ten times stronger than zinc in certain biological systems, and is notoriously difficult to remove. In addition, cadmium can replace magnesium and calcium in certain biological systems, although, these replacements are rare [Wikipedia 2009N].

As consequence of chronic exposure cadmium accumulates in the cell and suppresses the intracellular zinc supply.

Cadmium can be taken up via the breathing air, via food or via drinking water. Cadmium accumulates in the liver and especially in the kidneys. Heavy organ damage may be caused. Cadmium vapour may irritate the eyes and especially the respiratory tract. Inhalation may cause headache and oedemata of the lungs.

Chronic cadmium poisoning may lead to the loss of smelling capacity, yellow coloured teeth and anemia. Cadmium may cause osteoporosis and sever damage of the skeleton (Itai-Itai-disease in Japan).

Cadmium is an occupational hazard associated with industrial processes such as metal plating and the production of nickel-cadmium batteries, pigments, plastics and other synthetics. The primary route of exposure in industrial settings is inhalation. Inhalation of cadmium-containing fumes can result initially in metal fume fever but may progress to chemical pneumonitis, pulmonary edema, and death [Wikipedia 2009N].

Cadmium and several cadmium-containing compounds are known carcinogens and can induce many types of cancer [Wikipedia 2009N]. At high chronic exposure cadmium may cause prostate cancer [Parzefall 2001]. In addition Cadmium is suspected to be mutagenic for germ cells [DFG 2004]. Cadmium affects the repair mechanisms of DNA-damage and thus favours the formation of cancer.

Environmental effects

Cadmium emissions accumulate in the environment and are a potential environmental hazard. Human exposures to environmental cadmium are primarily the result of the burning of fossil fuels and municipal wastes. However, there have been notable instances of toxicity as the result of long-term exposure to cadmium in contaminated food and water.

Precautions

While working with cadmium it is important to do so under a fume hood or with the use of an appropriate respirator to protect against dangerous fumes. Solder, for example, which may contain cadmium, should be handled with care [Wikipedia 2009N].

8.2.2 Use

Cadmium use in batteries amounted to an estimated 83% of global consumption. The remaining 17% was distributed as follows: pigments, 8%; coatings and plating, 7%; stabilizers for plastics, 1.2%; and nonferrous alloys, photovoltaic devices, and other, 0.8%. The percentage of cadmium consumed globally for NiCd battery production has been increasing, while the percentages for the other traditional end uses of cadmium—specifically coatings, pigments, and stabilizers—have gradually decreased, owing to environmental and health concerns. A large percentage of the global NiCd battery market was concentrated in Asia [USGS 2009].

8.2.3 Occurence

Cadmium occurs in zinc ores in a proportion between 1:27 and 1:7,000 [Fleischer et al. 1974) and has an average crustal abundance by mass of 0.1 mg/kg [Alloway 1995]. Its availability in soils is dependent on the bio-geochemical parameters of soils.

Cadmium is a common impurity in zinc, and it is most often isolated during the production of zinc. Zinc sulfide ores are roasted in the presence of oxygen converting the zinc sulfide to the oxide. Zinc metal is produced either by smelting the oxide with carbon or by electrolysis in sulfuric acid. Cadmium is isolated from the zinc metal by vacuum distillation if the zinc is smelted, or cadmium sulfate is precipitated out of the electrolysis solution [Wikipedia 2009N].

Cadmium-containing ores are rare and when found they occur in small quantities. Greenockite (CdS), the only cadmium mineral of importance, is nearly always associated with sphalerite (ZnS). Consequently, cadmium is produced mainly as a by-product from mining, smelting, and refining sulfide ores of zinc, and to a lesser degree, lead and copper. Small amounts of cadmium, about 10% of consumption, are produced from secondary sources, mainly from dust generated by recycling iron and steel scrap [Wikipedia 2009N].

8.2.4 Events, Trends and Issues

Concern over cadmium’s toxicity has spurred various recent legislative efforts, especially in the European Union, to restrict the use of cadmium in most of its end-use applications. The final effect of this legislation on global cadmium consumption has yet to be seen. If recent legislation involving cadmium dramatically reduces long-term demand, a situation could arise, such as has been recently seen with mercury, where an accumulating oversupply of by-product cadmium will need to be permanently stockpiled [USGS 2009].

8.2.5 Production, Reserves, Prices

Table 8-2: Production, reserves, reserve-ranges and price of Cadmium as Cd [USGS 2001, 2009]

	Production in kt		Δ production 2000 to 2008 in %	Reserves in kt	Reserve base in kt	Resource potential in kt	Range in years			Price in USD/t		Δ prices 2000 to 2008 in %
	2000	**2008**					**of reserves**	**of reserve base**	**of resource potential**	**2000**	**2008**	
China	2.3	4.1	82	99	280		24	68				
Korea, Rep. of		3.5										
Kazakhstan	1.0	2.1	110	41	89		20	42				
Canada	2.4	2.1	-11	23	84		11	40				
Japan	2.6	2.0	-22									
Rest of world	13.7	9.0	-34	327	747		36	83				
World total	**19.3**	**20.8**	**8**	**490**	**1,200**	**6,000**	**24**	**58**	**288**	**220**	**6,860**	**3,012**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices
Resource = a concentration of a naturally occuring material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Most of the world's primary cadmium (approximately 51%) was being produced in Asia and the Pacific—specifically China, Japan, and the Republic of Korea—followed by North America (22%), Central Europe and Eurasia (18%), and Western Europe (6%).

Cadmium is generally recovered as a by-product from zinc concentrates. Zinc-to-cadmium ratios in typical zinc ores range from 200:1 to 400:1. Sphalerite (ZnS) is the most economically significant zinc mineral. Cadmium, which shares certain similar chemical properties with zinc, will often substitute for zinc in the sphalerite crystal lattice. The cadmium mineral greenockite (CdS) is frequently associated with weathered sphalerites and wurtzites [(Zn, Fe)S] but usually at microscopic levels. Estimated world identified resources of cadmium were about 6 million tonnes, based on identified zinc resources of 1.9 billion tonnes containing about 0.3% cadmium. Zinc-bearing coals of the Central United States and Carboniferous age coals of other countries also contain large subeconomic resources of cadmium [USGS 2009].

8.2.6 Recycling

Cadmium is mainly recovered from spent consumer and industrial NiCd batteries. Other waste and scrap from which cadmium can be recovered includes copper-cadmium alloy scrap, some complex nonferrous alloy scrap, and cadmium-containing dust from electric arc furnaces [USGS 2009].

Global secondary cadmium production accounted for approximately 20% of all cadmium metal production, and this percentage was expected to increase in the future [USGS 2009].

8.2.7 Substitutes

Lithium-ion and nickel-metal hydride batteries are replacing NiCd batteries in some applications. However, the higher cost of these substitutes restricts their use in less expensive products. Except where the surface characteristics of a coating are critical (e.g., fasteners for aircraft), coatings of zinc or vapor-deposited aluminum can be substituted for cadmium in many plating applications. Cerium sulfide is used as a replacement for cadmium pigments, mostly in plastics. Barium/zinc or calcium/zinc stabilizers can replace barium/cadmium stabilizers in flexible polyvinylchloride applications [USGS 2009].

8.3 Cobalt (Co)

8.3.1 Properties, Environmental/Health Impacts

Cobalt is a hard, lustrous, grey metal. Cobalt is found in various metallic-lustred ores for example cobaltite (CoAsS), but it is produced as a by-product of copper and nickel mining. The copper belt in the Democratic Republic of the Congo and Zambia yields most of the worldwide mined cobalt.

Cobalt is used in the preparation of magnetic, wear-resistant, and high-strength alloys. Cobalt blue (cobalt(II) aluminate, CoAl2O4) gives a distinctive deep blue color to glass, ceramics, inks, paints, and varnishes. Cobalt-60 is a commercially important radioisotope, used as a tracer and in the production of gamma rays for industrial use.

Table 8-3: Physical and chemical characterisation, labelling requirements and limit values for Cobalt [JRC 2009, Wikipedia 2009o, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name			Cobalt
Symbol			Co
Atomic Number			27
Element category			tranistion metals
Appearance			hard lustrous gray metal
Standard atomic weight in g/mol			58.9332
Density (at room temperature) in g/cm^3			8.9
Melting point in °C			1,495
Boiling point in °C			2,928
Mohs hardness			5
Standard voltage at pH=0 in V			-0.277
Mass share of earth crust in %			0.003
CAS registry number			7440-48-4
Labelling requirements according to directive 1967/548/EEC	Labels		Xn
	R-phrases		R: 42/43-53
	S-phrases		S: (2)-22-24-37-61
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H334 H317 H413
OSHA permissible exposure limits (PEL)	8-hour average in mg/m^3	total particulate	0.1
Austrian Grenzwerteverordnung	TRK-value	Daily average in mg/m^3	0.1 (respirable particulate)
		15 min average in mg/m^3	0.4 (respirable particulate)
	List of carcinogenic substances	A2 Substances which cause tumors with animals	cobalt and its compounds

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;
For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration TRK-value = technical compliance concentration.

Health Effects

Cobalt and cobalt compounds have caused local, injection-site tumors in experimental animals.

Pulmonary disease has been reported frequently in workers exposed to cobalt in the manufacture of cemented tungsten carbide. The adverse effect of exposure is generally chronic interstitial pneumonitis. Fatalities have been reported occasionally from exposures to cobalt at concentrations of 1 to 2 mg/m3 or less. An increase in serum A-2 globulin fraction was reported in the case of a welder exposed to fumes containing cobalt; the welder had a history of exertional dyspnea and an abnormal chest X-ray. Allergic dermatitis has been caused by contact with cobalt and its compounds [NIOSH 2009].

8.3.2 Use

There are many different applications of cobalt (see Table 8-4); most are high-tech applications such as batteries, super-alloys, catalysts and hard metals [Angerer et al. 2009].

In 2006 the global cobalt demand was caused 30 % by Europe, 29 % by the Americas, 20 % by Japan and also 20 % by China [Angerer et al. 2009].

Table 8-4: Application of cobalt [Angerer et al. 2009]

Application segment	Share in %	Technology and product examples
Batteries	22	Lithium-ion- and nickel-metal-hydride-accumulators
Super-alloys	22	Gas-turbine-blades, medical implantates for hips and knees
Catalysts	11	Fischer-Tropsch-synthesis for gas- and biomass-to-liquid fuels
Hard-metals	11	Cutting tools (cementing material for tungsten-, titanium- and tantalum-carbide)
Pigments	9	Glass, ceramics
High-temperature steels, surface layers	8	Turbine-blades, wear-resistant engine parts
Chemicals	8	Tire additives, cobalt soaps, ink-siccative
Magnetic alloys	7	Electro-engines, -generators, permanent magnets
Other	2	Magnetic tabes, medicaments, food additive

Alloys

The cobalt based superalloys consume most of the produced cobalt. The temperature stability of these alloys make them suitable for turbine blades within gas turbines and jet aircraft engines. The nickel-based single crystal alloys surpass the cobalt based in temperature stability, but the cobalt based are still in use. These alloys are also corrosion and wear-resistant. Special cobalt chromium molybdenum alloys are used for prosthetic parts such as hip and knee replacements. Some high speed steels also use cobalt to increase heat and wear-resistance. The special alloys of aluminium, nickel and cobalt, known as Alnico, and of samarium and cobalt (samarium-cobalt magnet) are used in permanent magnets, which can be used for recording media, cemented carbides (also called hard metals), and diamond tools.

Batteries

Lithium cobalt oxide ($LiCoO_2$) is widely used in Lithium ion battery electrodes. Nickel-cadmium (NiCd) and nickel metal hydride (NiMH) batteries also contain significant amounts of cobalt.

Catalyst

Several cobalt compounds are used in chemical reactions as catalysts. Cobalt acetate is used for the production of terephthalic acid as well as dimethyl terephthalic acid, which are key compounds in the production of PET. The steam reforming and hydrodesulfuration for the production of petroleum, which uses mixed cobalt molybdenum aluminium oxides as a catalyst, is another important application. Cobalt and its compounds, especially cobalt carboxylates (known as cobalt soaps), are good oxidation catalysts. They are used in paints, varnishes, and inks as drying agents through the oxidation of certain compounds. The same carboxylates are used to improve the adhesion of the steel to rubber in steel-belted radial tires.

Other uses

- Cobalt blue glass
- Electroplating due to its appearance, hardness, and resistance to oxidation
- Ground coats for porcelain enamels
- Purification of histidine-tagged fusion proteins in biotechnology applications [Wikipedia 2009o].

In the US cobalt was consumed in 2008 in following applications:

- 46% in superalloys, mainly in aircraft gas turbine engines;
- 8% in cemented carbides for cutting and wearresistant applications;
- 15% in various other metallic applications;
- and 31% in a variety of chemical applications.

The total estimated value of cobalt consumed in the US in 2008 was $850 million [USGS 2009].

Future use

The share of cobalt use for battery production has doubled from 11 % in 2003 to 22 % in 2006. Lithium-ion-accumulators seem to be the most promising electricity storage technology of the future. Development and industrial applications are driven by mobile electronic devices and electro-vehicles, both sectors with above-the-average growth expectations.

