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### COMPARATIVE LIFE-CYCLE ASSESSMENT OF NICKEL-CADMIUM (NiCd) BATTERIES USED IN CORDLESS POWER TOOLS (CPTs) VS. THEIR ALTERNATIVES NICKEL-METAL HYDRIDE (NiMH) AND LITHIUM-ION (Li-ION) BATTERIES

Summary Report

**PRELIMINARY RESULTS**

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## PART 1: LIFE CYCLE ASSESSMENT

### 0. Preamble

In the frame of the study “Comparative Life Cycle Assessment of Nickel-Cadmium (NiCd) batteries used in Cordless Power Tools (CPTs) vs. their alternatives Nickel-Metal-Hydride (NiMH) and Lithium-ion (Li-ion) batteries”, a workshop will be held by the European Commission in July 2011 to allow stakeholders to review the data and assumptions that served as a basis for the Life Cycle Assessment (LCA).

This document aims at preparing the stakeholder workshop by presenting the **preliminary LCA results** obtained so far in the frame of the study. **At this stage of the assessment, it is only possible to focus on the main environmental hotspots of the life-cycle of the batteries and to analyse the trends of comparative LCA results.** More detailed results will be presented by BIO Intelligence Service during the workshop.

Furthermore, due to confidentiality reasons, input data of the LCAs are not included in this report. Only the sources of information are presented, when possible.

### 1. Background and objectives

The Battery Directive 2006/66/EC aims at setting requirements on batteries and accumulators in order to minimise their negative impacts on the environment. To achieve this objective, the Directive necessitates specifications on certain batteries containing hazardous materials like cadmium sold in the EU. Under Article 4(4) of the Batteries Directive, the Commission is required to review the exemption from the cadmium ban provided for portable batteries and accumulators intended for use in Cordless Power Tools (CPTs), with a view to the prohibition of cadmium in batteries and accumulators.

Several studies have contributed to the current review of Article 4(4) carried out by the Commission. In 2009, the Swedish Environmental Protection Agency report on ‘Cadmium in power tool batteries - The possibility and consequences of a ban’<sup>1</sup> stated that it is possible to replace NiCd batteries in power tools with lithium-ion (Li-ion) batteries and nickel-metal hydride (NiMH) battery technologies. A further study carried out in 2010 by EWSI consortium for the Commission analysing a ban on NiCd batteries for CPTs also demonstrated that it is technically feasible to replace NiCd batteries used in CPTs by NiMH and Li-ion batteries<sup>2</sup>. On the other hand, this report also concluded that due to lack of Life Cycle Assessment (LCA) data for these battery types, the environmental and health benefits of banning NiCd batteries for CPT applications are prone to “high uncertainty”. In order to support a Commission proposal, a comparative Life Cycle Assessment (LCA) of these three battery types corresponding to their usage in CPTs is therefore required in order to facilitate an impact assessment of potential policy scenarios based on solid technical and scientific evidence.

<sup>1</sup> Swedish Environment Agency, 2009, Cadmium in power tool batteries: The possibility and consequences of a ban, [www.naturvardsverket.se/Documents/publikationer/978-91-620-5901-9.pdf](http://www.naturvardsverket.se/Documents/publikationer/978-91-620-5901-9.pdf)

<sup>2</sup> EWSI consortium, 2010, 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, [ec.europa.eu/environment/waste/batteries/pdf/cadmium\\_report.pdf](http://ec.europa.eu/environment/waste/batteries/pdf/cadmium_report.pdf)

The objective of this study is to conduct a comparative Life Cycle Assessment (LCA) of NiCd, NiMH and Li-ion batteries and chargers used in CPTs and present the corresponding environmental stakes and identify the main steps in the life-cycle of the batteries contributing to these environmental impacts in the EU context. This information is further used in the study to support an impact assessment which assists in identifying and evaluating various policy options to reduce the environmental impact and human exposure to cadmium associated with these batteries with a potential to withdraw the current exemption in the Batteries Directive (2006/66/EC) for cadmium use in batteries for in CPTs.

## 2. Methodology

### 2.1. Main principles of Life Cycle Assessment

A Life Cycle Assessment (LCA) aims at assessing the quantifiable environmental impacts of a service or product from the extraction of the materials required, to the treatment of these materials at the end-of-life stage.

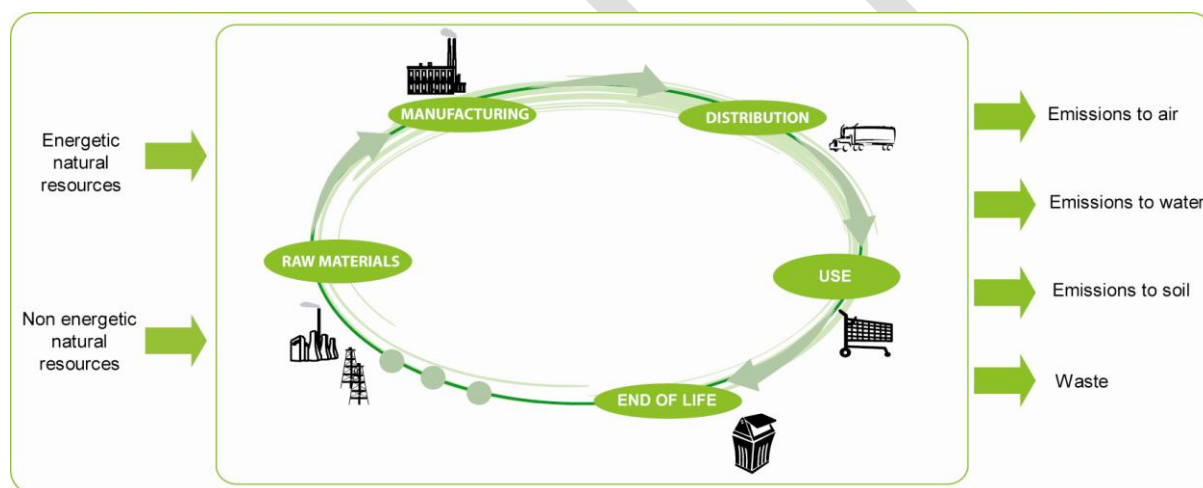


Figure 1. Simplified representation of LCA

This “cradle-to-grave” approach has been standardised at the international level through ISO 14040 and ISO 14044. The present study has been carried out following the methodological regulations developed in the ISO 14’s standards.

The methodology consists in carrying out exhaustive assessments of natural resources consumption, energy consumption and emissions into the environment (waste, emissions to air, water and ground), for each process studied.

