

RECYCLING AND DISPOSAL OF LITHIUM BATTERIES: AN ECONOMICAL AND ENVIRONMENTAL APPROACH

ATAUR RAHMAN^{1*}, RAFIA AFROZ² AND MOHD SAFRIN¹

¹Department of Mechanical Engineering, Faculty of Engineering,

²Department of Economics, Faculty of Economics and Management Sciences,
International Islamic University Malaysia,
Jalan Gombak, 53100 Kuala Lumpur, Malaysia.

*Corresponding author: arat@iium.edu.my

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ABSTRACT: The adoption of lithium-ion battery technology for electric vehicles/hybrid electric vehicles (EV/HEV) has recently received attention worldwide. The price of cobalt (Co) and lithium (Li) has increased due to the production of EV/HEV. A used lithium battery is a valuable source of active metals (Co, Li, and Al) and the optimal way of extracting these metals from this waste is still studied. The focus of this paper is to recover active metals using the hydrometallurgical method on a laboratory scale with a 48.8 Wh battery to reveal economic and environmental benefits. Calcination of extracted active metals as pre-thermal treatment has been conducted at 700°C to remove the organic compounds from the surface of active metals. The experiment has been conducted and the result shows that the recovery of active metals (cathode) is 41% of the cell cathode and 8.5% of the cell anode materials, which represent 48.8% and 23.4% of the cathode and anode cell material price, respectively. By recycling about 47.34% of the battery active metals, emissions can be reduced by 47.61% for battery metal production and 60.7% for disposal transportation of the used battery. The total emission can be reduced by about 52.85% by recycling the active metals in used batteries.

ABSTRAK: Adaptasi teknologi bateri Litium-ion ke dalam kenderaan elektrik/kenderaan elektrik hibrid (EV/HEV) telah mendapat perhatian seluruh dunia baru-baru ini. Harga kobalt (Co) dan litium telah bertambah hasil daripada EV/HEV. Penggunaan bateri litium adalah sumber berharga kepada logam-logam aktif (Co, Li dan Al) dan cara terbaik untuk mengekstrak logam-logam ini daripada sisa ini masih dipelajari. Fokus kertas ini adalah untuk mendapatkan logam aktif dengan menggunakan kaedah hidrometalurgikal dalam skala makmal dengan bateri 48.8 Wh untuk mendedahkan faedah ekonomi dan alam sekitar. Proses penulenan pada logam aktif yang diekstrak sebagai rawatan pre-haba telah dijalankan pada suhu 700 °C untuk membuang kompoun organik daripada permukaan logam aktif. Eksperimen telah dijalankan dan keputusan menunjukkan logam aktif didapati pada (katod) adalah 41% daripada sel katod dan anod adalah 8.5% daripada bahan sel anod, di mana 48.8% dan 23.4% daripada sel katod dan harga bahan sel anod, masing-masing. Dengan kitar semula logam aktif bateri sebanyak 47.43%, pelepasan boleh dikurangkan sebanyak 47.61% bagi penghasilan logam bateri dan 60.7% bagi pengangkutan pelupusan bateri terpakai. Pelepasan total boleh dikawal sebanyak 52.85% dengan mengitar semula logam aktif pada pengeluaran bateri.

KEYWORDS: Li-ion battery; electro-chemistry; calcination; recycling; economics and environmental values

1. INTRODUCTION

Demand for electric vehicles (EVs) is growing around the world fairly rapidly. The EV/HEV sales share will represent at least 50% of light-duty vehicle sales worldwide by 2050. The aim of EVs/HVs is to contribute greenhouse-gas emission reductions and deliver substantial benefits in terms of improved oil security, reduced urban area pollution, and noise. The actual penetration of EVs has been seen as a key factor in material demand because these vehicles require larger batteries [1].

Lithium-ion batteries play a major role in powering electric vehicles by meeting their torque and speed demands. However, there is a threat regarding the availability of the lithium needed for battery production. This threat has shifted focus towards ensuring a continuous supply of materials needed for the green revolution through reuse and recycling. The dominant chemistry used in electronics batteries of active metals like Ni, Co., and Al for LCA battery, Li, Fe and phosphate (P) for LFP and Li, manganese (M) and sulfate (S) for LMS battery electrochemistry, as shown in Table 1. The battery contains a weight percentage (wt%) of lithium carbonate that is less expensive compared to cobalt (Co) or nickel (Ni). The average lithium cost associated with Li-ion battery production is less than 3% of the production cost while the battery metal production cost is about 200% higher than the battery metal's recycle cost [2]. Intrinsic value for the Li-ion recycling business currently comes from valuable metals such as Co and Ni that are more highly priced than Li.

Table 1: Battery materials

System /Electrodes	LCA	LFP		
		Graphite	Graphite	MS TiO
Cathode	$\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$	LiFePO_4	LiMn_2O_4	LiMn_2O_4
Anode	Graphite	Graphite	Graphite	$\text{Li}_4\text{Ti}_5\text{O}_{12}$

Note: NCA: nickel, cobalt and aluminum; LFP: lithium iron phosphate; LMO: lithium manganese oxide; LMS: lithium manganese salt

General Motor's claim that "one million tons of lithium is enough to produce 395 million Chevrolet Volts each with the power capacity of 16 kWh and battery electrochemistry chemistry LiFePO_4 ", i.e. 158 g of lithium metal required per kWh battery and hence the lithium needs are in the range of 113-246 g per kWh lithium-ion battery development. In addition, the theoretical charge density of lithium metal from fundamental electrochemistry is 3.8 Ah/g, representing 1 g of lithium, could supply 3.8 A of electric current for 1 hour [3].

