Primary and secondary battery consumption trends in Sweden 1996-2013: method development and detailed accounting by battery type

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Abstract

In this article, a new method based on Material Flow Accounting is proposed to study detailed material flows in battery consumption that can be replicated for other countries. The method uses regularly available statistics on import, industrial production and export of batteries and battery-containing electric and electronic equipment (EEE). To promote method use by other scholars with no access to such data, several empirically results and their trends over time, for different types of batteries occurrence among the EEE types are provided. The information provided by the method can be used to: identify drivers of battery consumption; study the dynamic behavior of battery flows - due to technology development, policies, consumers behavior and infrastructures. The method is exemplified by the study of battery flows in Sweden for years 1996-2013. The batteries were accounted, both in units and weight, as primary and secondary batteries; loose and integrated; by electrochemical composition and share of battery use between different types of EEE. Results show that, despite a fivefold increase in the consumption of rechargeable batteries, they account for only about 14% of total use of portable batteries. Recent increase in digital convergence has resulted in a sharp decline in the consumption of primary batteries, which has now stabilized at a fairly low level. Conversely, the consumption of integrated batteries has increased sharply. In 2013, 61% of the total weight of batteries sold in Sweden was collected, and for the particular case of alkaline manganese dioxide batteries, the value achived 74%.

1 Introduction

The unsustainable way in which we use resources has resulted in environmental pollution, ecosystem degradation and raw materials exhaustion. One of the priority products for protection of the environment and resource recycling is batteries. In the last decades, batteries registered a huge consumption increase due to the fast growing of portable electronic equipment industry (Guevara-García and Montiel-Corona, 2012; Zand and Abduli, 2008). Metals are the major constituents of batteries and represent more than 50% of the weight of all types of batteries (Fisher, 2006). Some of these metals are valuable (Ag, Ni, Zn) while others are hazardous (Hg, Cd and Pb). Therefore, when batteries are disposed of improperly, harmful substances may cause damage to both humans and animals. Even in countries where batteries that contain hazardous metals are banned, such as the EU member states, old batteries containing heavy metals may be stored by consumers for a long time and enter the waste stream at a later date.

During the last two decades, the European Union adopted several regulations to ban or reduce specific hazardous metals that can be present in batteries. The 91/157/EEC Directive forbids marketing of batteries and accumulators containing more than 0.0005% of mercury, including where such batteries and accumulators are contained in appliances. The Directive was incorporated into Swedish law in 1997 by Ordinance 1997:645 on batteries, which was later replaced by the Ordinance 2008:834. Later, the EU Batteries Directive 2006/66/EC, mandate member states to ban the marketing of batteries and accumulators containing more than 0.002 % of cadmium. The prohibition of cadmium does not apply to portable batteries intended for use in emergency and alarm systems, including emergency lighting, medical equipment or cordless power tools

Separate collection of batteries is implemented in all the EU member states, as well as in Japan and Australia among other countries. Several EU countries have long experience of this type of collection with over 15 years of separate collection in the Scandinavian countries, the Netherlands, Belgium and

Germany. However, for the EU as whole, only approximately 32% of the consumed batteries are collected (EPBA, 2013). The collection of portable batteries in Europe is mandated by the Directive 2006/66/EC, which requires member states to achieve a collection rate of 25% by 2012 and 45% by 2016. Sweden has defined more ambitious collecting targets of 65% by 2012 and 75% by 2016. These collection targets were established in the Ordinance 2008:834, which from January 01, 2009 transfers the responsibility for battery collection and recycling from municipalities to producers of batteries and of electronic equipment containing them. At the same time, the Swedish EPA became the agency responsible for compiling statistics on battery sales and collection, why national statistics are only available from 2009. According to the Swedish EPA statistics, 64% of the batteries sold in Sweden in 2013 were collected. The statistics on collection of batteries prior to 2009 is spread between a number of actors, including waste treatment companies (delegated to by municipalities), the trade association for producers of electric and electronic equipment (EEE) (El-kretsen), the Swedish EPA and the industry organization for battery producers, among others. No compiled national statistics could be found for the sales and collection of batteries before 2009 and the available data is of high and different aggregation. The aim of the research project “Efficient battery collection with consumer focus”, grant 37684-1 by the Swedish Energy Agency is to assist in achievement of the Swedish ambitious goal of collecting 75% of all used batteries. The project consists of three parts, developing knowledge on 1) the battery consumption (physical flows); 2) available collection infrastructure and its effectiveness and 3) the users’ behavior. This article is a contribution to the study of the physical flows of batteries with an application to Sweden as a case study.

To date, few studies have been made on batteries flows accounting. The Material Flow Analysis (MFA) studies considered selected types of batteries (Chang et al., 2009; Espinoza et al., 2014). Other studies on battery flows include the European Portable Battery Association’s report on the collection rates of portable batteries by the members of the European Economic Area in 2012 (EPBA, 2013). To the best of our knowledge, no complete and systematic methodology for accounting battery flows has been published.

This article has the following objectives: i) to propose a method for accounting battery flows; ii) to account the consumption of portable batteries in Sweden between 1996 and 2013; iii) to identify the main characteristics and trends in battery consumption; iv) compare the total amount of batteries consumed with the total amount of batteries collected

2 Methods

2.1 Material Flow Analysis

Batteries can be divided into 3 main groups: portable batteries, industrial batteries and automobile batteries. Batteries and accumulators are considered portable when they are sealed and can be hand-carried, and are neither industrial batteries nor automotive batteries. Portable batteries are the focus of this study because they represent 98% of the total number of batteries placed on the market in Europe and, at the same time, are recycled to a much smaller degree than automobile and industrial batteries (EPBA, 2013). Portable batteries are in turn divided into primary (not rechargeable) and secondary batteries (can be recharged). In accordance with the Swedish standard, portable batteries or accumulators cannot weight more than 3 kg.

A method to account batteries consumption at a product level, based on a mass balance was developed in this study. The method follows the same concepts of other methods applied and developed by the Urban Metabolism Group of Chalmers University, in which resources consumption is accounted at product level (Rosado et al., 2014; 5a). Material Flow Analysis (MFA) and in particular Domestic Material Consumption indicator (DMC) is used to analyze battery flows. Material Flow Analysis is a systematic assessment of materials, and their stocks and flows, over time and space, within a defined system

(Brunner and Rechberger, 2004). In figure 1, a scheme of the method is present. Each step is described in detailed in the following paragraphs.

Figure 1 – Method developed to account batteries consumption at a product level

Step 1 – Batteries Identification by product code

The model applies an internationally accepted nomenclature to systematically assess the flows, the Combined Nomenclature classification (CN), used for foreign trade data. In the CN classification, each product type is assigned an 8-digit classification code, the codes may than be aggregated to a larger groups of products (Table 1). In this step, CN codes corresponding to primary and secondary batteries are identified and grouped by electrochemical composition, and by shape.

Table 1 – Examples of batteries and Electric and Electronic Equipment (EEE) CN codes

Step 2 – Batteries DMC quantification by electrochemical type

In the second step, the batteries consumption is accounted by battery type and electrochemical composition using the MFA indicator Domestic Material Consumption: DMC = Imports + Industrial Production – Exports. The balance was done in metric tons and units. The following equation shows an example on how DMC was accounted for alkaline cylindrical cells (Primary batteries – CN 85061011) in 2013.

$$DMC_{CN\ 85061011} = IMP_{CN\ 85061011} + IP_{CN\ 85061011} - EXP_{CN\ 85061011} \qquad \text{(Equation 1)}$$

$$DMC_{CN\ 85061011} = 5911 + 0 - 2949 = 2962\ tonnes$$

with DMC=Consumption, IMP=Imports, IP=Industrial Production, EXP=Exports, CN=Combined Nomenclature

Additionally the accounting of imports can be done by country of origin, while exports by country of destination.

Step 3 – DMC allocation by batteries types of use

The DMC is allocated to the three different batteries types by use: loose batteries, integrated batteries and for manufacture batteries. Loose, are the batteries sold separately and are mounted to the EEE by the consumer; integrated batteries are sold integrated in EEE, as for instance the ones sold embedded in mobile phones; for manufacture, are the batteries with destination to manufacturing or assembling EEE in the study region.

According to the European Commission (European Commission, 2003), only 30% of the portable batteries sold were integrated in EEE, of which only 10% were primary batteries. Therefore, it was assumed that primary batteries can be regarded as loose batteries. Intermediate and for manufacture primary batteries can be considered negligible.

