

## **Life-Cycle Assessment on Nickel-Metal Hydride Battery in Hybrid Vehicles: Comparison between Regenerated and New Battery**

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### **Abstract**

To reduce air pollution and avoid petroleum exhaustion problem, many advanced countries, especially Japan installed Hybrid Vehicles (HV). As the use of HV popularizes around the world, there will be a huge amount of End-of-Life HV in the near future, and the proper treatment of these End-of-Life HVs, especially the waste NiMH (Nickel-Metal Hydride) batteries, will become a serious problem. Currently, the recycling of NiMH battery is gaining substantial attention. However, instead of recycling waste NiMH batteries directly, regenerating and reusing a used NiMH battery for a secondhand HV will largely reduce waste battery generation and demand for new NiMH battery. However, the environmental impact of regenerating and reusing a waste NiMH battery was not clear and has not been compared with the situation when using a brand-new NiMH battery. The purpose of this research is to compare the environmental performance (CO<sub>2</sub> emission) of regenerated NiMH battery and brand-new NiMH battery in an HV from their production to usage stage and to discuss the validity of using a regenerated NiMH in Japan and in other countries using the Life-Cycle Assessment (LCA) approach. This research analyzed the composition of a NiMH battery and the CO<sub>2</sub> emission during the manufacture, transportation, regeneration and usage process of a NiMH battery. The data used in this research was collected from reports and data published by the government of Japan, vehicle makers and previous studies. Original field survey and interview research on battery regeneration operators were also performed. The result showed that there is not a big difference in

environmental effect. Moreover, by doing so, a huge amount of resource will be saved from battery manufacturing process while reducing waste generation. It is recommended that waste NiMH battery should be regenerated and reused in HV instead of being recycled directly in the future.

**Keywords:** Nickel-Metal Hydride Battery, Hybrid Vehicle, Reuse and Recycling, Life Cycle Assessment, Efficient use of Resources

## **1 Introduction**

To solve petroleum exhaustion and air pollution problem, Hybrid Vehicles (HV), which refers to vehicles consisting of both engine and driving battery, are gaining popularity in many advanced countries. Concretely, the sale of HV around the world increased by about four times in a 5-year period (2017 data). Japan occupies about 70% of global HV sale, which makes it the biggest HV market in the world. On the other hand, the Nickel-Metal Hydride (NiMH) batteries in HV will emerge as used batteries soon. Therefore, the proper treatment of these NiMH batteries is getting much attention. In fact, there will be around 20,000 used NiMH batteries in Japan waiting to be recycled properly (Ministry of Economy, Trade and Industry of Japan 2015). Ortego et al. (2018) evaluated the value of nickel, cobalt, and lithium in the vehicle and the significance to recycle these materials from the point of view of Thermodynamic. Ebin et al. (2018) focused on AA- and AAA-type of NiMH battery and pointed the need to ameliorate waste battery pretreatment before the recycling process. HV battery recycling technology to improve the recycling rate for nickel, cobalt and related rare earth has also been discussed (Hu et al. 2013; Korkmaz et al. 2018). Recycling method which could improve the rare earth elements' recycling rate while reducing environmental burden has been brought up (Yao et al. 2018). However, these articles are mainly discussing recycling technologies instead of battery reuse technologies. On the other hand, the environmental effect and the possibility to replace the lead-acid battery with regenerated LIB battery from electric vehicles in a stationary energy storage system have been analyzed (Richa et al. 2017). According to the result, by extending the life of LIB battery, the environmental burden generated during battery manufacture process can be shared with the stationary energy storage system. However, only LIB was studied and the environment effect of regenerating and reusing the waste battery into a vehicle again has not been considered. Actually, if waste NiMH battery can be regenerated and reused in HV, the amount of waste NiMH battery will be largely reduced, and the demand for repairing batteries will also be satisfied. However, the environmental impact of doing so is still unclear.