Recycled lithium is as much as five times the cost of lithium produced from the least costly brine-based process [4,5]. However, with the increasing number of EVs entering the market in the future, and with a significant supply crunch, recycling is expected to be an important factor for consideration in effective material supply for battery production. Metal compositions of Li-ion batteries are mainly Al, Cu, Co, Fe, and Li, as shown in Table 2. The anode typically consists of Cu foil covered by a fine layer of carbon while the cathode contains Al, Co, and Li metals. It is particularly interesting to focus research on the recycling of cathodes as the active material. Such components represent 41%, by weight, of the cell components or 48.8% of the cell price. The price of Al, Cu, Ni, Co and Li per kilogram are USD1.58, USD5.3, USD10.57, USD27.5 and USD9.5, respectively [1].

Research has been reviewed to identify an economical and easy recycling process [6, 7]. Several methods could be preferred to recycle used Li-ion batteries for metal recovery; hydrometallurgical-based and pyro-metallurgical-based processes are the most predominant. As the pyro-metallurgical process is expensive and consumes too much energy, most of the previous literature prefers the hydrometallurgical process for metal recovery. In this study, the recovery of Al, Co, Fe, and Li metals from the cathode of the used Li-ion battery is focused using hydrometallurgical processes [8]. The steps are associated with the hydrometallurgical processes: physical separation of the battery (dismantling), manual separation of anode and cathode, acid leaching for the cathode, and crystallization testing for recovery of the Co metal.

The global EV market will represent more than 7% of the light-duty vehicle market by 2020 and 70% of EVs are powered by Li-ion batteries. The green revolution, through reuse and recycling of batteries, has become a crucial topic in the automotive industry ensuring the availability of lithium needed for battery production. Recycling of used lithium batteries is the primary focuses of this work to extract active valuable metals such as cobalt (Co) and lithium (Li).

Table 2: Composition of lithium battery [6]

Components	Amount (wt%)
Cathode, Anode, and Electrode	40 ± 1.5%
Plastic case	22 ± 1
Steel case	11 ± 1.5
Copper foil	9 ± 0.5
Aluminum foil	6.5 ± 0.5
Electrolyte	5 ± 1.5
Solvent	5.5 ± 1
Electrical board and circuit	1.5 ± 0.5

2. MATERIALS AND METHODS

Recycling batteries is beneficial to the environment. It keeps them out of landfill, where heavy metals may leak into ground when the battery casing corrodes, causing soil and water pollution. The composition of an Li-ion battery is shown in Table 2.

2.1 Recycling and Disposal

The author [9] has developed a ‘hydrometallurgy’ process (Fig. 1) by modifying the hydrometallurgy process to recover the LiCoO₂ battery metals. Mechanical pre-treatment (Calcination) and physical separation are applied to recover the battery materials such as plastic, metal casings, Co, Li, Cu, Al, and Fe [7]. In the hydrometallurgical process, lithium batteries are first dismantled to separate plastic and iron scraps from the active electrode materials by physical separation using crushing, sieving, and magnetic separation. The leaching method involves a model to separate the battery electrodes by dissolving them into an aqueous solution HCl, and H₂SO₄ with and without H₂O₂. The used LiCoO₂ battery of 48.8 Wh capacity and 302 g weight has been used in this study to recover the metals. Mechanical treatment, breaking apart plastic and cells, and some physical separations have been performed by means of gravity and magnetism. Crushed plastics from shells can be separated by flotation. Using magnetism the steel parts of the containers are separated.

$$S_{cm(s)} = (c_{a(f)} - c_{a(i)}) + e \frac{k_m A \Delta t}{V} \quad (3)$$

with $\Delta t = (t_f - t_i)$. where, $S_{cm(s)}$ is the rate of cathode material accumulation in the solution $\text{kg}\cdot\text{mol}/\text{m}^3$.

The 3 M of HCl solution has been prepared by mixing 75 ml of HCl with 300 ml of distilled water based on reported work [8]. The cathode of the battery was cut into small pieces of 2g each and put into acid solution and stirred with a magnetic stirrer for 1 hr. The temperature of the solution was varied to identify the changes in leaching rate. The leaching test was performed at room temperature of 30 °C and by varying the temperature in the range of 60 °C - 80 °C with the inorganic acid solutions of HCl and H₂SO₄ with and without H₂O₂. The effect of H₂O₂ on the percentage of metal obtained from the leaching process was studied. From observation, the presence of H₂O₂ as the reducing agent of H₂SO₄ makes a ‘Piranha’ solution (H₂SO₅) and separates lithium and Co metal.

2.3 Physical Separation

The composition of the LiCoO₂ battery after physical separation is presented in Table 3. The peeled cobalt lithium oxide from aluminum foil is gained by the vacuum pyrolysis process, which is leached with inorganic acids such hydrochloric acid (HCl), and sulfuric acid (H₂SO₄). Hydrochloric acid can leach Co and Li more efficiently and economically. By adding H₂O₂ with H₂SO₄, the Co and Li leaching efficiencies have been increased. The optimal volume percentage of H₂O₂ is in the range of 1-10% and can be used in the leaching process [8, 9]. In this study, 2 vol% of H₂O₂ with 4 M H₂SO₄ were used. After leaching, the leaching solution and insoluble residue were separated by filtration for the precipitation, solvent extraction, and electrolysis processes to recover Co and crystallization test to identify the intensity of Cu, Li, CoSO₄ using the established X-ray diffraction (XRD) method.

