

Article

Managing Cd Containing Waste—Caught by the Past, the Circular Economy Needs New Answers

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Received: 18 December 2017; Accepted: 3 May 2018; Published: 8 May 2018



Abstract: What is understood by the circular economy concept is the re-use and recycling of used materials and waste. In many used products, hazardous compounds are found or might be present either because of the products' present intended use or former applications that have been banned in the meantime. Clearly, recycling activities should not endanger man and environment through carryover of contaminants. To learn more about how hazardous chemicals in waste impede the circular economy, it is necessary to investigate the ways in which products containing hazardous compounds have been handled up to now in order to avoid secondary contamination. For this study, cadmium (Cd) in NiCd batteries and accumulators and Cd compounds used as stabilisers for PVC profiles were selected as examples. The situation in the European Union was analysed, with a focus on legislation, collection, recycling, disposal and the further fate of “co-recycled” Cd. Insufficient collection rates, partially unsafe disposal and carryover were identified as the main problems. An advanced management strategy for Cd and its compounds is needed in order to mitigate problems in the circular economy. Used products containing hazardous substances ought to be recycled without contaminating the environment or recycled materials. The results suggest that circular economy is faced with different, partially insurmountable challenges.

Keywords: cadmium; NiCd batteries and accumulators; PVC profiles; recycling; re-use; circular economy; battery directive; waste framework directive; WEEE

1. Introduction

All waste management activities have to fulfil two different tasks: Firstly the removal of waste from human settlements, especially in the case of pathogenic or toxic constituents, and its safe disposal and secondly the extraction of useful resources or at least energy after processing the waste. The Global Waste Management Outlook (GWMO) prioritises the safeguarding of public health and prevention or mitigation of environmental pollution. This report describes a development within the second goal that changes “the fundamental thinking away from ‘waste disposal’ to ‘waste management’ and from ‘waste’ to ‘resources’” [1]. These goals are also at the focus of European legislation: The Waste Framework Directive (WFD) [2] urges the Member States to align decisions made by waste owners with a hierarchy of five steps, starting with “prevention” of waste production and followed, in descending order, by “preparing for re-use”, material “recycling”, “recovery” of energy and, as the last option, “disposal” (WFD Art. 4). In the proposed amendment to this directive [3], the European Commission aimed at the “transition to a Circular Economy with a broad set of measures to maintain the value of products, materials and resources for as long as possible, while minimising the generation of waste”. The EC focuses on resource efficiency as a new main goal along the value chain: “What was once

considered as waste can become a valuable resource. To realise the potential of these so called secondary raw materials, we have to remove the existing barriers to their trade, improve the waste management practices and guarantee high quality standards" [4]. Although the term "high quality standards" implies safe management of hazardous compounds in waste, the political discussion focuses on the "circular economy" vision, possibly losing sight of the hygienic basis of waste management.

The term "circular economy" is used widely but often understood quite differently: UNEP called for "the most efficient use and recycling of resources and environmental protection" with regard to the development of the Chinese economy and defined circular economy as a system with low consumption of energy, low emission of pollutants and high efficiency [5]. The European Commission introduced the term in the framework of its resources strategy [6,7] using "circular economy" as a synonym for "sustainable materials management" with special focus on the efficient use of minerals and metals. Ghisellini et al. [8] and Kirchherr et al. [9] provide an overview of definitions of the circular economy concept. According to Geissdoerfer et al. [10], most authors writing about this concept share the idea of closed loops. Two major management consultant companies define circular economy as "an industrial system that is restorative or regenerative by intention and design" in line with the phrase "A world without waste is possible", which was frequently used by former Commissioner Jan Potocnik, and their reports include a sort of "zero waste" goal: The consultants state that "the circular economy aims to design out waste" because "products are designed and optimised for a cycle of disassembly and re-use" and "consumables are made of biological ingredients or 'nutrients' that are at least non-toxic and possibly even beneficial, and can safely be returned to the biosphere" [11,12]. These reports promised "a trillion-dollar opportunity (This citation follows P. Lacy, Accenture. <http://www.eco-business.com/news/circular-economys-trillion-dollar-opportunity/>, accessed 15 October 2016), with huge potential for innovation, job creation and economic growth". They considerably influenced the European discussion on the amendment of the WFD [3] and other regulations (WEEE Directive, Packaging Directive . . .), as a whole known as the "waste package". Surprisingly, the Commission omitted to define the term "circular economy" in the draft WFD.

The ongoing discussion between European Commission, European Parliament, Member States and stakeholders basically focuses on increasing binding recycling targets and tools (like extended producer responsibility), which might help to achieve greater recovery of resources from waste.

"Circular economy" implies that secondary materials obtained from recycling processes fulfil all the technical requirements necessary to substitute virgin materials. This includes a certain quality standard for secondary materials with regard to by-products and contaminants. Besides general physical and chemical restrictions to "zero waste", which prevent the complete recycling of waste fractions [13–17], recycling of certain compounds from waste fractions may lead to toxicity-related problems:

- Technical requirements can vary from one application to another and this also holds true for toxicity thresholds, as has been intensively discussed for the migration of solvents from cardboard made from printed paper to food (cf. [18] and literature cited there).
- Technical standards for materials may change during the lifetime of a product. For secondary resources originating from a recycling process only current requirements are valid. This may turn out to be a crucial problem for material recovery in cases where certain contaminants are involved: Some important chemicals previously used in products have either been restricted to certain applications (e.g., compounds containing mercury, cadmium, lead) or banned completely (e.g., asbestos, PCBs, certain brominated diphenylethers). This is partially due to international conventions (e.g., POPs are regulated by the Stockholm Convention, mercury is regulated by the Minamata Convention) or is a result of regulations at European level based on specific directives (e.g., RoHS Directive [19]) or general chemicals regulations (e.g., restricted chemicals under the REACH regulation [20]).
- As the use of chemicals varies from region to region, widely depending on different regulations, secondary materials including certain additives from the first use of the material in question (plastics, fibres from textiles, cardboard . . .) may be allowed in some countries but not everywhere.

Global trade and transport of secondary materials may therefore lead to a proliferation of contaminants in parts of the world where these contaminants have already been banned [21,22].

Materials or waste containing contaminants above permitted concentration limits may no longer be used and must either be treated in order to separate the contaminants (if possible) or disposed of completely.

2. Scope and Structure of the Study

As the recycling of products after use is also vulnerable to dangerous compounds and materials contained in these waste streams, the question arises of how hazardous chemicals or materials in the respective products influence re-use and recycling. Our study centres on two questions:

- Some hazardous compounds are specifically regulated in products. To what extent separate collection and recycling and / or safe disposal of these products can be ensured?
- Will those hazardous compounds already regulated today appear in waste streams other than those intended?

Therefore it is reasonable to track the fate of products containing dangerous chemicals and to evaluate past and present experiences. This paper focuses on the interface of hazardous chemicals in products and the recovery of valuable materials from used products. Cadmium (Cd) was chosen as an example because products, emissions and waste containing Cd are regulated fairly well in Europe and partially also in other areas of the world. Cd is a non-essential and toxic element for humans. Because it is similar to the essential trace element zinc, Cd can be introduced into biochemical reactions in organisms in place of Zn. The primary target of Cd is the kidney, followed by the liver. The half-life of Cd in the body (predominantly in the adrenal cortex) is 10 to 30 years. The International Agency for Research on Cancer (IARC) classifies Cd in Group 1: Carcinogenic to humans [23]. The Regulation on classification, labelling and packaging of substances and mixtures (CLP [24]) warns of acute toxicity (oral and inhalation), mutagenicity, carcinogenicity, reproduction toxicity and water hazard. The critical level of Cd contamination is highlighted in a report by the European Food Safety Authority [25]: “Although adverse effects are unlikely to occur in an individual with current dietary exposure, there is a need to reduce exposure to cadmium at the population level because of the limited safety margin”.