The demand of super-alloys is driven by aeronautics industry (including military applications) and by high efficiency power plants (both with high growth expectations).

Gas- and biomass-to-liquid fuels show the potential to break the dominance of crude oil as basis for liquid fuels. The expectations for gas-to-liquid-fuels growth are very high, especially when the crude oil price stays at a high level for a longer period of time.

Cobalt is seen as being irreplaceable for high-performance cutting tools. It is used as cement for carbides, primarily tungsten-carbide but also niobium-, tantalum-, titanium- and chromium-carbide. These hard-metals are produced by means of powder metallurgy. They are irreplaceable with highest cutting velocities and satisfactory tool life spans for the efficient production of metal parts.

There are also high-growth-expectations for safe and long-lasting orthopedic implants, made mostly of titanium but reinforced at the most critical places by a wear resistant cobalt-chromium-molybdenum-alloy.

Table 8-5 shows the estimated cobalt demand for 3 emerging technologies in 2003 and in 2006 [Angerer et al. 2009].

Table 8-5: Cobalt demand for 3 emerging technologies [Angerer et al. 2009]

Technology	**Demand in kt**	
	2006	**2030**
Lithium-ion-high-performance-electricity-storage	12.0	20.4
Gas-/coal-/biomass-to-liquid-fuel production	Low	4.1
Orthopedic implants	0.8	2.4
Cobalt demand	12.8	26.9
Cobalt demand / cobalt production 2006	19 %	40 %

8.3.3 Events, Trends and Issues

During 2008, production from new operations or expansions of existing operations began in Australia, Canada, Congo (Kinshasa), Cuba, Finland, and Zambia. Numerous additional brownfield and greenfield projects that would add to future world cobalt supply were in the planning and development stages. The overall trend in the price of cobalt cathode was downward during the first 11 months of 2008. Low cobalt, copper, and nickel prices and the serious downturn in the global financial markets in late 2008 were expected, however, to delay financing, construction, and startup of some new production [USGS 2009].

The London Metal Exchange announced a plan to launch a cobalt contract during the second half of 2009. The global contract would include delivery to warehouses in Baltimore, Rotterdam, and Singapore; would trade in 1-tonne lots of minimum 99.3% cobalt; and be priced in dollars per kilogram [USGS 2009].

China was the world’s leading producer of refined cobalt, and much of its production was from cobalt-rich ore and partially refined cobalt imported from Congo (Kinshasa). As a result of restrictions on exports of unprocessed cobalt from Congo (Kinshasa), the Chinese cobalt industry was expected to develop more domestic and foreign sources of cobalt supply, to invest in African cobalt projects, to increase the recycling of cobalt scrap, to continue to shift its consumption towards more downstream materials, and to consolidate into fewer larger companies [USGS 2009].

8.3.4 Occurence

Cobalt is a ferromagnetic metal. Pure cobalt is not found in nature, but compounds of cobalt are common. Small amounts of it are found in most rocks, soil, plants, and animals. In nature, it is frequently associated with nickel, and both are characteristic minor components of meteoric iron.

Cobalt occurs in copper and nickel minerals and in combination with sulfur and arsenic in the sulfidic cobaltite ($CoAsS$), safflorite ($CoAs_2$) and skutterudite ($CoAs_3$) minerals. The mineral cattierite is similar to pyrite and occurs together vaesite in the copper deposits in the Katanga Province. If the sulfides come in contact with the atmosphere weathering starts transforming the minerals by oxidation. The products of the oxidation are for example pink erythrite ('cobalt glance': Co3(AsO4)2·8H2O) and sphaerocobaltite (CoCO3) [Wikipedia 2009o].

8.3.5 Production, Reserves, Prices

Table 8-6: Production, reserves, reserve-ranges and price of Cobalt (as Co) [USGS 2001, 2009]

	Production in kt		Δ production 2000 to 2008 in %	Reserves in kt	Reserve base in kt	Resource potential in kt	Range in years			Price of cobalt for cathodes in USD/t		Δ prices 2000 to 2008 in %
	2000	2008					of reserves	of reserve base	of resource potential	2000	2008	
Congo, D.R.	7.0	32.0	357	3,400	4,700		106	147				
Canada	5.0	8.3	66	120	350		14	42				
Zambia	4.0	7.8	95	270	680		35	87				
Australia	5.7	6.3	11	1,500	1,800		238	286				
Russia	4.0	5.8	45	250	350		43	60				
Rest of world	6.6	11.6	76	1,560	5,120	.	134	441				
World total	**32.3**	**71.8**	**122**	**7,100**	**13,000**	**15,000**	**99**	**181**	**209**	**34,171**	**89,065**	**161**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices
Resource = a concentration of a naturally occuring material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Identified world cobalt resources are about 15 million tonnes. The vast majority of these resources are in nickel-bearing laterite deposits, with most of the rest occurring in nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Australia, Canada, and Russia, and in the sedimentary copper deposits of Congo (Kinshasa) and Zambia. In addition, as much as 1 billion tonnes of hypothetical and speculative cobalt resources may exist in manganese nodules and crusts on the ocean floor [USGS 2009].

8.3.6 Recycling

Cobalt is expensive and scarce. Cobalt recovery from scrap and catalysts are state-of-the-art. More difficult and expensive is the recovery of cobalt from batteries. Here substantial recycling capacities need to be developed in future [Angerer et al. 2009].

In 2008 in the US, cobalt contained in purchased scrap represented an estimated 20% of cobalt reported consumption [USGS 2009]. A similar number may be true for Europe [Angerer et al. 2009].

8.3.7 Substitutes

In most applications, substitution of cobalt would result in a loss in product performance. Potential substitutes include barium or strontium ferrites, neodymium-iron-boron, or nickel-iron alloys in magnets; iron-cobaltnickel, nickel, cermets, or ceramics in cutting and wear-resistant materials; nickel-based alloys or ceramics in jet engines; nickel in petroleum catalysts; rhodium in hydroformylation catalysts; cobalt-manganese-nickel in lithium-ion batteries; and cerium, iron, lead, manganese, or vanadium in paints [USGS 2009].

8.4 Lithium (Li)

8.4.1 Properties, Environmental/Health Impacts

Lithium is a soft alkali metal with a silver-white color. Under standard conditions, it is the lightest metal and the least dense solid element. Like all alkali metals, lithium is highly reactive, corroding quickly in moist air to form a black tarnish. For this reason, lithium metal is typically stored under the cover of oil. When cut open, lithium exhibits a metallic lustre, but contact with oxygen quickly turns it back to a dull silvery grey color. Lithium is also highly flammable [Wikipedia 2009P].

Table 8-7: Physical and chemical characterisation, labelling requirements and limit values for Lithium [JRC 2009, Wikipedia 2009P, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name		Lithium
Symbol		Li
Atomic Number		3
Element category		alkali metals
Appearance		silvery white
Standard atomic weight in g/mol		6.941
Density (at room temperature) in g/cm³		0.53
Melting point in °C		181
Boiling point in °C		1,342
Mohs hardness		0.6
Standard voltage at pH=0 in V		-3.02
Mass share of earth crust in %		0.006
CAS registry number		7439-93-2
Labelling requirements according to directive 1967/548/EEC	Labels	C, F+
	R-phrases	R: 14/15-34
	S-phrases	S: (1/2)-8-43-45
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	H260 H314

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant.
For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively

Like other alkali metals, lithium has a single valence electron which it will readily lose to form a cation, indicated by the element's low electronegativity. As a result, lithium is easily deformed, highly reactive, and has lower melting and boiling points than most metals. These and many other properties attributable to alkali metals' weakly held valence electron are most distinguished in lithium, as it possesses the smallest atomic radius and thus the highest electronegativity of the alkali group.

Lithium has about half the density of water, giving solid sticks of lithium metal the odd heft of a light-to-medium wood such as pine. The metal floats in hydrocarbons; in the laboratory, jars of lithium are typically composed of black-coated sticks held down in hydrocarbon mechanically by the jar's lid and other sticks.

Lithium possesses a low coefficient of thermal expansion and the highest specific heat capacity of any solid element. Lithium has also been found to be superconductive below 400 µK. This finding paves the way for further study of superconductivity, as lithium's atomic lattice is the simplest of all metals [Wikipedia 2009P].

Health effects

Trace amounts of lithium are present in the oceans and in some organisms, though the element serves no apparent biological function in humans. Nevertheless, the neurological effect of the lithium ion Li+ makes some lithium salts useful as a class of mood stabilizing drugs.

Lithium metal, due to its alkaline tarnish, is corrosive and requires special handling to avoid skin contact. Breathing lithium dust or lithium compounds (which are often alkaline) can irritate the nose and throat; higher exposure to lithium can cause a build-up of fluid in the lungs, leading to pulmonary edema. The metal itself is usually a handling hazard because of the caustic hydroxide produced when it is in contact with moisture. Lithium should be stored in a non-reactive compound such as naphtha [Wikipedia 2009P].

8.4.2 Use

Lithium and its compounds have several commercial applications, including heat-resistant glass and ceramics, high strength-to-weight alloys used in aircraft, and lithium batteries. Lithium serves as the fusion fuel in staged thermonuclear weapons.

Because of its specific heat capacity, the highest of all solids, lithium is often used in heat transfer applications. It is an important ingredient in anode materials, used in Lithium-ion batteries because of its high electrochemical potential, light weight, and high current density. Large quantities of lithium are also used in the manufacture of organolithium reagents, especially n-butyllithium which has many uses in fine chemical and polymer synthesis.

Other uses of lithium are:

- Lithium batteries are disposable (primary) batteries that have lithium metal or lithium compounds as an anode. Lithium batteries are not to be confused with lithium-ion batteries which are high energy-density rechargeable batteries.
- Lithium chloride and lithium bromide are extremely hygroscopic and frequently used as desiccants.
- Lithium stearate is a common all-purpose high-temperature lubricant.
- Lithium is an alloying agent used to synthesize organic compounds.
- Lithium is used as a flux to promote the fusing of metals during welding and soldering. It also eliminates the forming of oxides during welding by absorbing impurities. This fusing quality is also important as a flux for producing ceramics, enamels, and glass.
- Lithium is sometimes used in glasses and ceramics including the glass for the 200-inch telescope at Mt. Palomar.
- Alloys of the metal with aluminium, cadmium, copper and manganese are used to make high performance aircraft parts.

- Lithium-aluminium alloys are used in aerospace applications, such as the external tank of the Space Shuttle, and is planned for the Orion spacecraft.
- Lithium niobate is used extensively in telecommunication products, such as mobile phones and optical modulators, for such components as resonant crystals. Lithium products are currently used in more than 60 percent of mobile phones.
- The high non-linearity of lithium niobate also makes a good choice for non-linear optics applications.
- Lithium peroxide, lithium nitrate, lithium chlorate and lithium perchlorate are used and thought of as oxidizers in both rocket propellants and oxygen candles to supply submarines and space capsules with oxygen.
- Lithium fluoride (highly enriched in the common isotope lithium-7) forms the basic constituent of the preferred fluoride salt mixture (LiF-BeF2) used in liquid-fluoride nuclear reactors.
- Lithium will be used to produce tritium in magnetically confined nuclear fusion reactors.
- Lithium hydroxide (LiOH) is a strong base, and when heated with a fat, it produces a lithium soap. Lithium soap has the ability to thicken oils and so is used commercially to manufacture lubricating greases.
- It is also an efficient and lightweight purifier of air.
- Lithium can be used to make red fireworks [Wikipedia 2009P].

Global end-use markets for lithium are estimated as follows:

- batteries, 25%;
- ceramics and glass, 18%;
- lubricating greases, 12%;
- pharmaceuticals and polymers, 7%;
- air conditioning, 6%;
- primary aluminum production, 4%;
- continuous casting, 3%;
- chemical processing 3%;
- and other uses, 22%.

Lithium use in batteries expanded significantly in recent years because rechargeable lithium batteries were being used increasingly in portable electronic devices and electrical tools [USGS 2009].

8.4.3 Occurence

Lithium is widely distributed on Earth, however, it does not naturally occur in elemental form due to its high reactivity. Estimates for crustal content range from 20 to 70 ppm by weight. In keeping with its name, lithium forms a minor part of igneous rocks, with the largest concentrations in granites. Granitic pegmatites also provide the greatest abundance of lithium-containing minerals, with spodumene and petalite being the most commercially viable mineral sources for the element. A newer source for lithium is hectorite clay, the only active development of which is through Western Lithium Corp in the USA.

According to the Handbook of Lithium and Natural Calcium, "Lithium is a comparatively rare element, although it is found in many rocks and some brines, but always in very low concentrations. There are a fairly large number of both lithium mineral and brine deposits but only comparatively a few of them are of actual or potential commercial value. Many are very small, others are too low in grade." The most important deposit of lithium is in the Salar de Uyuni area of Bolivia, which holds half of the world's reserves. The lithium reserves are estimated at 30 million tonnes in 2015.

Seawater contains an estimated 230 billion tonnes of lithium, though at a low concentration of 0.1 to 0.2 ppm.

On a commercial scale, lithium metal is isolated electrolytically from a mixture of lithium chloride and potassium chloride [Wikipedia 2009P].