In contrast, and according to the EPBA (EPBA, 2013), about 90 % of the sold secondary batteries are integrated in devices. Therefore all the batteries types of use have to be accounted. First, the amounts of loose and for manufacture batteries are accounted, by assigning the DMC accounted in Step 2 (See Equation 1). This is done by allocating the DMC to the economic activity (according to the international trade and Statistical classification of economic activities), which imported the battery. Further, it was assumed that batteries that were imported by the manufacture sector were used for integration in devices manufactured or assembled, i.e. for manufacture batteries. Batteries that were imported by other economic activities then Manufacture were assumed to be consumed as final products. For manufacture batteries will not be considered further in this study, since the consumed part will be accounted as integrated batteries. The following example shows the DMC allocation for nickel-cadmium (Secondary batteries – CN 85073020) in 2012.

$$DMC\ Manufacture_{CN} = \frac{IMPORTED_{manufacture}}{IMPORTED_{manufacture}+IMPORTED_{other}} \times DMC_{CN} \qquad \text{(Equation 2)}$$

$$DMC\ Manufacture_{CN\ 85073020} = \frac{0.51}{25.5} \times 19 = 0.38\ tonnes$$

with DMC=Consumption, CN= Combined Nomenclature

Step 4 –Batteries integrated in EEE

To account the number and weight of batteries sold integrated in EEE an extra step is necessary (Step 4 in figure 1). This step is dived in 3 sub-steps:

Step 4.1 – Identification of devices that may contain secondary batteries

The main types of EEE that contain secondary batteries were identified using a database of waste EEE (WEEE) collected in Sweden between the 01 March 2009 and the 30 June 2009 (El-Kretsen, 2013). The database covers 8,832 electronic devices that contain batteries, for which both the type (primary or secondary, shape and electrochemical composition) and the weights of the device and the battery are known. Selection rule 1: The types of EEE where at least 35% of the devices contained secondary batteries were selected, which resulted in 43 categories (3285 EEE from the 3582 of EEE containing secondary batteries). The remaining 27 categories were assumed to be regularly powered by primary batteries (i.e. primary batteries were inserted by the consumers after the device had been bought) and therefore not considered. However, cameras were excluded from this rule due to the fact that many cameras were powered by primary batteries before 2009, but increasingly use integrated batteries after this time. It is reasonable to assume that the categories of EEE containing different types of batteries found in this paper are valid for other countries due to the global EEE market.

From the selected categories of EEE with secondary batteries, the types of EEE that occurred more than 20 times were selected (representing in total 3151 EEE of the previous 3285 EEE selected). A category for string trimmer (CN 84331110) was added despite fewer than 20 occurrences, due to the considerable weight of the batteries (approximately 2.1 kg). The final selection comprised 15 EEE categories.

Step 4.2 – Accounting the consumption/sales of the most important categories of EEE that could contain secondary batteries

Sales statistics (Branchkansliet, 2014), International Trade Data (SCB, 2013) and Industrial Production Data (SCB, 2013) were compiled by type of device and number of units consumed/sold. A combination of these sources was necessary for all the selected EEE categories. The proportion of EEE devices that contain secondary batteries was also accounted. EEE may sometimes be powered either by battery or by plug-in electricity. To calculate the proportion of devices within the different EEE categories that are powered by batteries, another empirical database from the WEEE study was used (El-Kretsen, 2013). This database included the production years for the WEEE collected, and specified whether each device was a plug-in or battery powered. Three types of products, namely Hair cutters, Epilators and Shavers, were identified as products with variable power sources. The distribution between plug-in and battery driven devices for a certain year and EEE category was used to calculate the number of secondary batteries. Where no data on production year was available, the same proportion of battery-holding devices was assumed for all the studied years.

Step 4.3 –Accounting the weight of secondary integrated batteries for each type of EEE

The cumulative weight of the batteries included in each EEE category was estimated by multiplying the number of EEE devices with the average weight of the batteries observed for each category. Whenever possible, variations of the battery weight of each EEE through studied time period were considered. The importance of the EEE categories to the total weight of the batteries was estimated to

95.4% (i.e. 4.6% of the weight is not covered by the selected 15 categories), by dividing the weight of the categories chosen for further analysis by the total weight of all the secondary integrated batteries in the database. The factor 1.046 was used to correct the calculated annual flows of integrated batteries for this missing part.

Step 5 –Total battery consumption

In this step of the model, the total amount of loose batteries, accounted in Step 3 is summed with the amount of integrated batteries accounted in the previous step to produce the total batteries DMC.

Data analysis

Identification of the electrochemical composition of the consumed batteries allows the technological mix analysis. Time series of results allow trend analysis, for instance quantities (absolute and normalized by population) and types of consumed batteries. As an example, one can compare the primary and secondary batteries consumption. Complemented with information on the policies, technological change, income development etc. the effect of the implemented regulations, technology shifts and consumer behavior on the batteries consumption can be studied. Collection rates can also be calculated by comparing the consumption results with the amount of batteries collected.

2.2 Data sources

Data on industrial production and international trade by CN codes level 8 for the years 1996-2013 was acquired from the Swedish Statistical Service (SCB, 2014). The data is available on an annual basis in mass weight and/or number of units. The industrial production data expressed in units was converted to mass weight (tons), using the Eurostat Conversion Factors Table (Eurostat, 2014).The annual sales of EEE by type of equipment for the years 1996-2013 was acquired from the trade organization for Electric Household Equipment Suppliers (Branchkansliet, 2014). The type (primary or secondary), occurrence and weight of integrated batteries were based on the detailed study of collected waste EEE (WEEE) carried out in Sweden in March-July 2009 (El-Kretsen, 2013). Data on batteries sold in Sweden, reported by official national statistics, is available from 2009 (Swedish EPA, 2014a). The data is in tons annually for primary and secondary batteries and is provided by the sellers of batteries and EEE. The weight of the batteries collected through separate waste collection in 2009-2013 was acquired from the trade organization for WEEE management, El-kretsen (El-kretsen, 2013b) and the official national statistics (Swedish EPA, 2014a). Collection data is only available in weight. For consumer electronics and portable batteries, the trade association El-Kretsen is the dominating actor and provides the Swedish EPA with almost complete data for the national level. The data is collected from the pre-treatment plants, where the WEEE is dismantled and major components of plastic and metal are recovered. Electronic circuits, cables, batteries etc. are sent to other plants for further recovery. During the pre-treatment process all built in batteries are separated due to chemical properties and weighted (El-Kretsen, 2015a). The weight of the integrated batteries is reported separately from the portable batteries aggregated to the 10 categories of products specified in the 2012/19/EU Directive on WEEE (ANNEX II).

2.3 Limitations

Integrated lead batteries were only partially assessed, in particular for string trimmer and vacuum cleaners. Other products that use lead batteries, but were not accounted because they occurred less than 20 times in the WEEE database were torches, large toys and electric scooters. The uninterruptible power source (UPS) batteries would have the greatest effect on the consumed lead and total weigh of consumed batteries as they represent 19% of the total battery weigh in the WEEE database. However, although UPS batteries occurred 25 times in the database, they could not be analyzed at this time due to 1) the highly variable battery weigh 5 – 26,240 g; 2) no available sales figures and 3) the lack of a specific CN code; the CN codes 85437090 and 85044030, where the UPS batteries are included also cover a variety of other products. The national battery statistics from the Swedish EPA may include some UPS batteries, despite the fact that these are usually heavier than 3 kg (Swedish EPA,2014a).

Devices that may have secondary batteries were identified based on the El-Kretsen study of collected waste EEE (WEEE) carried out in Sweden in March-July 2009. Since Electronic Equipment is a technology in constant development, it is important that El-Kretsen study could be updated regularly (could be every 5 years), so that new devices that contain secondary batteries can be identified.

Integrated batteries were not accounted by electrochemical composition. The WEEE databases used in this study did not have detailed information on electrochemical composition of secondary batteries integrated in EEE by production year.

To assess the reliability of the proposed method, a comparison between obtained results and the results reported by an external institution was performed, as it will be showed in section 3.5.

3 Results and discussion

3.1 Primary batteries

The flows of primary batteries between 1996 and 2013 in Sweden are shown in Figure 2. The manufacture of primary batteries during the study years was null or negligible. For all the studied years, only a small proportion of the primary batteries were destined for the manufacturing sector. The highest proportion, 2.1% of the total weight, was observed in 2010. This low number reinforces the fact that primary batteries are mainly sold separately and not integrated in EEE.

European regulations are mostly focused on goals for the end of life of products, instead of focuses on the complete product life cycle. For instance, according with Sullivan and Gaines (Sullivan and Gaines, 2012), in energy terms, batteries manufacturing and assembly represents from a third to half of the total lifecycle impact of several studied batteries. In this regard, change of the origin of import for batteries in the last two decades in Sweden has implications on the lifecycle cost of the consumed batteries, as the production processes and environmental laws are different. In 1996 most of the primary batteries were imported from Europe (93% in 1996, in number of units), mainly from Germany and Belgium. In 2013, 58% of the batteries were imported from Europe and 42% from Asia, mostly from China.