Firstly, all incoming and outgoing flows are inventoried for each life-cycle phase: Flows of materials and energy, both extracted from the environment and released into it at each life-cycle phase. Secondly, they are aggregated to quantify environmental impact indicators. LCA is a multi-criteria approach: no global environmental mark is given. The results of the study are presented through several environmental impact indicators.

The LCA methodology allows to compare situations and to identify pollution transfers from one type of impact (e.g. global warming) of the natural environment to another (e.g. resource depletion), or from one life-cycle stage to another, between two different scenarios for the same system, or between two different systems. LCA can thus be used in the context of a “design for the environment” approach or for decision-making.

## 2.2. Products selection

The study focuses on batteries used in cordless power tools (CPT). The market for CPTs is split between the professional use (Pro) and the domestic use (Do It Yourself – DIY).

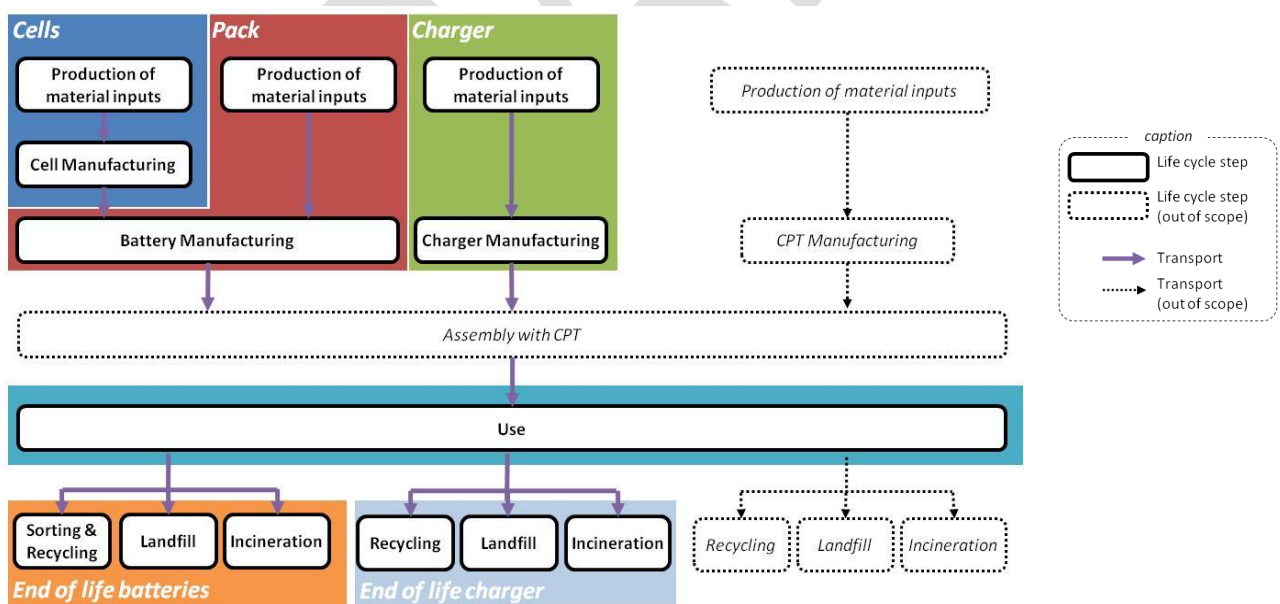
It was decided to focus the efforts on one particular application which could be considered as representative of the market. Since it can use the three battery types of interest, the cordless drill application has been considered, in agreement with the EC. The data collection focused on the Pro market segment which represents a significant market share for this specific application and for which the use phase is well known by manufacturers.

Furthermore, another methodological choice had to be made regarding the Li-ion batteries which cover a broad range of technologies. Thus, for the purpose of the study, it was decided to retain only the main Li-ion technology in terms of current market shares<sup>3</sup>: Lithium Iron Phosphate technology. In conclusion, the batteries studied here are the following: Nickel-Cadmium (NiCd) batteries, Nickel Metal Hydride (NiMH) batteries, Lithium Iron Phosphate (LiFePO<sub>4</sub>).

It has to be noted that cordless drills are mostly sold with two battery packs and a charger. Having two batteries allows using the tool with one battery while the other battery is being charged.

## 2.3. System Boundaries

The following figure presents the system boundaries considered for this study. The whole life-cycles of the battery and associated charger have been taken into account.



**Figure 2. System boundaries considered for the three battery types – all transport steps (purple arrows) are grouped into one single life-cycle step**

Concerning the CPT, a cross-checking of the Bills Of Materials (BOM) of the three drills<sup>4</sup> showed that, apart from the type of battery packs that they use, the CPTs do not significantly differ. Therefore, the CPT itself has

<sup>3</sup> Source: Recharge (International association for the promotion and management of portable rechargeable batteries through their life-cycle)

<sup>4</sup> BOMs provided by the European Power Tool Association (EPTA)

been excluded from the scope of the study as this will not have an impact of the comparative assessment and on the conclusions of the analysis.

Packaging has not been included in the study, due to the lack of complete data. However, this does not prevent from comparing the three battery types because this data is expected to be similar for the three battery technologies.

The life-cycle of batteries has been split into 7 life-cycle steps: “cells” (production of material inputs and cell manufacturing), “pack” (production of material inputs and battery pack manufacturing), “charger” (production of material inputs and charger manufacturing), “use” (electricity consumption to recharge the batteries), transport steps (all grouped in one single step called “transport”), “end-of-life - batteries” (i.e. landfilling, incineration or material recycling) and “end-of-life - charger” (i.e. landfilling, incineration or material recycling).

## 2.4. Functional Unit

In order to allow comparing different battery technologies and presenting the results in a comprehensive manner, a common reference needs to be defined. This common reference is used to scale the inputs and outputs (materials, energy, etc.) of each system studied. It is the so-called “Functional Unit” of the environmental assessment according to the ISO standard. The environmental impacts generated by the system considered must reflect the main service given by the battery, i.e. the delivery of electrical energy to the CPT. The environmental impacts computed over this life-cycle are then scaled to the functional unit: each flow involved over the life-cycle (e.g. material flow, energy flow) is thus related to this reference flow. In this study, the functional unit chosen is:

**“1 kWh of energy delivered by the battery to the CPT”**

## 2.5. Environmental impacts considered

In the frame of the present study, a full set of environmental impact indicators was assessed. However, only a selection of these indicators is presented in this interim report. They have been selected because they correspond to the major environmental stakes related to the life-cycle of batteries. It has been verified that for all other assessed impact indicators<sup>5</sup>, discrepancies between the three battery types were lower than a threshold of 20%, considered as the *minimum* uncertainty on LCIA (Life Cycle Impact Assessment) models. The following table presents the environmental impact indicators reported in this document, and the corresponding LCA methods, which are considered as the most robust ones.