8.4.4 Events, Trends and Issues

Subsurface brines have become the dominant raw material for lithium carbonate production worldwide because of lower production costs as compared with the mining and processing costs for hard-rock ores. Two brine operations in Chile dominate the world market; a facility at a brine deposit in Argentina produced lithium carbonate and lithium chloride. A second brine operation was under development in Argentina. Most of the lithium minerals mined in the world were used directly as ore concentrates in ceramics and glass applications rather than feedstock for lithium carbonate and other lithium compounds. Based on new information, lithium production was apparently discontinued in Russia during the early 1990s.

The market for lithium compounds with the largest potential for growth is batteries, especially rechargeable batteries.

Demand for rechargeable lithium batteries continued to grow for use in cordless tools, portable computers and telephones, and video cameras. Several major automobile companies were pursuing the development of lithium batteries for hybrid electric vehicles - vehicles with an internal combustion engine and a battery-powered electric motor. Most commercially available hybrid vehicles use other types of batteries, although future generations of these vehicles may use lithium. Nonrechargeable lithium batteries were used in calculators, cameras, computers, electronic games, watches, and other devices [USGS 2009].

8.4.5 Production, Reserves, Prices

Table 8-8: Production, reserves, reserve-ranges and price of Lithium as Li [USGS 2001, 2009]

	Production in kt						Range in years			Price in USD/t		
	2000	2008	Δ production 2000 to 2008 in %	Reserves in kt	Reserve base in kt	Resource potential in kt	of reserves	of reserve base	of resource potential	2000	2008	Δ prices 2000 to 2008 in %
Chile	5.5	12.0	118	3,000	3,000		250	250				
Australia	2.0	6.9	245	170	220		25	32				
China	2.0	3.5	75	540	1,100		154	314				
Argentina	0.2	3.2	1,500									
Canada	0.7	0.7	0	180	360		254	507				
Rest of world	2.6	1.1	-58	210	6,320		193	5,798				
World total (without US production)	**13.0**	**27.4**	**111**	**4,100**	**11,000**	**13,000**	**150**	**401**	**474**	**23,800**	**32,000**	**34**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices
Resource = a concentration of a naturally occuring material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Chile was the leading lithium chemical producer in the world; Argentina, China, and the United States also were major producers. Australia, Canada, Portugal, and Zimbabwe were major producers of lithium ore concentrates. The United States remained the leading consumer of lithium minerals and compounds and the leading producer of value-added lithium materials. Because only one company produced lithium compounds from domestic resources, reported production and value of production data cannot be published [USGS 2009].

The identified lithium resources total more than 13 million tonnes world wide [USGS 2009].

8.4.6 Recycling

Up to now recycling is insignificant, but increasing through the recycling of lithium batteries [USGS 2009].

8.4.7 Substitutes

Substitutes for lithium compounds are possible in batteries, ceramics, greases, and manufactured glass. Examples are calcium and aluminum soaps as substitutes for stearates in greases; calcium, magnesium, mercury, and zinc as anode material in primary batteries; and sodic and potassic fluxes in ceramics and glass manufacture.

Lithium carbonate is not considered to be an essential ingredient in aluminum potlines. Substitutes for aluminumlithium alloys as structural materials are composite materials consisting of boron, glass, or polymer fibers in engineering resins [USGS 2009].

8.5 Manganese (Mn)

8.5.1 Properties, Environmental/Health Impacts

Manganese is a gray-white metal, resembling iron. It is a hard metal and is very brittle, fusible with difficulty, but easily oxidized. Manganese metal and its common ions are paramagnetic. While manganese metal does not form a permanent magnet, it does exhibit strong magnetic properties in the presence of an external magnetic field.

Manganese is found as a free element in nature (often in combination with iron), and in many minerals. As a free element, manganese is a metal with important industrial metal alloy uses, particularly in stainless steels.

Manganese ions have various colors, depending on their oxidation state, and are used industrially as pigments. The permanganates of sodium, potassium and barium are powerful oxidisers. Manganese dioxide is used as the cathode (electron acceptor) material in standard and alkaline disposable dry cells and batteries [Wikipedia 2009Q].

Table 8-9: Physical and chemical characterisation, labelling requirements and limit values for Manganese [JRC 2009, Wikipedia 2009Q, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name			Manganese
Symbol			Mn
Atomic Number			25
Element category			tranistion metals
Appearance			silvery metallic
Standard atomic weight in g/mol			54.938
Density (at room temperature) in g/cm^3			7.43
Melting point in °C			1,536
Boiling point in °C			2,062
Mohs hardness			6
Standard voltage at pH=0 in V			-1.05
Mass share of earth crust in %			0.09
CAS registry number			7439-96-5
Labelling requirements according to directive 1967/548/EEC	Labels		F (powder)
	R-phrases		R: 11 (powder)
	S-phrases		S: 7-33-43-60(powder)
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H332 H302
OSHA permissible exposure limits (PEL)	8-hour average in mg/m^3	total particulate	5
Austrian Grenzwerteverordnung	MAK-value	Daily average in mg/m^3	0.5 (respirable particulate)
		Limit for short term exposure in mg/m^3	2 (respirable particulate)
		Duration of short term exposure in min	15
		Frequency of short term exposure per shift	4

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;
For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration TRK-value = technical compliance concentration.

8.5.2 Health Effects

Manganese(II) ions function as cofactors for a number of enzymes in higher organisms, where they are essential in detoxification of superoxide free radicals. The element is a required trace mineral for all known living organisms. In larger amounts, and apparently with far greater activity by inhalation, manganese can cause a poisoning syndrome in mammals, with neurological damage which is sometimes irreversible [Wikipedia 2009Q].

Symptoms of manganese poisoning range from sleepiness and weakness in the legs, to difficulty in walking and uncontrolled laughter. Health surveys of employees exposed to manganese fume have demonstrated a high incidence of pneumonia in these workers [NIOSH 2009].

8.5.3 Use

Industrially important compounds

Methylcyclopentadienyl manganese tricarbonyl is used as an additive in unleaded gasoline to boost octane rating and reduce engine knocking. The manganese in this unusual organometallic compound is in the +1 oxidation state.

Manganese(IV) oxide (manganese dioxide, MnO2) is used as a reagent in organic chemistry for the oxidation of benzylic alcohols (i.e. adjacent to an aromatic ring). Manganese dioxide has been used since antiquity to oxidatively neutralize the greenish tinge in glass caused by trace amounts of iron contamination. MnO2 is also used in the manufacture of oxygen and chlorine, and in drying black paints. In some preparations it is a brown pigment that can be used to make paint and is a constituent of natural umber.

Manganese(IV) oxide was used in the original type of dry cell battery as an electron acceptor from zinc, and is the blackish material found when opening carbon-zinc type flashlight cells. The same material also functions in newer alkaline batteries (usually battery cells), which use the same basic reaction, but a different electrolyte mixture.

Manganese phosphating is used as a treatment for rust and corrosion prevention on steel.

Permanganate (+7 oxidation state) manganese compounds are purple, and can color glass an amethyst color. Potassium permanganate, sodium permanganate and barium permanganate are all potent oxidizers. Potassium permanganate, also called Condy's crystals, is a commonly used laboratory reagent because of its oxidizing properties and finds use as a topical medicine (for example, in the treatment of fish diseases). Solutions of potassium permanganate were among the first stains and fixatives to be used in the preparation of biological cells and tissues for electron microscopy [Wikipedia 2009Q].

Metal alloys

Manganese is essential to iron and steel production by virtue of its sulfur-fixing, deoxidizing, and alloying properties. Steelmaking, including its ironmaking component, has accounted for most manganese demand, presently in the range of 85% to 90% of the total demand. Among a variety of other uses, manganese is a key component of low-cost stainless steel formulations and certain widely used aluminium alloys.

The metal is used in coins. The EU uses manganese in 1 and 2 Euro coins, due to greater and cheaper availability [Wikipedia 2009Q].

Most US ore consumption was related to steel production, directly in pig iron manufacture and indirectly through upgrading ore to ferroalloys. Additional quantities of ore were used for such nonmetallurgical purposes as production of dry cell batteries, in plant fertilizers and animal feed, and as a brick colorant. Manganese ferroalloys were produced at two smelters, although one operated sporadically throughout the year. Construction, machinery, and transportation end uses accounted for about 29%, 10%, and 10%, respectively, of manganese demand. Most of the rest went to a variety of other iron and steel applications [USGS 2009].

8.5.4 Production, Reserves, Prices

Table 8-10: Production, reserves, reserve-ranges and price of Manganese as Mn [USGS 2001, 2009]

	Production in kt		**Δ production 2000 to 2008 in %**	**Reserves in kt**	**Reserve base in kt**	**Resource potential in kt**	**Range in years**			**Price of manganese, cif US ports in USD/t**		**Δ prices 2000 to 2008 in %**
	2000	**2008**					**of reserves**	**of reserve base**	**of resource potential**	**2000**	**2008**	
South Africa, Rep. Of	1,500	3,000	100	95,000	4,000,000		32	1,333				
China	1,100	2,800	155	40,000	100,000		14	36				
Australia	875	2,200	151	68,000	160,000		31	73				
Gabon	1,000	1,600	60	52,000	90,000		33	56				
Brazil	660	1,300	97	35,000	57,000		27	44				
Rest of world	2,315	3,100	34	210,000	793,000		68	256				
World total	**7,450**	**14,000**	**88**	**500,000**	**5,200,000**		**36**	**371**		**239**	**1,297**	**443**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices
Resource = a concentration of a naturally occuring material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

South Africa accounts for about 80% of the world's identified manganese resources, and Ukraine accounts for 10% [USGS 2009].

8.5.5 Recycling

Manganese is recycled incidentally as a minor constituent of ferrous and nonferrous scrap; however, scrap recovery specifically for manganese was negligible. Manganese is recovered along with iron from steel slag [USGS 2009].

8.5.6 Substitutes

Manganese has no satisfactory substitute in its major applications, which are related to metallurgical alloy use. In minor applications, (e.g., manganese phosphating), zinc and sometimes vanadium are viable substitutes. In disposable battery manufacture, standard and alkaline cells using manganese will probably eventually be mostly replaced with lithium battery technology.

The overall level and nature of manganese use in the United States is expected to remain about the same in the near term. No practical technologies exist for replacing manganese with other materials or for using domestic deposits or other accumulations to reduce the complete dependence of the United States on other countries for manganese ore [Wikipedia 2009Q].

8.6 Nickel (Ni)

8.6.1 Properties, Environmental/Health Impacts

Nickel is a silvery-white lustrous metal with a slight golden tinge. It is one of the four ferromagnetic elements at about room temperature. The metal is hard and ductile, as well as corrosion-resistant, finding many uses in alloys, as a plating, in the manufacture of coins, magnets and common household utensils, as a catalyst for hydrogenation, and in a variety of other applications. Enzymes of certain life-forms contain nickel as an active center making the metal essential for them [Wikipedia 2009S].

Table 8-11: Physical and chemical characterisation, labelling requirements and limit values for Nickel [JRC 2009, Wikipedia 2009S, NIOSH 2009, MinEcon AT 2003, Seel 1973]

Name			Nickel
Symbol			Ni
Atomic Number			28
Element category			tranistion metals
Appearance			lustrous, metallic and silvery with a gold tinge
Standard atomic weight in g/mol			58.7
Density (at room temperature) in g/cm^3			8.9
Melting point in °C			1,453
Boiling point in °C			2,914
Mohs hardness			3.8
Standard voltage at pH=0 in V			-0.250
Mass share of earth crust in %			0.01
CAS registry number			7440-02-0
Labelling requirements according to directive 1967/548/EEC	Labels		T (powder)
	R-phrases		R: 40-43-48/23-52/53
	S-phrases		S: (2)-36/37/39-45-61
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes		H351-H317
OSHA permissible exposure limits (PEL)	8-hour average in mg/m^3	total particulate	1
Austrian Grenzwerteverordnung	TRK-value	Daily average in mg/m^3	0.5 (respirable particulate)
		15 min average in mg/m^3	2 (respirable particulate)
	List of carcinogenic substances	A1 - Substances which cause tumors with humans	nickel
		A2 Substances which cause tumors with animals	nickeltetracarbonyl

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;

For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively;
OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration TRK-value = technical compliance concentration.

Similar to the elements chromium, aluminium and titanium, nickel is a very reactive element, but is slow to react in air at normal temperatures and pressures. Due to its permanence in air and its slow rate of oxidation, it is used in coins, for plating metals such as iron and brass, for chemical apparatus, and in certain alloys such as German silver.

Nickel is chiefly valuable for the alloys it forms, especially many superalloys, and particularly stainless steel. Nickel is also a naturally magnetostrictive material, meaning that in the presence of a magnetic field, the material undergoes a small change in length. In the case of Nickel, this change in length is negative (contraction of the material), which is known as negative magnetostriction [Wikipedia 2009S].

Health Effects

Nickel is an essential substance for many organisms. It is unclear if this applies also for the human body. In high doses nickel may cause different diseases.

A variety of toxic effects results from exposure to nickel compounds. Soluble nickel salts cause contact dermatitis in sensitized individuals and eye irritation. Cases of asthmatic lung disease have been reported among nickel-plating workers [DFG 2004].