Figure 2 – Primary batteries flows in Sweden 1996-2013

It should be noted that the re-export of loose primary batteries from Sweden is substantial (Figure 2). As shown in Figure 3, more than 85% of the total number of batteries exported were re-exported to countries in the vicinity of Sweden (Finland, Norway, Denmark and Estonia). Sweden has the Scandinavia's largest container port, the Gothenburg port, which has immediate connection countries in the Scandinavian and Baltic region (Port of Gothenburg, 2014). This suggests that Sweden serves as a stock and re-distribution logistic hub for batteries in Scandinavia. In fact, the export trend follows the import trend and almost half of the primary batteries imported were later re-exported to other countries. These results are in line with other studies (Kalmykova et al., 2015b; Patrício et al., 2015; Rosado et al., 2015), which found that crossing flows (inputs of resources for later re-export) are important for several types of goods in Sweden and its cities. As a result, the fluctuations in primary battery consumption (DMC) from year to year are caused not only by battery consumption as such but also by stock effects, for example by the stock collected to be sent to other countries or placed on the market at a later time. In general, and as illustrated in Figure 4, the overall trend for primary battery consumption over the last 18 years is an increase, both in weigh and in number of units. Consumption was at its highest between 2003 and 2007, with values above 4,000 tons per annum. After this period, there was a slight decline, which can be explained by the emergence of digital convergence, discussed in detail in the following chapter.

Figure 3 – Destination of the primary batteries exported from Sweden 1996-2013

In 2009, the consumption of primary batteries in Sweden was 14 units per capita, twice the reported average consumption of the EU27 in the same year (EPBA, 2013). This high consumption can be explained by higher than average EEE sales. As an example, 23.5 kg EEE per capita was sold in Sweden in 2009, compared to 18.3 kg per capita in the EU27 (Eurostat, 2014). On the other hand, the estimation from the EPBA (EPBA, 2013) may be slightly on the low side, as only the most popular battery sizes were taken into account. The battery consumption in Sweden has stabilized at around 10 units per capita in the last 3 years despite increasing EEE sales, which again indicates a shift towards different types of devices and integrated batteries.

3.1.1 Drivers of primary battery consumption

As becomes apparent from Figure 4, the curves of the total and per capita consumption of batteries are very similar, both in numbers and in weight units. This suggests that primary batteries are almost exclusively used by households. In fact, the consumption of primary batteries is clearly connected to the use of certain consumer electronic devices. The major increase in the consumption of primary batteries that occurred between 2000 and 2007 (Figure 4) can be linked to the increase in sales of audio and video EEE, and to the increased popularity of MP3 players and portable digital cameras in particular (Branchkansliet, 2014). After 2007, a significant decrease in the battery consumption was observed, which continued until 2011. One possible explanation for this decrease is digital convergence: when electronic equipment, such as audio and video devices, started to place different type information in the digital domain and offer multiple functions. This has resulted in devices such as MP3 players, cameras etc. being replaced by a single device, such as a smart phone or other similar device. Furthermore, these new devices have a high power demand as well as high usage intensity, why they usually contain integrated secondary batteries. These two reasons could explain the decrease in the consumption of primary batteries after 2007, see Figure 4.

Figure 4 – Consumption of primary batteries in Sweden 1996-2013

3.2 Secondary batteries

Loose secondary batteries

One rechargeable battery may substitute dozens of single-use batteries, making it more environmentally friendly as well as more cost effective. In fact the lifetime of secondary batteries depends on the frequency in which they are recharged (Schneider et al., 2014). However, due to their higher energy density and ability to hold a charge for years when not in use, primary batteries are more suitable for low-draw devices such as remote controls and clocks. As shown in Figure 5, the consumption of loose secondary batteries is much lower than that of primary batteries (for example 16 times lower in 2013). Investigation of this relationship is a subject for future research, although it can probably be explained by social factors – that secondary batteries have not become popular; and by patterns of electronics consumption - the representative selection of electronics in a home and what type of batteries are likely to be used. Nonetheless, the number (i.e. units) of secondary batteries consumed has increased substantially over the last 18 years. Secondary batteries have very different weights; therefore any year on year variation in the types of batteries used causes larger fluctuations in weight than in number of units. Stock effects are also an important cause of fluctuations.

Figure 5 – Separated secondary batteries consumption that had wholesale as destination

Integrated secondary batteries

Based on the study of integrated batteries in WEEE (model step 4.1), 15 main categories of EEE containing secondary batteries were identified (Table 2 and Supplementary Table 1): The changes of the EEE shares for consumed batteries for 1996-2013 can be found in Figure 6. The total number of secondary batteries sold as part of EEE increased fivefold, from 1.9 million units in 1996 to 9.9 million units in 2013 (Figure 6).

Table 2 – Batteries Integrated in EEE in Sweden in 2013

Figure 6 – Integrated secondary batteries flows. The EEE categories with less than 3% share are not presented at the figure while drills and electric tools were joined. However, the trend line is based on the complete list of the EEE.

In many countries, including the EU member states, no separate data on weight of integrated batteries is available and estimation factors for battery weight are applied to the amount of EEE sold (EPBA, 2013). Such factors have been calculated for each of the battery-containing EEE categories, as well as for the total EEE consumption in Sweden in 2006-2012 (Table 3). In particular, the cumulative weight of the batteries found for a certain EEE category was divided by the total weight of the electronic devices sold in this category (Swedish EPA, 2014b). In general (i.e. for a Sweden as a whole), the batteries' share of the total weight of a product is increasing linearly (R^2=0.90), by on average 8.7% a year in the period 2008-2012. This increase is mostly due to the factor for IT and telecommunications equipment, which grew linearly (R^2=0.90) by on average 5.9% a year in the same time period. The obtained factors and their trends can be used to calculate the weight of the batteries placed on the market and collected, based on the sales and collection of EEE. The factor precision is higher for countries with similar EEE consumption patterns to Sweden (i.e. similar distribution between the products).

Table 3 – Average share (%) of batteries in the total weight of EEE sold in Sweden

3.3 Total portable batteries consumption

In spite of the fast growing consumption of secondary batteries (5 times in number and 3 times in weight between 1996 and 2013), they only represent14% of the total number of portable batteries consumed in 2013 (Figure 7). But the consumption in weight represents 33% of total. The increase in consumption of high energy demand electronic devices (e.g.: laptops), registered in the last 18 years in

Sweden, can be a possible explanation due to the heavy weight batteries incorporated in this type of products.

Figure 7 – Number and weight of primary and secondary batteries consumed in Sweden between 1996 and 2013

3.4 The chemical composition of batteries

Alkaline manganese dioxide batteries (alkaline batteries) dominate the primary battery market in Sweden. They have been gradually replacing other types of primary batteries and increased from 67% to 83% of the total number of primary batteries consumed during 1996-2013. These batteries dominate the EU market as a whole, with 70% of the total in 2009 (EPBA, 2013). This is also in line with the study performed by Bigum and Colleagues (2013), in which they came to the conclusion that in Denmark, approximately 80% of batteries disposed with the residual waste were alkaline batteries. Alkaline batteries can be found in a variety of shapes, cylindrical and button cells being the most common with a market share of 85% and 5%, respectively. The information of the chemical composition of consumed batteries can be important information to promote the batteries recycling (Bernardes et al., 2004), as well as its impacts (Almeida et al., 2006).

The sale of batteries with more than 0.0005% of mercury has been banned in Sweden since 1997, the result of which can be observed in Figure 8. The consumption of such batteries was relatively high in 1996, with a share of 13% of the total number of primary batteries consumed. In 1998, the exports were higher than the imports, as a result of stored mercury batteries, which no longer could be placed on the Swedish market being sent to other countries. In this particular case, the batteries were sent to Norway, where the sale of batteries containing more than 0.0005% of mercury was not banned until 1999.

In order to discourage the use of batteries containing nickel-cadmium, the Swedish Ordinance 2008:834 obliges producers of sealed nickel-cadmium batteries to pay a charge of SEK 300 per kg of batteries placed on the market. As is shown in Figure 8, NiMH and Lithium-ion accumulators successfully replaced nickel-cadmium accumulators, even before the restrictions were imposed in 2009. This may be partly due to the fact that the energy density of NiMH batteries is almost twice as high as that of cadmium batteries.