Table 3: Battery (48.8 Wh LiCoO₂) materials composition

Components	Amount (%)
Cathode, Anode, and Electrode	46.2
Plastic case	18.63
Steel case	10.56
Copper barrel	7.5
Aluminum foil	1.8
Electrical board and circuit	2.75
Others	12.56

2.4 Precipitation

The chemical precipitation method has been conducted for recovering Co and Li. The precipitation of the leaching processes was collected to recover Li. The ammonium oxalate [(NH₄)₂C₂O₄] 2 M was used with the precipitate for further precipitation of Co. The precipitation was then collected and treated with Na₂CO₃ to recover Li and Co. The Li was recovered about 82% with the Co impurities about 0.90%. The result can be supported by the findings [10-12]. While the Co was extracted to 84%.

2.5 Solvent Extraction

Solvent extractant Cyanex 272 (a dialkyl phosphine acid extractant) was used to

recover cobalt after leaching with H_2SO_4 without H_2O_2 based on the study with H_2O_2 [13,14]. The Co was recovered 81.78% by using of 1.5 M Cyanex 272 with the organics/aqueous ratio and 85.42% by using of 1.5 M Cyanex 272 with the organics/aqueous ratio (O/A) of 1.6. By using 0.5 M of Cyanex 272 with the O/A of 1, the 99% of the rest Co (14.58%) was recovered.

2.6 Electrolysis

The authors [14] have used the electrolysis process for Ni recovery from a leaching solution using H_2SO_4 with an H_2O_2 after-solvent extraction of Co with Cyanex 272. Nickel electrowinning was performed at 250 A/m^2 current density at $50 \text{ }^\circ\text{C}$, pH 3–3.2, with an electrolyte having about 50 g/l Ni and 20 g/l H_3BO_3 , produces a good aspect Ni deposit with a current efficiency of 87% and a specific energy consumption of 2.96 kWh/kg [15]. In this study, we have used the electrolysis process to recover Co from a leaching solution using H_2SO_4 with H_2O_2 after solvent extraction of Co with Cyanex 272. The Co electrowinning extraction was conducted with the current density of 240 A/m^2 at temperature $60 \text{ }^\circ\text{C}$. The pure Co was extracted about 92.01%.

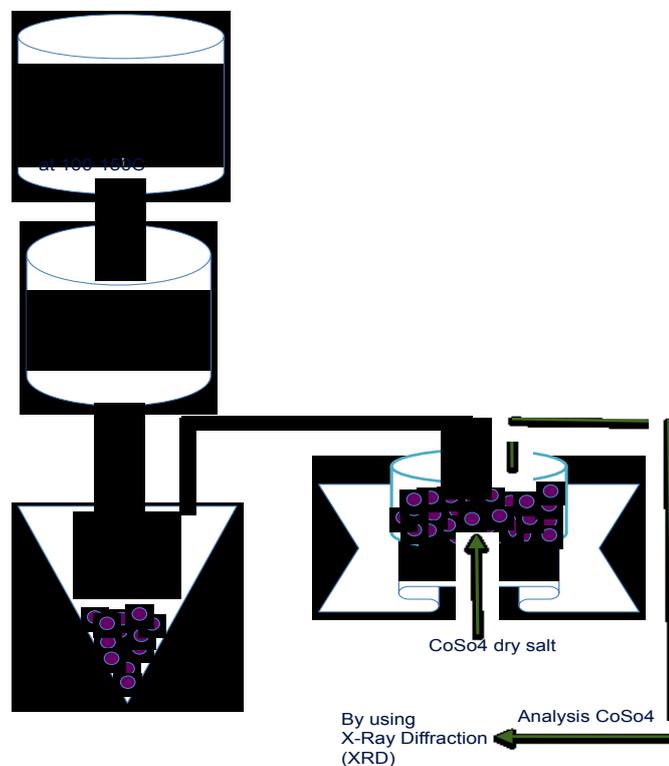


Fig. 2: Procedure of cathode separation.

2.7 Crystallization Test

A crystallization test was conducted to separate the cathode and the intensity of the cathode was identified using an X-ray diffraction test. A crystallization model (Fig. 2) has been developed from this study to analyze the cobalt sulphate (CoSO_4) electrolyte. The pure solution from the acid leaching process has been reheated with temperature in the range of $100\text{--}150 \text{ }^\circ\text{C}$ for 3–4 hours to obtain high pure CoSO_4 . The CoSO_4 was washed with acetone and filtered. The CoSO_4 was left dried and weighed and processed the sample for metal detection and analyzed by X-ray diffraction (XRD). The atomic plane of

CoSO₄ causes an incident beam of X-rays to interfere with one another. The phenomenon is called X-ray diffraction (XRD). It is a rapid analytical technique used for phase identification of a crystalline material.

