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A material flow of lithium batteries in Taiwan

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ABSTRACT

Li batteries, including secondary and cylindrical/button primary Li batteries, are used worldwide in computers, communications and consumer electronics products. However, there are several dangerous issues that occur during the manufacture, shipping, and storage of Li batteries. This study analyzes the material flow of lithium batteries and their valuable heavy metals in Taiwan for the year 2006 by material flow analysis. According to data from the Taiwan Environmental Protection Administration, Taiwan External Trade Development Council, Bureau of Foreign Trade, Directorate General of Customs, and the Li batteries manufactures/importers/exporters. It was found that 2,952,696 kg of Li batteries was input into Taiwan for the year 2006, including 2,256,501 kg of imported Li batteries and 696,195 kg of stock Li batteries in 2005. In addition, 1,113,867 and 572,215 kg of Li batteries was domestically produced and sold abroad, revealing that 3,494,348 kg of different types of Li batteries was sold in Taiwan. Of these domestically sold batteries, 504,663 and 146,557 kg were treated domestically and abroad. Thus, a total of 2,843,128 kg of Li batteries was stored by individual/industry users or illegally disposed. In addition, it was also observed that 2,120,682 kg of heavy metals contained in Li batteries, including Ni, Co, Al, Cu and Ni, was accumulated in Taiwan, with a recycled value of 38.8 million USD. These results suggest that these heavy metals should be recovered by suitable collection, recycling and reuse procedures.

1. Introduction

Nickel–metal hydride batteries (Ni–MH batteries), nickel–cadmium batteries (Ni–Cd batteries), and lithium batteries (Li batteries) are already used worldwide for computers, communications and consumer electronics products (3C products). Although the production technology for Ni–MH and Ni–Cd batteries are well developed, certain international regulation, such as the Waste Electrical and Electronic Equipment (WEEE) act, the Restriction of Hazardous Substances (RoHS) act of European Union, and the Mercury-containing and Rechargeable Battery Management Act of United States set control criteria to reduce the risk of lead, cadmium and mercury contained bacteria to the environment. On the other hand, Li batteries have the potential to replace the first two kinds of batteries due to their advantages such as high energy density, high power, light weight, wide range temperature application, small size, and low self-discharge electricity [1]. It has been reported that Li batteries contributed to 80% of exit cargo value of secondary batteries, and this amount will increase from 1.5 billion batteries of year 2004 to 2.5 billion by 2010 [2].

Taiwan is well known for its production of 3C products such as notebook computers and cell phones, which both use Li batteries. However, several kinds of salts, such as $LiPF_6$, $LiClO_4$, $LiSO_2$, and $LiBF_4$ are used as electrolytes in Li batteries. These salts can easily initiate chemical reactions with outside elements to produce hazardous materials such as hydrofluoric acid or cause fires. In addition, Li batteries can produce toxic materials under excessive charge, when exposed to high temperatures, after puncture, and when burned. This can result in upper respiratory tract damage, skin irritation, and central nervous system damage to human beings, as well as fire or explosive [3]. At least nine accidents have been reported in the United State aircraft due to fires from Li batteries, and Sony Coorporation has implemented recall project due to the overheating of Li batteries [4,5]. Without suitable treatment, the disposal of Li batteries can leak organic electrolytes as well as heavy metals contained in the batteries such as copper and nickel to contaminate the environment [6].

In addition, two important heavy metals, cobalt and lithium, which are an active cathode material, were contained in the Li batteries. It was measured that 5–15 wt.% of cobalt and 2–7 wt.% of lithium were contained in the Li batteries as important con-

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Table 1
Imports of lithium batteries from country in year 2006

Country	Li primary cells/batteries and accumulators (kg/year)		
	Lithium primary cells/batteries (1)	Lithium accumulators (2)	Subtotal in individual country (3) = (1) + (2)
China	182,363	698,444	880,807
Japan	189,708	636,680	826,388
Korea	29,570	294,913	324,483
Indonesia	50,475	85,741	136,216
Germany	18,514	142	18,656
Israel	16,568	2	16,570
United States	10,604	4,990	15,594
Canada	813	5,813	6,626
Hong Kong	3,524	1,289	4,813
Singapore	1,340	1,652	2,992
Malaysia	1,350	1,406	2,756
France	2,621	50	2,671
Switzerland	920	24	944
Hungary	559	14	573
Belgium	511	0	511
Denmark	309	64	373
Italy	142	95	237
Philippines	55	103	158
Sweden	72	37	109
Other countries	1,290	13,734	15,024
Total	511,308	1,745,193	2,256,501

Data source: Arranged from TAITRA.

stituents. Such high concentration of cobalt was considered to be economical for reclamation and reuse which was already studied by other researchers [1,6–9]. Thus, to understand the material flow of Li batteries will be an important issue in the future in Taiwan. [10].