Figure 8 – Share of number of batteries consumed by electrochemical composition

3.5 Method Evaluation

The MFA results were compared to the data reported by the Swedish EPA for 2009-2013 (Table 4). The difference between the total DMC and the total amounts sold is within 3%. For the secondary batteries the MFA results are lower, as the portable lead batteries were only partially accounted. The primary battery consumption, on the other hand, is slightly overestimated for the last two years due to the stock effects in the MFA accounting method. The MFA method considers the batteries to have been consumed once they have been imported into the country, however, they may not be sold until the following year. The Swedish EPA, on the other hand, counts the batteries after their sale.

Table – Batteries consumption (DMC, MFA) and according to the Swedish EPA (tons)

The fact that the data on battery consumption reported by official national statistics (Swedish EPA,2014a) is collected and reported in aggregated form, precludes analysis of the impact on the battery consumption of different products within the categories; the past, current and probable future trends for battery types (by EEE type, electrochemical composition, weight, shape etc.) and the number of batteries used. In contrast, the MFA allows analysis of all the factors mentioned above, which makes it a valuable tool for shaping education campaigns and collection systems, as well as for evaluation of recycling capacities.

3.6 Batteries collection

Starting in the 1970s, Sweden was one of the pioneer countries in implementing battery collection initiatives. The first nationwide campaign began in 1987, and it was performed by several institutions including Swedish Environmental Protection Agency (European Commission, 2015). Since then regular campaigns have been frequently conducted. To evaluate the collection rates the consumption was compared with the amount of batteries collected (Table 5). The results show an increasing trend of the share of weight of batteries collected between 2009 and 2013. In 2013, 61% of the total amount of batteries sold was collected. The collected share achieved in 2012 was 2.4 times higher than the targets defined by European Union (25% of batteries collected in 2012), but didn´t reach the targets defined by Swedish laws (65% of batteries collected in 2012). It should be noted that these values have to be analyzed with care, since it is very likely that secondary batteries sold integrated in devices will have a lifetime longer than one year (e.g.: batteries sold integrated in laptops or mobile phones). Furthermore, and as shown in chapter 3.3, the share of secondary batteries in the total batteries consumption have been increasing in the last years. The previous effect may also happen with primary batteries but to a smaller extent (batteries consumed in one year but that will be collected in a different year). If we look specifically for alkaline manganese dioxide batteries (primary batteries), which represent the largest share of batteries consumed in Sweden with more than 50% (Table 5) of the overall market, it is possible to observe that the collection share in 2013 reached 74%. This collection rate is higher than the value defined by the Swedish laws for 2012, and is near the collection rate defined for 2016 (75% of batteries collected).

Table 5 – Batteries collected (Swedish EPA) and batteries consumed (MFA results) between 2009 and 2013 in tonnes

3.7 Batteries Recycling

Depending on their chemical properties separated batteries are sent to different plants nationally and internationally for recycling. The information for recycling capacity was not possible to collect from the plants. In particular, Lead batteries are recycled by Boliden AB, Sweden's largest mining and metallurgical concern; NiMh batteries are recycled by Norilsk Nickel Plant in Russia, one of the Europes largest metallurgical plants; NiCd batteries are recycled by SAFT AB in Sweden, which also produces NiCd batteries for different applications; Hg batteries are treated by NQR (Nordische Quecksilber Rückgewinning GMBH) in Germany; and Li batteries are incinerated by Sakab, Sweden. Alkaline manganese dioxide batteries are also recycled in Sweden. In this particular case, the batteries are crushed and the metals are recovered. According to El-Kretsen (El-Kretsen, 2015b), there is still 35 to 55% of each alkaline manganese dioxide battery collected, which corresponds to the manganese part that is disposed in landfill. Ongoing research is been done in to find techniques to convert it into useful raw material (El-Kretsen, 2015b). In fact, and according with the literature, the recovery of alkaline batteries is not economically feasible without supplemental funding, mostly due to the low value of the end products (Bonhomme et al., 2013; Ferella et al, 2008). The alkaline batteries are a good example that shows that is not enough to have a good collection system if there is still a large part of the collected batteries that has landfill as final destination. It is important to have a better link between the collection and treatment systems, by doing an integrated approach of batteries waste management.

4 Conclusions

A new method, based on material flow analysis (MFA) was developed to analyze the flows of loose primary and secondary batteries, as well as of integrated batteries. The method was demonstrated by compilation of the detailed battery flows for a time series of 18 consecutive years for Sweden. The method was validated by comparing the obtained results to the national statistics, which are based on figures reported by sellers of batteries and battery-containing electronics. The difference in the data from the two sources is within 5% and was explained by the data reporting differences. The method enables more detailed than the national statistics results, which allows several types of analysis aimed at understanding the patterns, drivers and future implications of the battery flows.

During the studied period in Sweden, the consumption of all types of batteries increased. However, the consumption of primary batteries has stabilized since 2010, at 10 new batteries per capita per year, which is still higher than the EU-average of 7 batteries per capita per year. The electronics consumption in Sweden is also above the EU average. We suggest that the recent decline in the primary battery consumption is due to the increasing digital convergence, where one device provides several services and therefore replaces a number of separate devices. Sales trends for the selected categories of electronic devices and the increased consumption of integrated batteries prove this hypothesis. The sharp increase in integrated battery consumption is dominated by batteries in laptops, mobile phones and hand drills.

The consumption of batteries was compared with the amount of batteries collected between 2009 and 2013. In 2012, 60% of the total amount of batteries consumed in Sweden were collected, share that is 2.4 times higher than the targets defined by European Union (25%). However the targets defined by Swedish laws for 2012 were not achieved (65%). Considering only the alkaline manganese dioxide batteries, that in Sweden represented the largest share of consumed batteries (more than 50% of the total share in weight), 73% of the total amount of this type of batteries was collected in 2013. However, 35% to 55% of collected alkaline manganese dioxide batteries still go to landfill, which indicate the absence of an integrated approach to batteries waste management.

Future studies concerning physical flows of batteries include assessment of stocks in Swedish homes and projection of future flows for recycling in terms of numbers and types of batteries, and the availability of recyclable materials. In addition, the effects on the collection efficiency for used batteries of different types of infrastructure for battery collection and of household attitudes and practices will be studied.

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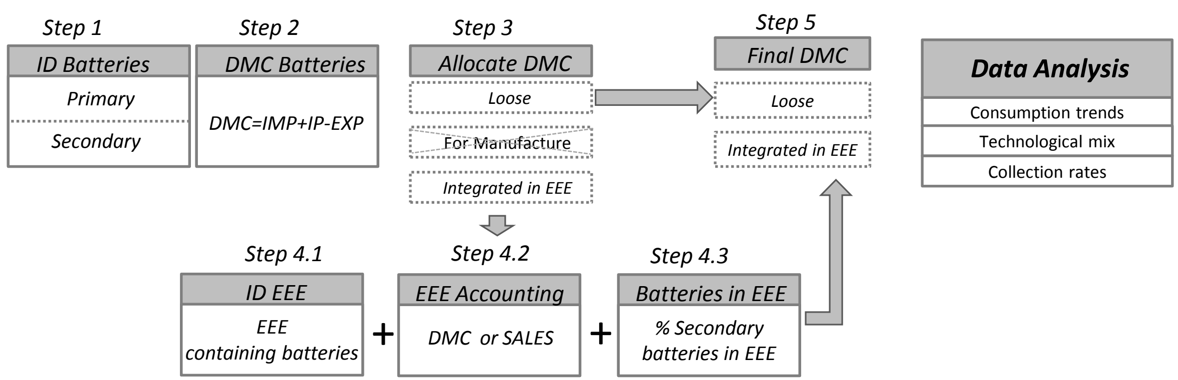
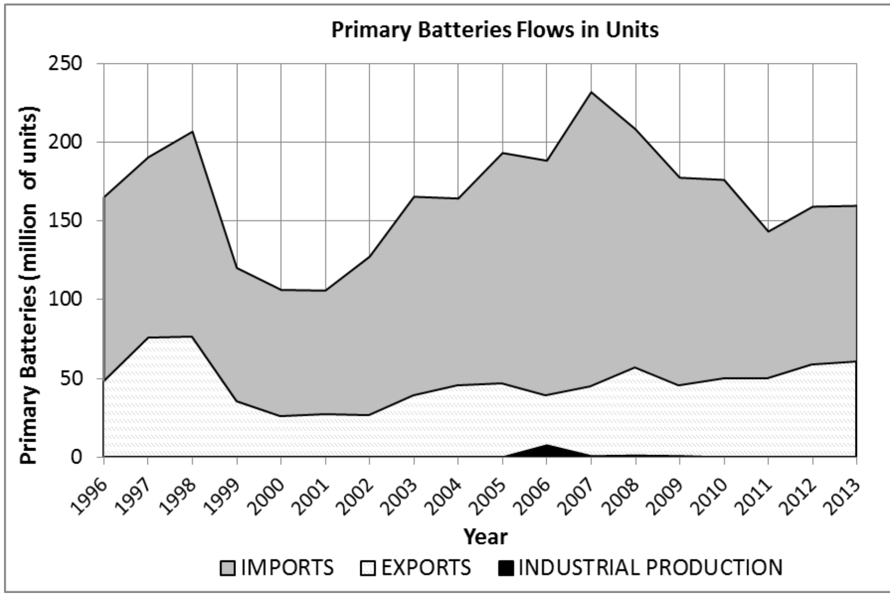
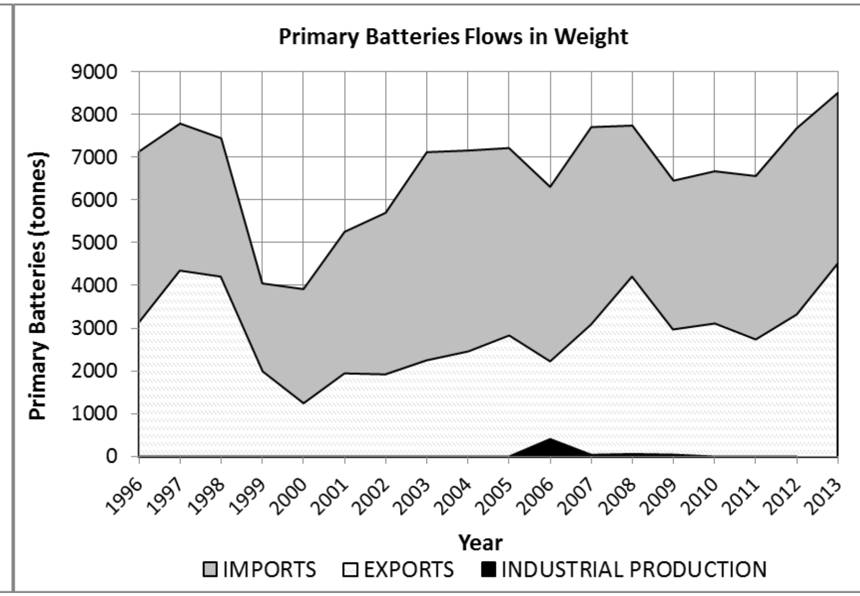