2.8 Emission Estimation

Transportation is essential for battery collection prior to recycling or disposal in a landfill. When fuel is burned in an engine combustion chamber, most of the carbon is eventually oxidized to CO₂ and emitted to the atmosphere. The emission of CO₂ can be improved drastically if the battery is processed for recycling rather than disposal. The emission of carbon can be estimated using equation [16]:

$$C_{emission} = M_c \square (FC)_{oxidized} \quad (4)$$

$$\text{with } M_c = Q_{fuel} \square sf_{cc(coeff)} \text{ and } Q_{fuel} = V_{fuel} \square Hv_{fuel}$$

where, M_c is the mass of carbon content in fuel in kg, $sf_{cc(coeff)}$ is the coefficient of carbon content in fuel in kg/J, Q_{fuel} is the fuel combustion energy in J, V_{fuel} is the volume of fuel in l, Hv_{fuel} is the heating value of fuel in J/l. Equation (4) can be rewritten:

$$C_{emission} = V_{fuel} \square Hv_{fuel} \square sf_{cc(coeff)} \square (FC)_{oxidized} \quad (5)$$

where, $(FC)_{oxidized}$ is the fraction of carbon oxidized in percentage.

$$CO_{2(emission)} = C_{emission} \square \frac{CO_2(m.w)}{C(m.w)} \quad (6)$$

where, $m.w$ represents molecular weight and $C_{emission}$ is the amount of carbon emission in kg. Equation (6) can be re-written by using Eqs. (5) and (6):

$$CO_{2(emission)} = V_{fuel} \square Hv_{fuel} \square sf_{cc(coeff)} \square (FC)_{oxidized} \square \frac{CO_2(m.w)}{C(m.w)} \quad (7)$$

where, V_{fuel} is the volume of fuel in liters. The amount of fuel (volume) can be estimated directly from the vehicle mobile source.

3. RESULTS AND DISCUSSION

The separation of Co metal by leaching with 4 M of HCl and H₂SO₄ with and without H₂O₂ has been studied for the temperature of 60-80°C and is presented in Table 5. The leaching rate of Co metal extraction has increased 45% for the leaching with HCL and increased 21% for changing temperature from 60 to 70 °C and decreased 6% due to the removal of the impurities from the surface of Co metal. The leaching rate of Co metal extraction has increased 7% for changing temperature from 60 to 70 °C and decreased 2.5% for changing temperature from 70 to 80 °C. Overall, the Co leaching rate was lower than the leaching rate for the acid HCl and H₂SO₄ without H₂O₂. This could be the decomposition of H₂O₂ resulting in the evolution of oxygen onto the Co. The conclusion can be supported by the research work of the authors [18]. Furthermore, the weight of Co extraction by using HCl and H₂SO₄ without H₂O₂ is more than by using H₂SO₄ with H₂O₂. This is due to the formation of Caro acid (H₂SO₅). Caro acid has an acidic property and a higher oxidizing potential, which has the high potentiality to remove impurities and residue from the surface of Co. The conclusion can be supported by the authors' published research work [17-18]. Based on the results exhibited in Table 5, it is concluded that the leaching rate of the Co by HCl is more than the H₂SO₄ without H₂O₂ and H₂SO₄ with

H₂O₂ because of the boiling temperature in the range of 60-80 °C. In this case, the H₂SO₄ with and without H₂O₂ are stronger than the HCl. Fewer impurities remained on the surface of the Co when it was leached by H₂SO₄, with and without H₂O₂.

Table 4: Leaching of the Co for temperature of 30 °C

Acid solution	Concentration (M)	Leaching rate (%)
HCl	1	37.5
	2	47.6
	3	55.7
	4	60.5
H ₂ SO ₄	1	48.6
	2	71.8
	3	85.3
	4	99.0
H ₂ SO ₄ with 2% vol. of H ₂ O ₂	1	40.2
	2	67.8
	3	78.9
	4	83.0

Table 5: Temperature effect on acidic leaching process

Acid Solution	Temp. (°C)	Weight of Co (g)			Leaching Rate (%)
		Initial	Final	Difference	
4 M HCl	60	2.00	1.10	0.90	55.0
	70	2.00	1.43	0.57	71.5
	80	2.00	1.58	0.42	79.0
H ₂ SO ₄	60	2.00	0.98	1.02	49.0
	70	2.00	1.4	0.60	70.0
	80	2.00	1.45	0.55	64.0
H ₂ SO ₄ with 2% vol. of H ₂ O ₂	60	2.00	0.74	1.26	37.0
	70	2.00	0.88	1.12	44.0
	80	2.00	0.83	1.17	41.5

Table 6: Metal extraction

Metal Extracted	Purity of metal extracted (%)				
	Precipitation		Solvent extraction with H ₂ SO ₄		Electrolysis (electro-winning)
	(NH ₄) ₂ C ₂ O ₄	Na ₂ CO ₃	with H ₂ O ₂	without H ₂ O ₂	
Lithium (%)	-	82	-	-	-
Cobalt (%)	84	-	85.42	81.78	92.01

Table 6 shows the lithium and Cobalt extraction from the leached solution by three different processes with the leached solution, which was made with 4 M H₂SO₄ + 2% H₂O₂. The electrowinning process is a promising process of the hydrometallurgy family of techniques. Table 7 shows the composition of the powder of Li-ion battery, which was found from the recycling of a 48.8 Wh battery (weight 302.7 g). The amount of Cobalt (Co) 9.11% (27.85 g) in the battery mass (or 13.8% the total amount of anode, cathode and

electrolyte mass) is greater than the other anode and cathode materials. The amount of total recycled active metals (Co, Li, Cu and Al) is 29.78%.