Material flow analysis (MFA) is a tool to analyze the metabolism of materials in order to analyze material flows and stocks within a given system. It can evaluate the importance and relevance of theses flows and stocks, and control material flows and stocks to support certain goals, such as sustainable development [11]. In the past several decades, MFA has been successfully applied to assess resource utilization and environmental impacts. Long-term environmental management policy and resource management strategy are then proposed based on such assessment [12]. Other studies have shown MFA to be a useful method and it has already been used to understand and control the material flow of heavy-metal containing batteries. Rydh et al. [13,14] analyzed the material flow of Ni–Cd batteries in Sweden by MFA and found that 25% of batteries were recycled while 75% of batteries, corresponding to 18.8 tonnes, were disposal into landfills or incinerated. That study also suggested that to increase the collection efficiency of the batteries is more important than the recycling technical efficiency. Hawkins et al. [15] also used MFA to investigate Ni–Cd batteries in United States, finding that Ni–Cd batteries are main products using cadmium as a component. In addition, no more than 20% of the cadmium in Ni–Cd batteries could be recovered by arc furnace process.

In order to use MFA to clearly understand the material flow of Li batteries in Taiwan for 2006, this study interviewed several institutes related to Li batteries, such as the Taiwan Environmental Protection Administration (Taiwan EPA), the Taiwan External Trade Development Council (TAITRA), the Bureau of Foreign Trade, the Directorate General of Customs, and the Li batteries manufactures/importers/exporters. The results of this survey can also serve as a reference for the control, management, and treatment of Li batteries in Taiwan.

2. Materials and methods

2.1. Material flow analysis

This study used MFA to analyze the material flow of Li batteries in Taiwan. MFA is a tool to help decision-makers to understand the metabolism of their region. Briefly, the MFA examines the materials flowing into a given system, the stocks and flows within this system, and the resulting outputs from the system to other systems. [11]. As described below, the following five main steps were used: identification of objectives and effectiveness, identification of system boundary and components, data acquisition and inventory, formulation and balance for material flow system framework, and interpret result of MFA for Li batteries:

(a) Identification of objectives and effectiveness.

Table 2
Li battery types of domestic manufacture and sold domestic in Taiwan

	Cylindrical primary Li batteries	Button primary Li batteries	Secondary Li batteries	Total
Domestic manufacture				
Imported	93,950	188,449	800,388	1,082,787
Exported	46,666	35,399	490,150	572,215
Domestic sales				
Stock from 2005	55,725	46,541	493,929	696,195
Imported	93,950	188,449	800,388	1,082,787
Domestic produced or reproduced	7,679	5,089	1,702,598	1,715,366
Subtotal	157,354	240,079	2,996,915	3,494,348

Data source: Arranged from the Taiwan EPA (year 2006, unit: kg/year).