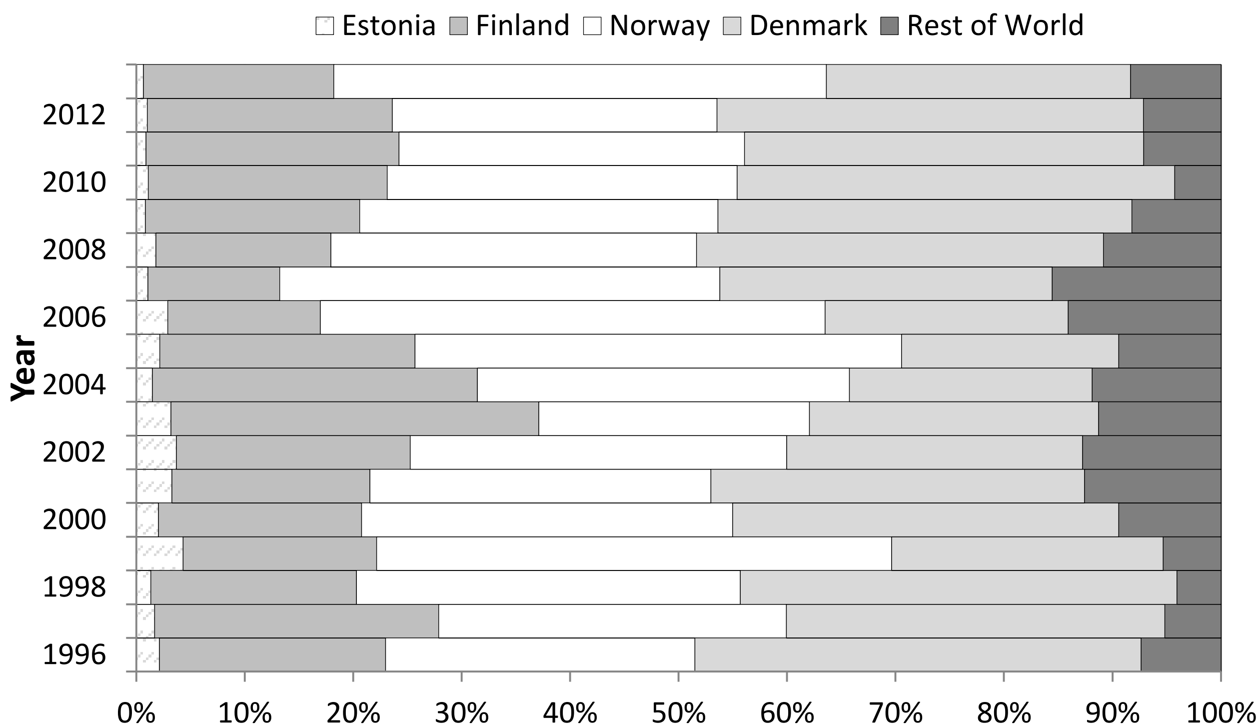
Step 1
ID Batteries
Primary
Secondary
Step 2
DMC Batteries
DMC=IMP+IP-EXP
Step 3
Allocate DMC
Loose
For Manufacture
Integrated in EEE
Step 5
Final DMC
Loose
Integrated in EEE
Data Analysis
Consumption trends
Technological mix
Collection rates
Step 4.1
ID EEE
EEE
containing batteries
+
Step 4.2
EEE Accounting
DMC or SALES
+
Step 4.3
Batteries in EEE
% Secondary
batteries in EEE



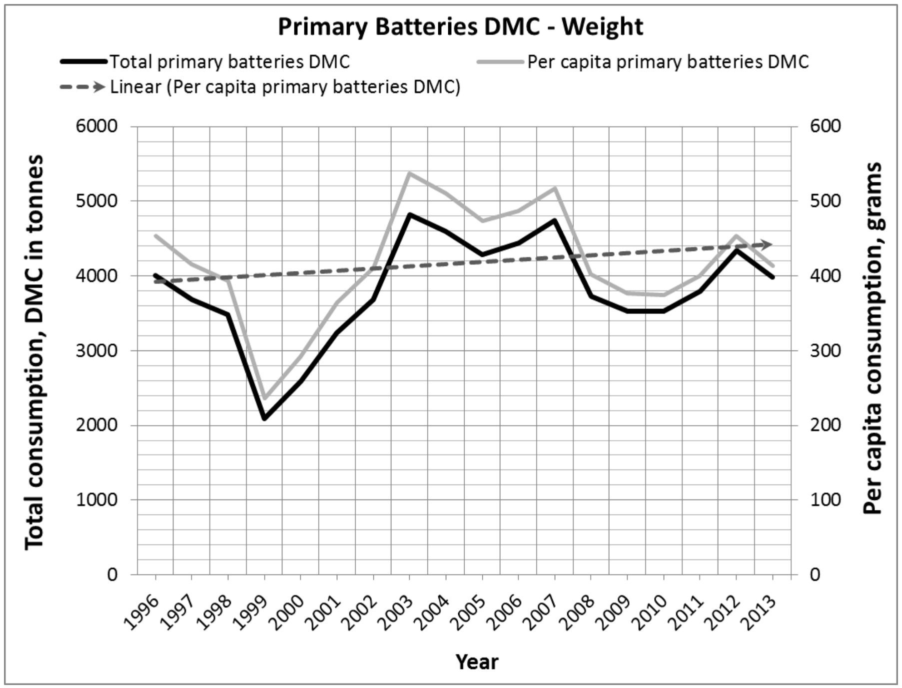
Primary Batteries Flows in Units
Primary Batteries (million of units)
250
200
150
100
50
0
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
Year
IMPORTS
EXPORTS
INDUSTRIAL PRODUCTION