Table 7: Battery’s metal obtained after recycling

Components	Weight (g)	Amount (wt%)
Plastic	56.27	18.63
Steel (battery pack cover)	12.56	3.98
Lithium	8.58	4.03
Cobalt	27.85	13.08
Aluminum	7.45	2.46
Copper	15.84	5.25
Electrical board and circuit	8.32	2.75
Others (including electrolyte)	55.14	18.25

} *Anode and Cathode extracted 24.82%*

Table 8 shows the metal obtained from recycling for the equivalent of a 1000 Wh battery. The economic value of Co obtained from the 48.8 Wh battery is USD 0.77 while for the 1000 Wh battery it is approximately USD 15.7. The economic values of the recycled LiCoO₂ battery of a 48.8 Wh is USD 0.91 while for the 1000 Wh battery, it is approximately USD 20.29. If an electric vehicle is equipped with a LiCoO₂ battery with a capacity of 33 kWh (standard power pack for an electric car), the recycled value of anode and cathode materials is USD 669.57; where the value of Co is USD 528.00. For 100 EV batteries, each with 33 kWh of electrochemistry LiCoO₂, the recycled values of Co is only USD 52800.00. Fig. 3 shows that the cleavage faces of the anode, cathode, and crystalline electrolyte appear to reflect X-ray beams at certain angles of incidence (theta, θ). Results show the cleavage faces 111, 200, 220, 222, 311, and 511 for the atoms of an anode, cathode, and electrolyte. The shape of the incident beam or counts depends on the focal projection of the filament onto and from the anode material. Cu (atomic number 29) is suitable for most diffraction examinations and is the most widely used anode material. Co (atomic number 27) is often used with ferrous samples, Fe (atomic number 26) fluorescence radiation would cause interference and cannot be eliminated by other measures. Li (atomic number 3) is the lightest metal and the least dense solid element.

Table 8: Economic values of recycled cathode and anode materials

Materials	Materials extracted (g)		International Price (USD/kg)	Values of extracted materials (USD)	
	48.8 Wh	1000 Wh		48.8 Wh	1000 Wh
Lithium	8.58	175.82	9.5	0.082	3.41
Cobalt	27.85	570.65	27.5	0.77	15.7
Aluminum	7.45	152.65	1.58	0.012	0.24
Copper	15.84	324.56	5.3	0.046	0.94
Total price of extracted materials of battery (USD)				0.91	20.29

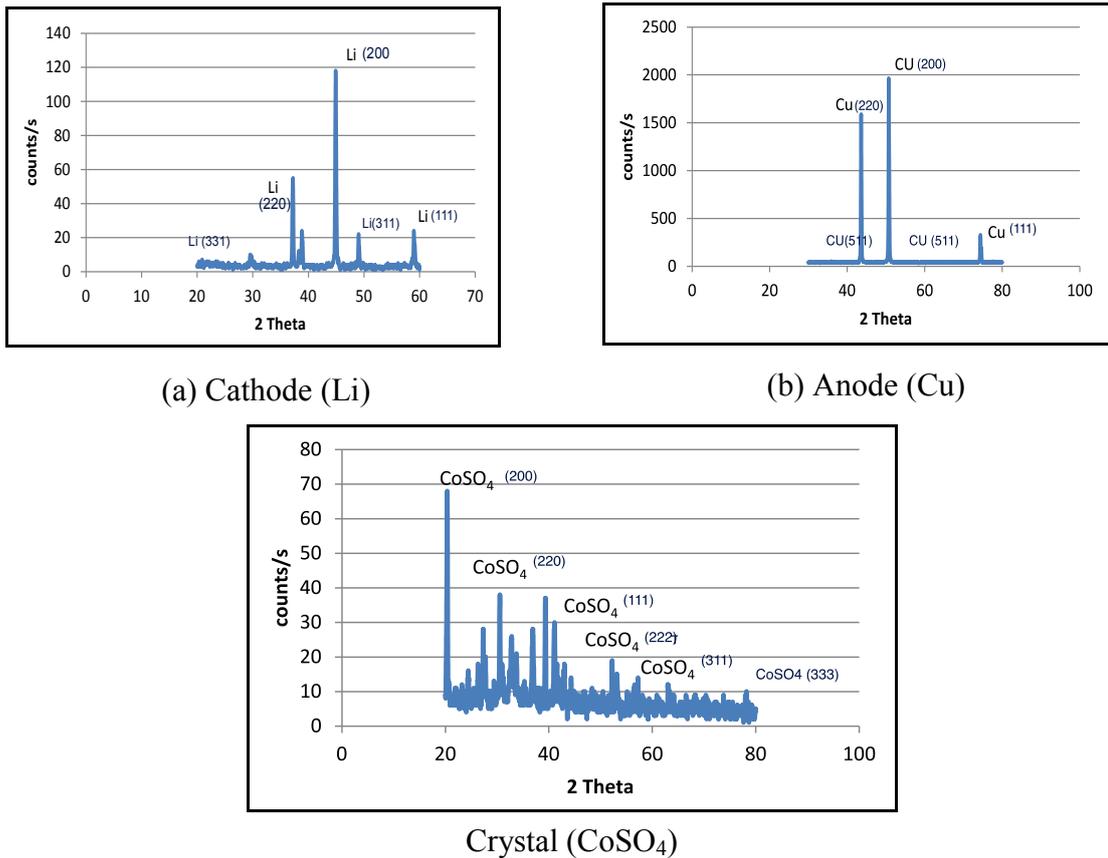


Fig. 3: X-ray analysis for LiCoO₂ battery.