Global Cd production increased during the 1970–2004 period from about 17,000 Mg year^{−1} to about 22,000 Mg year^{−1}. Between 1995 and 2006, global consumption remained constant at around 20,000 Mg year^{−1} [26]. According to the U.S. Geological Survey, in 2015 the world’s primary Cd production (excluding the USA) amounted to 23,200 Mg [27,28]. Current data for the USA are not available; in 2010, primary Cd production ranged between 600 and 800 Mg year^{−1} [29], which is above the estimated US manufacturing demand of 500 Mg year^{−1} (2005) or below [30]. According to Ellis & Mirza [31], worldwide Cd consumption concentrates on batteries; about 80% of marketed Cd is used for NiCd batteries and accumulators. On the European market, NiCd batteries represent 89% of all Cd consumed [32]. It is estimated that recycled Cd at the beginning of this century accounted for 3500 Mg year^{−1}, equating to about 18% of total global supply [26]. According to a current source, secondary Cd production is assumed to make up approximately a quarter of all Cd metal production [33]. The exact mass of Cd recycled on a global basis is unknown.

The major difference between overall production and the mass of secondary material used as input for production is remarkable, both in view of a more or less constant production and consumption of Cd as well as with respect to the toxicity of Cd and its compounds.

Lig and Held [34] published a balance for Europe for 2004 that included waste streams containing Cd as only a minor component. These results showed—despite many data gaps and contradictory statistics critically commented by the authors themselves—a total production of about 6400 Mg of Cd, of which about 2200 Mg was used in products for the European market too. Data from the International Cadmium Association [35] reveal that 9020 Mg year^{−1} of Cd were imported into the EU in 2007–2008 and 6900 Mg year^{−1} were exported from the EU. Exports were dominated by NiCd

batteries ($1600 \text{ Mg year}^{-1}$) and Cd oxide ($5000 \text{ Mg year}^{-1}$) intended for battery production [36]. Cd is imported to Europe as part of products (e.g., batteries ...) or as unwrought metal.

According to the Pollution Release and Transfer Register (PRTR), which publishes data on emissions from European point sources, 9.33 Mg of Cd were released to air and 12.8 Mg of Cd to water in 2015 [37]. These mass flows are very low compared to former emissions in Europe and present emissions in China with its rapidly growing non-ferrous metal industry. According to different sources, China's total Cd emissions are estimated at about 744 Mg for 2009, of which industrial processes and combustion sources contributed approximately 56.6% and 43.4% respectively. Non-ferrous metal smelters, including copper, lead and zinc, ranked as the main source, accounting for about 40.6% of the total [38]. Shao et al. [39] calculated atmospheric Cd emissions in China of 2186 Mg in 2010. A comparison between developments in Europe and China shows

- the successful implementation and enforcement of regulations for the reduction of emissions from point sources in Europe
- the increasing relevance of diffuse sources in Europe in parallel to the restriction of emissions from point sources
- the growing importance of the waste sector, that means opportunities for recycling Cd, but
- risks from new diffuse sources due to cross-contamination from recycling operations or leaching from landfills

The following Cd compounds are investigated in this study:

- Cd in NiCd batteries and accumulators
- Cd (used as an organic salt) in window frames made from PVC

EC regulations have been in place for many years for Cd applications. In the case of NiCd batteries and accumulators, the use of Cd is still allowed but strictly limited, depending on different international (EU) regulations. The use of Cd compounds in window frames and other construction products is banned in the EU (for details see Section 3.1).

Obviously, these two product groups represent only some of the opportunities and risks for the recycling of used products or materials from separated waste streams. Others, such as persistent organic molecules (volatile or non-volatile) or dangerous fibres, should be investigated, too.

This study relies on experience gathered in Europe (EU) and especially Germany. German, Swedish, Danish, Dutch and some other European governments have often acted as forerunners, together with countries outside Europe (e.g., Japan, amongst others), with respect to environmental legislation. In these countries, control and enforcement strategies for waste management as well as for hazardous chemicals have been gradually introduced since the 1970s, which allows a review of processes already regulated over a long period. It can be assumed that Europe is a model example for action taken against contamination by the compounds mentioned above in contrast to many other regions, where no specific regulations exist, implementation is delayed and enforcement is lacking.

Examples from other countries are taken into consideration if interesting legislative approaches exist there that differ considerably from the European approach. If detailed European figures were not available, facts and figures from Germany or other Member States, which are representative for advanced implementation and enforcement of environmental standards, were used instead. German legislation for the products in question is in line with the corresponding European directives. There are some German standards and recommendations in cases where European standards are lacking.

This study is based on intensive desktop research, discussions with experts from collection systems, recycling companies, associations in the battery and PVC industries, and environmental agencies as well as own experience in the waste management of fractions containing cadmium.

3. Cadmium (Cd)

3.1. Important Regulations

The European Commission's strategy for the prevention of hazards from Cd comprises five main pillars:

- Severe restriction of Cd and its compounds in products intended to be diffused or used in close contact with the environment
- Growing restrictions for products that remain on the market, in the case of batteries combined with waste management aimed at closing the loop through take-back and recycling targets
- Threshold limits for emissions from point sources
- Quality standards for air, water and agricultural soil
- Limits for food and drinking water contamination

3.1.1. Use of Cd and Cd-Bearing Products

The use of Cd compounds has been widely restricted, starting from what are known as open applications, i.e., plating, pigments, which are directly exposed to the atmosphere and/or water and thus potentially lead to local contamination through abrasion or solution. Due to the persistence of Cd, local contamination may spread over large distances, depending on the chemical properties of the specific Cd compound. Phosphate fertilisers are a significant source of Cd in agricultural soils, where Cd content depends on the origin of the raw phosphate. There is no threshold value for Cd in fertilisers at EU level, but many Member States have introduced statutory national regulations, e.g., Germany (50 mg Cd kg⁻¹ P₂O₅ [40]) or Denmark (110 mg Cd kg⁻¹ P [32]). In 2016, the European Commission [41] proposed maximum levels of heavy metal contamination for CE marked fertilisers; for Cd a gradual reduction from an initial 60 to 40 mg kg⁻¹ after three and to 20 mg kg⁻¹ after twelve years. At the end of October 2017, the European Parliament accepted this proposal but shortened the time limit to nine years [42]. In contrast to mineral fertilisers, Cd content in sludge for use in agriculture is limited by an EC regulation (20 to 40 mg kg⁻¹ dry mass) [43].

The following section lists the most important European regulations concerning Cd. Within REACH Annex XII [20]:

- Cd compounds must not be used in polymers with a limit of 0.01% *w/w*; an exception is valid for mixtures and articles containing recovered PVC to facilitate the recycling of used PVC profiles from the building sector (see Section 3.3).
- Cd pigments must not be used in paints, with the general exception of mixtures where Cd is used for safety reasons and with the exception of zinc-based products (>10% *w/w* Zn).
- Cd must no longer be used for plating (this does not apply to articles put on market before 10 December 2011), with the exception of articles used in the aeronautical, aerospace, mining, offshore and nuclear sectors as far as high safety standards are required. The ban does not apply to safety devices in road and agricultural vehicles, railway rolling stock, and vessels as well as to electrical contacts if needed to ensure the reliability of the apparatus in question.
- Cd in brazing fillers must not exceed 0.01% *w/w*, with the exception of aerospace, military and safety applications.
- Cd is prohibited in jewellery put on market after 10 December 2011 (0.01% *w/w* threshold limit).

Cd and its compounds are included in a list of chemicals subject to export notification procedures in accordance with the Rotterdam Convention (PIC = "Prior Informed Consent") [44].