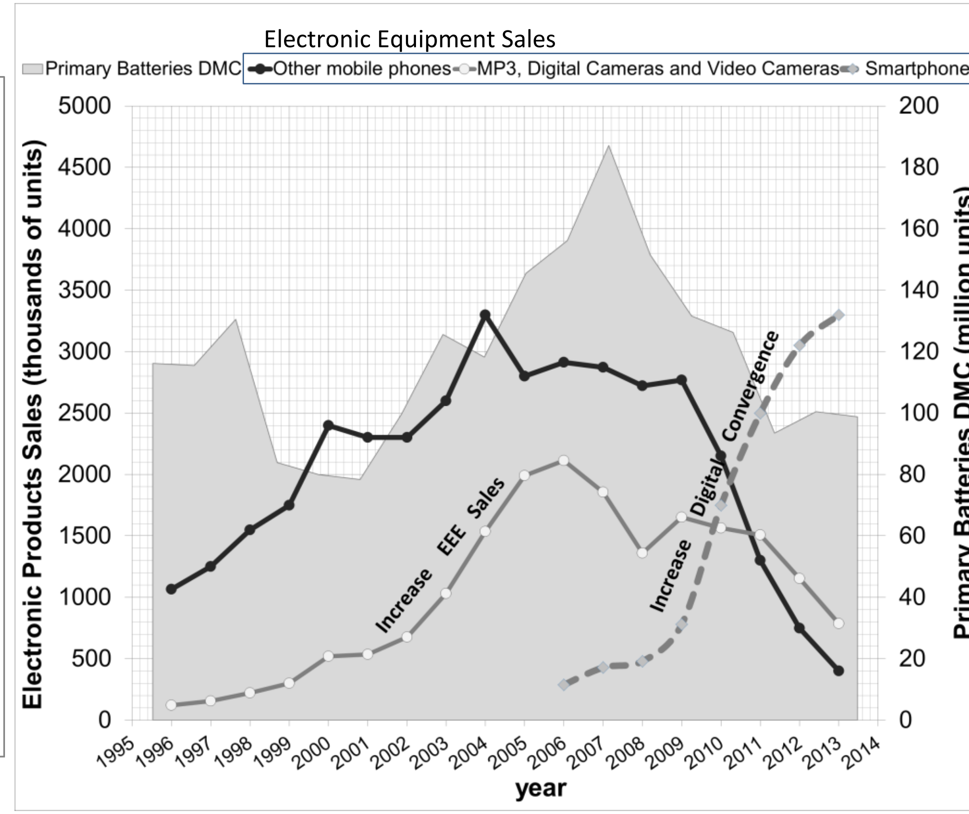


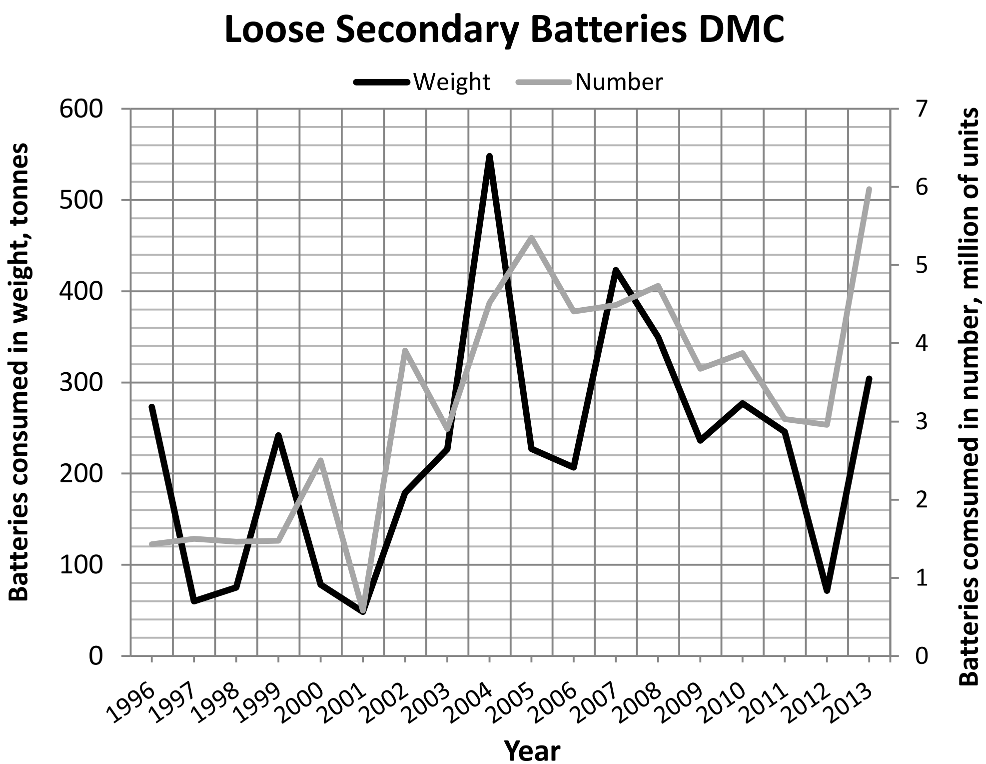
Primary Batteries Flows in Weight
Primary Batteries (tonnes)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
Year
IMPORTS
EXPORTS
INDUSTRIAL PRODUCTION



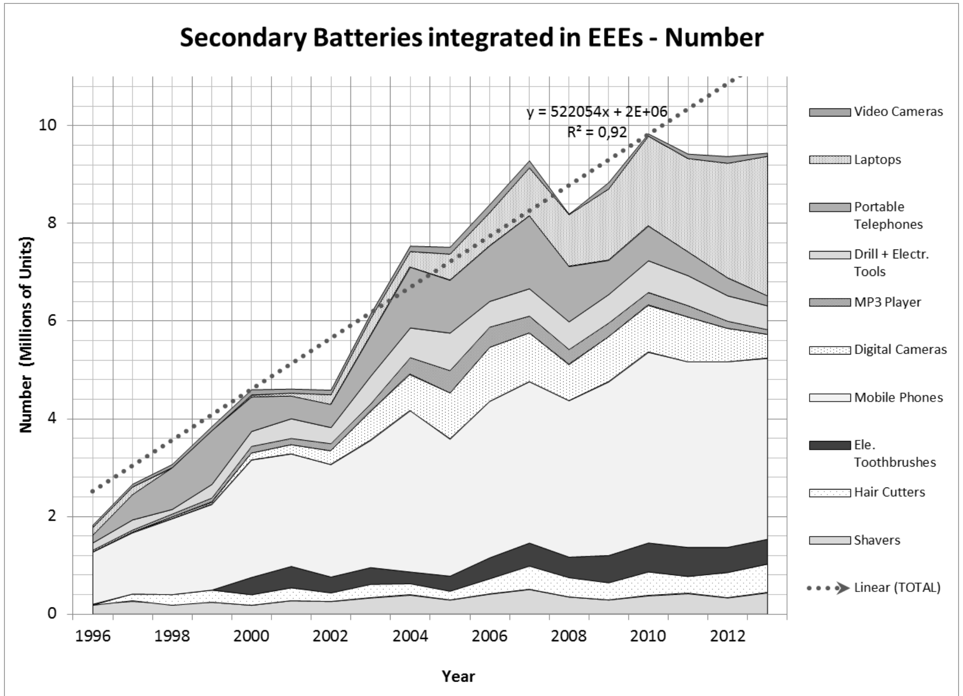
Estonia
Finland
Norway
Denmark
Rest of World
Year
2012
2010
2008
2006
2004
2002
2000
1998
1996
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

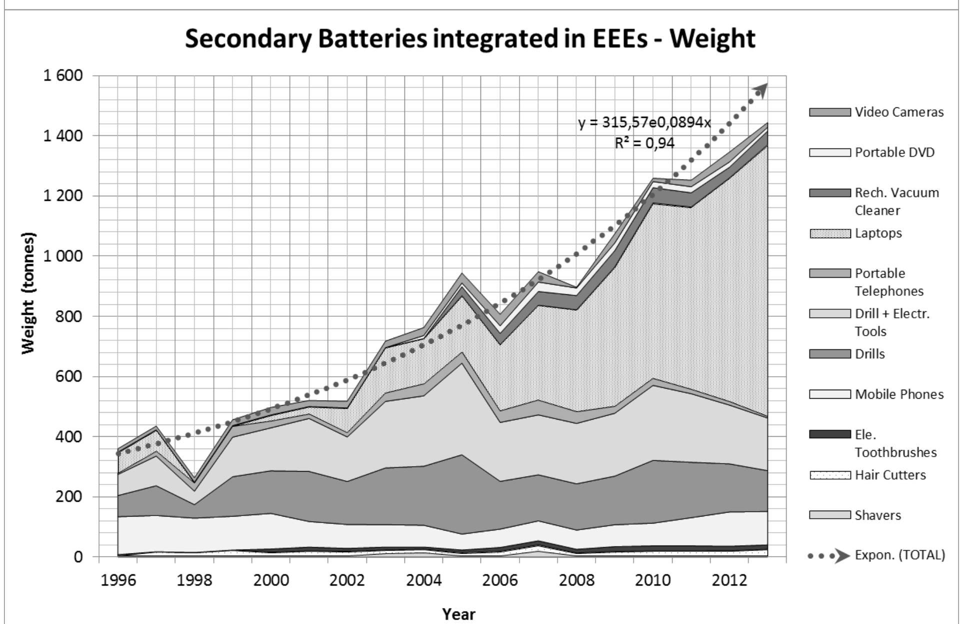

Primary Batteries DMC - Weight
Total primary batteries DMC
Per capita primary batteries DMC
Linear (Per capita primary batteries DMC)
Total consumption, DMC in tonnes
Per capita consumption, grams
Year
0
1000
2000
3000
4000
5000
6000
0
100
200
300
400
500
600
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