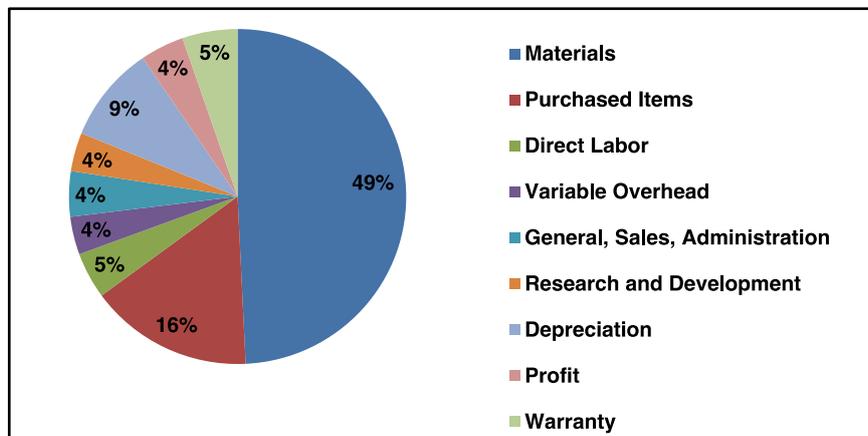


Fig. 4: Overall cost breakdown of battery production [18].

3.1 Economic Benefit of Recycling

Recycling of automotive batteries has economic benefit. Recycling means saving natural resources and energy, generating income, and reducing imports. In addition, the biological activities of Co are largely confined to its role in the vitamin B12 series of coenzymes and the Cu presents in a variety of proteins and enzymes, including cytochrome oxides, an enzyme in respiratory chains [19]. Therefore, battery recycling is a much better option than disposal in landfills. The recycling cost can be limited by the steps involved in the metallurgical process. Stewardship Ontario program pays USD1.24 per kg of batteries for recycling, compensating recyclers USD1,240. The estimated cost to

recycle batteries is about USD2,000 per ton, while the cost for the hydrometallurgical process is about USD1,500 per ton [20].

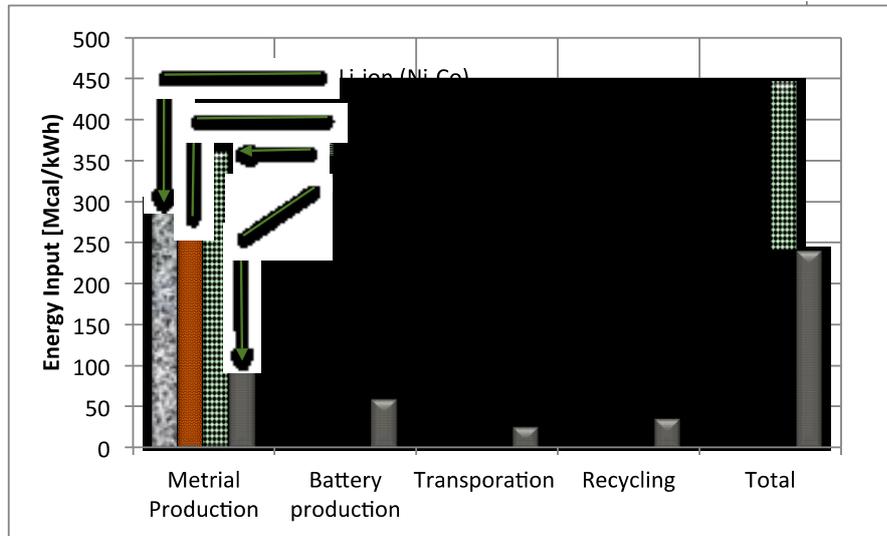


Fig. 5: Reproduce energy for battery production [2].

Table 9: Battery pack for EV and its baseline cost [24].

Battery Parameter	Baseline
Electric vehicle range, km	50
Number of battery pack	1
Number of cells per pack	52
Battery system total energy, kWh	8.7
Cell capacity, Ah	43
Module (2S2P) capacity, Ah	86
Battery system capacity, Ah	86
Battery Nominal voltage, V (OCV at 50% SOC)	100
Cost for baseline battery with total price to OEM: USD 2528	

The recycled metal is USD 20.03/kWh, which will reduce the material cost. Electrode cost is USD 140 per kWh battery. It is calculated that the recycled metal can save 14% of the total cost of active metal per kWh battery. If an EV battery power pack equivalent to 33 kWh is recycled, its production cost can be reduced USD 660 by using the recycled materials.

Figure 4 shows the breakdown of unit costs for baseline battery with total price to OEM of USD 2,528. The total battery cost to the OEM, including pack integration components but excluding thermal management external to the pack USD 2,923 [21-22]. Figure 5 shows that the metal production for the battery is 3 times more than the battery production while it is 300 times more than the recycling process. By recycling, the cathode and anode are obtained by 41% and 8.5% by weight of the cell components respectively, which is USD 20.03/kWh of the battery.