<sup>5</sup> Namely: Ozone Depletion Potential, Particulate matter formation Potential, Ionising radiation Potential, Freshwater eutrophication Potential, Marine eutrophication Potential, Agricultural land occupation Potential, Urban land occupation Potential, Natural land transformation Potential, Water depletion Potential.

**Table 1. Environmental impact indicators considered (and LCIA methods to assess them)**

LCIA method	Potential environmental impact indicator	Unit
ReCiPe	Global Warming Potential (GWP)	kg CO <sub>2</sub> eq
	Photochemical oxidant formation Potential (POFP)	kg NMVOC eq <sup>6</sup>
	Terrestrial Acidification Potential (TAP)	kg SO <sub>2</sub> eq
CML	Abiotic resource depletion potential (ADP)	kg Sb eq <sup>7</sup>
USEtox	Human Toxicity Potential (HTP)	cases <sup>8</sup>
	Freshwater Aquatic Ecotoxicity Potential (FAEP)	PAF m <sup>3</sup> day <sup>9</sup>

Human toxicity and ecotoxicity impacts have been quantified both with and without long-term emissions, due to specific issues raised by landfilling of the batteries (this point is further explained in §3.3.2. ).

In addition, a classical flow indicator is assessed and reported in this document, as shown in the following table.

**Table 2. Flow indicator considered**

Source	Flow indicator	Unit
Ecoinvent data	Cumulative Energy Demand (CED)	MJ

LCIA methods and environmental impact indicators are described in appendix, page 24.

## 3. Data and assumptions

### 3.1. Sources of data

Primary data were collected from manufacturers of CPTs and batteries and industry associations.

Most background inventories (generic data, also called “secondary data”) were taken from the Ecoinvent v2.2 database.

The life-cycle inventory for the production of the LiFePO<sub>4</sub> compound has been recalculated, based on data from Majeau-Bettez et al. [2].

The life-cycle inventory for the production of LaNi<sub>5</sub> was taken from the database of GaBi 4 LCA software<sup>10</sup>.

Inventories for recycling from Ecoinvent v2.2 have been recalculated for each battery type, based on data from ERM [3].

### 3.2. Use patterns

The data for the use patterns were provided by industry associations [1].

<sup>6</sup> Non-Methane Volatile Organic Compound

<sup>7</sup> Sb is the chemical symbol of Antimony.

<sup>8</sup> Estimated increase in morbidity in the total human population (cases), taking into account cancer and non-cancer cases.

<sup>9</sup> Estimate of the potentially affected fraction of species (PAF) integrated over time and volume (PAF m<sup>3</sup> day).

<sup>10</sup> <http://www.gabi-software.com>

The batteries have a theoretical lifespan of 800 cycles, meaning that after 800 cycles the capacity of the battery decreases drastically. Before reaching 800 cycles, the capacity is considered to be constant for the NiCd and NiMH batteries, whereas for the first 800 cycles of the LiFePO<sub>4</sub> batteries, a linear decrease (from 100% to 75% of the nominal capacity) was considered<sup>11</sup>.

For a drill application, intensity during use ranges from 10 to 35 A. An average intensity usage of 20 A was considered in this study.

The CPT was considered to have a lifespan of 165 hours of use [1]. Batteries were assumed to have a useful lifespan of 82.5 hours of use, for the following reasons:

- For the three battery types, it was verified that the theoretical lifespan of the battery (800 cycles) exceeds half of the lifespan of the CPT<sup>12</sup>.
- Since the market share of CPTs sold without batteries is small compared to the market share of CPTs sold together with battery packs<sup>13</sup>, it has been considered that users cease to use the CPT and the 2 batteries at the same time, which means 82.5 hours of use for each battery.

This means that batteries are not used after 82.5 hours of use each and thus do not reach the end of their theoretical lifespan (800 cycles).

### 3.2.1. Charging parameters

The European electricity<sup>14</sup> was considered for the electricity consumption during charging. The following table presents the charging parameters that were considered for the three battery technologies. These parameters are averages by battery technology.

**Table 3. Simplified modelling of the charging phase for the three battery technologies**

Phase	Current drawn (A)	Duration of phase (h)	Voltage (V)
<b>NiCd</b>			
Active charging phase 1	2.6	0.917	21.2
Active charging phase 2	1.3	0.33	21.6
Maintenance charging <sup>15</sup>	0.25	0.753	21.5
<b>NiMH</b>			
Active charging phase 1	3.47	0.917	21.2
Active charging phase 2	1.73	0.33	21.6
Maintenance charging	0.33	0.753	21.5
<b>LiFePO<sub>4</sub></b>			
Active charging phase 1	6	0.666	21.6
Active charging phase 2	3	0.166	21.6
Maintenance charging	0	1.166	0

<sup>11</sup> Source: EPTA

<sup>12</sup> If we take the example of NiCd batteries (2.4 Ah capacity), since two batteries are sold with the CPT, and given the intensity usage retained in this study (20 A), 688 cycles are required for each battery in order for the CPT to be used during 165 hours:

$$\frac{165 \text{ h} \times 20 \text{ A}}{2.4 \text{ Ah}} \times \frac{1}{2 \text{ batteries}} = 687.5 \text{ cycles/battery}$$

<sup>13</sup> Source: EPTA

<sup>14</sup> EcoInvent dataset: Electricity, low voltage, production RER, at grid/RER

<sup>15</sup> Maintenance charging: the battery is fully charged but still plugged.

NiCd charging parameters were taken from [1]. Charging parameters for NiMH batteries were considered to be similar to those of NiCd batteries. The current drawn during the charging phase has been scaled in order to reflect the NiMH battery capacity.

Charging parameters for LiFePO<sub>4</sub> batteries were provided by a CPT manufacturer. The particularity of the LiFePO<sub>4</sub> battery is that the maintenance charging equals to zero, i.e. there is no current drawn while the battery is plugged and fully charged. This is due to the presence of an electronic system (included in the charger) that prevents the battery from over-charging (LiFePO<sub>4</sub> batteries can indeed be degraded by over-charging).

As a consequence, LiFePO<sub>4</sub> consumes approximately 20% less electricity during charging than the two other battery technologies, as can be seen in the following table.

**Table 4. Charging efficiency<sup>16</sup> per battery type**

	NiCd	NiMH	LiFePO <sub>4</sub>
<b>Charging efficiency (-)</b>	0.68	0.68	0.83

### 3.3. Focus on data for the end-of-life

End-of-life covers all different processes that occur after the user throws the CPT (with its two batteries) away.