In this research, the environmental impact of making and using a newly-repaired NiMH and a regenerated repaired battery will be compared using Life-Cycle Assessment (LCA) measure. The impact of resource-saving as well as waste reduction effect will also be analyzed. Based on the result, the proper reuse and recycling policy for waste NiMH batteries in the future will be proposed. In this research, “repaired battery” refers to batteries which will be used in an HV when the original battery is broken. The repaired battery could be a secondhand battery. In the next section, basic information (such as the material and weight, etc.) about NiMH in HV will be introduced.

## **2 Basic Information of NiMH**

There are mainly two kinds of NiMH battery for HV, the circle shape and square shape NiMH battery. The most common type is square-shaped NiMH battery nowadays. Therefore, the research object in this thesis will be a square-shaped NiMH battery used in the Prius (3rd generation). The weight of a NiMH battery is around 39.07kg and consists a battery case and 28 battery modules. Each module weighs 1.04kg. The voltage is 201.6V and the capacity is 6.5Ah, the power capacity is estimated to be 1,310Wh.

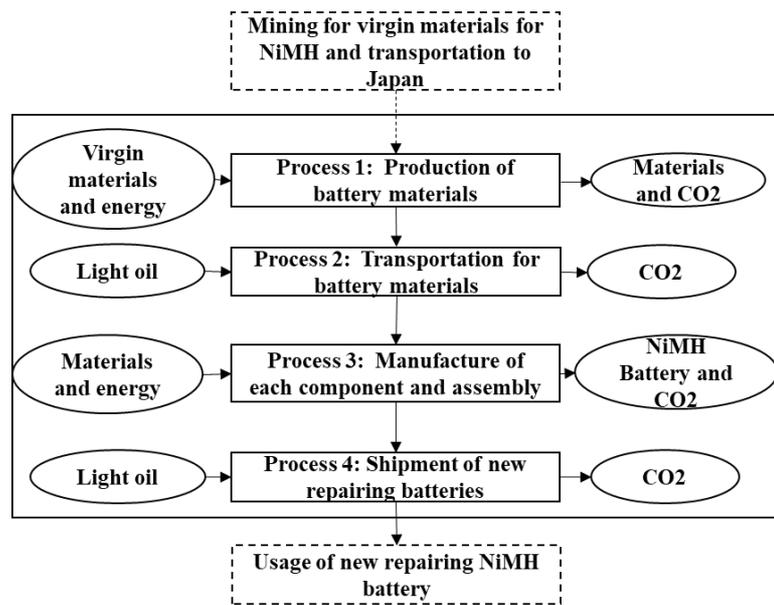
When comparing the environmental impact of multiple products using LCA method, research objects should be unified into the same functional unit. Therefore, in this research, the function of a NiMH battery is defined as “to assist vehicles’ engine and improve vehicles’ fuel consumption” and the functional unit is “one repaired battery in HV”. The life span of a NiMH battery is estimated to be five years which is the same as the battery warranty period.

## **3. LCA Scope for NiMH Battery**

LCA scope covers the environmental impact of each process from production to shipment and associated with CO<sub>2</sub> emission. The method for unification is by multiplying the resources and energy used during each process by their CO<sub>2</sub> emission intensities. The recycling method for repairing battery (both new and regenerated one) is considered to be the same so the CO<sub>2</sub> emission should have no diversity, hence, the final recycling process is not included in this research. Therefore, only the process in full line is in the research scope and the process in short dashes line is not analyzed. Moreover, the environmental impact during the usage process will be mentioned afterwards.

### **3. 1 LCA Scope for New NiMH Battery**

As shown in Fig.1, the research scope for the newly repaired battery includes the manufacture of raw material for battery, the shipment of raw material, the production and assembly of each component and the batteries’ shipment process.