According to RoHS II [45], the use of Cd in new electrical and electronic equipment must not exceed 0.01% *w/w* in homogeneous material, with the exception of electrical contacts, filter glasses and glasses used for reflectance standards, printing inks (enamels) to be applied on glasses, Cd alloys on solder joints (only in the case of high-powered loudspeakers) and Cd and CdO in thick-film pastes

used on aluminium-bonded beryllium oxide. The general prohibition of the use of Cd in electrical appliances based on the RoHS Directive does not apply to PV panels as these are excluded from the scope of application.

Following the ELV Directive [46] and its Annex II, amended in November 2017 [47], a maximum concentration value for cadmium up to 0.01% *w/w* in homogeneous material shall be tolerated. The most important exemption allows the use of Cd in batteries as spare parts for electrical vehicles (batteries) put on market before 31 December 2008.

There are some special limit thresholds for Cd compounds in toys, taking into account that children tend to lick their toys and may bite off pieces [48].

Following the Battery Directive [49], portable batteries and accumulators that contain more than 0.002% Cd *w/w* are prohibited. An exemption rule for accumulators integrated in cordless power tools expired at the end of 2016. The scope of the directive does not cover security interests, such as arms, munitions and material sent into space. The Cd concentration limit does not include non-portable items, i.e., industrial batteries, automotive batteries and accumulators (see Table 1 for further details).

According to the European Portable Battery Association [50], around 95% of industrial batteries are lead-based. About 2% to 4% are lithium batteries for e-vehicles. The small remaining amount comprises special batteries with a broad scope of applications (partially of increasing importance, such as renewable energy applications) as can be seen in Table 1.

Table 1. Examples of “industrial” and “portable” NiCd accumulators; cf. [49].

Batteries for Industrial Use	Portable Batteries
Emergency or back-up power supply (hospitals, airports, offices)	Emergency and alarm systems, including emergency lighting
Use in trains or aircraft	Cordless power tools (expired)
Use on offshore oil rigs or in lighthouses	Medical equipment
Hand-held payment terminals, bar code readers	
Professional video equipment	
Miners’ and diving lamps attached to helmets	
Electrical vehicles (cars, wheelchairs, bicycles . . .)	
Back-up for electric doors to prevent blocking	
Use in connection with renewable energy applications	

As far as packaging is concerned, the sum of concentration levels of lead, cadmium, mercury and hexavalent chromium present in packaging or packaging components shall not exceed 100 mg kg^{−1} [51].

3.1.2. Waste and Waste Classification Regulations

Since CLP Regulation [24] classifies Cd compounds as hazardous, waste with significant Cd content is treated as hazardous waste in accordance with the European Waste Catalogue [52]. There is also the separate waste code number 16 06 02* for NiCd batteries. Cd-bearing waste features on the red list of the Basel Convention [53]; apart from Cd scrap itself, scrap and other waste on the yellow list should not contain any Cd (“B1020 Clean, uncontaminated metal scrap, including alloys, in bulk finished form (sheet, plate, beams, rods, etc.), of ... Cadmium scrap”).

Often, however, the waste producer has no precise knowledge of the composition of his waste or of those ingredients relevant to its classification as hazardous waste. Heavy metals are usually only analysed as a total concentration and without considering the various forms of binding. In this case, classification of the waste must be based on a worst case assumption. According to Behrend [54], waste with a Cd concentration of 1000 mg kg^{−1} (0.1% *w/w*) has to be classified as hazardous as long as the respective individual compounds are unknown. If the waste producer can prove, for example by means

of further analyses, that the Cd concentration in the waste is attributable to a Cd compound that is not classified as hazardous (such as Cd pigments, e.g., Cd sulphoselenide, (CdS,Se), CAS No. 11112-63-3), this compound is not taken into account in waste classification. However, the Cd compounds named explicitly in the CLP Regulation are predominantly classified—inter alia—as carcinogenic and/or as highly carcinogenic (limit value in each case: 0.1% *w/w*). Almost all Cd compounds not named explicitly are classified as hazardous to the environment (limit value 0.25% *w/w*). However, according to Annex VI of the CLP Regulation, a specific limit of 0.1% *w/w* applies (Products containing such cadmium compounds are classified as harmful from a concentration of 1000 mg kg^{−1} upwards (Xn; R20/21/22)) [54] for these compounds.

Many types of batteries contain hazardous substances (Pb, Cd, Hg) as well as valuable metals (Pb, Co, Li, Fe, Mn . . .). Battery and accumulator manufacturers are therefore obliged to collect all identifiable items separately by size and treat and recycle them. For portable batteries, the Batteries Directive specifies a collection target that corresponds to the mass of all batteries collected in relation to the mass of batteries put on market within a given timeframe (see next chapter) [55].

Emissions from incinerators, power stations, smelters etc. to air and water are mostly regulated as part of BREFs for specific industrial facilities, which are used as the basis for targets in European directives, e.g., waste incineration (Cd in exhaust gas: <0.005–0.05 ng Nm^{−3} [56]), flue gas and dust from the non-ferrous metal industry depending on the type of operation [57].

3.1.3. Environmental Standards

With regard to the environment, threshold limits have been introduced for soil in cases where sewage sludge is used (see above) to avoid or decelerate the accumulation of Cd in soil. Moreover, there are quality standards for ambient air (5 ng m^{−3} [58]) and water; the latter is based on the Water Framework Directive [59] and provides different environmental quality standards for inland and other surface water bodies.

The strategy thus focuses on the minimisation of Cd emissions and transfer to man and on the control of Cd streams in the market with the aim of closing the loop for the remaining articles (batteries etc.), which can be separated from other waste streams. There are no incentives to collect Cd-bearing products from other application areas, e.g., pigments or plating. This is clearly due to the fact that identifying these items and separating them from other waste streams of numerous origins is extremely difficult.

The following section focuses on the implementation and enforcement of these regulations, which are intended to control Cd flow in two partially restricted products after use.

3.2. Recycling of NiCd Batteries and Accumulators

NiCd systems are widely used as batteries and accumulators due to their resistance to electrical stress, high number of charging cycles, reliability and versatility. Their metal content (*w/w*) comprises 10% to 15% Cd, 20% to 30% Ni, 30% to 45% Fe and up to 1% Co. From a study performed in Korea in 2012 [60], average lifetimes for NiCd accumulators were calculated on the basis of an examination of about 600 spent items:

- Electrical and electronic devices: 7.0 years
- Construction (e.g., emergency systems): 9.0 years
- Transportation (e.g., locomotives): 9.8 years

3.2.1. Production and Marketing

Until the mid 1990s, the share of NiCd batteries and accumulators in the global market for accumulators was up to 80%, which then decreased due to competing NiMH cells and Li ion accumulators [61]. Despite some important restrictions (see above), NiCd batteries and accumulators are still in use in many electrical and electronic devices, especially in industry and traffic (Table 1).

The use of portable NiCd batteries and accumulators has been limited in the last twenty years. The end of portable NiCd batteries and accumulators is not foreseeable on a global scale due to different regulations in various regions. The number of NiCd batteries and accumulators (Figure 1, violet line) put on the European market has decreased continuously since the beginning of the century, whereas the number of rechargeable Li batteries has increased enormously, substituting NiCd as well as other battery and accumulator types. Li rechargeable (orange line) and button cells (green line) are the fastest growing types in Europe.