Critical issues regarding the modelling of the end-of-life phase are the breakdown of the different disposal routes (landfill, incineration, recycling), and the definition of the material and energy inputs as well as emissions of substances for each type of disposal. These issues are presented in the following paragraphs.

#### 3.3.1. End-of-life routes

The breakdown of the different end-of-life routes corresponds to the quantity of products that are either recycled, incinerated or landfilled, with respect to the quantity of products that are disposed (or “available for collection”) at a given time.

A particular issue concerning the end-of-life of CPTs and batteries is the so-called “hoarding effect”, i.e. the fact that end-users often keep the CPTs for a long time (10 to 20 years as an order of magnitude) at home or workplace before sending them to the recycling chain or to final disposal (landfilling or incineration).

Therefore, in the situation of an evolving market, the collection waste stream and sales at a given year are completely decorrelated. Consequently, the collection rate should be calculated as a percentage of spent batteries available for collection, and not as a percentage of sales.

However, data on collected quantities, sales, and hoarded rates over the last two decades, at EU-27 level, and for the specific case of CPTs are hardly available. Furthermore, the collection rate of batteries used in CPTs based on the quantity of spent batteries available for collection could be derived from the collection rate based on sales, using estimates on hoarding and market growth rates at EU-27 level [7], but again these parameters are hardly accessible.

To overcome these difficulties, a 25% collection rate, which is the target for battery collection by September 2012 according to the Batteries Directive, was assumed for the reference scenario. There are some limitations to this assumption: the Batteries Directive is not specific to batteries used in CPTs, and it concerns secondary

<sup>16</sup> Charging efficiency = Energy delivered to the battery / Energy consumed during charging

and primary batteries. Furthermore, the collection rate considered by the directive is calculated based on the sales over the last three years.

Therefore, the value of 25% is to be considered as a ‘working assumption’. A sensitivity analysis on higher collection rates will be carried out in the next steps of the study. This will allow, notably, to take into account the fact that hoarding may have a “positive” influence on the environmental impacts, because one could benefit from an increased collection efficiency and optimized recycling and incinerating processes in the future.

*Note: any reliable value on collection rate for batteries used in CPTs at EU level would be welcome.*

The share of not collected batteries (75%) is split between landfilling (75.5% of the total not collected) and incineration with energy recovery (24.5%) [8].

**Table 5. End-of-life routes for each battery type for the reference scenario**

End-of-life route	NiCd	NiMH	LiFePO <sub>4</sub>
<b>Separate collection, sorting and recycling</b>	<b>25%</b>	<b>25%</b>	<b>25%</b>
<i>Pyrometallurgical process</i>	25%	25%	12.5%
<i>Hydrometallurgical process</i>	-	-	12.5%
<b>Municipal solid waste</b>	<b>75%</b>	<b>75%</b>	<b>75%</b>
<i>Landfill</i>	57%	57%	57%
<i>Incineration with energy recovery</i>	18%	18%	18%

### 3.3.2. Modelling the disposal types

#### ◆ Recycling

Inventories for recycling processes are taken from ERM [3].

For NiCd and NiMH pyrometallurgical processes, the quantity of recovered materials was adapted from ERM study, in order to match the specific compositions of the batteries.

For LiFePO<sub>4</sub>, ERM inventories describe the recycling of the different Lithium-based batteries. The flow of lithium-based batteries is treated as a whole by recyclers, and thus it is difficult to identify which impacts are specific to LiFePO<sub>4</sub> batteries. The reference scenario considers a 50/50 split between hydrometallurgical and pyrometallurgical processes. Moreover, these inventories were adapted from ERM so that the nature and quantity of recovered materials reflect the specific composition of LiFePO<sub>4</sub> batteries.

The recovered fraction of materials is assumed to replace virgin materials. Therefore, the impacts of recycling are calculated as the impacts of the recycling process itself, from which the impacts of the production of the corresponding virgin material are subtracted. Since the production of secondary (recycled) metal often generates fewer impacts than the production of virgin (primary) metal, environmental benefits can be generated by recycling, as illustrated in the following table.

**Table 6. Qualitative description of the environmental benefits of recycling**

	Case 1	Case 2
Environmental impacts of production of recycled (secondary) material (1)	low	high
Environmental impacts of production of virgin (primary) material (2)	high	low
Impact Balance for recycling: (1) – (2)	Impacts < 0	Impacts > 0
	↓ Environmental benefits	↓ Environmental burdens

The allocation of the environmental benefits of recycling of the metallic parts in the batteries was made following the recommendation of the French environmental labelling framework [5]: as the demand for secondary (recycled) metals is considered to be higher than the supply of old scrap metal, the benefits of recycling are allocated to the product that provides the materials to be recycled.

#### ◆ Incineration

The incineration of batteries in a municipal solid waste incinerator (MSWI) generates environmental impacts, notably through emissions of substances to air, and also through emissions to water after the landfilling of incineration residues. These impacts are assessed with the dedicated EcoInvent tool, which allows modelling the incineration of a product based on its precise composition.

The present study considers energy recovery for incineration. The energy that is produced avoids thermal and electrical energy production by conventional sources<sup>17</sup>. As for the benefits of recycling, related environmental benefits were fully allocated to the batteries.

#### ◆ Landfilling

The landfilling of the batteries in a sanitary landfill generates environmental impacts, notably through emissions of substances to water due to leachage. These impacts are assessed with the dedicated EcoInvent tool, which allows modelling the landfilling of a product based on its precise composition.

#### ***Long-term emissions of heavy metals from landfills***

Through leachage, metals contained in batteries are slowly released in the environment over thousands of years. In a short term perspective, e.g. less than 100 years for a landfill, the battery mostly behaves like inert waste, meaning that metals contained in the cells remain 'locked' inside their housing. However, from a long term (LT) perspective, a fraction of metals contained in the battery will eventually end-up in the environment.

The environmental impact assessment of these long term emissions of metals from landfills carries several limits:

- There is a high level of uncertainty on the ratio of metals contained in the battery that will eventually be released in the environment. Some identified chemical mechanisms have a stabilising effect on metals in landfills.

<sup>17</sup> For avoided impacts, the European electrical mix has been considered for electrical energy and natural gas furnace has been considered for thermal energy.

- With its focus on the emitted mass only, **LCA is poorly equipped to handle the dilution in time of emissions**, i.e. to make the difference between emissions slowly occurring over thousands of years and other emissions occurring in the life-cycle, within days.
- Moreover, the USEtox method used to assess toxicity impacts proposes only “interim” characterisation factors for metals, meaning that they bear a high level of uncertainty.

Therefore, Human toxicity and freshwater ecotoxicity were assessed both excluding and including long-term emissions: the so-called “**short-term perspective**” means that only short-term emissions are considered (long-term emissions are excluded), and the so-called “**long-term perspective**” means that both short-term and long-term emissions are included.