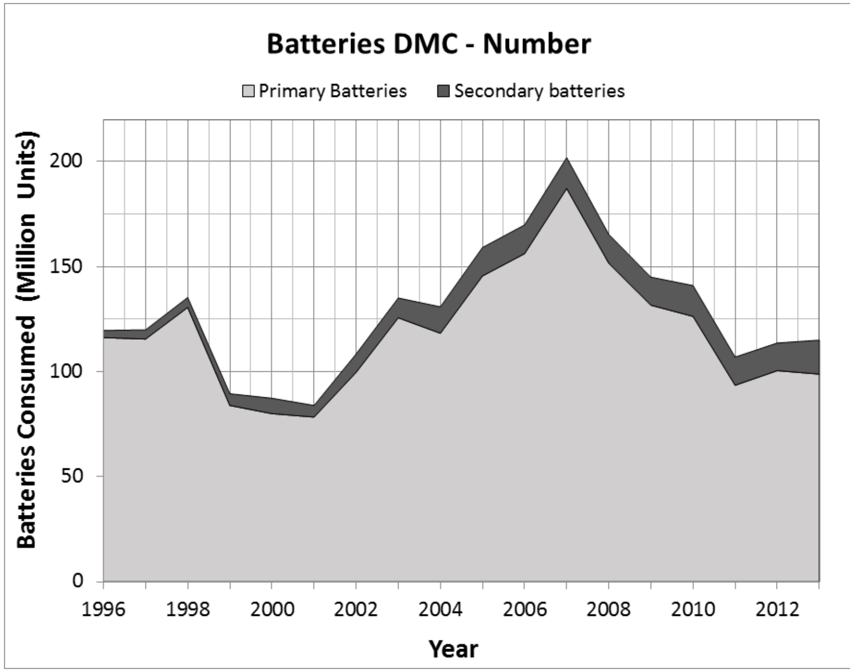

Electronic Equipment Sales
Primary Batteries DMC
Other mobile phones
MP3, Digital Cameras and Video Cameras
Smartphones
Electronic Products Sales (thousands of units)
Primary Batteries DMC (million units)
Increase EEE Sales
Increase Digital Convergence
year
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
20
40
60
80
100
120
140
160
180
200
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014



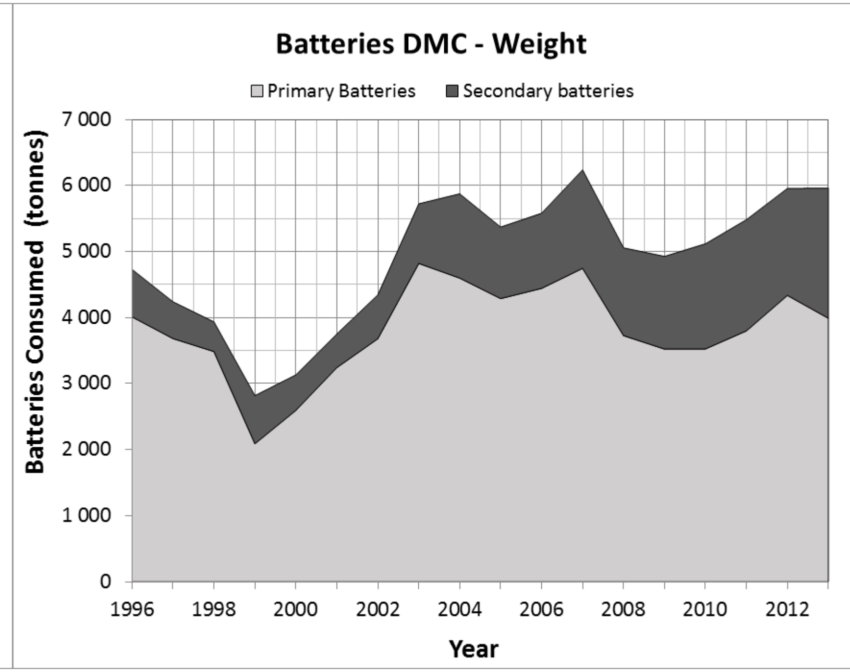
Loose Secondary Batteries DMC
Weight
Number
Batteries consumed in weight, tonnes
Batteries comsumed in number, million of units
0
100
200
300
400
500
600
0
1
2
3
4
5
6
7
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Year


Secondary Batteries integrated in EEEs - Number
y = 522054x + 2E+06
R² = 0,92
Number (Millions of Units)
Year
Video Cameras
Laptops
Portable Telephones
Drill + Electr. Tools
MP3 Player
Digital Cameras
Mobile Phones
Ele. Toothbrushes
Hair Cutters
Shavers
Linear (TOTAL)

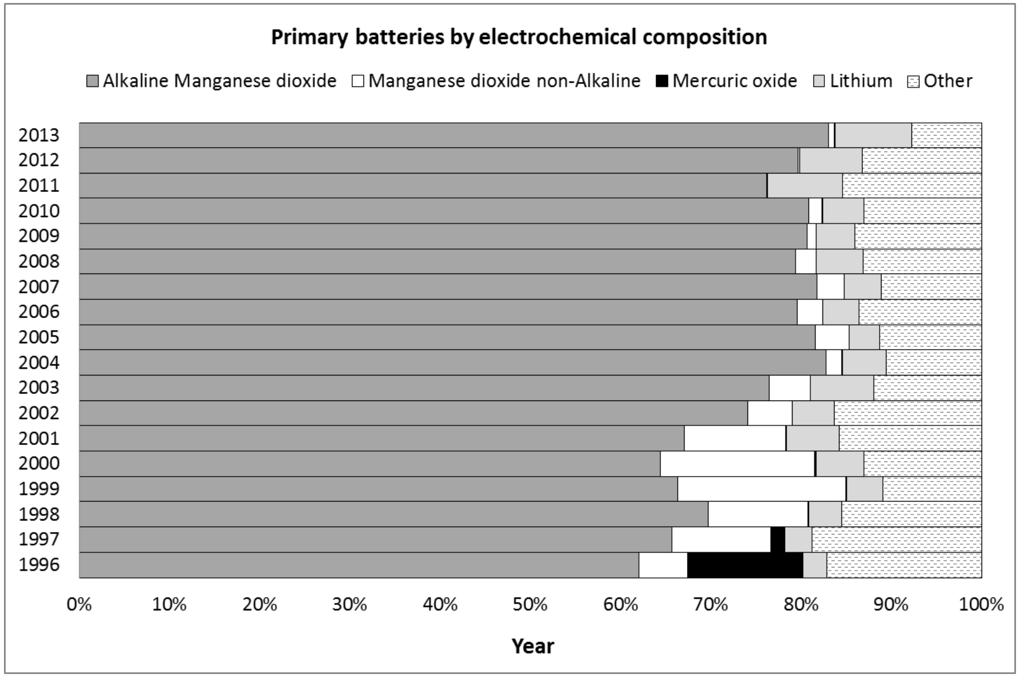

Secondary Batteries integrated in EEEs - Weight
y = 315,57e0,0894x
R² = 0,94
Weight (tonnes)
Year
Video Cameras
Portable DVD
Rech. Vacuum Cleaner
Laptops
Portable Telephones
Drill + Electr. Tools
Drills
Mobile Phones
Ele. Toothbrushes
Hair Cutters
Shavers
Expon. (TOTAL)