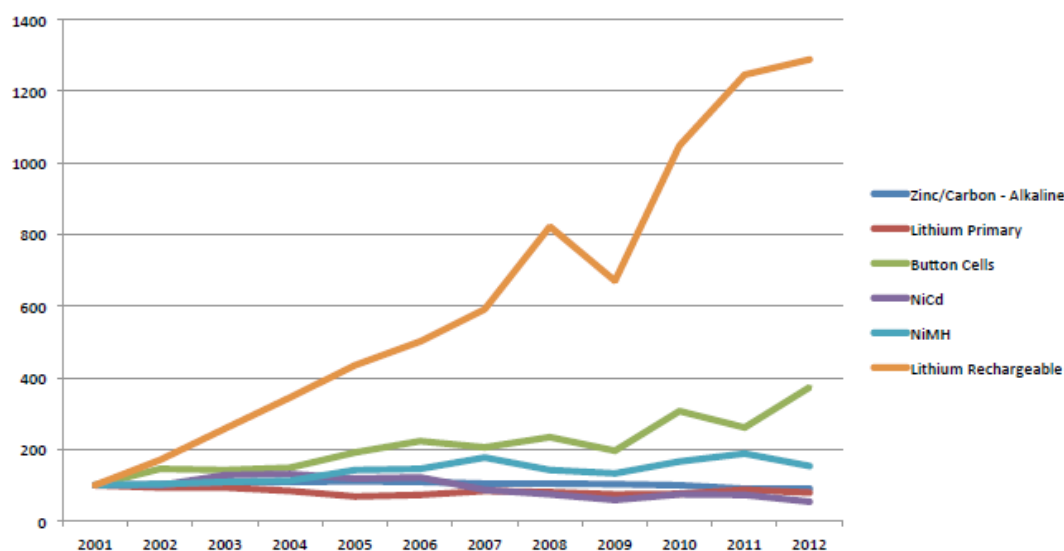


Figure 1. Growth of battery types in Europe (2001 = 100%) [62].

The production of NiCd batteries and accumulators has mostly shifted to Asia. As far as Europe is concerned, we estimate that the SAFT GROUPE (France) is the most important manufacturer. Special items for regions with extreme climatic conditions are produced in Germany (GAZ Geräte-und Akkumulatorenwerk Zwickau).

3.2.2. Collection

In some industrialised countries (EU, USA, Canada, Taiwan), endeavours to collect NiCd batteries and accumulators date back to the end of the 1980s. The first European Batteries Directive [63] (no longer in force) regulated portable NiCd batteries and accumulators, amongst others. Following the extension of the directive [49], the Member States were obliged to make arrangements which enabled end-users to dispose of all spent batteries and accumulators at local collection points and have them taken back by the producers free of charge. The target collection rate of at least 25% had to be reached by 26 September 2012 and of 45% by 26 September 2016. Collection targets are valid for the total sum of all portable batteries and accumulators. The target is calculated on the basis of the amount of batteries and accumulators collected in one year divided by the mean amount of batteries put on market in that calendar year and the two preceding years. There is no specific collection target for NiCd batteries. According to the amendment to the Batteries Directive [55], it must be possible to remove batteries and accumulators easily and safely. Member States also have to ensure that batteries and accumulators that have been collected are treated and recycled using best available techniques. As far as the recycling of WEEE is concerned [64], integrated batteries must be removed in the first step of the procedure (dismantling); they are generally classified as hazardous. For batteries and accumulators destined for industrial use (=non-portable, cf. Table 1), producers “shall not refuse to take back waste industrial batteries and accumulators from end-users”. The legislators assume that collection and recycling of these batteries and accumulators are ensured thanks to close collaboration between producers and

industrial users. With regard to producers' and importers' obligation to take back used items from users and the ban on landfilling and incineration of batteries (Art. 8 (3, 4) and Art. 14), the Commission argues that "nearly 100% of industrial and automotive batteries are already being collected: ... NiCd batteries are collected because there is a well-developed collection system in place" [65].

Recent mass-based data on portable NiCd batteries for the EU are presented in Figure 2 (data obtained from Recharge [66]).

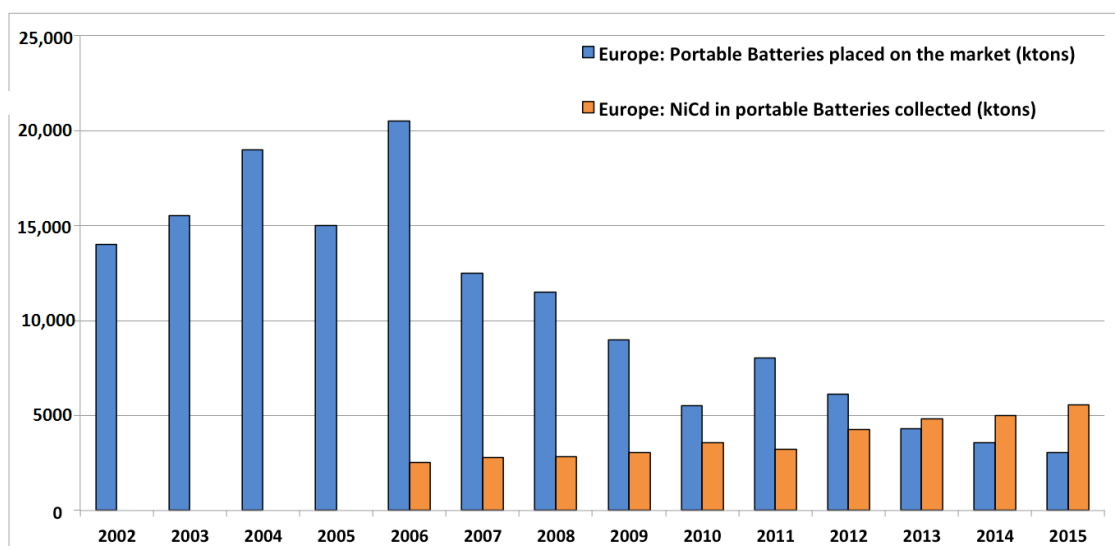


Figure 2. Portable NiCd batteries (Mg year⁻¹) placed on market (blue columns) and taken back (orange columns) (Own graph, data obtained from Recharge [66]).

In 2004, batteries and accumulators with a total mass of about 700 Mg of Cd (corresponding to 3961 Mg of NiCd batteries) were put on the German market [67] (cf. Table 2).

Table 2. NiCd batteries and accumulators sold and collected (Data from [67,68]). Collection rate = mass of collected batteries in relation to the average weight (=mass) of batteries sold in the calendar year and the two preceding years.

Year	NiCd Battery Sales in Germany (Mg)	NiCd Batteries Collected in Germany (Mg)	Collection Rate
2004	3961	1182	
2005	3132	1078	
2006	4185	1022	27%
2007	2687	1089	33%
2008	2476	1230	39%
2009	803	1141	57%
2010	1191	1034	69%
2011	1336	1013	91%
2012	1009	1183	100%
2013	775	1349	130%
2014	568	1416	181%
2015	501	1383	225%
2016	415	1442	292%

The data in Table 2 for Germany show a decline in sales of NiCd batteries and accumulators between 2010 and 2015, which is obviously due to the ban on their use in the most important portable items. Similar developments can be observed for other countries. For example in Denmark, NiCd battery sales (placed on the market) dropped from 238 Mg (2010) to 48 Mg (2014), primarily as the result of a decrease in portable and automotive batteries, whereas the mass of industrial batteries only

decreased from 36 to 22 Mg [69]. With respect to the European market (EU28 + Norway + Switzerland), the mass of industrial batteries sold ($\sim 8000 \text{ Mg year}^{-1}$) exceeds the mass of portable batteries, which is decreasing continuously since 2012 (7000 Mg (2012); 5000 Mg (2013); 4700 Mg (2014); 3500 Mg (2015); figures were taken from the Urban Mine Platform (www.urbanmineplatform.eu). However, the figures presented there for foregoing years are not consistent with this time series). The high collection rates from 2010 to 2016 presented in Table 2 reflect the long lifetime of NiCd accumulators used in former areas of application, which contradict the definition of collection rates in the Batteries Directive. Collection rates may also be influenced by small industrial batteries collected at public take-back points, whereas the figures for batteries put on market only represent portable batteries.