This allows assessing impacts when all metals are leached (with LT)<sup>18</sup> and when few metals are leached (without LT). An intermediate situation has also been considered, where 5% of the metals are leached to the environment in the long term. This corresponds to the assumption made in the ERM study [3].

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<sup>18</sup> The full release of metals to the environment should be considered as a maximum potential release and not to the actual released quantity.

### 3.4. Representativeness of the study

#### 3.4.1. Temporal representativeness

Primary data were collected directly from selected stakeholders between February and June 2011.

Secondary data were taken from the Ecoinvent v2.2 database, published in 2010.

#### 3.4.2. Geographical representativeness

The study is representative of a European context: Production reflects the supply chain of CPTs manufactured for the European market.

The use phase is also representative of a European context (European electric mix is considered).

#### 3.4.3. Technological representativeness

The composition of the cells that have been considered is representative of the ones used in CPTs. Secondary data is mainly representative of European technologies. However, when possible, secondary data used for processes were adapted in order to take the electrical mix of the considered country into account.

### 3.5. Summary of the main differences between the three battery technologies

The following table summarizes the main differences between the three batteries considered in terms of life-cycle characteristics. These differences are to be kept in mind when interpreting the results.

**Table 7. Summary of the main differences between the three battery types**

	NiCd	NiMH	LiFePO <sub>4</sub>
<b>Cells (BOM)</b>	Contains cadmium and nickel	Higher nickel content than NiCd	Contains copper
<b>Pack (BOM)</b>	-	-	Contains electronic components
<b>Charger (BOM)</b>	-	-	Contains more electronic components than the NiCd/NiMH charger
<b>Use phase (charging)</b>	-	-	No maintenance charging (no current drawn when the battery is fully charged and still plugged)
<b>Use phase (evolution of the capacity)</b>	No capacity decrease throughout the lifespan	No capacity decrease throughout the lifespan	Capacity decrease from 100 to 75% of the nominal capacity throughout the 800 cycles
<b>Recycling</b>	57% of the pack is recovered: Recovery of cadmium, nickel and iron	59% of the pack is recovered: Recovery of nickel, cobalt and iron	24% of the pack is recovered: recovery of copper and aluminium
<b>Landfilling (main long-term emissions)</b>	Potential emissions of cadmium and nickel to water	Potential emissions of nickel to water	Potential emissions of copper to water

## 4. Results obtained for the reference scenario

**NB: The following results should be considered as preliminary. They reflect the assumptions and boundaries considered at this stage of the study.**

The following table presents the total of the potential environmental impacts of the three battery types considered.

**Table 8. Total environmental Impacts for 1 Functional Unit for the three battery types**

Potential impact indicator	Unit	NiCd	NiMH	LiFePO <sub>4</sub>
Global Warming Potential (GWP)	kg CO2 eq.	1,2	1,4	1,0
Photochemical oxidant formation Potential (POFP)	kg NMVOC-eq	0,0036	0,0045	0,0031
Terrestrial Acidification Potential (TAP)	kg SO2 eq.	0,011	0,013	0,0050
Abiotic resource depletion potential (ADP)	kg Sb eq.	0,055	0,010	0,008
Cumulative Energy Demand (CED)	MJ	25	26	21
Human Toxicity Potential (HTP) <i>with LT emissions</i>	cases	3,2E-06	1,1E-06	1,1E-06
Freshwater Aquatic Ecotoxicity Potential (FAEP) <i>with LT emissions</i>	PAF.m3.day	77	93	67
Human Toxicity Potential (HTP) <i>5% long-term emissions</i>	cases	2,7E-07	1,8E-07	2,1E-07
Freshwater Aquatic Ecotoxicity Potential (FAEP) <i>5% long-term emissions</i>	PAF.m3.day	4,2	5,1	4,3
Human Toxicity Potential (HTP) <i>without long-term emissions</i>	cases	1,1E-07	1,3E-07	1,6E-07
Freshwater Aquatic Ecotoxicity Potential (FAEP) <i>without long-term emissions</i>	PAF.m3.day	0,39	0,44	1,0

Before analyzing these impacts in a comparative way, the three following paragraphs aim at interpreting the results for the three battery technologies separately, in order to better understand which are the life-cycle steps contributing the most to the overall environmental impacts of each battery type, and what are the main sources of impact, for each environmental impact indicator.

For that, the following figures present the breakdown of the environmental impacts of the three battery types per life-cycle step, for one Functional Unit (1 kWh delivered by the battery to the CPT).

As previously mentioned, impacts are split between: cells (materials inputs and manufacturing), pack (materials inputs and manufacturing), charger (materials inputs and manufacturing), transports (supplies, distribution and transports to disposal facilities), end-of-life of the batteries (cells+pack), and end-of-life of the charger.

The following colour code is used:

	> 50%
	20% < <50%
	5% < <20%
	0% < <5%
	< 0%

#### 4.1. LCA results for NiCd battery

**Table 9. Results for NiCd battery**

	Cells	Pack	Charger	Transport	Use	End-of-life batteries	End-of-life Charger
Global Warming Potential	Yellow	Green	Yellow	Green	Red	Green	Green
Cumulative Energy Demand	Yellow	Green	Yellow	Green	Red	Green	Green
Photochemical Oxidant Formation Potential	Orange	Green	Yellow	Yellow	Orange	Green	Green
Terrestrial acidification Potential	Red	Green	Yellow	Green	Orange	Green	Green
Abiotic Resource Depletion Potential	Red	Green	Green	Green	Yellow	Green	Green
Human Toxicity Potential without LT	Yellow	Green	Orange	Green	Orange	Green	Green
Freshwater Aquatic Ecotoxicity Potential without LT	Orange	Green	Orange	Green	Orange	Green	Green
Human Toxicity Potential with LT	Yellow	Green	Yellow	Green	Yellow	Red	Green
Freshwater Aquatic Ecotoxicity Potential with LT	Yellow	Green	Green	Green	Green	Red	Yellow

This table allows identifying environmental “hotspots” of NiCd batteries:

- First of all, it can be noticed that the pack (materials inputs and manufacturing) as well as transport have a low contribution to all impacts, except the contribution of the transport to the photochemical oxidant formation potential (still less than 20%).
- The cells (materials inputs and manufacturing) contribute significantly to the abiotic resources depletion potential (mainly due to the extraction of cadmium) and the terrestrial acidification potential (mainly due to the emissions of sulphur dioxide to air related to the nickel production).
- Use phase is electricity consumption only, so the environmental impacts related to that phase are those of electricity production (a European electrical mix is considered, which contains about 50% fossil fuels). The use phase contribution to the global warming potential (mainly due to the emission of carbon dioxide to the air) and the cumulative energy demand (mainly due to the use of coal and uranium for energy production) are dominant.
- The end-of-life of the batteries contributes mainly to human toxicity and freshwater ecotoxicity potentials (when both short and long-term emissions are taken into account). These impacts are mainly related to the potential release of metals in landfills, namely cadmium for human toxicity, and cadmium and nickel for freshwater ecotoxicity. For all other indicators, the end of life of the battery shows environmental benefits, due to the recycled fraction of batteries, except for human toxicity potential without long-term emissions.
- The end-of-life of the charger contributes mainly to the freshwater ecotoxicity potentials (when both short and long-term emissions are taken into account). For all other indicators except global warming potential, the end of life of the charger shows environmental benefits, due to the recycled fraction of batteries.