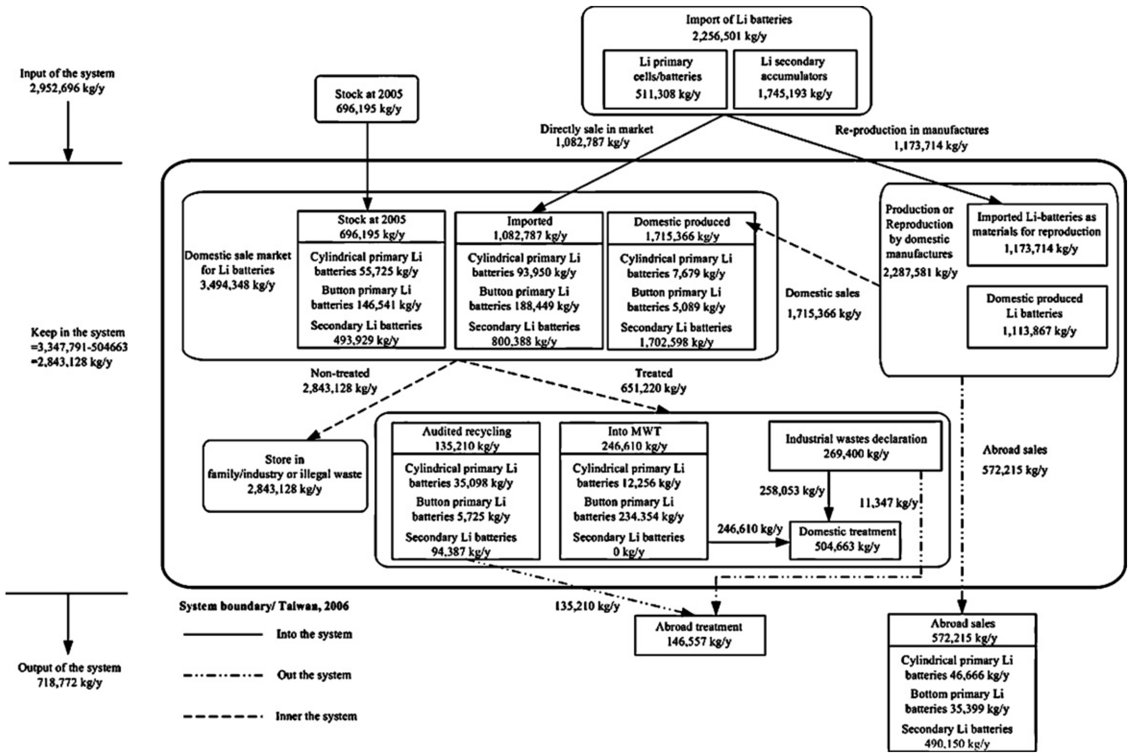

Fig. 1. Material flow analysis for lithium batteries in Taiwan for the year 2006.

To investigate the material flow of Li batteries and related valuable substances, this step set up a preliminary framework for the MFA system.

(b) Identification of system boundary and components.

It is necessary to decide the target and the boundaries of time and space before using the MFA method. In this study, the target was to establish the material flow system of Li batteries, including primary cells (cylindrical and button types) and secondary cells, among the imports, exports, domestic manufacture, and waste in Taiwan. The time margin was the year 2006 and the space margin was Taiwan.

(c) Data acquisition and inventory.

To construct the system and confirm the stocks and flows within the system, a great deal of information must be collected, such as paper reviews, market research, expert judgment, best estimation, and direct interviews with the manufacturers, importers, exporters, Taiwan EPA, and Directorate General of Customs of Taiwan.

(d) Formulation and balance for material flow system framework.

This step constructs the system to use the data collected above. When some data was not acquired, the mass balance or so-called mass conservation, i.e., mass-in is equal to mass-out, can be used to balance the materials.

(e) Interpreting MFA result for Li batteries.

According to the above analysis, this step interprets the results of MFA analysis for Li batteries.

Table 3
Average concentration of heavy metals in Li battereis

Components	Button primary batteries (wt.%)	Cylindrical primary or secondary batteries (wt.%)
Lithium	1.8	10.0
Cobalt	0.1	11.0
Aluminum	–	14.3
Copper	–	9.8
Nickel	3.0	14.9
Total	4.9	60.1

Data source: Averaged from refs. [2,7,8,10,18].

2.2. Estimating the quantity of Li batteries

In this study, the optimized results of the material flow of Li batteries were obtained by broad data collection for the year 2006 and calculated using the following equation:

$$F_{\text{Li\_batteries}} = \sum_{1}^{N} F_{\text{production},i(2006)} + \sum_{1}^{N} F_{\text{import},i(2006)} - \sum_{1}^{N} F_{\text{export},i(2006)} + \sum_{1}^{N} S_{i(2006)} - \sum_{1}^{N} S_{i(2005)} \quad (1)$$