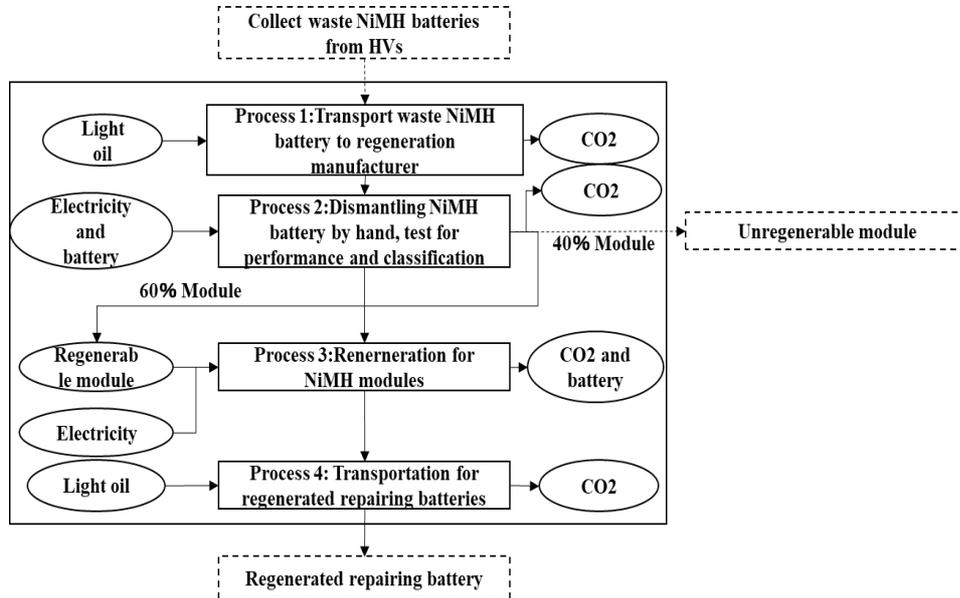
*Fig. 1: Research Scope of new repairing NiMH batteries for HV  
Figure 1 was created by the author*

To make a new repairing NiMH battery, necessary materials should be refined first. In this research, all the waste NiMH batteries were considered to be recycled and stored within Japan and, therefore, overseas mining and transportation are not considered. These materials are transported to a battery manufacturing plant and disassembled into battery components. After that, each component will be assembled into new repairing NiMH batteries and shipped out.

### **3. 2 LCA Scope for Regenerated NiMH Battery**

The scope for the regenerated repairing NiMH batteries includes collection, performance test, regeneration and shipment process. After waste NiMH batteries were collected from dismantlers and transported to a regeneration plant, battery regeneration manufacturer will dismantle the NiMH battery to module-level by hand. After that, each module's capacity will be tested and classified into regenerable and unregenerable modules. Regenerable modules will be regenerated by repeating charge-discharged circulation. According to the regeneration manufacturer, regenerated NiMH will share 80%~85% of a new NiMH batteries' capacity. Based on the interview result from the battery regeneration operator, the capacity for regenerated NiMH is set to be 80%. Regenerated batteries will be transported to each dealer, while unregenerable modules will be sent to the recycling plant and are out of the research scope (Fig.2).

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*Fig. 2: Research scope of regenerated repairing NiMH batteries for HV  
Figure 2 was created by the author*

## 4 Inventory Assessment of NiMH Battery

In inventory assessment, resources and energy consumption during NiMH battery (both new and regenerated) production to shipment processes should be grasped first. And these consumptions will be multiplied by their CO<sub>2</sub> emission intensities, the result will be rounded off to integral number.

### 4.1 Inventory Assessment of regenerated batteries

For regenerated batteries, the data for all process is gathered from interview research on a battery regeneration company in Japan. According to battery regeneration traders, used NiMH batteries are mainly collected through dual routes: recycling subcontractors (86%, 50 per month) and their own company (14%, 8 per month). When these batteries were collected from recycling subcontractors, they were estimated to be collected from Kyushu district (1,138km, 10 NiMH batteries) and Kansai district (550km, 40 NiMH batteries). The transportation of recycled battery is done through a courier and is considered to be one-way transportation. On the other hand, when the batteries were collected from their own company, it is dismantled from End-of-Life HV, but the amount is comparatively small (14%). Therefore, only the CO<sub>2</sub> emission during battery transportation from recycling subcontractors is calculated. CO<sub>2</sub> emission during transportation is calculated by the ton-kilometer method