## 4.2. LCA results for NiMH battery

**Table 10. Results for NiMH battery**

	Cells	Pack	Charger	Transport	Use	End-of-life batteries	End-of-life Charger
Global Warming Potential	Orange	Green	Yellow	Green	Red	Green	Green
Cumulative Energy Demand	Yellow	Green	Yellow	Green	Red	Green	Green
Photochemical Oxidant Formation Potential	Red	Green	Yellow	Yellow	Orange	Green	Green
Terrestrial acidification Potential	Red	Green	Yellow	Green	Orange	Green	Green
Abiotic Resource Depletion Potential	Orange	Green	Yellow	Green	Red	Green	Green
Human Toxicity Potential without LT	Orange	Green	Orange	Green	Orange	Green	Green
Freshwater Aquatic Ecotoxicity Potential without LT	Orange	Green	Orange	Green	Orange	Green	Green
Human Toxicity Potential with LT	Orange	Green	Orange	Green	Orange	Yellow	Green
Freshwater Aquatic Ecotoxicity Potential with LT	Yellow	Green	Green	Green	Green	Red	Yellow

This table allows identifying environmental “hotspots” of NiMH batteries:

- First of all, it can be seen that pack (materials inputs and manufacturing) as well as transport have a low contribution to all impacts, except a less minor contribution of transport to photochemical oxidant formation potential.
- Cells (materials inputs and manufacturing) contribute significantly to the photochemical oxidant formation potential (mainly due to emissions of nitrogen oxides to air related to the production of LaNi<sub>5</sub>) and the terrestrial acidification potential (mainly due to the emissions of sulphur dioxide to air related to the production of nickel and LaNi<sub>5</sub>).
- Use phase is electricity consumption only, so the environmental impacts related to that phase are those of electricity production (a European electrical mix is considered, which contains about 50% fossil fuels). Contributions of use phase to global warming potential (mainly due to the emission of carbon dioxide to the air), cumulative energy demand (mainly due to the use of coal and uranium for energy production) and to abiotic resource depletion potential (mainly due to the extraction of coal) are dominant.
- The end-of-life of the batteries contributes mainly to freshwater ecotoxicity potential (when both short and long-term emissions are taken into account). This impact is mainly related to the potential release of metals in landfills, namely the emission of nickel. For all other indicators, the end of life of the battery shows environmental benefits, due to the recycled fraction of batteries, except for human toxicity potential without long-term emissions.
- The highest contribution of the end-of-life of the charger is for freshwater ecotoxicity potential (long-term perspective). For all other indicators except global warming potential, the end of life of the charger shows environmental benefits, due to the recycled fraction of batteries.

### 4.3. LCA results for LiFePO<sub>4</sub> battery

**Table 11. Results for LiFePO<sub>4</sub> battery**

	Cells	Pack	Charger	Transport	Use	End-of-life batteries	End-of-life Charger
Global Warming Potential	Yellow	Yellow	Yellow	Green	Red	Green	Green
Cumulative Energy Demand	Yellow	Yellow	Yellow	Green	Red	Green	Green
Photochemical Oxidant Formation Potential Potential	Yellow	Yellow	Orange	Yellow	Orange	Green	Green
Terrestrial acidification Potential	Orange	Yellow	Orange	Green	Red	Green	Green
Abiotic Resource Depletion Potential	Yellow	Yellow	Orange	Green	Red	Green	Green
Human Toxicity Potential without LT	Red	Yellow	Red	Green	Orange	Green	Green
Freshwater Aquatic Ecotoxicity Potential without LT	Yellow	Yellow	Red	Green	Yellow	Green	Green
Human Toxicity Potential with LT	Red	Yellow	Red	Green	Yellow	Green	Green
Freshwater Aquatic Ecotoxicity Potential with LT	Yellow	Green	Yellow	Green	Green	Orange	Orange

This table allows identifying environmental “hotspots” of LiFePO<sub>4</sub> batteries:

- First of all, it can be seen that transport has a low contribution to all impacts, except for photochemical oxidant formation potential.
- Cells (materials inputs and manufacturing) contribute significantly to human toxicity potential, both for the perspective without long-term emissions (mainly due to the emissions of lead, arsenic, cadmium and zinc to air during the production of copper) and for the long-term perspective (mainly due to the long-term emissions of arsenic and zinc to water during the production of copper).
- The charger (materials inputs and manufacturing) contributes significantly to human toxicity potential, both for the long-term perspective (mainly due to the emissions of lead, arsenic, cadmium and zinc to air during the production of electronic components) and the long-term perspective (mainly due to long-term emissions of zinc and arsenic to water related to the manufacturing of electronic components included in the charger). The charger also shows a significant contribution to freshwater aquatic ecotoxicity potential when considering the short-term perspective, due to the emission of zinc to water related to the production of electronic components.
- Use phase is electricity consumption only, so the environmental impacts related to that phase are those of electricity production (a European electrical mix is considered, which contains about 50% fossil fuels). The contributions of use phase to global warming potential (mainly due to the emission of carbon dioxide to the air), cumulative energy demand (mainly due to the use of coal and uranium for energy production), abiotic resource depletion potential (mainly due to the extraction of coal) and terrestrial acidification potential (mainly due to the emissions of sulphur dioxide to air) are dominant.
- For all indicators, except freshwater ecotoxicity potential with long-term emissions, the end of life of the battery shows environmental benefits, due to the recycled fraction of batteries.
- The end-of-life of the charger contributes to freshwater ecotoxicity potential (when both short and long-term emissions are taken into account). For all other indicators except global warming potential and human toxicity potential, the end of life of the charger shows environmental benefits, due to the recycled fraction of batteries.

## 5. Comparative assessment

The following figure shows the relative environmental impacts of the NiMH and LiFePO<sub>4</sub> batteries for one Functional Unit (1 kWh delivered by the battery to the CPT) compared to the impacts of the NiCd battery considered as the reference (i.e. 100% for each indicator).