Exposure to soluble nickel at low levels and for relatively short durations causes pathological changes in the lungs of experimental animals. The results of animal studies suggest that some soluble nickel compounds are potentially carcinogenic [NIOSH 2009]. Especially highly soluble nickel compounds such as nickel acetate and nickel sulfids are suspected to be carcinogenic.

The Austrian TRK-value (limiting the concentration at the working place) of Nickel-powder is 0.5 mg/m³.

8.6.2 Use

Nickel is used in many industrial and consumer products, including stainless steel, magnets, coinage, rechargeable batteries, electric guitar strings and special alloys. It is also used for plating and as a green tint in glass. Nickel is pre-eminently an alloy metal, and its chief use is in the nickel steels and nickel cast irons, of which there are many varieties. It is also widely used in many other alloys, such as nickel brasses and bronzes, and alloys with copper, chromium, aluminum, lead, cobalt, silver, and gold.

The amounts of nickel used for various applications are

- 60% used for making nickel steels,
- 14% used in nickel-copper alloys and nickel silver,
- 9% used to make malleable nickel, nickel clad, Inconel and other superalloys,
- 6% used in plating,
- 3% use for nickel cast irons,
- 3% in heat and electric resistance alloys, such as Nichrome,
- 2% used for nickel brasses and bronzes
- with the remaining 3% of the nickel consumption in all other applications combined.

In the laboratory, nickel is frequently used as a catalyst for hydrogenation, most often using Raney nickel, a finely divided form of the metal alloyed with aluminum which adsorbs hydrogen gas. Nickel is often used in coins, or occasionally as a substitute for decorative silver. The American 'nickel' five-cent coin is 75% copper and 25% nickel. Various other nations have historically used and still use nickel in their coinage [Wikipedia 2009S].

Nickel end uses in the US in 2008 were as follows:

- transportation, 30%;
- chemical industry, 15%;
- electrical equipment, 10%;
- construction, 9%;
- fabricated metal products, 8%;
- household appliances, 8%;
- petroleum industry, 7%;
- machinery, 6%;
- and other, 7% [USGS 2009].

The credit crisis put severe financial pressures on motor vehicle manufacturers, causing them to reassess the post-2010 marketplace. Nickel-metal hydride (NiMH) batteries continue to be widely used in hybrid motor vehicles, despite inroads made by lithium-ion batteries. Sales in the United States of hybrid electric passenger vehicles have risen steadily to 350,000 in 2007 from 9,370 in 2000. Several automobile manufacturers were readying prototype plug-in hybrids or fully electric vehicles for commercial production. High prices for jet fuel encouraged major air carriers to order more fuel-efficient aircraft, increasing the demand for superalloys.

The nuclear power industry was in the early stages of a renaissance because of high prices for natural gas. U.S. utilities were considering constructing 15 to 33 additional nuclear powerplants-facilities that would require sizeable amounts of austenitic stainless steel and other nickel-bearing alloys.

Construction of new wind farms could require significant numbers of nickel-based batteries for energy storage and load leveling [USGS 2009].

8.6.3 Occurence

Nickel occurs most often in combination with sulfur and iron in pentlandite, with sulfur in millerite, with arsenic in the mineral nickeline, and with arsenic and sulfur in nickel galena. Nickel is commonly found in iron meteorites as the alloys kamacite and taenite.

The bulk of the nickel mined comes from two types of ore deposits. The first are laterites where the principal ore minerals are nickeliferous limonite: (Fe, Ni)O(OH) and garnierite (a hydrous nickel silicate): (Ni, Mg)3Si2O5(OH). The second are magmatic sulfide deposits where the principal ore mineral is pentlandite: (Ni, Fe)9S8.

In terms of supply, the Sudbury region of Ontario, Canada, produces about 30 percent of the world's supply of nickel. The Sudbury Basin deposit is theorized to have been created by a meteorite impact event early in the geologic history of Earth. Russia contains about 40% of the world's known resources at the Norilsk deposit in Siberia. The Russian mining company MMC Norilsk Nickel obtains the nickel and the associated palladium for world distribution. Other major deposits of nickel are found in New Caledonia, France, Australia, Cuba, and Indonesia. Deposits found in tropical areas typically consist of laterites which are produced by the intense weathering of ultramafic igneous rocks and the resulting secondary concentration of nickel bearing oxide and silicate minerals. Recently, a nickel deposit in western Turkey had been exploited, with this location being especially convenient for European smelters, steelmakers and factories.

Based on geophysical evidence, most of the nickel on Earth is postulated to be concentrated in the Earth's core. Kamacite and taenite are naturally occurring alloys of iron and nickel. For kamacite the alloy is usually in the proportion of 90:10 to 95:5 although impurities such as cobalt or carbon may be present, while for taenite the nickel content is between 20% and 65%. Kamacite and taenite occur in nickel-iron meteorites [Wikipedia 2009S].

8.6.4 Events, Trends and Issues

Although slightly lower than that of 2007, world nickel mine production was at a relatively high level in 2008 despite the global financial crisis. Stainless steel accounted for two-thirds of primary nickel use, with more than one-half of the steel going into the construction, food processing, and transportation sectors. U.S. production of austenitic (nickel-bearing) stainless steel slipped to 1.35 million tonnes in 2007, 21% less than the record-high 1.71 million tonnes in 2006.

China was the leading consumer of nickel, with an estimated apparent consumption of 348,000 tonnes in 2007. China produced 5.52 million tonnes of austenitic stainless steel in 2007, exceeding the combined output of Japan and the United States.

Declining metal prices, fears of recession, and the tightening of credit forced nickel producers to halt mining at less profitable operations and delay early stage development projects. Three world-class laterite mining complexes were in the final stages of commissioning. In early 2008, Australia’s leading nickel producer began ramping up production at its new $2.2 billion Ravensthorpe Mine, which is northwest of Esperance. Nickel and cobalt were being leached from the ore and converted onsite to a mixed hydroxide intermediate, which was then shipped to Yabulu, Queensland, for refining.

The $3.2 billion laterite mining complex at Goro, New Caledonia, was scheduled to begin production of mixed hydroxide in early 2009. The New Caledonian nickel was being recovered onsite as an oxide using advanced pressure-acid-leach technology.

Work was also underway on two traditional ferronickel plants in the Brazilian States of Goias and Para. The Onca Puma mining complex in Para State was scheduled to begin production of ferronickel in January 2009 [USGS 2009].

8.6.5 Production, Reserves, Prices

Table 8-12: Production, reserves, reserve-ranges and price of Nickel as Ni [USGS 2001, 2009]

	Production in kt		Δ productio	Reserves in kt	Reserve base in kt	Resource potential in kt	Range in years			Price of nickel, LME in USD/t		Δ prices
	2000	2008					of	of	of	2000	2008	

			n 2000 to 2008 in %				reserves	reserve base	resource potential			2000 to 2008 in %
Russia	265	276	4	6,600	9,200		24	33				
Canada	194	250	29	4,900	15,000		20	60				
Indonesia	94	211	126	3,200	13,000		15	62				
Australia	168	180	7	26,000	29,000		144	161				
New Caledonia	120	93	-23	7,100	15,000		77	162				
Rest of world	390	600	54	22,200	68,800		37	115				
World total	**1,230**	**1,610**	**31**	**70,000**	**150,000**	**150,000**	**43**	**93**	**93**	**8,613**	**21,360**	**148**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices
Resource = a concentration of a naturally occuring material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.
LME = London Metal Exchange

Identified land-based resources averaging 1% nickel or greater contain at least 130 million tonnes of nickel. About 60% is in laterites and 40% is in sulfide deposits. In addition, extensive deep-sea resources of nickel are in manganese crusts and nodules covering large areas of the ocean floor, particularly in the Pacific Ocean [USGS 2009].

Nickel prices peaked at unprecedented levels in mid-2007, but gradually declined during the next 18 months as the world economy weakened. In October 2008, the London Metal Exchange cash mean for 99.8%-pure nickel averaged $12,133 per metric tonne ($5.50 per pound), down 61% from the mean in October 2007 [USGS 2009].

8.6.6 Recycling

About 77,300 tonnes of nickel was recovered in the US from purchased scrap in 2008. This represented about 38% of reported secondary plus apparent primary consumption for the year [USGS 2009].

8.6.7 Substitutes

To offset high nickel prices, engineers have begun substituting low-nickel, duplex, or ultrahighchromium stainless steels for austenitic grades in a few construction applications.

Nickel-free specialty steels are sometimes used in place of stainless steel within the power generating and petrochemical industries.

Titanium alloys or specialty plastics can substitute for nickel metal or nickel-based alloys in highly corrosive chemical environments.

Cost savings in manufacturing lithium-ion batteries allow them to compete against NiMH in certain applications [USGS 2009].

8.7 Rare-Earth Metals - Lanthanides

According to IUPAC, rare-earth elements or rare earth metals are a collection of seventeen chemical elements in the periodic table, namely scandium, yttrium, and the fifteen lanthanoids. Scandium and yttrium are considered rare earths since they tend to occur in the same ore deposits as the lanthanoids and exhibit similar chemical properties. Cerium is the most abundant of the rare earth elements [Wikipedia 2009T].

8.7.1 Properties, Environmental/Health Impacts

Cerium is a silvery metal, belonging to the lanthanoid group. It resembles iron in color and luster, but is soft, and both malleable and ductile. Cerium has the longest liquid range of any non-radioactive element: 2648 C° (795 °C to 3443 °C).

Although cerium belongs to the chemical elements group called rare earth metals, it is in fact more common than lead. Cerium is available in relatively large quantities (68 ppm in Earth's crust). It is used in some rare-earth alloys.

Among rare-earth elements, only europium is more reactive. It tarnishes readily in the air. Alkaline solutions and dilute and concentrated acids attack the metal rapidly. Cerium oxidizes slowly in cold water and rapidly in hot water. The pure metal can ignite if scratched.

Cerium(IV) (ceric) salts are orange red or yellowish, whereas cerium(III) (cerous) salts are usually white or colorless. Both oxidation states absorb ultraviolet light strongly. Cerium(III) can be used to make glasses that are colorless, yet absorb ultraviolet light almost completely. Cerium can be readily detected in rare earth mixtures by a very sensitive qualitative test: addition of ammonia and hydrogen peroxide to an aqueous solution of lanthanides produces a characteristic dark brown color if cerium is present [Wikipedia 2009T].

Table 8-13: Physical and chemical characterisation, labelling requirements and limit values for Cerium [JRC 2009, Wikipedia 2009T, NIOSH 2009, Grenzwerteverordnung]

Name		Cerium
Symbol		Ce
Atomic Number		58
Element category		lanthanides
Appearance		silvery white
Standard atomic weight in g/mol		140.12
Density (at room temperature) in g/cm³		6.78
Melting point in °C		798
Boiling point in °C		3,426
Mohs hardness		2.5
Mass share of earth crust in %		0.0046
CAS registry number		7440-45-1
Labelling requirements according	Labels	F

to directive 1967/548/EEC	R-phrases	R: 11
	S-phrases	S: 17
Labelling requirements according to Regulation (EC) No 1272/2008	H-codes	cerium oxide isostearate: H413

Note:
Labels: C = corrosive, E = explosive, F = flammable, N = hazardous to environment, O = oxidising, T = toxic, T+ = very toxic, Xn = harmful, Xi = irritant;
For the meaning of the shown R-, S- and H- codes see Annex B, C and D, respectively.

Health effects

Cerium, like all rare-earth metals, is of low to moderate toxicity. Cerium is a strong reducing agent and ignites spontaneously in air at 65 to 80 °C. Fumes from cerium fires are toxic. Water should not be used to stop cerium fires, as cerium reacts with water to produce hydrogen gas. Workers exposed to cerium have experienced itching, sensitivity to heat, and skin lesions. Animals injected with large doses of cerium have died due to cardiovascular collapse.

Cerium(IV) oxide is a powerful oxidizing agent at high temperatures and will react with combustible organic materials. While cerium is not radioactive, the impure commercial grade may contain traces of thorium, which is radioactive. Cerium serves no known biological function [Wikipedia 2009T].

8.7.2 Use

The use structure of rare earths is dominated by technical properties which are in use for some time:

- Ceriumoxide e.g. in vehicle-exhaust-catalysts increases the activity of rhodium for the reduction of nitrogen oxides. Also lanthanum and lutetium are increasingly used as catalysts.
- Nearly all high-value polished glasses, including mirrors and precision lenses, are treated with ceriumoxide.
- As metallurgical additive (for oxygen and sulfur removal in steel production) and as alloy component mostly a mix of rare-earth-metals or yttrium are used.
- In cathode-ray-equipment, field emitter displays, plasma display panels and fluorescent lamps yttrium, euterbium, gadolinium, terbium and cerium are used as light emitters [Angerer ET AL. 2009].

Rare earth elements are incorporated into many modern technological devices, including superconductors, miniaturized magnets, electronic polishers, refining catalysts and hybrid car components. Rare earth ions are used as the active ions in luminescent materials used in optoelectronics applications, most notably the Nd:YAG laser. Phosphors with rare earth dopants are also widely used in cathode ray tube technology such as television sets.