as written in Eq. (1) (Ministry of Land, Infrastructure, Transport and Tourism of Japan 2016a), where  $E_{CO_2}$  means CO<sub>2</sub> emission,  $D_{t-k}$  is ton-kilo of transportation,  $I_f$  is transport vehicles fuel efficacy,  $Cal.$  is calorific value of the fuel and  $I_{CO_2}$  is CO<sub>2</sub> emission intensity of the fuel.

$$E_{CO_2} = D_{t-k} * I_f * 1/1000 * Cal. * I_{CO_2} * 44/12 \quad (1)$$

The assumption that when the batteries are transported from Kyushu district, they were transported by a 4-ton truck, and the load factor is around 58%. When the batteries were collected from Kansai district, they were transported by a 2-ton truck, and the load factor is about 80%. Thus, the CO<sub>2</sub> emission for batteries from Kyushu is 150kg in total, and 15kg for each (10 batteries at one time) and is 350kg for batteries from Kansai and 8.8kg for each (40 batteries at one time). That is to say, to collect one used battery from recycling subcontractors, 10kg CO<sub>2</sub> will be discharged on the average.

However, as battery regeneration manufacturers claim, only 60% of the module in one used NiMH batteries can be regenerated on the average. Consequently, 1.7 wasted batteries will be needed to make a regenerated battery. Based on this assumption, to transport one regenerable battery to the plant will cause about 17kg CO<sub>2</sub> emission.

As to exam used battery function, recycled batteries will be dismantled into modules first, and the remaining capacity of each module will be evaluated. After that, these modules will be classified as “regenerable” and “non-regenerable” module, based on the difference of capacity of each battery module and the discharge time. On average, it will cost 2kWh electricity to examine one module as battery regeneration operators claimed. As mentioned before, since it will cost 1.7 used battery to make a regenerated battery, 3.4kWh electricity will be used during this process. CO<sub>2</sub> emission in this process is calculated by Eq. (2) (Federation of Electric Power Companies of Japan 2017), where  $E_{CO_2}$  means CO<sub>2</sub> emission,  $E_b$  stands for the energy consumption for regenerate one battery, and  $I_e$  means the intensity for energy generation, which is 0.531kg-CO<sub>2</sub>/kWh in Japan.

$$E_{CO_2} = E_b * I_e \quad (2)$$

The result shows that the dismantlement, examination and classification process will discharge about 2kg CO<sub>2</sub>. As for NiMH battery regeneration process, to regenerate one NiMH battery, it will cost 10kWh electricity, and no other components such as BMS (Battery Management System) or cooper connector are needed. Therefore, the CO<sub>2</sub> emission is mainly from electricity consumption (calculated by Eq. 2, and the result is 5kg- CO<sub>2</sub>/battery). Also, regenerated batteries' capacity is assumed to be 80% compared to a new NiMH battery. After waste batteries are

regenerated, they will be shipped to dealers around the world. On the average, 30 regenerated batteries will be shipped by couriers. However, a specific destination is not clear. In this research, the distance between shipping destination and regeneration plant is assumed to be around 200km and is transported by a 2-ton truck with 60% load rate (Ministry of Land, Infrastructure, Transport and Tourism of Japan 2016a). The CO<sub>2</sub> emission in this process is calculated by Eq. 1 and is 4kg for each regenerated battery.

Based on previous inventory analysis, to make one regenerated NiMH, about 28kg CO<sub>2</sub> will be produced. When looking at each process, process 1 occupies the most emission (61%), process 2 occupies the least (7%) of the overall emission.