where F is the flow, S is the stock, $F_{\text{Li\_batteries}}$ is the total amount of Li batteries in the system which can be potential waste Li batteries, $F_{\text{production},\, i(2006)}$ is the Li batteries type i (i = cylindrical primary cells, button primary cells, and secondary cells) that are domestically produced in the year 2006, $F_{\text{import},\, i(2006)}$ is the Li batteries of type i imported into the system boundary in the year 2006, $F_{\text{export},\, i(2006)}$ is the Li batteries type of i exported from the system boundary in the year 2006, including fresh batteries and waste batteries from abroad and $S_{i(2005)}$ and $S_{i(2006)}$ are the stock of Li batteries type of i within the system boundary for the year 2005 (for consumer use only) and 2006 (for manufacture is only), respectively.

Since very few Li batteries was stocked by manufactures, item $S_{i(2006)}$ can be omitted. In addition, the Li batteries stored by consumers can be expressed as the sale amount minus the recycled amount, so the above Eq. (1) can be transferred as Eq. (2).

$$F_{\text{Li\_batteries},i} = \sum_{1}^{N} F_{\text{production},i(2006)} + \sum_{1}^{N} F_{\text{import},i(2006)} - \sum_{1}^{N} F_{\text{export},i(2006)} + \sum_{1}^{N} \text{Market\_Li\_batteries},\ i(2005) - \sum_{1}^{N} \text{Recycling\_Li\_batteries},\ i(2005) \quad (2)$$

where Market_Li_battereis,i(2005) and Recycling_Li_batteries, i(2005) are the total sale amount and total recycled amount for the year 2005.

2.3. Estimating the quantity of valuable substances in Li batteries

This study further identified the MFA of valuable substances, including cobalt, copper, aluminum, nickel, and lithium in Li batteries, as described in Eqs. (3–6).

$$F_{\text{co}} = \sum W_{\text{cells}} \times M_{\text{co}} \quad (3)$$

$$F_{\text{Cu}} = \sum W_{\text{cells}} \times M_{\text{Cu}} \quad (4)$$

$$F_{\text{Al}} = \sum W_{\text{cells}} \times M_{\text{Al}} \quad (5)$$

$$F_{\text{Ni}} = \sum W_{\text{cells}} \times M_{\text{Ni}} \quad (6)$$

$$F_{\text{Li}} = \sum W_{\text{cells}} \times M_{\text{Li}} \quad (7)$$

where F_{Co}, F_{Cu}, F_{Al}, F_{Ni}, and F_{Li} are the flows of cobalt, copper, aluminum, nickel and lithium, W_{cells} is the overall weight of Li batteries in year 2006 and M_{Co}, M_{Cu}, M_{Al}, M_{Ni}, and M_{Li} are the weight percentage of cobalt, copper, aluminum, nickel and lithium in the Li batteries.

3. Results and discussions

3.1. Import and export analysis

The Li batteries are classified into three different types, i.e., Li primary cells, Li primary batteries, and Li accumulators, according to the Chinese Commercial Code system. In order to identify the importing countries of the above three kinds of Li batteries, this study surveyed the manufacturing countries and kinds/quantities of Li batteries from the database of the Taiwan external trade development council for the year 2006, as shown in Table 1.

Table 1 shows that 511,308 and 1,745,193 kg of Li primary batteries and Li accumulator were imported in year 2006, for an overall amount of 2,256,501 kg from more than 20 countries. The first four countries from which most Li batteries were imported were China (880,807 kg), Japan (826,388 kg), Korea (324,483 kg) and Indonesia (136,216 kg), respectively. This showed that these four countries contributed to 96.07% of the total imported Li batteries.

Generally, the primary Li cells/batteries can be sold as cylindrical/bottom Li primary batteries, while the Li accumulators can be sold as secondary Li batteries. In addition, the above imported Li cells/batteries/accumulators could further be sold directly or remanufactured in Taiwan. According Taiwan EPA data, 1,082,787 kg of different types of imported Li batteries, i.e., 93,950, 188,449 and 800,388 kg for cylindrical primary Li batteries, button primary Li batteries and secondary Li batteries were sold in Taiwan directly, corresponding to 8.6, 17.4 and 74.0% of directly imported sales Li batteries, which as shown in Table 2. The other 1,173,714 kg of imported Li batteries were used for domestic manufacturing and then sold domestically or abroad.