The overall collection mass of spent batteries compared to the mass of batteries and accumulators put on market can be used as a first insight into the potential mass of waste accumulators: Around 222,000 Mg of portable batteries and accumulators (or an estimated 10.5 billion) were reported to have been placed on the market in the European Union and Switzerland in 2015, while around 91,000 Mg of waste portable batteries and accumulators were reported as collected. According to the figures published by the European Portable Battery Association (EPBA) [50], this corresponds to a collection rate on a current year basis of 41%, up from 25% in 2010. According to an ex-post evaluation of the Batteries Directive [70], 3264 Mg of portable and 3367 Mg of industrial NiCd batteries were collected in 2012. RECHARGE [66] reported that 4244 Mg portable batteries were collected in 2012 (The figures in the ex-post evaluation are based on reports by the European Battery Recycling Association (EBRA). The difference between the EBRA and the RECHARGE data may be the result of recycling by non-EBRA companies either in or outside Europe. Another reason could be lack of clarity in the definition of portable batteries).

The authors of the ex-post evaluation of the Batteries Directive assume that 60.2% of NiCd batteries were collected. This information can be doubted, as there is no linear relationship between the mass of batteries placed on the market and the batteries collected, as can be seen in Figure 2 for Europe and Table 2 for Germany. Obviously, accumulators are far longer in use than just two or three years. Assuming a lifetime of about seven years for portable items [60] and re-calculating the collection rates based on the first and the second column of Table 2, rates between 17% and 49% are obtained.

From the few data available on the number of waste portable batteries and accumulators collected, it is estimated that around 18% of batteries and accumulators are collected in relation to the number marketed. Japan, with its some 20-year history in the collection and recycling of Cd products, can be used for comparison purposes. Portable rechargeable batteries have been subject to labelling and take-back obligations since April 2001, but there are no collection targets [50]. As to NiCd batteries and accumulators, the mass of discarded items decreased from 1495 Mg in 2004 to 908 Mg in 2008, whereas recovery increased from 178 to 196 Mg, i.e., from 12% to 22% [71].

3.2.3. Recycling

Recycling processes for spent NiCd batteries and accumulators were already introduced in the 1970s. In 2009, nine major NiCd battery and accumulator recycling plants in the United States, Europe and Japan were in operation, with a capacity of approximately 20,000 Mt for NiCd batteries and accumulators and the corresponding manufacturing scrap [72].

Pyrometallurgy of used NiCd cells is an appropriate technique due to cadmium's low boiling point. Battery processing comprises the reduction of $\text{CdO}/\text{Cd}(\text{OH})_2$ followed by Cd distillation (volatilisation and condensation) and its recovery in a pure form. Nickel can be separated in slag alloyed with iron to be processed further. The hydrometallurgical process for recycling NiCd batteries and accumulators is based on leaching with sulphuric acid followed by metals recovery and separation using ion exchange [31,73].

According to the EU's statutory requirements for batteries and accumulators [74], recycling efficiency for NiCd batteries and accumulators must exceed 75% and the recovery of Cd must be maximised. The term "recycling efficiency" expresses the percentage of returned products in relation to input battery and accumulator weight (According to [74], the cadmium (Cd) contained in slag at the end of the recycling

process is not accounted for in the rate of recycled cadmium content). The new EU requirements cannot be satisfied by conventional metallurgical processing of batteries and accumulators, as such processes will release a large part of the Cd content due to its high fugacity at normal pressure and high temperature. The use of spent batteries as aggregates in steel mills would be even worse. Vacuum distillation using a vertical thermal reactor (VTR) meets the directive's requirements. In the case of the Accurec process, the reactor runs at between 50 and 1 mbar, with the temperature gradually increasing up to 850 °C. In this way, highly purified Cd (>99.9%) can be separated from the reaction mixture with nearly zero emissions to air and water [75]. Depending on the recycling company, about 150 kg of Cd and 630 kg of Ni/Fe scrap can be recovered from 1000 kg of NiCd batteries and accumulators. The Cd content in the Ni/Fe scrap does not exceed 50 mg kg⁻¹ [76]. If the temperature exceeds 900 °C and pressure is below 0.1 mbar, Cd can be completely (99.9%) recovered [77]. Similar processes based on vacuum technology have been under development in Asia in the past [78].

3.2.4. Batteries in WEEE

In recent years, a considerable number of accumulators have been used in cordless power tools and other items, also in Europe due to their exemption from a general ban (see above [55]). The overall collection rate for used electrical and electronic appliances in the 28 European Member States (2015) is about 35% compared to the mass of appliances put on market, ranging from about 1.5 kg per capita in Romania (2014) and 12.2 kg per capita in Sweden [79]. There are no separate figures for cordless power tools, most of which are categorised as small household equipment. ('Cordless power tool' means any hand-held appliance powered by a battery or accumulator and intended for maintenance, construction or gardening activities [48]). Generally speaking, the collection rate of batteries integrated in WEEE is lower than the average battery collection rate [70]. According to a pilot study [80] on the return of used electrical devices, more than 70% of consumers do not separate the battery from the appliance in the case of special accumulators. An unknown but presumably high percentage of NiCd accumulators from cordless power tools placed on the market therefore enter the WEEE recycling process.

According to state-of-the-art recycling processes (e.g., the WEEELABEX standard [81]), batteries and accumulators must be separated from WEEE during dismantling in order to prevent the loss of precious compounds from batteries and to avoid contamination of the WEEE fractions to be further processed. As experience has shown [82], many batteries and accumulators delivered to battery recycling facilities are severely damaged and cannot be recovered from technical and safety reasons. This indicates that WEEE was shredded in order to separate the batteries, which is contrary to the prescribed procedure.

Batteries and accumulators that are not collected separately or separated from WEEE by means of dismantling will mostly remain in residual waste or possibly in other waste fractions or in used electrical and electronic appliances.

If destroyed batteries and accumulators remain in WEEE after shredding, Cd enters different metallurgical processes depending on the scrap metals, which are of economic interest. The following are important:

- In integrated copper and other non-ferrous metal mills, Cd is not separated for recovery. Due to its fugacity, Cd and its compounds form part of the flue dust (No 10 06 03*, European Waste Catalogue) (One of the major European non-ferrous metal mills informed us on request that this waste is disposed of in a former salt mine suitable for hazardous waste.) or are emitted via the flue gas. In 2015 in Germany, 60% (=903 kg) of the Cd emissions reported in the German e-PRTR (1516 kg) were released by the metal industry ("Production of pig iron or steel (primary or secondary melting) including continuous casting >2.5 Mg h⁻¹"), with three emitters (ThyssenKrupp Steel Europe AG, Schwelgern plant: 257 kg, Salzgitter Flachstahl GmbH, Salzgitter plant: 135 kg, ThyssenKrupp Steel Europe AG, Breekerwerth plant: 121 kg) all above 100 kg year⁻¹ [83].
- As a trace metal in ferrous metal recycling, Cd is separated into electric arc furnace dust (together with Zn), which should be treated in order to remove the Cd. Zn can then be recovered in an imperial smelting furnace [84].

3.2.5. Fate of Batteries Not Collected Separately

If used, damaged or destroyed NiCd batteries and accumulators remain in residual waste, they are landfilled or incinerated.

In Central, Western and Northern Europe, residual waste is mainly incinerated for energy and metal recovery, whereas in Southern, Southwest and Eastern Europe the overwhelming proportion of residual waste is still landfilled without (thermal) pretreatment. Separate collection and recycling rates are usually lower in countries that landfill residual waste (see, for example, [85]). Most of the batteries and accumulators used in those countries are likely to end up in landfill. This equates with an assessment for the USA that 83% of Cd from batteries found their way into municipal solid waste (MSW) landfills at the end of their life [30].