## 4.2 Inventory Assessment of New NiMH Batteries

As mentioned before, NiMH battery consists of battery modules and battery case. Battery modules include the positive electrode, separator, negative electrode, electrolyte and battery jar (Oshitani 2008; Nittetsu 2017). The positive electrode is mainly made of nickel hydroxide while the negative electrode is made of AB<sub>5</sub> type hydrogen-absorbing alloy (Ikoma and Fukuda 1997). The separator is made of PP, the electrolyte is made of calcium hydroxide, and the battery jar is made of steel. Since detailed materials and constitution of NiMH are not published by vehicle or battery makers, these data are mainly collected from previous studies and were calculated by weight ratio. The constitution and weight of each material is listed in table 1, data No.1 and No.4 tend to observe less nickel hydroxide in the NiMH. The reason could be that the nickel hydroxide is calculated as metal in these studies. Data No.5 calculated the positive and negative electrode separately, and the overall ratio surpassed 100% already. Also, when comparing data No.3 and No.2, the latter is more detailed. Therefore, the constitution and material of HVs' new NiMH are evaluated based on the data from the Japanese Ministry of Economy, Trade and Industry. On the other hand, the material and weight of battery case are based on the result of interview research on battery regeneration manufacturing. The material and weight of battery modules and case are listed below.

*Table 1: Information of material for NiMH in previous research.*

Material and constitution of NiMH battery in percent																		
	Hydrogen absorbing alloy	Ni(OH) <sub>2</sub>	Ni	Porous nickel	Co(OH) <sub>2</sub>	Fe	ZnO	Cu	Aluminium alloy	KOH	PTFE	PP	ABS	Others	Total	Object	Publish year	Researcher
NO.1	5		29.2		1.7	43.5	-	-	-	9	1	5	-	5.6	100	-	2006	Kaziyama et al.
NO.2	31.7	20	2.2	4.9	2.2	8.8	1.1	0.8	3.7	13.2	1	9.9	0.4	0.1	100	-	2008	Ministry of Economy, Trade and Industry of Japan
NO.3	31.7	23.3	1.6	4.9	-	9.9	-	-	3.7	13.2	1	2.1	8.1	0.5	100	Modules	2008	Sakai
NO.4	7		23		4	36	-	-	-	9	1	18	2		100	-	2010	Nickel Institute
NO.5	28		23			21	-	-	-	13	-	3	13	-	101	Modules	2013	Larsson et al.

*(Kaziyama et al. 2006; Ministry of Economy, Trade and Industry of Japan 2008; Sakai 2008, Nickel Institute 2010; Larsson et al. 2013)*

*Table 2: Material and weight for NiMH battery (Module and Case)*

Modules	Material	Weight (kg)
Alloy for negative electrode	Hydrogen absorbing alloy	9.23
Active material for positive electrode	Ni(OH) <sub>2</sub>	5.81
Active material for positive electrode	Co(OH) <sub>2</sub>	0.64
Active material for positive electrode	ZnO	0.33
collector for negative electrode	Plate Fe-Ni	1.55
Plate for negative electrode	Plate nickel(0.15mm)	0.25
collector for positive electrode	Porous nickel	1.44
Plate for positive electrode	Plate nickel (0.15mm)	0.24
binding materia for negative electrode	Coating PTFE	0.28
Pole	Plate Fe-Ni	0.92
Battery erector	Plate Cu-Ni	0.23
Bolt	Plate Fe-Ni	0.23
Electrolyte	KOH	3.84
Safety valve (PP)	PP	2.31
Separator(PP)	PP	0.57
Battery module cover (ABS)	ABS	0.11
Back-up plate	Iron	0.06
Reinforcing materials	Aluminium alloy	1.08
Sum		29.12
Attachment: Battery case	Material	Weight (kg)
Case and bar to keep modules	Iron and plastic	1.6
Top cover of battery case	Iron	1.75
Side cover of battery case	Iron	0.65
Bottom of battery case	Iron and harness	4.5
Fan	Plastic	0.7
Others (Plastic and cable)	Plastic and cooper	0.75
Sum		9.95