In addition, Table 2 also shows that these domestic manufactures sold 572,215 kg of Li batteries, including 46,666, 35,399 and 490,150 kg of cylindrical primary, button primary and secondary Li batteries, to foreign countries, corresponding to 8.2, 6.1 and 85.7% of the exported Li batteries. Thus, it was observed that secondary Li batteries are the main goods both for export goods and domestic sales in Taiwan

3.2. Domestic stock and manufacturer of Li batteries

From statistical data of the Taiwan EPA, 753,195 kg of Li batteries were sold on the domestic market of Taiwan in the year 2005, and 57,000 kg of Li batteries was recycled into the treatment processes. Thus, 696,195 kg of batteries could be sold in the domestic market at year 2006, compared of 55,752, 146,541 and 493,929 kg of cylindrical primary, button primary and secondary Li batteries.

In addition, 2,287,581 kg of Li batteries was produced by local factories or re-produced from the imported Li cells/batteries/accumulators. Since 1,082,787 of imported Li batteries were directly sold on the domestic market, the other 1,173,714 kg of imported Li batteries was consumed as re-manufacturing by domestic manufacturers. This indicated that 1,113,867 kg of Li batteries was produced domestically in the year 2006. On the other hand, since 572,215 kg of Li batteries was exported, as shown in Table 2, thus 1,715,714 kg of Li batteries was sold domestically in Taiwan for the year 2006. This reveals that 75% of the domestically produced/re-produced Li batteries was sold in Taiwan, while the other 25% was exported to foreign countries. In addition, if stock of Li batteries in the year 2005 was added, a total of 3,494,348 kg of Li batteries was sold in the domestic market in the year 2006, as shown in Fig. 1.

3.3. Domestic market of Li batteries

As described in Section 3.2, the domestic market of Li batteries was calculated to be 3,494,348 kg in the year 2006, as shown in Table 2. Moreover, 2,996,915 kg of secondary batteries, i.e., 85.8% of the total batteries, was sold in Taiwan in the year 2006. Secondary Li batteries are a suitable power supply for portable 3C products, such as notebook computers, cell phones, and CD players, as well as motor-driven machines and even motor-driven vehicles. Among these secondary Li-batteries, 56.8% of the batteries was produced or reproduced by domestic manufacturer, while the other 26.7 and 16.5% of batteries was from imports or stock in the year 2005, respectively.

On the contrary, for primary cylindrical/button Li batteries, only 4.9 and 2.1% of the batteries were produced or reproduced by domestic manufacturers. It was also found that 59.7 and 78.5% of the primary cylindrical and button batteries were imported. Table 2 also shows that the domestic manufacturers produced/re-manufactured 1,715,366 kg of Li batteries in year 2006. It was found that 99.3% of the domestic produced/re-manufactured Li batteries were secondary batteries, while only 0.4 and 0.3% were primary cylindrical and primary button batteries.

3.4. Analysis of Used Li batteries

Li batteries are used by two kinds of users: individual consumers and industrial users. For individual consumers, the used