In the case of landfilling, metals from batteries and accumulators can dissolve in the long term and might be transported by leachate. The mechanism strongly depends on environmental conditions, such as pH, oxygen concentration, presence of inorganic and organic molecules capable of forming complexes with heavy metals, amongst others. Insoluble CdS and other Cd salts might be solubilised under aerobic conditions which also lowers the pH [86]. Many Cd as well as Zn compounds are more soluble under mildly acidic conditions than other heavy metals, which is also indicated by the ratio of Cd in leachates compared to Pb, Cr and other non-ferrous metals (see, for example, the “LEACH 2000” database [87]).

In case of incineration, Cd salts are concentrated in the fly ash due to their fugacity. According to extensive measurements conducted in a Swiss incinerator, the partition coefficient between Cd in waste and Cd in fly ash is in the range of 0.85 to 0.90 (ash from the electrostatic precipitator (ESP) plus boiler ash, cf. [88]). ESP and boiler ash are classified as hazardous waste (No 19 01 07*, European Waste Catalogue). Treatment depends on regional circumstances, e.g., backfilling in former salt mines (Germany), solidification with cement and land filling (e.g., France) or use for neutralisation of waste acid and storage in lime mines (e.g., Norway), amongst others. Air pollution control (APC) residues are sometimes used as aggregate filler in cement or cement-like materials and asphalt. According to an overview by the ISWA WtE Working Group [89], “spreading of contaminants, e.g., heavy metals, via construction materials should be avoided. In case of utilisation for construction purposes, the materials should be used in major projects controlled by the authorities and the fate of the materials after demolition should be determined beforehand.” This means that ISWA accepts only landfilling underground or at surface level after solidification as environmentally sound disposal methods.

3.3. Recycling of Cd Compounds in PVC Profiles

The most important area of application for PVC profiles is window and door frames as well as roller shutters. PVC profiles have to be stabilised against thermal stress during processing and against weathering and corrosion caused by sunlight, fluctuating temperatures, moisture etc. in the use phase.

3.3.1. Production and Use

The stabilisers used in the EU up until the end of the 1990s consisted of a mixture of Ba, Pb (The use of lead stabilisers has also been restricted. Calcium/zinc stabiliser systems today account for more than 50% of the European market) and Cd organic salts, using Cd stearate or Cd laurate. Since the stabilisers contained between 1% and 15% Cd and the stabiliser content of the finished PVC generally varied between 0.5% and 2.5% [35], the Cd content in the finished profile was at most 0.3% w/w or 3000 mg kg^{-1} .

The use of Cd stabilisers (see also Section 3.1) has been prohibited in Europe since 2001. Restrictions for Cd stabilisers in virgin PVC in the EU were widened in 2011 [90] as a further amendment to REACH Annex XII: Generally, Cd concentration in plastic materials should not exceed 100 mg kg^{-1} (0.01% w/w) with the exception of recovered PVC waste mixtures and items, which may contain up to 1000 mg kg^{-1} (0.1% w/w). Higher contaminated materials can be used for:

- profiles and rigid sheets for building applications

- doors, windows, fences, shutters, walls, blinds, roof gutters, cable ducts
- pipes for non-drinking water, if the secondary PVC is only used in the middle layer of the pipe surrounded by layers made of virgin PVC in compliance with the 100 mg kg^{-1} Cd limit

These products must be visibly, legibly and indelibly marked as follows: “Contains recovered PVC” or with a pictogram (Figure 3) [90]:



Figure 3. Pictogram for marking PVC products containing recovered PVC (2001 = 100%) [90].

Cd containing stabilisers for PVC are still produced and marketed outside Europe, (e.g. by Valtris (Independence, OH, USA), Alibaba (Hangzhou, China), PAU TAI Industrial Corporation (Taipei City, Taiwan), amongst others), and in Europe, too (Flaurea Chemicals (Ath, Belgium)).

On the basis of detailed production, import and export statistics, model calculations by Bräutigam et al. [61] showed that the Cd freight introduced into building stock through window profiles in Germany decreased from 105 Mg in 1995 to 16 Mg in 2000, in sum about 287 Mg Cd for this period. If the 1995 value (105 Mg year^{-1}) is used to estimate the Cd load in the period from 1960 to 1994, the result is a freight of 3675 Mg of Cd and in total (from 1960 to 2000) of around 3962 Mg of Cd in windows with PVC profiles installed in Germany. In view of the useful life of PVC profiles of about 30 years, these will to a large extent still be present in the stock.

Materials such as aluminium, wood, PVC and combined materials, e.g., Al/wood or PVC/Al, compete with each other in the market for doors and window frames. The market share of PVC profiles in Germany would seem to remain at a level of 50% to 60%, whereas the production of PVC window units (1 unit = 1.69 m^2) in Germany decreased from 12.6 million (1996) to 7.6 million (2013) [91].

3.3.2. Recycling of PVC Profiles

VinylPlus, an organisation of the European PVC industry, reported that 514,913 Mg of PVC waste were recycled in 2015 within its VinylPlus framework. The windows and profiles sector continued to drive recycling volumes, accounting for nearly 50% of the total [92], as can be seen in Figure 4.

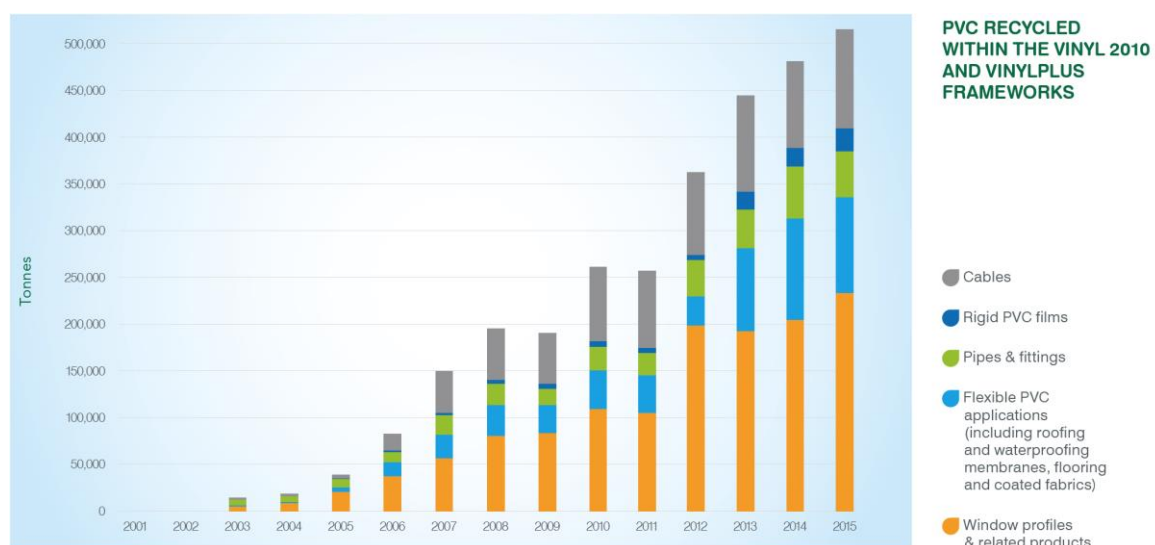


Figure 4. PVC recycled within the Vinyl 2010 and VinylPlus frameworks [92], in tonnes (=Mg).