*Table 2 was created by the author*

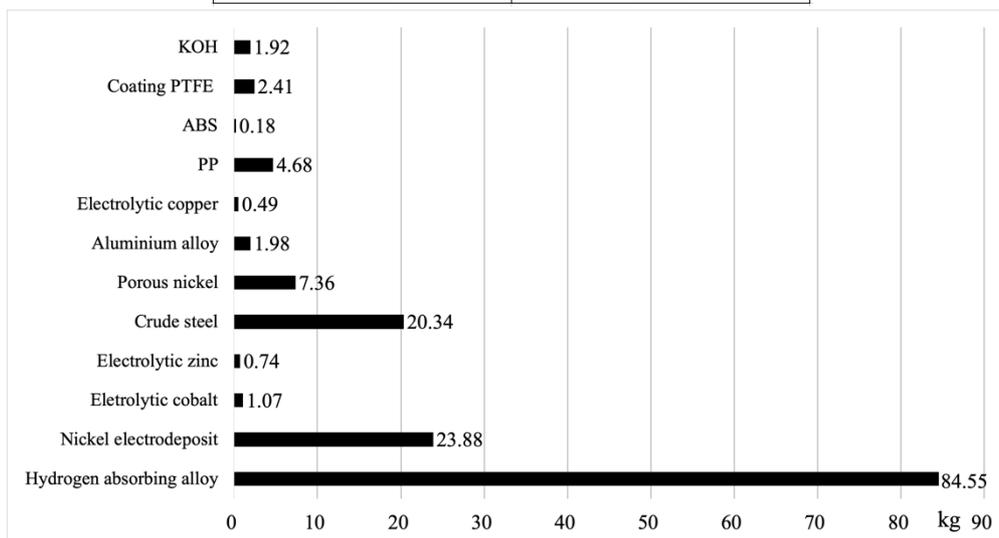
As shown in table 2, 76% of NiMH module (22.01kg) is made from the metal resource. Specifically, hydrogen-absorbing alloy and nickel hydroxide occupied 52% of the NiMH module. Plastic is 11%, while electrolyte is about 13%. On the other hand, the material for battery case is mainly iron, despite some small quantity of other materials. Since more detailed information is unavailable, material “iron and plastic” and “iron harness” are all calculated as iron, and “plastic and cooper” is classified as plastic. Also, all the types of plastic are considered as PP.

Part of the CO<sub>2</sub> emission intensity for the material is not published yet, therefore, these materials are replaced by other materials. And the CO<sub>2</sub> emission intensity is collected from previous studies, refining plants and, Life Cycle Assessment Society of Japan (JLCA). Replaced materials are shown in table 3, and CO<sub>2</sub> emission for producing each material is shown in Fig. 3.

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*Table 3: Material replacement for NiMH battery*

Material	Replaced Material
Hydrogen absorbing alloy	Hydrogen absorbing alloy
Ni(OH) <sub>2</sub>	Nickle
Co(OH) <sub>2</sub>	Electrolytic cobalt
ZnO	Electrolytic zinc
Plate Fe-Ni	Crude steel
Plate nicke	Nickle
Porous nickel	Porous nickel
Aluminium alloy	Aluminium alloy
Plate Cu-Ni	Electrolytic copper
Iron	Crude steel
Iron and plastic	Crude steel
Iron and harness	Crude steel
Plastic and cooper	PP
PP	PP
ABS	ABS
Coating PTFE	Coating PTFE
KOH	KOH