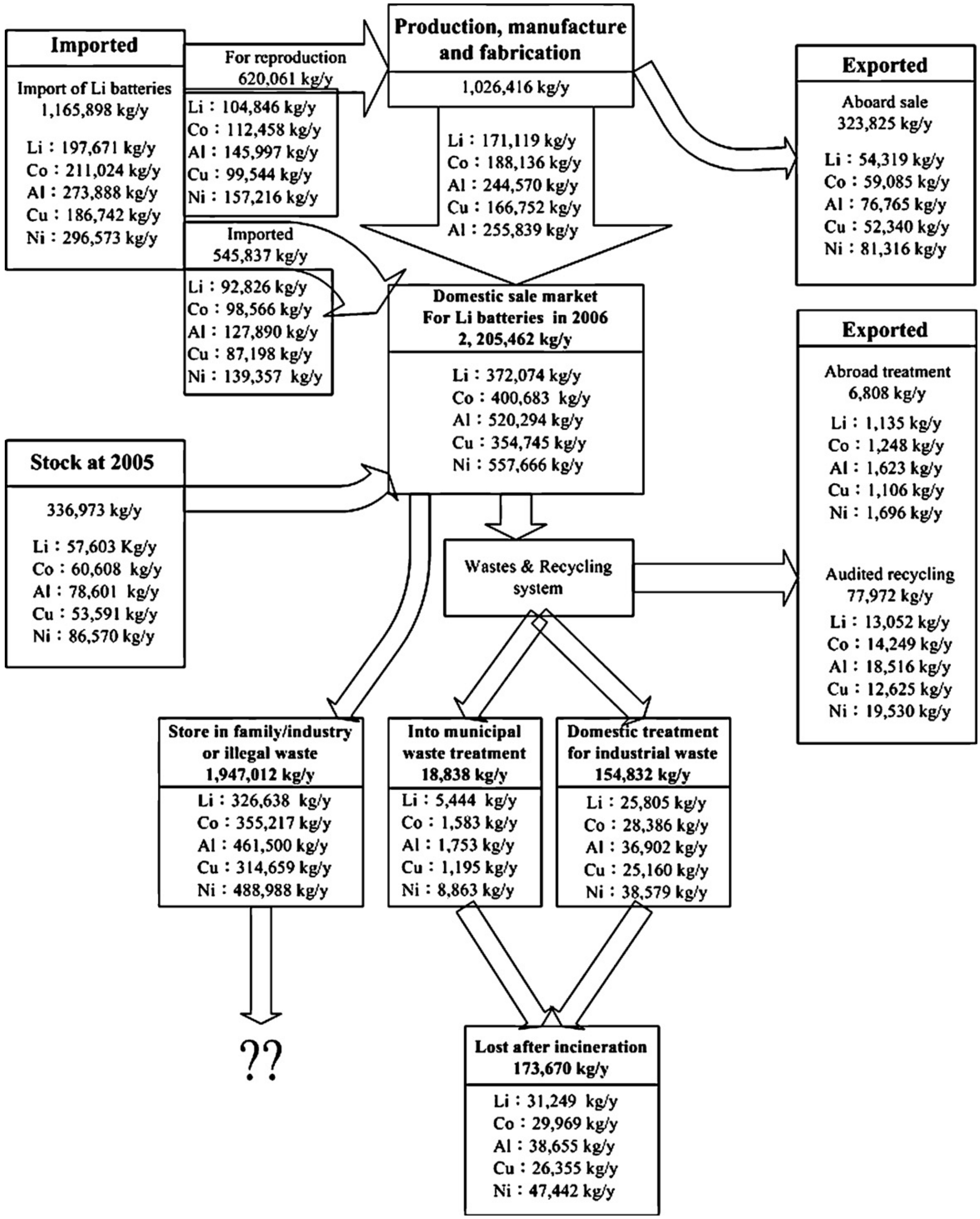

Fig. 2. Valuable heavy metals contained in Li batteries at year 2006.

Li batteries could be disposed either into the recycling system or directly into the municipal waste treatment system. For industrial users, a declaration to Taiwan EPA via internet is necessary before disposing of used Li batteries. According to the data of Taiwan EPA, 269,400 kg of Li batteries was declared to be disposed in the year 2006. Of these disposed batteries, 146,577 and 11,347 kg were treated offshore and domestically, respectively. For individual users, 135,210 and 246,610 kg of used batteries were disposed into audited recycling and municipal waste treatment systems, respectively. It was also found that all of the audited recycling of Li batteries was done abroad, while all the used batteries collected from municipal waste treatment system were treated domestically. Thus, according to the above data, 504,663 and 146,577 kg of waste batteries were treated domestically and abroad, respectively. It should be noted that 3,494,348 kg of Li batteries was sold domestically in the year 2006. It was also found that 651,220 kg of the used batteries was well treated, including 135,210 kg via audited recycling system, 246,610 kg via municipal waste treatment system, and 269,400 kg via industrial wastes declaration system. This revealed that 81.4% or 2,843,128 kg of domestically sold Li batteries was still in use, stored at home or industry, and disposed of as illegal waste.