Table 9 shows the capacity of a 8.7 kWh battery for the short travelling range of an electric vehicle (about 50 km), which has been developed and tested [22]. The total cost of

the battery was USD 2528. The battery lifespan was considered as 5 years based on the OEM. The recycled materials value for 8.7 kWh batteries is 14% of the active cost and 8% of the battery OEM baseline price. The battery electrodes values are estimated as $0.49 \times \text{USD } 2528$ or USD 1238 and the recycled material values as $\text{USD } 20.03 \times 8.7$ or USD 174.26.

Table 10: Emission on battery metal production and transportation

Metal Production					
Description		Energy Required		Emission (CO ₂) (g)	
		(MCal/kWh)	Gasoline (Litre)	1 kWh	33 kWh
Metal Production	Wo-RC (need 100% materials)	290	0.042	92.4	3049
	Wi-RC (Reduces 47.43% metals production)	153.7	0.022	48.4	1597.2
Transportation					
		Fuel consumption for each 33 kWh battery pack (litre)		Emission (CO ₂) (g)	
*Transportation (used battery)	Wo-RC	0.26		572	
	Wi-RC	0.05		110	

Note: Wo-RC = without recycling; Wi-RC = with recycling

Assumption

- (i) *Fuel consumption of a pick-up van with 500 kg payload = 0.121 liter/km.
- (ii) Source of energy = Diesel
- (iii) Standard battery capacity for an EV= 33 kWh
- (iv) 33 kWh battery mass = 264 kg
- (v) CO₂ emission = 2.2 kg/liter
- (vi) Distance:
 - EV battery exchanging workshop to landfill = 20 km
 - Battery exchanging workshop to recycling plant = 0 km
 - Recycling plant to landfill = 8 km

It is also estimated that the if the battery capacity of 34 kWh for an EV with a range of 117 km (AEO recommended), the recycled material values of the battery materials (cathodes and anodes) would be USD 681. If the 100,000 EVs each of battery capacity 34 kWh will be under recycled (i.e, 3400,000 kWh battery), the material would save 833.77 g/kWh battery and its values would be USD68102 which is very much profitable for a small scale company. The recycled values of the material of batteries 41 % and 48.8% price of the cathode and anode are 8.5% and 23.4% price of the anode. It shows that by recycling the electrodes of the battery, consisting mainly of cobalt, nickel, and lithium, will save up to 48.8% of new battery manufacturing cost. This indicates that in a lithium-ion battery recycled component values can be higher and would encourage people to set up recycling plants to recycle large-scale batteries. This not only contributes economically but also environmentally.

3.2 Environmental Benefit of Recycling

The battery powered EV is increasing significantly to improve the environment for living planets. Furthermore, batteries in the modern day world have become universal. They make available energy for a wide range of products that are used across all sections of economic activity, from households to large industrial enterprises. They also provide backup power for activities that involve an uninterruptible power supply (UPS). The battery is categorized as hazardous waste at the end of its life as it can damage human health or the environment [23]. Furthermore, mining and processing ores (e.g., SO_x emissions from smelting of sulfide ores, such as those that yield copper, nickel, and cobalt) creates significant negative environmental impacts. These are avoided if the materials can be recycled [24]. If usable materials used batteries can be recovered, excessive battery materials production cost can be avoided, which could be 200% more than the battery production, as shown in Fig. 5. It should be mentioned that the higher input on the material production causes more CO_2 emission than the battery production as the motorized system uses for the material production, which is powered by the IC engine or electrical motor.

Table 10 shows the amount of emission (CO_2) on battery metal production and transportation. Table 6 shows that the valuable anode and cathode metals can be recycled by 24.82% while total metal recycled, including plastic and steel, is 47.43%. The result indicates that the metal production decreases by about 47.43%, which reduces the energy consumption. Fig. 5 shows the energy required for metal production is 290 Mcal per kWh of LiCoO_2 battery. It is considered that the energy required also decreases by 47.43%, which causes the CO_2 reduction by 47.61%. Furthermore, if the battery is disposed of in a landfill some distance away from the recycling center, the emission of CO_2 will be increased, as the CO_2 emission is directly proportional with the engine fuel consumption. The emission of CO_2 is estimated at about 2.2 kg per liter of diesel using Eq. (9). A diesel pick-up van (engine capacity of 2.4 liter) is considered for transportation, which reduces fuel by 1 liter for every 8 km. The van is considered to go to & from the disposal point. It is estimated that the CO_2 reduction from transportation with recycling is 80.7% lower than that of without recycling. Total emission (CO_2) can be controlled by recycling is about 52.85%.

7. CONCLUDING REMARKS

The cobalt and lithium recovery from used lithium batteries is discussed in this work. The hydrometallurgical method is used for the extraction of materials from the waste. Calcination was chosen for thermal pretreatment of Co, Li, and Cu black masses from the used portable lithium batteries. Calcination was conducted at 700 °C for 60 minutes to remove the organic impurities before leaching process. The leaching process has been conducted mainly with different concentrations, mainly of acid H_2SO_4 , with and without an H_2O_2 reducing agent at varying temperature 60 °C - 80 °C.