In Germany, approximately 70% of all PVC waste is generated by the construction sector. Window and door profiles, roller shutters and larger cables are generally collected separately, sorted and crushed. Wallpapers, films and usually also floor coverings made from PVC are among the mixed construction waste. In 2015, about 455,000 Mg of plastic waste were produced in the construction sector, of which only 125,000 Mg (27%) were recycled whilst the overwhelming proportion was used for energy recovery [93]. Heterogeneity in the composition of high-quality plastics with their numerous additives makes recycling more difficult. For this reason, endeavours are made to use recycled material as far as possible in the same application field in order to avoid quality loss. This is the case with PVC profiles: Recycled PVC is usually only used for internal parts (“core”) when manufacturing new profiles, meaning that Cd stabilisers from former PVC frames are concentrated in the core of new profiles. In an analysis of post-use granulated, dissolved or pulverised PVC, all samples contained significant amounts of Cd [94]. Obviously, the relatively high concentrations of Cd in post-use PVC were the reason for raising the former threshold for Cd in recycled PVC from 100 mg kg^{−1} to 1000 mg kg^{−1} (see above).

The percentage of PVC profiles that are recycled and used as raw material for new PVC is difficult to calculate (According to industry journals, use of recycled PVC is not common in several European countries due to producers’ marketing policy). Figures for the German market published by a network of PVC manufacturers and recycling companies (Table 3) allow an analysis of the mass flow for 2013 [95] (Rewindo’s mass flow communication for 2015 did not include a Sankey diagram to visualise PVC material flows [96]. The mass flow for 2015 is therefore incomprehensible). Rewindo issues its statement each year, which is based on surveys.

An analysis of Rewindo’s mass flow communication shows that window manufacturers account for 58% of used window collection. Compared to the volume of production waste, the volume of material recycled (by Rewindo and other companies) is low (34%).

Window profiles are supposed to be disposed of separately during renovation or demolition. It is, however, known that—completely in line with the EU waste hierarchy—many discarded window profiles are taken by Eastern European construction workers for re-use in their respective home country. However, this cannot be quantified exactly. According to Rewindo [96], this “re-use” amounts to between 2800 and 2900 Mg a^{−1}, which is less than 10% of the total mass of end-of-life PVC profiles from windows, doors and shutters.

Table 3. Mass flow of used PVC windows in Germany, 2013 (Data from Rewindo [95]; bold lines contain the reference values for the respective rows below).

Collection of Used Windows (Pure PVC)	42,740 Mg	100%
Production of windows	24,810 Mg	58%
Demolition	8890 Mg	21%
Disposal companies	6760 Mg	16%
Residential construction	2280 Mg	5%
Whereabouts of used windows (pure PVC)	42,740 Mg	100%
Re-use	2850 Mg	7%
Recycling (pure PVC)	39,890 Mg	93%
Recycling of used windows (pure PVC)	39,890 Mg	93%
Material recycling by Rewindo	22,330 Mg	52%
Material recycling by other companies	3264 Mg	8%
Energetic recovery by other companies	14,296 Mg	33%
For comparison: Production waste (pure PVC)	75,030 Mg	

3.3.3. Fate of PVC Profiles Not Collected Separately

If PVC profiles are not separated from other materials during the demolition or renovation of buildings, they will become part of mixed demolition or construction waste. Demolition waste is usually landfilled or used for infrastructure projects such as road foundations or landscaping. In cases where disposal costs are high, mixed construction waste is often sorted off-site, but there is no uniform scheme.

Used wood, scrap (fittings, tubes, armouring irons), large plastic parts (foils, tubes . . .) will potentially be recycled. If PVC profiles from windows stabilised with Cd compounds are sorted and recycled together with other rigid PVC fragments, re-extrusion will lead to carryover of Cd into new products. Recycled material can comply with the 100 mg kg^{-1} threshold value for Cd in plastics, this depends on the mixture at source of plastic parts with or without Cd. In some Member States, there are tight restrictions on the landfilling of organic waste; in Germany, waste with TOC $> 1\%$ is not authorized for deposition on landfills with only a geological barrier. Thermal treatment of PVC is limited because of the formation of HCl during incineration. As a rule, municipal solid waste incinerators (MSWI) do not accept waste with high PVC content to minimize the content of corrosive HCl in the flue gas. The same is true for cement kilns that aim to keep the chlorine concentration in fuel below 0.5% to $1\% \text{ w/w}$ [97]. Moreover, the calorific value of PVC is low (18 MJ kg^{-1}) compared to PE, PP, PS (up to 40 MJ kg^{-1}). Especially in countries with low incineration capacities, waste PVC will primarily be landfilled. The environmental behaviour of rigid PVC in landfills was the subject of a European Commission study [98]. In the case of landfilling, the migration rate and mobility of Cd from PVC is very low because Cd is fixed in the PVC matrix. Considering the very long timespan PVC materials will be exposed to landfill conditions, a very slow degradation process will also contribute to landfill emissions.

4. Discussion

Despite the enormous data gaps detected during our work and reported in the previous chapter, the magnitude of unsolved problems for the two evaluated waste streams is clear: Even if the collection rate stated in the Batteries Directive were met (this is not the case), a loss of about 50% of portable NiCd batteries that are not collected separately has to be taken into account. A rough estimate arrives at about $1000 \text{ Mg Cd year}^{-1}$, which are disposed of from this source. No data are available on Cd salts in PVC outside Europe; a very rough calculation results in about 100 Mg year^{-1} of Cd to be disposed of or recycled with PVC frames and other PVC products within Europe.

Apart from the products/waste investigated here, there are many material streams that contain Cd as a minor component, e.g., zinc ores, wrought metal, various scraps and products. In these cases, a small Cd concentration means that a considerable freight is entering the technosphere due to the enormous mass flow of iron, steel, zinc and some alloys sold as scrap. The authors of two Cd balances for Europe for 2004 [34] and Austria for 2005 [99] deplore a “high level of uncertainty of how heavy metals in waste streams are related to heavy metals in the original products”. The specific figures for batteries are more reliable due to reporting obligations [49], but even in this case there are important gaps:

- The unknown number of portable batteries used or stored in households impedes a reliable calculation of the amount stored in the technosphere.
- The number of batteries integrated in electric appliances, which are not separated from WEEE, is unknown.
- There is no information concerning the number of industrial batteries imported into the EU and their recycling in Europe or elsewhere.

The assessment above shows that Cd freight in product and waste streams by far exceeds the emission freights from point sources into air and water. On the basis of this fact, the question arises of how to optimise the collection of used products containing Cd or its compounds from waste, with the aim of interrupting further contamination of the environment (especially emissions from landfills) and recycled products. The opportunities, problems and risks associated with the recovery of materials from waste streams can be assessed by means of a simple scheme that was developed empirically from studies on the life cycle of hazardous compounds and complex waste streams [100–103]. The scheme covers seven “obstacles” that have to be considered with regard to intended collection, recycling and recovery operations. Some of these obstacles can help to answer the question of how to optimise the collection of used products containing Cd or its compounds.

4.1. Economic Perspective

The market prices for cadmium, nickel, copper and zinc have been subject to considerable fluctuations in the last ten years (cf. Table 4): Prices have fallen since 2011, except the price for Zn which remained at a constant level. Although Cd is a relatively scarce metal from a geological perspective, the price is as low as that of Zn and often lower.

Table 4. Development of market prices [$\$ \text{kg}^{-1}$] for several non-ferrous metals [27,28]; prices as of 7 May 2017: Shanghai Metal Exchange Market.