The use of rare earth elements in modern technology has increased dramatically over the past years. For example, dysprosium has gained significant importance for its use in the construction of hybrid car motors. Unfortunately, this new demand has strained supply, and there is growing concern that the world may soon face a shortage of the materials. All of the world's heavy rare earths (such as dysprosium) are sourced from Chinese Rare Earth sources such as the polymetallic Bayan Obo deposit. High Rare Earth prices have wreaked havoc on many rural Chinese villages, as many illegal rare earth mines have been spewing toxic waste into the general water supply [Wikipedia 2009T].

Uses of cerium in metallurgy:

- Cerium is used in making aluminium alloys.
- Adding cerium to cast irons opposes graphitization and produces a malleable iron.
- In steels, cerium degasifies and can help reduce sulfides and oxides.
- Cerium is used in stainless steel as a precipitation hardening agent.
- 3 to 4% cerium added to magnesium alloys, along with 0.2 to 0.6% zirconium, helps refine the grain and give sound casting of complex shapes. It also adds heat resistance to magnesium castings.
- Cerium is used in alloys that are used to make permanent magnets.
- Cerium is used as an alloying element in tungsten electrodes for gas tungsten arc welding.
- Cerium is a major component of ferrocerium, also known as "lighter flint". Although modern alloys of this type generally use Mischmetal rather than purified cerium, it still is the most prevalent constituent.
- Cerium is used in carbon-arc lighting, especially in the motion picture industry.
- Cerium oxalate is an anti-emetic drug.

Cerium(III) oxide

- As a catalytic converter for the reduction of CO emissions in the exhaust gases from motor vehicles.
- In ceramic form, together with Tin(II) oxide (SnO) it is used for illumination with UV light.
- In the cerium(IV) oxide-cerium(III) oxide cycle.

Cerium(IV) oxide

- The oxide is used in incandescent gas mantles, such as the Welsbach mantle, where it was combined with thorium, lanthanum, magnesium or yttrium oxides .
- The oxide is emerging as a hydrocarbon catalyst in self cleaning ovens, incorporated into oven walls.
- Cerium(IV) oxide has largely replaced rouge in the glass industry as a polishing abrasive.
- Cerium(IV) oxide is finding use as a petroleum cracking catalyst in petroleum refining.
- Cerium(IV) additives to diesel fuel cause that to burn more cleanly, with less resulting air-pollution.
- In glass, cerium(IV) oxide allows for selective absorption of ultraviolet light.
- Cerium(IV) oxide, doped with other rare earth oxides, has been investigated as a solid electrolyte in intermediate temperature solid oxide fuel cells.
- The cerium(IV) oxide-cerium(III) oxide cycle or CeO_2/Ce_2O_3 cycle is a two step thermochemical process based on cerium(IV) oxide and cerium(III) oxide for hydrogen production.
- Cerium(IV) sulfate is used extensively as a volumetric oxidizing agent in quantitative analysis.

Other uses

- Ceric ammonium nitrate is a useful one-electron oxidant in organic chemistry, used to oxidatively etch electronic components, and as a primary standard for quantitative analysis.
- Cerium compounds are used in the manufacture of glass, both as a component and as a decolorizer.
- Cerium in combination with titanium gives a golden yellow color to glass.
- Cerium compounds are used for the coloring of enamel.
- Cerium(III) and cerium(IV) compounds such as cerium(III) chloride have uses as catalysts in organic synthesis [Wikipedia 2009T].

The estimated 2007 distribution of rare earths by end use in the US was as follows:

- glass polishing and ceramics, 34%;
- automotive catalytic converters, 30%;
- rare-earth phosphors for computer monitors, lighting, radar, televisions, and x-ray-intensifying film, 14%;
- chemicals and petroleum refining catalysts, 11%;
- ceramics, 3%;
- pharmaceuticals and pharmaceutical equipment, 3%;
- permanent magnets, 2%;
- metallurgical applications and alloys, 1%;
- laser and scintillator crystals, 1%;
- and other, 1% [USGS 2009].

Rare earths in emerging technologies

Rare earths are important for certain lasers and high-performance magnets:

- Neodyme is added to synthetic yttrium-aluminium-garnets in order to achieve lasers of certain wave lengths. Also ytterbium, erbium and holmium are used in different laser crystals.
- The use of rare earths for magnets has revolutionized this technology. First samarium and since 1984 Nd-Fe-B-alloys have been used for high performance magnets. The magnets are and also in future will be used in miniaturized information and communication technologies (e.g. iPods), electro- and hybride cars.

Table 8-14 shows that the market penetration of high-performance magnets is expected to have a big effect on the year 2030 world neodyme demand [Angerer et al. 2009].

Table 8-14: Neodyme demand for 2 selected emerging technologies [Angerer ET AL. 2009]

Technology	Demand in kt	
	2006	2030
Lasers for material cutting	low	Low
High-performance-magnets	4	27.9
Sum	4	27.9
Neodyme demand / neodyme production 2006	55 %	382 %

8.7.3 Occurence

A rare earth mineral is a mineral whose principal element is a rare earth element. Yttrium is found in almost all rare earth minerals. Rare earth minerals are usually found in association with alkaline to per-alkaline igneous complexes, in pegmatites associated with alkaline magmas and in or associated with carbonatite intrusives. Perovskite mineral phases are common hosts to rare earth elements within the alkaline complexes. Mantle derived carbonate melts also are carriers of the rare earths. Hydrothermal deposits associated with alkaline magmatism contain a variety of rare earth minerals.

The following includes the relatively common hydrothermal rare earth minerals and minerals which often contain significant rare earth substitution:

- aeschynite
- allanite $(Ca, Ce, La, Y)_2(Al, Fe)_3(SiO_4)_3(OH)$
- apatite

- bastnäsite (Ce, La, Y)CO_3F
- britholite
- brockite
- cerite
- fluocerite
- fluorite
- gadolinite
- monazite (Ce, La, Th, Nd, Y)PO_4
- parisite
- stillwellite
- synchisite Ca(Ce, La, Nd, Y)$(CO_3)_2F$
- titanite
- xenotime
- zircon ($ZrSiO_4$)
- zirconolite

Well-known minerals that contain yttrium include gadolinite, xenotime, samarskite, euxenite, fergusonite, yttrotantalite, yttrotungstite, yttrofluorite (a variety of fluorite), thalenite, yttrialite. Small amounts occur in zircon, which derives its typical yellow fluorescence from some of the accompanying heavy lanthanides. The zirconium mineral eudialyte, such as is found in southern Greenland, also contains small but potentially useful amounts of yttrium. Of the above yttrium minerals, most played a part in providing research quantities of lanthanides during the discovery days. Xenotime is occasionally recovered as a by-product of heavy sand processing, but has never been nearly as abundant as the similarly recovered monazite (which typically contains a few percent of yttrium). Uranium ores processed in Ontario have occasionally yielded yttrium as a by-product.

Cerium is the most abundant of the rare earth elements, making up about 0.0046% of the Earth's crust by weight. Monazite and bastnäsite are presently the two most important sources of cerium. Cerium is most often prepared via an ion exchange process that uses monazite sands as its cerium source. It is never found in nature as the free element.

Over the years, monazite (marine sands from Brazil, India, or Australia; rock from South Africa), bastnäsite (from Mountain Pass California, or several localities in China), and loparite (Kola Peninsula, Russia) have been the principal ores of cerium and the light lanthanoids.

A few sites are under development outside of China, the most significant of which are the Nolans Project in Central Australia, the remote Hoidas Lake project in northern Canada and the Mt. Weld project in Australia. The Hoidas Lake project has the potential to supply about 10% of the $1 billion of rare earth consumption that occurs in North America every year

Large deposits of monazite, allanite, and bastnäsite will supply cerium, thorium, and other rare-earth metals for many years to come [Wikipedia 2009T].

8.7.4 Events, Trends and Issues

The rare-earth separation plant at Mountain Pass, CA, resumed operations in 2007 and continued to operate in 2008.

Bastnäsite concentrates and other rare-earth intermediates and refined products continued to be sold from mine stocks at Mountain Pass. Exploration for rare earths continued strong in 2008, and economic assessments continued at Nolans in Australia, Hoidas Lake and Thor Lake in Canada, and Kangankunde in Malawi, Africa. Removal of overburden at the Mt. Weld rare-earth deposit in Australia commenced in early 2008, and initial mining of the open pit was completed in June, recovering 773,300 t of ore at an average grade of 15.4% rare-earth oxides (REO) [USGS 2009].

Neodyme seems to be the metal which controlled the mining of rare earth minerals (bastnäsite). The concentrations of the rare earths in bastnäsite, however, do not comply with their commercial demand. Thus 25 % of the rare earths produced remain unused [Angerer et al. 2009].

8.7.5 *Production, Reserves, Prices*

Table 8-15: Production, reserves, reserve-ranges and price of Rare earths as rare-earth oxides (REO) [USGS 2001, 2009]

	Production in kt		Δ production 2000 to 2008 in %	Reserves in kt	Reserve base in kt	Range in years		Price of Bastnäsite concentrate, rare-earth oxide basis in USD/t		Δ prices 2000 to 2008 in %
	2000	**2008**				**of reserves**	**of reserve base**	**2000**	**2008**	
China	70	120	71	27,000	89,000	225	742			
India	2.7	2.7	0	1,100	1,300	407	481			
Brazil	1.4	0.7	-54	48	84	74	129			
Malaysia	0.3	0.4	52	30	35	79	92			
United States	5.0		-100	13,000	14,000					
Rest of world	1.6	0.3	-84	46,822	45,581	173,415	168,819			
World total	**81**	**124**	**53**	**88,000**	**150,000**	**710**	**1,210**	**2,870**	**8,820**	**207**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices

Consumption increased for cerium compounds used in automotive catalytic converters and in glass additives and glass polishing compounds; rare-earth compounds used in automotive catalytic converters and many other applications; yttrium compounds used in color televisions and flat-panel displays, electronic thermometers, fiber optics, lasers, and oxygen sensors; and phosphors for color televisions, electronic thermometers, fluorescent lighting, pigments, superconductors, x-ray-intensifying screens, and other applications. Consumption was also higher for mixed rare-earth compounds and for rare-earth metals and their alloys used in armaments, base-metal alloys, lighter flints, permanent magnets, pyrophoric alloys, and superalloys. U.S. consumption, however, was substantially lower for rare-earth chlorides used in the production of fluid cracking catalysts used in oil refining. The trend is for a continued increase in the use of rare earths in many applications, especially automotive catalytic converters, permanent magnets, and rechargeable batteries for electric and hybrid vehicles [USGS 2009].

Rare earths are relatively abundant in the Earth’s crust, but discovered minable concentrations are less common than for most other ores. U.S. and world resources are contained primarily in bastnäsite and monazite. Bastnäsite deposits in China and the United States constitute the largest percentage of the world’s rare-earth economic resources, while monazite deposits in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the United States constitute the second largest segment. Apatite, cheralite, eudialyte, loparite, phosphorites, rare-earth-bearing (ion adsorption) clays, secondary monazite, spent uranium solutions, and xenotime make up most of the remaining resources. Undiscovered resources are thought to be very large relative to expected demand [USGS 2009].

Prices were higher in 2008 than in 2007 for most rare-earth products amid increased consumption and a stable supply [USGS 2009].

8.7.6 Recycling

Small quantities, mostly permanent magnet scrap [USGS 2009].

8.7.7 Substitutes

Substitutes are available for many applications, but generally are less effective [USGS 2009].

8.8 Fluorite - Fluorspar

8.8.1 *Properties, Environmental/Health Impacts*

Fluorite (also called fluorspar) is a mineral composed of calcium fluoride, CaF_2.

It is a common mineral in deposits of hydrothermal origin and has been noted as a primary mineral in granites and other igneous rocks and as a common minor constituent of dolostone and limestone.

Fluorite is a widely occurring mineral which is found in large deposits in many areas. Notable deposits occur in Germany, Austria, Switzerland, England, Norway, Mexico, and Ontario in Canada. Large deposits also occur in Kenya in the Kerio Valley area within the Great Rift Valley [Wikipedia 2009z6].

Table 8-16: Physical and chemical characterisation, labelling requirements and limit values for [Wikipedia 2009z6, NIOSH 2009, Grenzwerteverordnung]

Name			Fluorspar
Symbol			CaF_2
Appearance			Colorless, white, purple, blue, blue-green, green, yellow, brownish-yellow, pink or red
Density (at room temperature) in g/cm³			3.2
Mohs hardness			4
OSHA permissible exposure limits (PEL)	8-hour average in mg/m³	total particulate	2.5
Austrian Grenzwerteverordnung	MAK-value	Daily average in mg/m³	2.5 (respirable particulate)
		Limit for short term exposure in mg/m³	12.5 (respirable particulate)
		Duration of short term exposure in min	30
		Frequency of short term exposure per shift	2
Note:OSHA = U.S. Occupational Safety and Health Administration; MAK-value = maximum working place concentration TRK-value = technical compliance concentration.			