*Table 3 was created by the author*

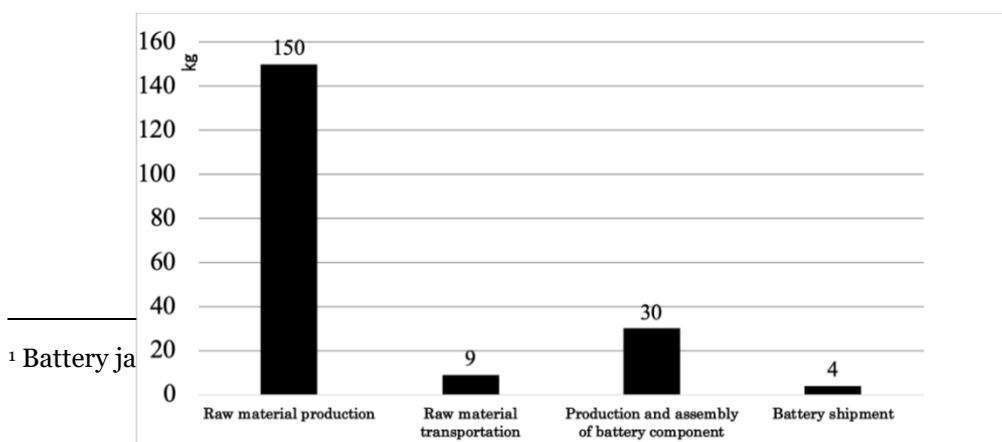
*Fig 3: CO<sub>2</sub> emission during raw material production process (LCI data for nickel electrodeposit referenced from Onishi and Miyazawa 2014; LCI data for electrolytic cobalt referenced from Japanese Ministry of the Environment 2001; LCI data for electrolytic zinc referenced from Mitsui Mining & Smelting 2012; LCI data for crude steel referenced from Japan Iron and Steel Federation 2013; LCI data for electrolytic copper referenced from Narita et al. 2001; LCI data for aluminum alloy, PP and ABS referenced from Life Cycle Assessment Society of Japan; LCI data for hydrogen absorbing alloy, porous nickel, coating PTFE and KOH referenced from Sakai 2008)*

The result shows that during the material production process, about 150kg CO<sub>2</sub> are being discharged. Among all the materials, production

of nickel hydroxide comes with most CO<sub>2</sub> emission (52%), and production of nickel electrodeposit is the second (16%), which means CO<sub>2</sub> emission reduction during nickel hydroxide production process is important. This goal may be achieved by using alternative material.

In NiMH battery manufacturing process, battery materials are divided into cathode material, anode material, electrolyte, and battery cover (Sakai 2008)<sup>1</sup>. CO<sub>2</sub> emission for transporting these materials from material plants to battery manufacture plant (Primeearth EV Energy, Omori Plant) are calculated. Cathode material is made by SUMITOMO Metal Mining (516km, 22% of overall weight), anode material is made by CHUO DENKI KOGYO (385km, 29% of overall weight), electrolyte is made by AGC HUB (354km, 11% of overall weight) (Ministry of Finance 2016) and battery cover is made by Pacific Industrial (715km, 38% of overall weight). Battery manufacture plant will receive 10 tons of material for one time. After the reception, trucks will return to their separate plant. CO<sub>2</sub> emission during raw material transportation is calculated by their weight ratio and Eq. (1) mentioned before.

As Fig.4 shows, to transport 10 tons of battery raw material, 2,377 tons of CO<sub>2</sub> will be discharged. Since 10 tons of raw material can make 256 batteries, CO<sub>2</sub> emission during raw material transportation process for one battery is 9kg. The delivered raw material will be made into batteries' components first, and then, components will be assembled into modules, and finally NiMH batteries. In this research, the assemble and production process is considered to be the same (Rantik 1999: 17). This process is considered to cause about 30kg CO<sub>2</sub> emission. Most new NiMH batteries are used in new HVs rather than a secondhand HV, which means that new repairing NiMH batteries made for secondhand vehicles are little. Therefore, the shipment process of new repairing batteries is considered to be the same as normal new batteries, and the shipment for one new repairing battery will cause about 4kg of CO<sub>2</sub> emission. Therefore, CO<sub>2</sub> emission from battery production to shipment is around 193kg, this number is almost the same with the assumption made by the previous study (Wu, 2017), and the raw material production process occupies about 78% of that emission.