When discrepancies between two batteries are lower than a threshold of 20% (considered as the *minimum* uncertainty on LCIA models), they are not considered significant (grey cells).

For the comparative assessment, the following colour code is used:

	> 150%
	130% < <150%
	120% < <130%
	80% < <120%
	50% < <80%
	< 50%

**Table 12. Comparative results for the three battery types (reference: NiCd battery)**

	NiCd	NiMH	LiFePO <sub>4</sub>
Global Warming Potential	<i>reference</i>		
Cumulative Energy Demand	<i>reference</i>		
Photochemical Oxidant Formation Potential	<i>reference</i>		
Terrestrial acidification Potential	<i>reference</i>		
Abiotic Resource Depletion Potential	<i>reference</i>		
Human Toxicity Potential without LT	<i>reference</i>		
Freshwater Aquatic Ecotoxicity Potential without LT	<i>reference</i>		
Human Toxicity Potential, 5% LT	<i>reference</i>		
Freshwater Aquatic Ecotoxicity Potential, 5% LT	<i>reference</i>		
Human Toxicity Potential with LT	<i>reference</i>		
Freshwater Aquatic Ecotoxicity Potential with LT	<i>reference</i>		

### 5.1. Analysis per environmental impact indicator

#### ***Global Warming Potential and Cumulative Energy Demand***

There is no significant difference between the three batteries for these indicators. These impacts are mainly generated by the use phase for the three battery types. Since the energy consumption is similar for the three technologies (see Table 4 page 10), total impacts on global warming potential and cumulative energy demand lay in the same range for the three battery types.

### ***Photochemical Oxidant Formation Potential***

The NiMH battery shows a higher photochemical oxidant formation potential, due to a higher contribution of the cells to this impact. This is mainly due to emissions of nitrogen oxides related to the production of LaNi<sub>5</sub>.

### ***Terrestrial Acidification Potential***

The NiMH battery shows a higher impact on acidification due to a higher contribution of the cells to this impact. This impact is mainly due to the emissions of sulphur dioxide to air related to the production of nickel and LaNi<sub>5</sub>. NiMH cells have a higher nickel content, hence the impact difference with NiCd. Furthermore, since the production of the LiFePO<sub>4</sub> compound emits less acidifying substances than the production of nickel, the LiFePO<sub>4</sub> battery shows a lower acidification potential than the other battery types.

### ***Abiotic Resource Depletion Potential***

The NiCd battery has a significantly higher potential impact on this indicator than the two other battery types. This is mainly due to the fact that NiCd contains cadmium that contributes highly to abiotic resource depletion, because of its high scarcity.

### ***Human Toxicity and Freshwater Aquatic Ecotoxicity Potentials***

- Human Toxicity Potential - without long-term emissions

For this indicator, LiFePO<sub>4</sub> has higher potential impacts than the two other battery types. The difference is due to a higher impact of the cells (mainly due to the emissions of lead, arsenic, cadmium and zinc to air during the production of copper) and the charger (mainly due to the emissions of lead, arsenic, cadmium and zinc to air during the production of electronic components). The charger of LiFePO<sub>4</sub> batteries contains more electronic components than the charger of other battery technologies.

- Freshwater Aquatic Ecotoxicity Potential - without long-term emissions

For this indicator, LiFePO<sub>4</sub> has higher potential impacts than the two other battery types. The difference is due to the higher impact of the pack (emission of zinc to water and copper to air related to the manufacturing of electronic components) and the charger (mainly due to the emission of zinc to water related to the production of electronic components).

- Human Toxicity Potential with long-term emissions

The NiCd battery has higher potential impacts than the two other battery types, mainly because of the presence of cadmium in the cells and subsequently its potential emissions to water in landfills.

- Freshwater Aquatic Ecotoxicity Potential with long-term emissions

The NiMH battery shows higher potential impacts than the two other battery types, mainly because of the emissions of nickel to water in landfills.

- Human Toxicity Potential and Freshwater Aquatic Ecotoxicity Potential, 5% long-term emissions

We now consider an intermediate situation, where only 5% of the long-term emissions are released in the environment: the trends are the same as for the release of all the metallic content of the batteries, showing that long-term emissions have a higher contribution to toxicity impacts than the short-term emissions, even when only 5% of the total content in metallic substances present in the batteries is assumed to be released in the environment in the long-term.

## 5.2. Preliminary conclusions of the comparative assessment

It is not possible to state that one battery shows environmental advantages on global warming potential and on cumulative energy demand: these impacts are mainly generated by the use phase for the three battery types. Since the energy consumption is not very different for the three technologies (see Table 4page 10), the overall impacts for these two indicators do not discriminate the three battery types.

The recovery of material for the recycled fraction of batteries generates environmental benefits that lead to low impacts or negative impacts<sup>19</sup> for the end-of-life of the batteries, except for toxicity and ecotoxicity indicators that consider long-term emissions. In that case, the environmental benefits of recycling are completely cancelled by the impacts of long-term emissions in landfills.

Batteries are ranked differently in terms of potential impacts on human toxicity and freshwater ecotoxicity, depending on the inclusion or exclusion of long-term emissions. Thus, it is not possible to conclude on the superiority of one particular battery type without additional studies on this specific topic.

## 6. Conclusions of the Life Cycle Assessment

As a reminder, these conclusions are only valid under the assumptions considered at this stage of this study.

The main differences between batteries used in CPTs are on the following impacts: Abiotic Resource Depletion Potential, Terrestrial acidification Potential, Human Toxicity Potential and Freshwater Ecotoxicity Potential.

Regarding **Abiotic Resource Depletion Potential**, NiCd battery shows higher potential impacts than the two other technologies, due to the presence of cadmium in its composition.

Regarding **Terrestrial acidification Potential**, NiMH and NiCd batteries show higher impacts than LiFePO<sub>4</sub> because of the presence of nickel in their composition. The production of nickel generates emissions of acidifying substances (sulphur dioxide) to the air.

For **Human toxicity and freshwater ecotoxicity**, batteries are ranked differently, depending on whether only short-term emissions are considered or both short- and long-term potential emissions are considered:

- *Short term emissions only:* LiFePO<sub>4</sub> battery contains more electronic components (both in pack and charger). The production of these components mainly generates short-term emissions, leading to higher impacts for LiFePO<sub>4</sub> battery in comparison to the two other technologies. Also, the higher content of copper in LiFePO<sub>4</sub> cells contributes to a higher impact for this battery type, due to the emissions of metal to air associated with copper production.
- *Both long-term and short-term emissions:* Long-term emissions are mainly generated by metal emissions to groundwater coming from batteries in landfills. When adding short-term and long-term emissions, LCA results show that NiCd battery has the highest potential impact on human toxicity. Regarding freshwater ecotoxicity potential, LiFePO<sub>4</sub> battery has a lower impact than the two other technologies, due to the fact that its materials are less toxic than nickel, which is present in the composition of the two other technologies.