8.8.2 *Use*

In the US about 85% of reported fluorspar consumption went into the production of hydrofluoric acid (HF) and aluminum fluoride. HF is the primary feedstock for the manufacture of virtually all organic and inorganic fluorine-bearing chemicals and is also a key ingredient in the processing of aluminum and uranium. The remaining 15% of the reported fluorspar consumption was as a flux in steelmaking, in iron and steel casting, primary aluminum production, glass manufacture, enamels, welding rod coatings, cement production, and other uses or products.

An estimated 52,000 tonnes of fluorosilicic acid (equivalent to about 92,000 tonnes of 92% fluorspar) was recovered in the US from phosphoric acid plants processing phosphate rock. Fluorosilicic acid was used primarily in water fluoridation [USGS 2009].

8.8.3 Production, Reserves, Prices

Table 8-17: Production, reserves, reserve-ranges and price of Fluorspar [USGS 2001, 2009]

	Production in kt		Δ production 2000 to 2008 in %	Reserves in kt	Reserve base in kt	Resource potential in kt	Range in years			Price of metallurgical grade fluorspar, cif US port in USD/t	
	2000	2008					of reserves	of reserve base	of resource potential	2004	2008
China	2,400	3,200	33	21,000	110,000		7	34			
Mexico	542	980	81	32,000	40,000		33	41			
Mongolia	150	400	167	12,000	16,000		30	40			
South Africa, Rep. of	220	340	55	41,000	80,000		121	235			
Russia		200			18,000		0	90			
Rest of world	1,168	720	-38	124,000	206,000		172	286			
World total	**4,480**	**5,840**	**30**	**230,000**	**470,000**	**500,000**	**39**	**80**	**86**	**83**	**104**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices
Resource = a concentration of a naturally occuring material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Identified world fluorspar resources were approximately 500 million tonnes of contained fluorspar.

The quantity of fluorine present in phosphate rock deposits is enormous. Current U.S. reserves of phosphate rock are estimated to be 1.0 billion tonnes, which at 3.5% fluorine would contain 35 million tonnes of fluorine, equivalent to about 72 million tonnes of fluorspar. World reserves of phosphate rock are estimated to be 18 billion tonnes, equivalent to 630 million tonnes of fluorine and 1.29 billion tonnes of fluorspar [USGS 2009].

Acid-grade fluorspar prices increased dramatically and reached historic highs in 2008. A reduction in Chinese exports of fluorspar was the leading cause, but other factors such as increasing costs in China (production, domestic transport, and taxes), high ocean shipping rates, and inflationary pressures contributed to the rise in prices. Published prices for Chinese acid-grade fluorspar delivered to the U.S. Gulf of Mexico increased from a range of $300 to $305 per metric tonne at the beginning of the year to $530 to $550 per tonne in early October. These steep price increases were reflected, although to a lesser degree, in prices for Mexican and South African acid-grade fluorspar. During the same time period, Mexican prices (for low-arsenic product) increased from a range of $270 to $280 per tonne to $400 to $420, while South African prices (free on board Durban) increased from $175 to $204 per tonne to $250 per tonne [USGS 2009].

8.8.4 Recycling

A few thousand tonnes per year of synthetic fluorspar is recovered—primarily from uranium enrichment, but also from petroleum alkylation and stainless steel pickling. Primary aluminum producers recycle HF and fluorides from smelting operations. HF is recycled in the petroleum alkylation process [USGS 2009].

8.8.5 Substitutes

Aluminum smelting dross, borax, calcium chloride, iron oxides, manganese ore, silica sand, and titanium dioxide have been used as substitutes for fluorspar fluxes. By-product fluorosilicic acid from phosphoric acid production has been used as a substitute in aluminum fluoride production, and also has the potential to be used as a substitute in HF production [USGS 2009].

8.9 Graphite

8.9.1 Properties, Environmental/Health Impacts

The mineral graphite is one of the allotropes of carbon. There are three principal types of natural graphite, each occurring in different types of ore deposit: (1) Crystalline flake graphite (or flake graphite for short) occurs as isolated, flat, plate-like particles with hexagonal edges if unbroken and when broken the edges can be irregular or angular; (2) Amorphous graphite occurs as fine particles and is the result of thermal metamorphism of coal, the last stage of coalification, and is sometimes called meta-anthracite. Very fine flake graphite is sometimes called amorphous in the trade; (3) Lump graphite (also called vein graphite) occurs in fissure veins or fractures and appears as massive platy intergrowths of fibrous or acicular crystalline aggregates, and is probably hydrothermal in origin.

HOPG (Highly Ordered Pyrolytic Graphite) is an artificial form used in research.

Graphite has various other characteristics. Thin flakes are flexible but inelastic, the mineral can leave black marks on hands and paper, it conducts electricity, and displays superlubricity. Its best field indicators are softness, luster, density and streak [Wikipedia 2009V].

Table 8-18: Physical and chemical characterisation, labelling requirements and limit values for Carbon and Graphite [JRC 2009, Wikipedia 2009V, NIOSH 2009, Grenzwerteverordnung]

Name			Carbon	Graphite
Symbol			C	
Atomic Number			6	
Element category			nonmetals	nonmetals
Appearance			Black (Graphite), Clear (Diamond	black
Standard atomic weight in g/mol			12.011	
Density (at room temperature) in g/cm³			2.62	2.2
Melting point in °C			3,827	
Boiling point in °C			4,197	
Mohs hardness			0.5-10	1-2
Mass share of earth crust in %			0.09	
CAS registry number			7440-44-0	7782-42-5
OSHA permissible exposure limits (PEL)	8-hour average in mg/m³	total particulate		15
		respirable particulate		5

Note:
OSHA = U.S. Occupational Safety and Health Administration.

Health Effects

Early reports established that graphite deposited in the lungs of occupationally exposed workers caused pneumoconiosis. Subsequent research described the condition produced by exposure to graphite as anthracosilicosis, a pulmonary condition similar to that seen in coal miners, based on radiographic and histologic examinations in exposed individuals. The fibrotic changes seen in graphite workers appear to be related to the silica content of the graphite [Niosh 2009].

8.9.2 Use

Uses of natural graphite

According to the USGS, U.S. consumption of natural graphite in 2005-06 averaged 41,850 tonnes in end uses such as refractories, steelmaking, expanded graphite, brake linings, and foundry facings-lubricants. Graphite Advocate News import-export statistics for 2006 and 2007 indicate the consumption will continue at that level unless steelmaking carbon raiser takes a drastic drop.

Graphene, which occurs naturally in graphite, is the strongest substance known to man, according to a study released in August 2008 by Columbia University. However, the process of separating it from graphite will require some technological development before it is economical enough to be used in industrial processes.

Refractories

The order of importance of graphite’s use as refractory is alumina-graphite shapes, carbon-magnesite brick, monolithics (gunning and ramming mixes), and then crucibles, used to hold molten metal. Crucibles began using very large flake graphite, and carbon-magnesite brick requiring not quite so large flake graphite; for these and others there is now much more flexibility in size of flake required, and amorphous graphite is no longer restricted to low-end refractories. Alumina-graphite shapes are used as continuous casting ware, such as nozzles and troughs, to convey the molten steel from ladle to mould, and carbon magnesite bricks line steel converters and electric arc furnaces to withstand extreme temperatures. Graphite Blocks are also used in parts of blast furnace linings where the high thermal conductivity of the graphite is critical. High-purity monolithics are often used as a continuous furnace lining instead of the carbon-magnesite bricks.

Almost all of the above refractories are used to make steel and account for 75% of refractory consumption; the rest is used by a variety of industries, such as cement.

Steelmaking

Natural graphite in this end use mostly goes into carbon raising in molten steel, although it can be used to lubricate the dies used to extrude hot steel. Supplying carbon raiser is very competitive, therefore subject to cut-throat pricing from alternatives such as synthetic graphite powder, petroleum coke, and other forms of carbon. A carbon raiser is added to increase the carbon content of the steel to the specified level.

Expanded graphite

Expanded graphite is made by immersing natural flake graphite in a bath of chromic acid, then concentrated sulfuric acid, which forces the crystal lattice planes apart, thus expanding the graphite.

The expanded graphite can be used to make graphite foil or used directly as "hot top" compound to insulate molten metal in a ladle or red-hot steel ingots and decrease heat loss, or as firestops fitted around a fire door or in sheet metal collars surrounding plastic pipe, (during a fire, the graphite expands and chars to resist fire penetration and spread.), or to make high-performance gasket material for high-temperature use. After being made into graphite foil, the foil is machined and assembled into the bipolar plates in fuel cells. The foil is made into heat sinks for laptop computers which keeps them cool while saving weight, and is made into a foil laminate that can be used in valve packings or made into gaskets. Old-style packings are now a minor member of this grouping: fine flake graphite in oils or greases for uses requiring heat resistance.

Brake linings

Natural amorphous and fine flake graphite are used in brake linings or brake shoes for heavier (nonautomotive) vehicles, and became important with the need to substitute for asbestos. This use has been important for quite some time, but nonasbestos organic (NAO) compositions are beginning to cost graphite market share. A brake-lining industry shake-out with some plant closings has not helped either, nor has an indifferent automotive market.

Foundry facings and lubricants

A foundry facing or mold wash is a water-based paint of amorphous or fine flake graphite. Painting the inside of a mold with it and letting it dry leaves a fine graphite coat that will ease separation of the object cast after the hot metal has cooled. Graphite lubricants are specialty items for use at very high or very low temperatures, as a wire die extrusion lubricant, an antiseize agent, a gear lubricant for mining machinery, and to lubricate locks. Having low-grit graphite, or even better no-grit graphite (ultra high purity), is highly desirable. It can be used as a dry powder, in water or oil, or as colloidal graphite (a permanent suspension in a liquid).

Other uses

Natural graphite has found uses as the marking material in common pencils, in zinc-carbon batteries, in electric motor brushes, and various specialized applications [Wikipedia 2009V].

Uses of synthetic graphite

Electrodes

Graphite electrodes carry the electricity that heats electric arc furnaces, the vast majority steel furnaces. They are made from petroleum coke after it is mixed with petroleum pitch, extruded and shaped, then baked to sinter it, and then graphitized by heating it above the temperature that converts carbon to graphite. They can vary in size up to 3.3 m long and 0.75 m in diameter. An increasing proportion of global steel is made using electric arc furnaces, and the electric arc furnace itself is getting more efficient and making more steel per tonne of electrode.

Powder and scrap

The powder is made by heating powdered petroleum coke above the temperature of graphitization, sometimes with minor modifications. The graphite scrap comes from pieces of unusable electrode material (in the manufacturing stage or after use) and lathe turnings, usually after crushing and sizing. Most synthetic graphite powder goes to carbon raising in steel (competing with natural graphite), with some used in batteries and brake lining.

Other uses

Graphite (carbon) fiber and carbon nanotubes are also used in carbon fiber reinforced plastics, and in heat-resistant composites such as reinforced carbon-carbon. Products made from carbon fiber graphite composites include fishing rods, golf clubs,bicycle frames,and pool sticks and have been successfully employed in reinforced concrete. The mechanical properties of carbon fiber graphite-reinforced plastic composites and grey cast iron are strongly influenced by the role of graphite in these materials. In this context, the term "(100%) graphite" is often loosely used to refer to a pure mixture of carbon reinforcement and resin, while the term "composite" is used for composite materials with additional ingredients.

Synthetic graphite also finds use as a matrix and neutron moderator within nuclear reactors. Its low neutron cross section also recommends it for use in proposed fusion reactors. Care must be taken that reactor-grade graphite is free of neutron absorbing materials such as boron, widely used as the seed electrode in commercial graphite deposition systems.

Graphite has been used in at least three radar absorbent materials. It was mixed with rubber in Sumpf and Schornsteinfeger, which were used on U-boat snorkels to reduce their radar cross section. It was also used in tiles on early F-117 Nighthawks. Modern gunpowder is coated in graphite to prevent the buildup of static charge.

Graphite also has the interesting property that, under certain conditions, it can serve as a form of armor against nuclear weapons. While there is no practical military application for this, graphite is a common material proposed for the pusher plate of a nuclear pulse rocket; a space vehicle that propels itself by ejecting nuclear explosives through the rear and detonating them [Wikipedia 2009V].

The major uses of natural graphite in the US in 2008 were

- refractory applications, 28%;
- steelmaking and foundry operations, 23%;
- brake linings, 12%;
- batteries and lubricants, 4%;
- and other applications, 33% [USGS 2009].

Occurence, mining and processing

Minerals associated with graphite include quartz, calcite, micas, iron meteorites, and tourmalines. China is usually the top producer of graphite, followed by India and Brazil [Wikipedia 2009V].

Graphite is mined around the world by both open pit and underground methods. While flake graphite and amorphous graphite are both mined open pit and underground, lump (vein) graphite is only mined underground in Sri Lanka. The open pit mines usually employ equipment (i.e. bulldozers) to scoop up the ore, which is usually put in trucks and moved to the plant. Since the original rock is usually lateritized or weathered, this amounts to moving dirt with flecks or pieces of graphite in it from the pit (blasting is seldom required). The underground graphite mines employ drilling and blasting to break up the hard rock (ore), which is then moved by mine cars pulled by a locomotive, or moved by automotive vehicles, to the surface and then to the plant. In less-developed areas of the world, the ore can be mined by pick and shovel and transported by mine cars pushed by a laborer or by women carrying baskets of ore on their heads.