3.5. The overall material flow of Li batteries in Taiwan by the MFA method

According to the data discussed in Sections 3.1–3.4, Fig. 1 shows the diagram of the material flow of Li batteries via the MFA method. Generally, the overall input of Li batteries for the year 2006 was 2,952,696 kg, including 696,195 kg of stock batteries in 2005 and 2,256,501 kg of imported batteries in 2006. On the contrary, the overall output of the Li batteries was 718,772 kg, including 572,215 kg for sales abroad and 146,557 kg for treatment abroad. Thus, 2,233,924 kg of input batteries was calculated to be present in the system. In addition, 1,113,867 kg of Li batteries was produced domestically, implying that a total of 3,347,791 kg of Li batteries was retained in the system. Of this 3,347,491 kg of Li batteries, 504,663 kg of Li batteries was treated domestically, while the other 2,843,128 kg, or 84.9% of the Li batteries in the system, was still in use, stored at home or industry, and disposed of as illegal waste. Thus, how to manage the non-treated Li batteries is an important issue for Taiwan in the future.

3.6. Material flow for potential metal recycling of lithium batteries

To construct a sustainable and recycling-oriented society, it is necessary to recover all the valuable elements of the Li batteries, especially the lithium, cobalt, aluminum, copper and nickel. Thus, this study further analyzed the material flow of the above heavy metals of Li batteries by MFA method. Table 3 shows the average concentration of heavy metals in different types of Li batteries. It was observed that the concentrations of valuable heavy metals in button primary batteries are less than in cylindrical primary or secondary batteries. For button primary batteries, only 4.9 wt.% valuable heavy metals, of which nickel and lithium were predominant. On the contrary, for cylindrical primary or secondary batteries 60.1 wt.% was valuable heavy metals. The Li, Co, Al, Cu, and Ni concentrations in cylindrical primary or secondary batteries were similar and ranged from 9.8 to 14.9%. Since the secondary and cylindrical primary batteries represented 90.3% of the domestic sold Li batteries, a great quantity of heavy metals contained in these two types of batteries needs to be recycled after they are disposed.

To explain the material flow of these valuable metals in Taiwan, Fig. 2 shows the calculated results of the heavy metals contained in Li batteries from Fig. 1 and Table 3. It can be seen that 2,205,462 kg of heavy metals, including 372,074 kg, 400,683 kg, 520,294 kg, 354,745 kg, and 557,666 kg of Li Co, Al, Cu, and Ni, was distributed into Taiwan due to sales of Li batteries. If 84,780 kg (=6808 + 77,972) of heavy metals was collected and treated abroad, 2,120,682 kg of heavy metals was accumulated in Taiwan. This can be divided into two groups, i.e., 173,670 kg that was lost after incineration and 1,947,012 that was stored by individual/industry or disposed as illegal waste. This contributed to 357,887, 385,186, 500,155, 341,014 and 536,440 kg of Li Co, Al, Cu, and Ni. It was also found that the cost of these above heavy metals at April of 2008 were 7.95, 40.50, 3.04, 8.89, and 29.43 USD per kg, respectively. This would be a total of 38.8 million USD if recovered. Some references tried to recover the valuable metal in lithium batteries by chemical or physical technologies. Nan et al. [16] recovered more than 98% of the copper and 97% of the cobalt by chemical deposition and solvent extraction procedure. Paulino et al. [17] established two procedures to recover the cobalt and manganese.

Moreover, it has previously been reported that the recovered Li and Co can be successfully reused as the cathode material ($LiCoO_2$) to produce secondary Li batteries [18]. Thus, how to collect, recycle and reuse the heavy metals contained in waste Li batteries is an important issue to be addressed in the future.

4. Conclusion

Since Li batteries are an increasing of important portable power supply for many devices, this study analyzed the material flow of lithium batteries and their valuable heavy metals in Taiwan for the year 2006 by material flow analysis. It was found that 3,494,348 kg of different types of Li batteries was sold in the year 2006. It was also found that 504,663 kg of the domestically sold Li batteries were wasted and treated domestically, while 146,557 kg were treated abroad. In addition, 2,843,128 kg of Li batteries was stored by individual/industry users or illegally disposed. It was also observed that 2,120,682 kg of heavy metals contained in Li batteries, including 357,887 kg of Ni, 385,186 kg of Co, 500,155 kg of Al, 341,014 kg of Cu and 536,440 kg of Ni, was accumulated in Taiwan. This had a value of 38.8 million USD if further recovered by suitable collection, recycling and reuse procedures.

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