The sensitivity of the results to a variation of the collection rate will be tested in the next steps of the study.

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<sup>19</sup> i.e. environmental benefits

## 7. Limitations and uncertainties of the study

The main limitations of the study are the following:

- **Uncertainty on collection rate:** in order to assess the influence of the uncertainty on this parameter, a sensitivity analysis will be performed in the next steps of the study.
- **Uncertainty on the amount of metals that is eventually released in the environment** when a battery is disposed in a landfill. The assessment of human toxicity and ecotoxicity impacts with a long-term perspective show that this data is of major importance. The release of 100% of the metallic content of the batteries is a maximizing assumption that should be considered as a 'potential release', not an actual release of metals in the environment.
- **The characterisation of human toxicity and ecotoxicity impacts:** once the quantity of released metals has been determined (see previous point), impacts on humans and on the environment have to be characterised. For this, the USEtox methodology has been used. This method, though consensual amongst the LCA community, has been recently developed. Its characterisation factors for metals are classified as 'interim', and thus should be refined in the future.

DRAFT

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## 9. Appendix: description of LCIA methods and environmental impacts

**ReCiPe (PRé Consultants, CML, University of Leiden, Radboud University Nijmegen, NL 2008) [10].** This methodology has been recently developed by the main developers of LCIA methodologies in Europe with the objective to develop a method that is harmonised in terms of modelling principles and choices and which offers results at both midpoint and endpoint levels.

**Centre of Environmental Science (CML 2002), Leiden NL [9].** This life cycle impact assessment methodology is based on a midpoint approach covering all emission and resource related impacts, for which practical and acceptable characterization methods are available [9]. Best available characterization methods have been selected based on an extensive review of existing methodologies world-wide. For most impact categories, a baseline and a number of alternative characterization methods are recommended and for these methods, comprehensive lists of characterization and also normalization factors are supplied.

**USEtox [11]** has been recently developed to evaluate toxicity (human toxicity and aquatic ecotoxicity) issues in LCA. As for ReCiPe, the methodology is harmonised in terms of modelling principles and choices and based on a consensus within European experts specialised on this topic.

**Table 13. Description of environmental impacts**

Source	Impact	Description	Unit
ReCiPe	<b>Terrestrial Acidification potential (AP)</b>	Acidification consists in the accumulation of acidifying substances (e.g. sulphuric acid, hydrochloric acid) in water particles in suspension in the atmosphere. Deposited onto the ground by rains, acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings).	kg SO <sub>2</sub> eq.
	<b>Global warming potential (GWP)</b>	Global warming refers to the increase in the average temperature of the Earth's surface, due to an increase in the greenhouse effect, caused by anthropogenic emissions of greenhouse gases (carbon dioxide, methane, nitrous oxide, fluorocarbons (e.g. CFCs and HCFCs), and others).	kg CO <sub>2</sub> eq.
	<b>Photochemical oxidation potential (POCP)</b>	This pollution results mainly from chemical reactions induced by solar light between nitrogen oxides and volatile organic compounds (VOC), commonly emitted in the combustion of fossil fuels. It provokes high levels of ozone and other chemicals toxic for humans and flora.	kg NMVOC eq.
CML	<b>Abiotic resource depletion potential (ADP)</b>	Resource depletion can be defined as the decreasing availability of natural resources. The resources considered in this impact are fossil and mineral resources, excluding biotic resources, and associated impacts such as species extinction and loss of biodiversity.	kg Sb eq.
USEtox	<b>Human Toxicity Potential (HTP)</b>	Human toxicity potential assesses the impact of toxic substances released in the environment on the human health by providing an estimation of the increase in morbidity in the total human population (cases). Both cancer and non-cancer cases are taken into account.	cases
	<b>Freshwater Aquatic Ecotoxicity Potential (FAEP)</b>	Freshwater Aquatic Ecotoxicity Potential assesses the impact of toxic substances released in the environment on the ecosystem by providing an estimation of the potentially affected fraction of species (PAF) integrated over time and volume.	PAF m <sup>3</sup> day
<i>Flow indicator</i>	<b>Cumulative Energy Demand</b>	Primary energy is raw energy available in nature. The main non-renewable primary energies are: oil, coal, natural gas, and nuclear energy. The main renewable primary energies are biomass, wind, geothermal, solar and hydro energy.	MJ

## PART 2: IMPACT ASSESSMENT

The key objective of the Impact Assessment is to assess the likely economic, social, and environmental impacts of three policy options to reduce the environmental impact and human exposure to cadmium associated with these batteries, while considering the potential to withdraw the current exemption in the Batteries Directive for cadmium (NiCd) use in batteries used in cordless power tools (CPTs).

The policy analysis conducted in this study is based on the Commission's Impact Assessment Guidelines<sup>20</sup>. The Impact Assessment is therefore divided into the following six sections:

1. Defining the problem
2. Defining the policy objectives
3. Identification of policy options
4. Analysis of impacts
5. Comparison of options
6. Monitoring and evaluation

Findings of the Impact Assessment allows for a solid basis to select the most feasible and optimal recommendations.

The three policy options analysed in the Impact Assessment are as per following:

■ **Option 1 – Baseline scenario (no withdrawal of the exemption)**

In this option, the current situation would continue, meaning there would be no withdrawal of the exemption of the use of NiCd batteries in CPTs. Collection and treatment rates would continue based on current legislation.

■ **Option 2 – Immediate withdrawal of the exemption (2012/2013)**

This option would immediately (2012/2013) withdraw the exemption, banning the use of NiCd batteries in CPTs. The collection and treatment rate of NiCd would remain the same based on rates specified under the Batteries Directive. This option also assumes that viable substitutes exist for NiCd battery technology for CPTs.

■ **Option 3 – Delayed withdrawal of the exemption (2016)**

This option would withdraw the exemption in force in **2016** thus banning the use of NiCd batteries in CPTs. The collection and treatment rate of NiCd would remain the same based on rates specified under the Batteries Directive. This option also assumes that viable substitutes exist for NiCd battery technology for CPTs.

<sup>20</sup> Commission's internal Guidelines on IA as updated on 15 January 2009:  
[ec.europa.eu/governance/impact/docs/key\\_docs/iag\\_2009\\_en.pdf](http://ec.europa.eu/governance/impact/docs/key_docs/iag_2009_en.pdf)