Graphite usually needs beneficiation, although thick-bedded amorphous graphite and vein graphite is almost always beneficiated, if beneficiated at all, by laborers hand-picking out the pieces of gangue (rock) and hand-screening the product. The great majority of world flake graphite production is crushed and ground if necessary and beneficiated by flotation. Treating graphite by flotation encounters one big difficulty: graphite is very soft and "marks" (coats) the particles of gangue. This makes the "marked" gangue particles float off with the graphite to yield a very impure concentrate. There are two ways of obtaining a saleable concentrate or product: regrinding and floating it again and again (up to seven times) to obtain a purer and purer concentrate, or by leaching (dissolving) the gangue with hydrofluoric acid (for a silicate gangue) or hydrochloric acid (for a carbonate gangue).

In the milling process, the incoming graphite products and concentrates can be ground before being classified (sized or screened), with the coarser flake size fractions (above 8 mesh, 8 mesh to 20 mesh, 20 mesh to 50 mesh) carefully preserved, and then the carbon contents are determined. Then some standard blends can be prepared from the different fractions, each with a certain flake size distribution and carbon content. Custom blends can also be made for individual customers who want a certain flake size distribution and carbon content. If flake size is unimportant, the concentrate can be ground more freely. Typical final products include a fine powder for use as a slurry in oil drilling; in zirconium silicate, sodium silicate and isopropyl alcohol coatings for foundry molds; and a carbon raiser in the steel industry (Synthetic graphite powder and powdered petroleum coke can also be used as carbon raiser). Rough graphite is typically classified, ground, and packaged at a graphite mill; often the more complex formulations are also mixed and packaged at the mill facility. Environmental impacts from graphite mills consist of air pollution including fine particulate exposure of workers and also soil contamination from powder spillages leading to heavy metals contaminations of soil. Dust masks are normally worn by workers during the production process to avoid worker exposure to the fine airborne graphite and zircon silicate [Wikipedia 2009V].

8.9.3 Events, Trends and Issues

Graphite was in near supply-demand balance worldwide in 2008. Leading sources for graphite imports were: flake graphite from China, Canada, Mexico, Brazil, and Madagascar (in descending order of tonnage), graphite lump and chip from Sri Lanka; and amorphous graphite from Mexico and China (in descending order of tonnage). China produced the majority of the world’s graphite from deposits clustered in the Shandong and Heilongjiang producing regions, and China’s graphite production is expected to continue growing as producers there collaborate with western graphite producers. In the past few years, Canada has had a number of new graphite mines begin production, and this trend is expected to continue through the next few years.

Advances in thermal technology and acid-leaching techniques that enable the production of higher purity graphite powders are likely to lead to development of new applications for graphite in high-technology fields. Such innovative refining techniques have enabled the use of improved graphite in carbon-graphite composites, electronics, foils, friction materials, and special lubricant applications. Flexible graphite product lines, such as graphoil (a thin graphite cloth), probably will be the fastest growing market. Large-scale fuel-cell applications are being developed that could consume as much graphite as all other uses combined [Wikipedia 2009V].

8.9.4 Production, Reserves, Prices

Table 8-19: Production, reserves, reserve-ranges and price of Graphite [USGS 2001, 2009]

	Production in kt		**Δ production 2000 to 2008 in %**	**Reserves in kt**	**Reserve base in kt**	**Resource potential in kt**	**Range in years**			**Price of Sri Lankan lump & chip graphite at foreign ports in USD/t**		**Δ prices 2000 to 2008 in %**
	2000	**2008**					**of reserves**	**of reserve base**	**of resource potential**	**2000**	**2008**	
China	300	800	167	74,000	140,000		93	175				
India	150	130	-13	5,200	11,000		40	85				
Brazil	65	76		360	1,000		5	13				
DPR Korea		30										
Canada		28										
Rest of world	205	46	-78									
World total	**720**	**1,110**	**54**	**90,000**	**220,000**	**800,000**	**81**	**198**	**721**	**1,150**	**3,026**	**163**

Note:
Reserves = that part of the reserve base which could be economically extracted orproduced at the time of determination.
Reserve base = That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices
Resource = a concentration of a naturally occuring material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

World’s inferred reserve base exceeds 800 million tonnes of recoverable graphite [USGS 2009].

8.9.5 Recycling

Refractory brick and linings, alumina-graphite refractories for continuous metal castings, magnesiagraphite refractory brick for basic oxygen and electric arc furnaces, and insulation brick led the way in recycling of graphite products. The market for recycled refractory graphite material is growing with material being recycled into products such as brake linings and thermal insulation.

Recovering high-quality flake graphite from steelmaking kish is technically feasible, but not practiced at the present time. The abundance of graphite in the world market inhibits increased recycling efforts. Information on the quantity and value of recycled graphite is not available (USGS 2009).

8.9.6 Substitutes

Manufactured graphite powder, scrap from discarded machined shapes, and calcined petroleum coke compete for use in iron and steel production. Finely ground coke with olivine is a potential competitor in foundry facing applications. Molybdenum disulfide competes as a dry lubricant but is more sensitive to oxidizing conditions [USGS 2009].

9 ANNEX B – R-Phrases

R-phrases (short for Risk-Phrases) are defined in Annex III of **European Union Directive 67/548/EEC**: Nature of special risks attributed to dangerous substances and preparations. The list was consolidated and republished in **Directive 2001/59/EC**, where translations into other EU languages may be found[51].

R1: Explosive when dry

R2: Risk of explosion by shock, friction, fire or other sources of ignition

R3: Extreme risk of explosion by shock, friction, fire or other sources of ignition

R4: Forms very sensitive explosive metallic compounds

R5: Heating may cause an explosion

R6: Explosive with or without contact with air

R7: May cause fire

R8: Contact with combustible material may cause fire

R9: Explosive when mixed with combustible material

R10: Flammable

R11: Highly flammable

R12: Extremely flammable

R14: Reacts violently with water

R15: Contact with water liberates extremely flammable gases

R16: Explosive when mixed with oxidising substances

R17: Spontaneously flammable in air

R18: In use, may form flammable/explosive vapour-air mixture

R19: May form explosive peroxides

R20: Harmful by inhalation

R21: Harmful in contact with skin

R22: Harmful if swallowed

R23: Toxic by inhalation

R24: Toxic in contact with skin

R25: Toxic if swallowed

R26: Very toxic by inhalation

R27: Very toxic in contact with skin

R28: Very toxic if swallowed

R29: Contact with water liberates toxic gas.

R30: Can become highly flammable in use

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[51] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2001:225:0001:0333:EN:PDF

R31: Contact with acids liberates toxic gas

R32: Contact with acids liberates very toxic gas

R33: Danger of cumulative effects

R34: Causes burns

R35: Causes severe burns

R36: Irritating to eyes

R37: Irritating to respiratory system

R38: Irritating to skin

R39: Danger of very serious irreversible effects

R40: Limited evidence of a carcinogenic effect

R41: Risk of serious damage to eyes

R42: May cause sensitisation by inhalation

R43: May cause sensitisation by skin contact

R44: Risk of explosion if heated under confinement

R45: May cause cancer

R46: May cause heritable genetic damage

R48: Danger of serious damage to health by prolonged exposure

R49: May cause cancer by inhalation

R50: Very toxic to aquatic organisms

R51: Toxic to aquatic organisms

R52: Harmful to aquatic organisms

R53: May cause long-term adverse effects in the aquatic environment

R54: Toxic to flora

R55: Toxic to fauna

R56: Toxic to soil organisms

R57: Toxic to bees

R58: May cause long-term adverse effects in the environment

R59: Dangerous for the ozone layer

R60: May impair fertility

R61: May cause harm to the unborn child

R62: Possible risk of impaired fertility

R63: Possible risk of harm to the unborn child

R64: May cause harm to breast-fed babies

R65: Harmful: may cause lung damage if swallowed

R66: Repeated exposure may cause skin dryness or cracking

R67: Vapours may cause drowsiness and dizziness

R68: Possible risk of irreversible effects

Combinations

R14/15: Reacts violently with water, liberating extremely flammable gases

R15/29: Contact with water liberates toxic, extremely flammable gases

R20/21: Harmful by inhalation and in contact with skin

R20/22: Harmful by inhalation and if swallowed

R20/21/22: Harmful by inhalation, in contact with skin and if swallowed

R21/22: Harmful in contact with skin and if swallowed

R23/24: Toxic by inhalation and in contact with skin

R23/25: Toxic by inhalation and if swallowed

R23/24/25: Toxic by inhalation, in contact with skin and if swallowed

R24/25: Toxic in contact with skin and if swallowed

R26/27: Very toxic by inhalation and in contact with skin

R26/28: Very toxic by inhalation and if swallowed

R26/27/28: Very toxic by inhalation, in contact with skin and if swallowed

R27/28: Very toxic in contact with skin and if swallowed

R36/37: Irritating to eyes and respiratory system

R36/38: Irritating to eyes and skin

R36/37/38: Irritating to eyes, respiratory system and skin

R37/38: Irritating to respiratory system and skin

R39/23: Toxic: danger of very serious irreversible effects through inhalation

R39/24: Toxic: danger of very serious irreversible effects in contact with skin

R39/25: Toxic: danger of very serious irreversible effects if swallowed

R39/23/24: Toxic: danger of very serious irreversible effects through inhalation and in contact with skin

R39/23/25: Toxic: danger of very serious irreversible effects through inhalation and if swallowed

R39/24/25: Toxic: danger of very serious irreversible effects in contact with skin and if swallowed

R39/23/24/25: Toxic: danger of very serious irreversible effects through inhalation, in contact with skin and if swallowed

R39/26: Very Toxic: danger of very serious irreversible effects through inhalation

R39/27: Very Toxic: danger of very serious irreversible effects in contact with skin

R39/28: Very Toxic: danger of very serious irreversible effects if swallowed

R39/26/27: Very Toxic: danger of very serious irreversible effects through inhalation and in contact with skin

R39/26/28: Very Toxic: danger of very serious irreversible effects through inhalation and if swallowed

R39/27/28: Very Toxic: danger of very serious irreversible effects in contact with skin and if swallowed

R39/26/27/28: Very Toxic: danger of very serious irreversible effects through inhalation, in contact with skin and if swallowed

R42/43: May cause sensitization by inhalation and skin contact

R48/20: Harmful: danger of serious damage to health by prolonged exposure through inhalation

R48/21: Harmful: danger of serious damage to health by prolonged exposure in contact with skin

R48/22: Harmful: danger of serious damage to health by prolonged exposure if swallowed

R48/20/21: Harmful: danger of serious damage to health by prolonged exposure through inhalation and in contact with skin

R48/20/22: Harmful: danger of serious damage to health by prolonged exposure through inhalation and if swallowed

R48/21/22: Harmful: danger of serious damage to health by prolonged exposure in contact with skin and if swallowed

R48/20/21/22: Harmful: danger of serious damage to health by prolonged exposure through inhalation, in contact with skin and if swallowed

R48/23: Toxic: danger of serious damage to health by prolonged exposure through inhalation

R48/24: Toxic: danger of serious damage to health by prolonged exposure in contact with skin

R48/25: Toxic: danger of serious damage to health by prolonged exposure if swallowed

R48/23/24: Toxic: danger of serious damage to health by prolonged exposure through inhalation and in contact with skin

R48/23/25: Toxic: danger of serious damage to health by prolonged exposure through inhalation and if swallowed

R48/24/25: Toxic: danger of serious damage to health by prolonged exposure in contact with skin and if swallowed

R48/23/24/25: Toxic: danger of serious damage to health by prolonged exposure through inhalation, in contact with skin and if swallowed

R50/53: Very toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment

R51/53: Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment

R52/53: Harmful to aquatic organisms, may cause long-term adverse effects in the aquatic environment

R68/20: Harmful: possible risk of irreversible effects through inhalation

R68/21: Harmful: possible risk of irreversible effects in contact with skin

R68/22: Harmful: possible risk of irreversible effects if swallowed

R68/20/21: Harmful: possible risk of irreversible effects through inhalation and in contact with skin

R68/20/22: Harmful: possible risk of irreversible effects through inhalation and if swallowed

R68/21/22: Harmful: possible risk of irreversible effects in contact with skin and if swallowed

R68/20/21/22: Harmful: possible risk of irreversible effects through inhalation, in contact with skin and if swallowed

10 ANNEX C – S-Phrases

S-phrases (short for Safety-phrases) are defined in Annex IV of **European Union Directive 67/548/EEC**: Safety advice concerning dangerous substances and preparations. The list was consolidated and republished in **Directive 2001/59/EC**, where translations into other EU languages may be found[52].

These safety phrases are used internationally.