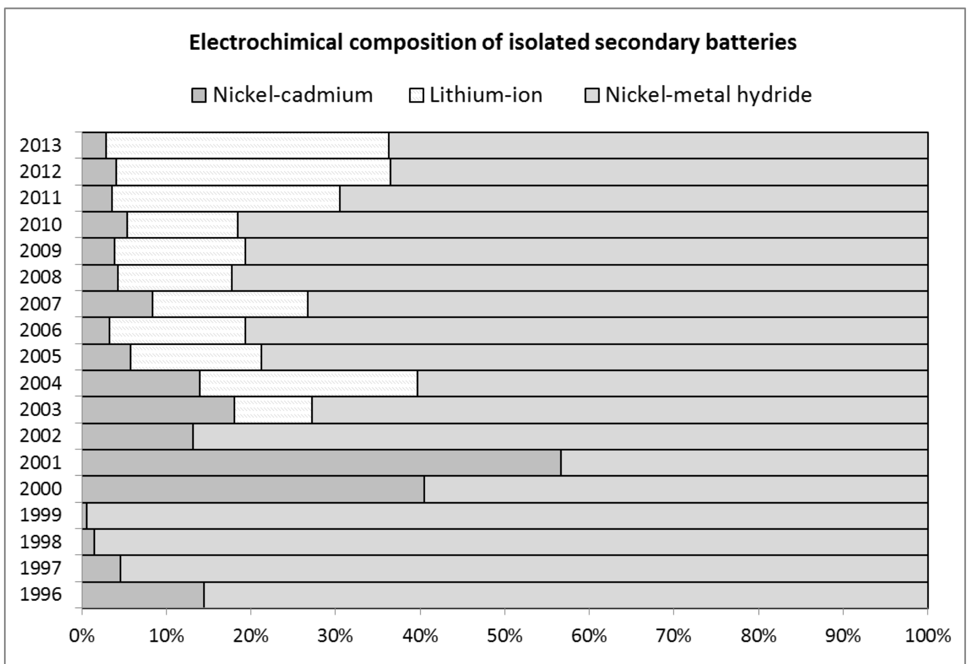
Batteries DMC - Number
Primary Batteries
Secondary batteries
Batteries Consumed (Million Units)
0
50
100
150
200
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year



Batteries DMC - Weight
Primary Batteries
Secondary batteries
Batteries Consumed (tonnes)
0
1 000
2 000
3 000
4 000
5 000
6 000
7 000
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year



Primary batteries types	2013
Alkaline manganese dioxide, cylindrical	75,4%
Alkaline manganese dioxide, non cylindrical	7,7%
Non-alkaline manganese dioxide, cylindrical	0,5%
Non-alkaline manganese dioxide, non cylindrical	0,1%
Silver oxide, button cells	1,9%
Lithium, cylindrical cells	2,5%
Lithium, button cells	5,5%
Lithium, other	0,5%
Air-zinc, button cells	4,7%
other	1,2%



Primary and secondary battery consumption trends in Sweden 1996–2013: Method development and detailed accounting by battery type

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	Data SOURCE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Shavers	IT DATA	266 275	339 304	269 031	318 042	236 670	358 264	323 078	414 631	485 063	360 841	511 989	585 545	407 060	336 856	434 819	485 850	385 390	504 403
Epilators	IT DATA	0	66 889	66 151	74 392	54 952	148 675	70 445	131 016	218 985	272 872	321 446	266 333	220 954	202 143	341 690	328 840	207 141	158 568
Hair cutters	IT DATA	0	198 576	252 085	324 346	278 999	342 423	219 282	347 026	293 135	225 327	393 054	555 891	459 860	408 631	568 277	410 263	604 268	686 735
Electric toot	SALES	0	0	0	0	415 000	510 000	380 000	400 000	280 000	360 000	500 000	550 000	490 000	650 000	690 000	690 000	600 000	590 000
Rech. vacuu	SALES	0	0	0	0	0	0	0	0	0	88 000	110 000	135 000	140 000	160 000	150 000	140 000	105 000	135 000
Mobile Phor	SALES	1 065 000	1 250 000	1 550 000	1 750 000	2 400 000	2 300 000	2 300 000	2 600 000	3 300 000	2 800 000	3 200 000	3 300 000	3 200 000	3 550 000	3 900 000	3 800 000	3 800 000	3 700 000
Digital Cam	IT DATA	0	0	28 487	35 365	139 722	191 467	293 233	639 204	813 559	1 036 449	1 214 904	1 096 881	809 460	1 009 975	1 063 683	1 008 045	750 143	533 906
Video Came	IT DATA	52 399	57 374	68 876	90 061	115 683	93 942	103 718	100 278	122 389	154 272	177 636	159 681	11 136	142 705	51 761	100 841	152 921	71 849
MP3 Player	SALES	70 000	100 000	125 000	175 000	265 000	250 000	280 000	290 000	600 000	800 000	720 000	600 000	540 000	500 000	450 000	400 000	250 000	180 000
Portable DV	SALES	0	0	0	0	0	0	0	0	40 000	50 000	100 000	125 000	100 000	100 000	80 000	80 000	70 000	50 000
Drills - Rech	IT DATA	149 434	209 776	95 215	279 541	300 942	353 513	303 588	400 625	416 741	559 850	337 225	325 315	326 276	343 321	443 410	391 054	339 559	288 064
Electromech	IT DATA	0	0	0	0	5 213	50 037	26 384	166 183	192 776	210 240	189 559	235 709	241 358	241 253	206 487	223 678	181 850	200 772
Portable Te	IT DATA	177 798	564 539	926 327	1 189 935	760 849	511 561	519 709	904 110	1 341 603	1 166 599	1 227 583	1 614 285	1 222 561	755 196	765 399	526 664	393 313	224 221
Laptops <1(	IT DATA	150 474	154 162	0	0	44 627	48 768	191 077	342 887	322 457	536 767	684 013	981 042	1 062 366	1 462 868	1 841 263	1 910 279	2 349 095	2 852 404
String Trim	IT DATA	62 868	62 868	62 868	62 868	34 288	34 288	34 288	40 361	40 361	40 361	86 432	79 805	72 240	73 256	73 256	120 375	120 375	120 375

EEE Type	Data Source	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Shavers	IT DATA	13,4%	11,3%	7,8%	7,4%	4,7%	6,9%	6,4%	6,1%	5,7%	4,2%	5,2%	5,5%	4,4%	3,4%	3,9%	4,6%	3,7%	4,9%
Epilators	IT DATA	0,0%	2,2%	1,9%	1,7%	1,1%	2,9%	1,4%	1,9%	2,6%	3,2%	3,3%	2,5%	2,4%	2,0%	3,1%	3,1%	2,0%	1,5%
Hair cutters	IT DATA	0,0%	6,6%	7,3%	7,5%	5,5%	6,6%	4,3%	5,1%	3,5%	2,6%	4,0%	5,2%	4,9%	4,1%	5,1%	3,9%	5,9%	6,7%
Electric toot	SALES	0,0%	0,0%	0,0%	0,0%	8,2%	9,8%	7,5%	5,9%	3,3%	4,2%	5,1%	5,2%	5,3%	6,5%	6,2%	6,5%	5,8%	5,7%
Rech. vacuu	SALES	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	1,0%	1,1%	1,3%	1,5%	1,6%	1,4%	1,3%	1,0%	1,3%
Mobile Phor	SALES	53,4%	41,6%	45,0%	40,7%	47,5%	44,3%	45,6%	38,4%	39,0%	32,3%	32,7%	31,1%	34,4%	35,7%	35,3%	35,8%	36,9%	35,9%
Digital Cam	IT DATA	0,0%	0,0%	0,8%	0,8%	2,8%	3,7%	5,8%	9,4%	9,6%	12,0%	12,4%	10,3%	8,7%	10,2%	9,6%	9,5%	7,3%	5,2%
Video Came	IT DATA	2,6%	1,9%	2,0%	2,1%	2,3%	1,8%	2,1%	1,5%	1,4%	1,8%	1,8%	1,5%	0,1%	1,4%	0,5%	0,9%	1,5%	0,7%
MP3 Player	SALES	3,5%	3,3%	3,6%	4,1%	5,2%	4,8%	5,6%	4,3%	7,1%	9,2%	7,4%	5,7%	5,8%	5,0%	4,1%	3,8%	2,4%	1,7%
Portable DV	SALES	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,5%	0,6%	1,0%	1,2%	1,1%	1,0%	0,7%	0,8%	0,7%	0,5%
Drills - Rech	IT DATA	7,5%	7,0%	2,8%	6,5%	6,0%	6,8%	6,0%	5,9%	4,9%	6,5%	3,5%	3,1%	3,5%	3,5%	4,0%	3,7%	3,3%	2,8%
Electromech	IT DATA	0,0%	0,0%	0,0%	0,0%	0,1%	1,0%	0,5%	2,5%	2,3%	2,4%	1,9%	2,2%	2,6%	2,4%	1,9%	2,1%	1,8%	1,9%
Portable Te	IT DATA	8,9%	18,8%	26,9%	27,7%	15,1%	9,9%	10,3%	13,3%	15,8%	13,5%	12,6%	15,2%	13,1%	7,6%	6,9%	5,0%	3,8%	2,2%
Laptops <1(	IT DATA	7,5%	5,1%	0,0%	0,0%	0,9%	0,9%	3,8%	5,1%	3,8%	6,2%	7,0%	9,2%	11,4%	14,7%	16,6%	18,0%	22,8%	27,7%
String Trim	IT DATA	3,2%	2,1%	1,8%	1,5%	0,7%	0,7%	0,7%	0,6%	0,5%	0,5%	0,9%	0,8%	0,8%	0,7%	0,7%	1,1%	1,2%	1,2%