Year	Cadmium	Nickel	Copper	Zinc
2006	3.0	24.2	89.0	3.5
2007	7.6	37.2	82.0	3.4
2008	5.9	21.1	210.0	2.0
2009	2.9	14.6	158.0	1.7
2010	3.9	21.8	221.0	2.3
2011	2.8	22.9	349.0	2.3
2012	2.0	17.5	150.0	2.1
2013	1.9	15.0	112.0	2.1
2014	1.9	16.9	119.0	2.4
2015	1.5	11.8	77.0	No data
7 May 2017	1.9	10.7	58.8	3.1

It should be noted that average costs for recycling of NiCd batteries and accumulators range from €1600 to 2000 Mg^{-1} [104]; revenues from scrap (mostly NiFe) are in the range of €700 Mg^{-1} . Clearly the market does not provide an economic incentive for recycling. This is true for PVC, too (economic figures for PVC recycling including used profiles from windows are not available). The price of granulated rigid PVC on the European market is about €500 Mg^{-1} [105]. The efforts undertaken by PVC manufacturers and recyclers to establish a threshold limit for Cd in recovered PVC waste mixtures and items tenfold higher compared to other plastics indicate that lower (more ambitious) limit values cannot be reached at economically viable costs.

4.2. Entropy Perspective

According to statistical thermodynamics, entropy can be used as a yardstick for the disorder of a closed system (see, for example, [106]). It is very difficult to recover valuable materials encased in products and energy is needed for their separation. According to a model based on information theory [107], the profitability of a recycling operation can be derived from just a few economic figures and physical data, including the absolute measure of material mixture within a used product. The entropy dilemma is critical for Cd in PVC profiles because Cd concentration is low and no recycling techniques are available for Cd. Present efforts at PVC recycling lead to an even greater entropy dilemma due to the “dilution” of recovered PVC powder in new profiles. As far as NiCd batteries are concerned, their high Cd content makes separation easier, but also demands high energy input.

4.3. Application and Consumption

Consumption of goods means a dissipative dispersion of products. Waste management companies collect dissipated goods after use. The higher the dissipation rate, the less devices can be collected separately in relation to the number of devices sold (see, for example, [108]). Portable batteries are globally dissipated since they are found in almost every household. A high rate of separately collected items requires:

- identification of the type of battery, also in the case of accumulators integrated in electrical appliances
- take-back stations that are easily accessible for citizens

- public awareness and incentives for the return of batteries

Even in Europe, these requirements are only partially met. Large accumulators for industrial use are only used in a comparatively small number of facilities. The potential for high return rates is therefore better, as can be seen in European statistics ([70], see chapter 3). Because of their use in mobile equipment (e.g., locomotives), a second dimension to dissipation emerges when second-hand vehicles etc. are exported. The level of dissipation of PVC profiles is also very high and it is not clear yet how many new frames containing secondary PVC are on the market, related to the mass of waste PVC. It is important to note that window frames can be re-used in other countries where Cd stearate has not been banned for use in the construction industry.

4.4. Time Perspective

Time is a crucial challenge for waste management. Firstly, chemicals banned for use in new products are still present in products in use and in different waste streams, and thus disrupt recycling processes. Secondly, consumption habits change with time and thus lead to unforeseen changes in the volume/mass and/or the composition of waste. A further problem arises through different legislative restrictions for Cd compounds in other regions. It is not clear when and to what extent legislators abroad (especially in China, the USA) will copy European regulations, particularly because this issue is often an integral part of overall trade policy.

5. Conclusions

5.1. Management of Cd-Bearing Products and Waste

When NiCd batteries are landfilled, medium-term release of Cd (and Ni) is probable due to their decomposition by battery acid, with a resulting risk for groundwater. With regard to incineration, Cd emissions decreased dramatically following the enforcement of the EU's Waste Incineration Directive, which stipulates a 0.05 mg Nm^{-3} threshold limit for the sum of Cd and Tl. Modern incineration plants usually do not exceed $0.001 \text{ mg Cd} + \text{Tl Nm}^{-3}$, as was found in the emission reports for 185 German incineration plants in 2015 (average: $0.00094 \text{ mg Cd} + \text{Tl Nm}^{-3}$) [109]. The disposal of compounds containing Cd in regions with state-of-the-art MSWI plants (according to the EU's Waste Incineration Directive [56] therefore does not harm the environment. As the overwhelming percentage of Cd from waste is found in air pollution control (APC) residues (including fly ash and ESP ash), the potential use of APC residues in construction material could be a new source of Cd entering the environment during or after use. Further use of APC residues should therefore be banned generally unless there is prior separation of metals, e.g., Cd.

Figures for sales and take-back of NiCd batteries and accumulators are superimposed by a relatively long period of use (about seven years) that does not match with the collection target (two to three years) defined in the Batteries Directive (see Section 3.2). European authorities are therefore unable to calculate correctly the percentage of NiCd batteries and accumulators collected separately for further treatment in relation to the numbers and/or mass put on market.

The complete substitution of NiCd batteries is technically possible and could be pursued in the remaining areas of application. An alternative would be to increase the return rate of welded accumulators by means of a deposit, which at the same time represents an incentive for their return. It is currently not possible to track how many industrial batteries are placed on and withdrawn from the market since there are no reporting requirements. A related extension of the EU's Batteries Directive is therefore required.

The data presented here show that only a small fraction of PVC profiles containing Cd salts is collected separately and recycled or re-used. The use of recycled material in new products leads to further dilution and hence to a dissipation of Cd. As Cd-free stabilisers are already available on the market, there is no reason to produce hard PVC profiles with secondary PVC containing Cd. Europe's strategy should therefore be to encourage the disposal of heavily contaminated material by no longer

allowing an exemption for Cd-bearing profiles. Information and a discussion on the use of Cd stabilisers are required at global level. With respect to the figures published by PVC recyclers (Section 3.3), more precise statistics are needed in order to verify the mass flow of used hard PVC profiles.

Generally speaking, the import of products with low Cd concentrations cannot be excluded due to the continuing use of Cd in other parts of the world, which may or may not be in line with EU regulations (A study conducted by Germany's Federal Environment Agency (UBA) in 2011 compared the concentration of heavy metals (Cd, Pb, Hg) in commercially available batteries and those incorporated in devices with the existing thresholds. The test used several battery types from different manufacturers that had been placed on the German market. The investigations performed as part of this study discovered violations of Hg and Cd limits in a number of cases in zinc-carbon and zinc-chloride mono cells). Undetected contamination can also occur in "unsuspicious" products. In both cases, an additive Cd flow has to be taken into account.

5.2. Circular Economy Approaches

As far as materials streams are concerned, it is only possible to manage those that can also be measured. Clear reporting obligations for the manufacturers, distributors and recyclers of hazardous compounds such as Cd are therefore necessary in order to allow reliable material flow analyses that can be used as a basis for a material balance. Only such a balance will enable authorities to decide whether or not to take action.

Despite the many advances made in assessing the hazardousness of substances, it cannot be predicted how our knowledge of individual substances or groups of substances will develop in the future. As a result, additives in plastics can massively hinder the recycling of large quantities of plastic products (for example Cd stearate in PVC profiles). This is a warning sign for technical and biological cycles. It is scarcely possible to retract contaminants from the market of which the hazardous potential is recognised at a very late stage. Self-imposed withdrawal and return obligations (for example for NiCd batteries) have so far proven to be inadequate within the framework of EU legislation. Leasing models [11] are proposed for securing the return of long-lived products, but this presupposes the economic stability of the leasing company over decades.

The case studies discussed here make clear that a "circular economy" has to cope with enormous challenges concerning the management of pollutants contained in products or wastes. Although Cd compounds have already been partially regulated for two decades (which is not the case for thousands of other chemicals), the problem of dissemination and dilution is still unsolved.

Author Contributions: H.F. has taken part in conceptualizing, writing and checking the paper. B.Z.-L. has taken part in conceptualizing, writing and checking the paper. A.B. has taken part in writing and checking the paper.

Acknowledgments: We really appreciated the discussion with the peer reviewers who helped us to make the article more readable.

Conflicts of Interest: The authors declare no conflict of interest.

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