(S1): Keep locked up

(S2): Keep out of the reach of children

S3: Keep in a cool place

S4: Keep away from living quarters

S5: Keep contents under ... (appropriate liquid to be specified by the manufacturer)

S6: Keep under ... (inert gas to be specified by the manufacturer)

S7: Keep container tightly closed

S8: Keep container dry

S9: Keep container in a well-ventilated place

S12: Do not keep the container sealed

S13: Keep away from food, drink and animal feedingstuffs

S14: Keep away from ... (incompatible materials to be indicated by the manufacturer)

S15: Keep away from heat

S16: Keep away from sources of ignition - No smoking

S17: Keep away from combustible material

S18: Handle and open container with care

S20: When using do not eat or drink

S21: When using do not smoke

S22: Do not breathe dust

S23: Do not breathe gas/fumes/vapour/spray (appropriate wording to be specified by the manufacturer)

S24: Avoid contact with skin

S25: Avoid contact with eyes

S26: In case of contact with eyes, rinse immediately with plenty of water and seek medical advice

S27: Take off immediately all contaminated clothing

S28: After contact with skin, wash immediately with plenty of ... (to be specified by the manufacturer)

S29: Do not empty into drains

S30: Never add water to this product

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[52] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2001:225:0001:0333:EN:PDF

S33: Take precautionary measures against static discharges

S35: This material and its container must be disposed of in a safe way

S36: Wear suitable protective clothing

S37: Wear suitable gloves

S38: In case of insufficient ventilation wear suitable respiratory equipment

S39: Wear eye/face protection

S40: To clean the floor and all objects contaminated by this material use ... (to be specified by the manufacturer)

S41: In case of fire and/or explosion do not breathe fumes

S42: During fumigation/spraying wear suitable respiratory equipment (appropriate wording to be specified by the manufacturer)

S43: In case of fire use ... (indicate in the space the precise type of fire-fighting equipment. If water increases the risk add - Never use water)

S45: In case of accident or if you feel unwell seek medical advice immediately (show the label where possible)

S46: If swallowed, seek medical advice immediately and show this container or label

S47: Keep at temperature not exceeding ... °C (to be specified by the manufacturer)

S48: Keep wet with ... (appropriate material to be specified by the manufacturer)

S49: Keep only in the original container

S50: Do not mix with ... (to be specified by the manufacturer)

S51: Use only in well-ventilated areas

S52: Not recommended for interior use on large surface areas

S53: Avoid exposure - obtain special instructions before use

S56: Dispose of this material and its container at hazardous or special waste collection point

S57: Use appropriate containment to avoid environmental contamination

S59: Refer to manufacturer/supplier for information on recovery/recycling

S60: This material and its container must be disposed of as hazardous waste

S61: Avoid release to the environment. Refer to special instructions/safety data sheet

S62: If swallowed, do not induce vomiting: seek medical advice immediately and show this container or label

S63: In case of accident by inhalation: remove casualty to fresh air and keep at rest

S64: If swallowed, rinse mouth with water (only if the person is conscious)

Combinations

(S1/2): Keep locked up and out of the reach of children

S3/7: Keep container tightly closed in a cool place

S3/7/9: Keep container tightly closed in a cool, well-ventilated place

S3/9/14: Keep in a cool, well-ventilated place away from ... (incompatible materials to be indicated by the manufacturer)

S3/9/14/49: Keep only in the original container in a cool, well-ventilated place away from ... (incompatible materials to be indicated by the manufacturer)

S3/9/49: Keep only in the original container in a cool, well-ventilated place

S3/14 Keep in a cool place away from ... (incompatible materials to be indicated by the manufacturer)

S7/8: Keep container tightly closed and dry

S7/9: Keep container tightly closed and in a well-ventilated place

S7/47: Keep container tightly closed and at temperature not exceeding ... °C (to be specified by the manufacturer)

S20/21: When using do not eat, drink or smoke

S24/25: Avoid contact with skin and eyes

S27/28: After contact with skin, take off immediately all contaminated clothing, and wash immediately with plenty of ... (to be specified by the manufacturer)

S29/35: Do not empty into drains; dispose of this material and its container in a safe way

S29/56: Do not empty into drains, dispose of this material and its container at hazardous or special waste collection point

S36/37: Wear suitable protective clothing and gloves

S36/37/39: Wear suitable protective clothing, gloves and eye/face protection

S36/39: Wear suitable protective clothing and eye/face protection

S37/39: Wear suitable gloves and eye/face protection

S47/49: Keep only in the original container at temperature not exceeding ... °C (to be specified by the manufacturer)

11 H-codes (Hazard-codes) according to Regulation (EC) No 1272/2008:

Hazard statements for physical hazards

H200 | 2.1 —Explosives, Unstable explosives |

H201 | 2.1 —Explosives, Division 1.1 | - Explosive; mass explosion hazard

H202 | 2.1 —Explosives, Division 1.2 | Explosive, severe projection hazard. |

H203 | 2.1 —Explosives, Division 1.3 | Explosive; fire, blast or projection hazard. |

H204 | 2.1 —Explosives, Division 1.4 | Fire or projection hazard. |

H205 | 2.1 —Explosives, Division 1.5 | May mass explode in fire. |

H220 | 2.2 —Flammable gases, Hazard Category 1 | Extremely flammable gas. |

H221 | 2.2 —Flammable gases, Hazard Category 2 | Flammable gas. |

H222 | 2.3 —Flammable aerosols, Hazard Category 1 | Extremely flammable aerosol. |

H223 | 2.3 —Flammable aerosols, Hazard Category 2 | Flammable aerosol. |

H224 | 2.6 —Flammable liquids, Hazard Category 1 | Extremely flammable liquid and vapour. |

H225 | 2.6 —Flammable liquids, Hazard Category 2 | Highly flammable liquid and vapour. |

H226 | 2.6 —Flammable liquids, Hazard Category 3 | Flammable liquid and vapour. |

H228 | 2.7 —Flammable solids, Hazard Category 1, 2 | Flammable solid. |

H240 | 2.8 —Self-Reactive Substances and Mixtures, Type A2.1.5 —Organic Peroxides, Type A | Heating may cause an explosion. |

H241 | 2.8 —Self-Reactive Substances and Mixtures, Type B2.1.5 —Organic Peroxides, Type B | Heating may cause a fire or explosion. |

H242 | 2.8 —Self-Reactive Substances and Mixtures, Types C, D, E, F2.1.5 —Organic Peroxides, Types C, D, E, F | Heating may cause a fire. |

H250 | 2.9 —Pyrophoric Liquids, Hazard Category 12.10 —Pyorphoric Solids, Hazard Category 1 | Catches fire spontaneously if exposed to air. |

H251 | 2.11 —Self-Heating Substances and Mixtures, Hazard Category 1 | Self-heating: may catch fire. |

H252 | 2.11 —Self-Heating Substances and Mixtures, Hazard Category 2 | Self-heating in large quantities; may catch fire. |

H260 | 2.12 —Substances and Mixtures which, in contact with water, emit flammable gases, Hazard Category 1 | In contact with water releases flammable gases which may ignite spontaneously. |

H261 | 2.12 —Substances and Mixtures which, in contact with water, emit flammable gases, Hazard Category 2 | In contact with water releases flammable gases. |

H270 | 2.4 —Oxidising Gases, Hazard Category 1 | May cause or intensify fire; oxidiser.

H271 | 2.13 —Oxidising Liquids, Hazard Category 12.14 —Oxidising Solids, Hazard Category 1 | May cause fire or explosion; strong oxidiser. |

H272 | 2.13 —Oxidising Liquids, Hazard Category 2, 32.14 —Oxidising Solids, Hazard Category 2, 3 | May intensify fire; oxidiser. |

H280 | 2.5 —Gases under pressure:Compressed gasLiquefied gasDissolved gas | Contains gas under pressure; may explode if heated. |

H281 | 2.5 —Gases under pressure: Refrigerated liquefied gas | Contains refrigerated gas; may cause cryogenic burns or injury. |

H290 | 2.16 —Corrosive to metals, Hazard Category 1 | May be corrosive to metals. |

Hazard statements for health hazards

H300 | 3.1 —Acute toxicity (oral), Hazard Category 1, 2 | Fatal if swallowed. |

H301 | 3.1 —Acute toxicity (oral), Hazard Category 3 | Toxic if swallowed. |

H302 | 3.1— Acute toxicity (oral), Hazard Category 4 | Harmful if swallowed. |

H304 | 3.10— Aspiration hazard, Hazard Category 1 | May be fatal if swallowed and enters airways. |

H310 | 3.1— Acute toxicity (dermal), Hazard Category 1, 2 | Fatal in contact with skin. |

H311 | 3.1— Acute toxicity (dermal), Hazard Category 3 | Toxic in contact with skin. |

H312 | 3.1— Acute toxicity (dermal), Hazard Category 4 | Harmful in contact with skin. |

H314 | 3.2— Skin corrosion/irritation, Hazard Category 1A, 1B, 1C | Causes severe skin burns and eye damage. |

H315 | 3.2— Skin corrosion/irritation, Hazard Category 2 | Causes skin irritation. |

H317 | 3.4— Sensitisation — Skin, Hazard Category 1 | May cause an allergic skin reaction. |

H318 | 3.3— Serious eye damage/eye irritation, Hazard Category 1 | Causes serious eye damage. |

H319 | 3.3— Serious eye damage/eye irritation, Hazard Category 2 | Causes serious eye irritation. |

H330 | 3.1— Acute toxicity (inhalation), Hazard Category 1, 2 | Fatal if inhaled. |

H331 | 3.1— Acute toxicity (inhalation), Hazard Category 3 | Toxic if inhaled. |

H332 | 3.1— Acute toxicity (inhalation), Hazard Category 4 | Harmful if inhaled. |

H334 | 3.4— Sensitisation — Respirat., Hazard Category 1 | May cause allergy or asthma symptoms or breathing difficulties if inhaled. |

H335 | 3.8— Specific target organ toxicity — Single exposure, Hazard Category 3, Respiratory tract irritation | May cause respiratory irritation. |

H336 | 3.8— Specific target organ toxicity — Single exposure, Hazard Category 3, Narcosis | May cause drowsiness or dizziness. |

H340 | 3.5— Germ cell mutagenicity, Hazard Category 1A, 1B | May cause genetic defects. |

H341 | 3.5— Germ cell mutagenicity, Hazard Category 2 | Suspected of causing genetic defects. |

H350 | 3.6— Carcinogenicity, Hazard Category 1A, 1B | May cause cancer. |

H350i | May cause cancer by inhalation. |

H351 | 3.6— Carcinogenicity, Hazard Category 2 | Suspected of causing cancer. |

H360 | 3.7— Reproductive toxicity, Hazard Category 1A, 1B | May damage fertility or the unborn child <state specific effect if known

H360F | May damage fertility. |

H360D | May damage the unborn child. |

H360Df | May damage the unborn child. Suspected of damaging fertility.

H360FD | May damage fertility. May damage the unborn child. |

H360Fd | May damage fertility. Suspected of damaging the unborn child. |

H361 | 3.7— Reproductive toxicity, Hazard Category 2 | Suspected of damaging fertility or the unborn child

H361d | Suspected of damaging the unborn child. |

H361f | Suspected of damaging fertility. |

H361fd | Suspected of damaging fertility. Suspected of damaging the unborn child. |

H362 | 3.7— Reproductive toxicity, Additional category, Effects on or via lactation | May cause harm to breast-fed children.

H370 | 3.8— Specific target organ toxicity — single exposure, Hazard Category 1 | Causes damage to organs

H371 | 3.8— Specific target organ toxicity — Single exposure, Hazard Category 2 | May cause damage to organs

H372 | 3.9— Specific target organ toxicity — Repeated exposure, Hazard Category 1 | Causes damage to organs

H373 | 3.9— Specific target organ toxicity — Repeated exposure, Hazard Category 2 | May cause damage to organs

Hazard statements for environmental hazards

H400 | 4.1— Hazardous to the aquatic environment — AcuteHazard, Category 1 Very toxic to aquatic life. |

H410 | 4.1— Hazardous to the aquatic environment — Chronic Hazard, Category 1 | Very toxic to aquatic life with long lasting effects. |

H411 | 4.1— Hazardous to the aquatic environment — Chronic Hazard, Category 2 | Toxic to aquatic life with long lasting effects. |

H412 | 4.1— Hazardous to the aquatic environment — Chronic Hazard, Category 3 | Harmful to aquatic life with long lasting effects. |

H413 | 4.1— Hazardous to the aquatic environment — Chronic Hazard, Category 4 | May cause long lasting harmful effects to aquatic life. |

Supplemental hazard information

Physical properties

EUH 001 Explosive when dry.

EUH 006 Explosive with or without contact with air. |

EUH 014 Reacts violently with water. |

EUH 018 In use may form flammable/explosive vapour-air mixture.

EUH 019 May form explosive peroxides.

EUH 044 Risk of explosion if heated under confinement.

Health properties

EUH 029 Contact with water liberates toxic gas.

EUH 031 Contact with acids liberates toxic gas.

EUH 032 Contact with acids liberates very toxic gas.

EUH 066 Repeated exposure may cause skin dryness or cracking.

EUH 070 Toxic by eye contact.

EUH 071 Corrosive to the respiratory tract.

Environmental properties

EUH 059 Hazardous to the ozone layer.

Supplemental label elements/information on certain substances and mixtures

EUH 206 Warning! Do not use together with other products. May release dangerous gases (chlorine).

EUH 207 Warning! Contains cadmium. Dangerous fumes are formed during use. See information supplied by the manufacturer. Comply with the safety instructions.