The electrolysis process can be considered as it could achieve the cobalt compound of very high purity from lithium battery since it does not introduce other substances and avoid impurities. This process has the disadvantage of consuming too much electricity and the safety. The recovery of the cathode (Li, Co and Al) is 41% of cell cathode and anode (Cu) is 8.5% of the cell anode materials, which are 48.8% and 23.4% of the cathode and anode cell material price, respectively. This could be considered as the motivation and encouragement to recycle large-scale used batteries.

Based on the recycled metals, it is found that the emission reduced by 47.61% for metal production of battery and 80.7% for transportation of used battery disposal. In overall, emission for the metal production and transportation can be controlled by 52.85% if the battery active materials will be recycled and used in battery production.

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REFERENCES

- [1] CODEFF Data research on lithium within the REduce Project Partners Countries, (2011). <http://www.reduce.org/en/blog/lithium-extraction-chilean-north>.
- [2] Habashi F. (1997). Principle of Extractive metallurgy. vol. IV: Lithium. Wiley-VCH, Weinheim, 1997.
- [3] William T. (2010) How Much Lithium does a LiIon EV battery really need?- Meridian International Research France- <http://www.meridian-int-res.com/>
- [4] Linda G. (2009). Lithium Ion Battery Recycling Issues, Linda Gaines, Argonne National Laboratory. Retrieved date: 21/5/09.
- [5] Lain MJ. (2001) Recycling of lithium ion cells and batteries. *J Power Sources*, 97-98:736-738.
- [6] Li J, Zha OR, He X. (2009) Preparation of LiCoO₂ cathode materials from spent lithium-ion batteries, *Ionics*, Springer Berlin, 15(1):111-113.
- [7] Rahman A, Rafia A. (2017) Lithium battery recycling management and policy. *International Journal of Energy Technology and Policy*, 13(3):278-291.
- [8] Ferreira DA, Prados LM, Mansur MB. (2009) Hydrometallurgical separation of aluminium, cobalt, copper and lithium from spent Li-ion batteries. *J Power Sources* 187:238-246.
- [9] Alexandre C, Beata P. (2013). A brief review on hydrometallurgical technologies for recycling spent lithium-ion batteries. *J Chem Technol Biotechnol* 88:1191-1199.
- [10] Paulino JF, Busnardo NG, Afonco JC. (2008) Recovery of valuable elements from spent lithium batteries. *Journal of Hazardous Materials*, 150:843-849.
- [11] Nan J, Han D, Zuo X. (2005) Recovery of metal values from spent lithium-ion batteries with chemical deposition and solvent extraction. *Journal of Power Sources*, 152:278-284.
- [12] Xia ZD, Xie XQ, Shi YW, Lei YP, Guo F. (2008) Recycling cobalt from spent lithium ion battery. *Mater. Sci.*, 2(3):281-285.
- [13] Kang J, Senanayake G, Sohn J, Shin SM.(2010) Recovery of cobalt sulfate from spent lithium ion batteries by reductive leaching and solvent extraction with Cyanex 272. *Hydrometallurgy*, 100:168-171.
- [14] Lupi C, Pasquali M. (2003) Electrolytic nickel recovery from lithium-ion batteries. *Minerals Engineering*, 16:537-542.
- [15] Xu J, Thomas HR, Francis RW, Lum K, Wang J, Liang B, (2008) A review of processes and technologies for the recycling of lithium-ion secondary batteries. *J. Power Sources*, 177:512-527.
- [16] Rahman A, Fadhilah R, Rafia A, Mohiuddin AKM, Hawlader MNA. (2015) Power generation from waste of IC engines. *Renewable and sustainable energy reviews*, 51:382-395.
- [17] Adebayo AO, Ipinmoroti KO, Ajayi OO. (2003). Dissolution Kinetics of Chalcopyrite with Hydrogen Peroxide in Sulfuric acid Medium. *Chemical and Biochemical Engineering Quarterly*, 17(3):213-218.
- [18] Ferella FI, Michelis D, Veglio F (2011). Process for the recycling of alkaline and zinc-carbon spent batteries. *Journal of Power Sources*, 183(2):805-811.
- [19] Olubambi PA, Borode JO, Sdlovu S. (2006). Sulfuric acid leaching of zinc and copper from Nigerian Complex Sulfide Ore in the presence of hydrogen peroxide. *The Journal of the Southern African Institute of Mining and Metallurgy*, 106:765-770.
- [20] Raymond C. (2005). *Physical chemistry for the bioscience*, University Science Book, Sausalito California (www.uscibooks.com), Retrieved date: August 2016.
- [21] Rahman A, Farhan S, Ahmed H, Hawlader, MNA, (2014). Development of evaporative battery cooling system for EVs/HEVs. *International Journal of Electric and Hybrid Vehicle System*, Inderscience, 8(2):233-240.

- [22] Rahman A, Helmi A, Hawlader, MNA. (2017) Two-phase evaporative cooling battery thermal management system for electric vehicle. *International Journal of Automotive Technology*, 18 (3):72-882.
- [23] Rahman A, Afroz R, Alam Z. (2014) Development of electric vehicle: public perception and attitude, the Malaysian approach. *World Review of Intermodal Transportation Research*, 5(2):149-167.
- [24] Dunn J, Gaines L, Sullivan MQ. (2012). The impact of recycling on cradle to gate energy consumption and green gas emissions of automobile lithium-ion batteries. *Environ. Sci. Technol.* 46:12704-12710.