<sup>1</sup> Battery ja

*Fig 4: CO<sub>2</sub> emission during new repairing battery production process to shipment process*

*Figure 4 was created by the author*

## **5 Life-Cycle Inventory Assessment: Results**

For the result of inventory assessment for a new NiMH battery, the production to shipment process will discharge 193kg of CO<sub>2</sub> and only 28kg for a regenerated NiMH battery. That is to say, by using regenerated repairing batteries, about 165kg CO<sub>2</sub> emission can be saved (Fig. 5). Since the transportation process occupies 75% CO<sub>2</sub> emission for a regenerated NiMH battery, CO<sub>2</sub> reduction by using a low-emission vehicle or improving recycling rate is expected. In comparison, for a new repairing battery, since most CO<sub>2</sub> (78%) is discharged from raw material production process, usage of recycled material or materials with lower CO<sub>2</sub> intensity are recommended.

Next, the environmental impact of a new and a regenerated NiMH battery will be compared with resource efficiency concept written in Eq. (3) (Matsuto et al. 2007). In Eq. (3),  $E_r$  means resource efficiency, and  $V$  is the value of one product, which is calculated by multiplying the batteries' performance against the lifespan in this research.  $I_r$  stands for the resource input and refers to CO<sub>2</sub> emission reduction effect during all process.

$$E_r = V / I_r \quad (3)$$

In Eq. (3), the result is called "Factor X", as the factor X becomes larger, the product will be considered to be more environmentally friendly. Generally, in advanced countries, this number is expected to be larger than four in the present time and over 10 in the middle of the 21st century.

As the basic scenario for this research, the performance of the regenerated repairing battery equals to 80% of new repairing battery, and the lifespan is the same. Resource inputs for regenerated repairing battery are only 15% compared to new repairing battery. Consequently, the resource efficiency for regenerated repairing battery is  $0.8 \times 1 / 0.15 = 5.3$  and is larger than four (4). On the other hand, to promote new repairing batteries' resource efficiency to the recommended level (factor X over 4), overall CO<sub>2</sub> emission should be under 140kg.

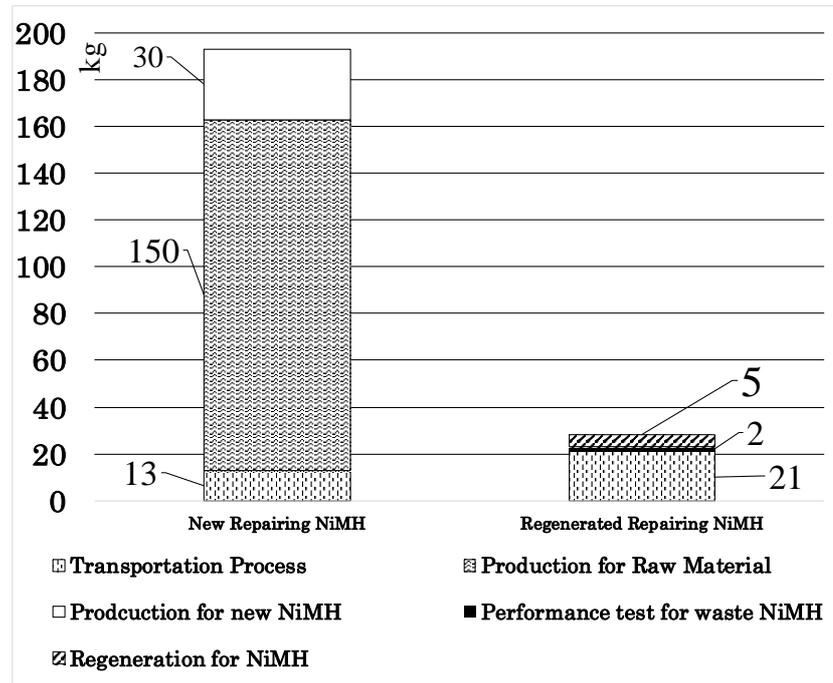


Fig 5: CO<sub>2</sub> emission in each process  
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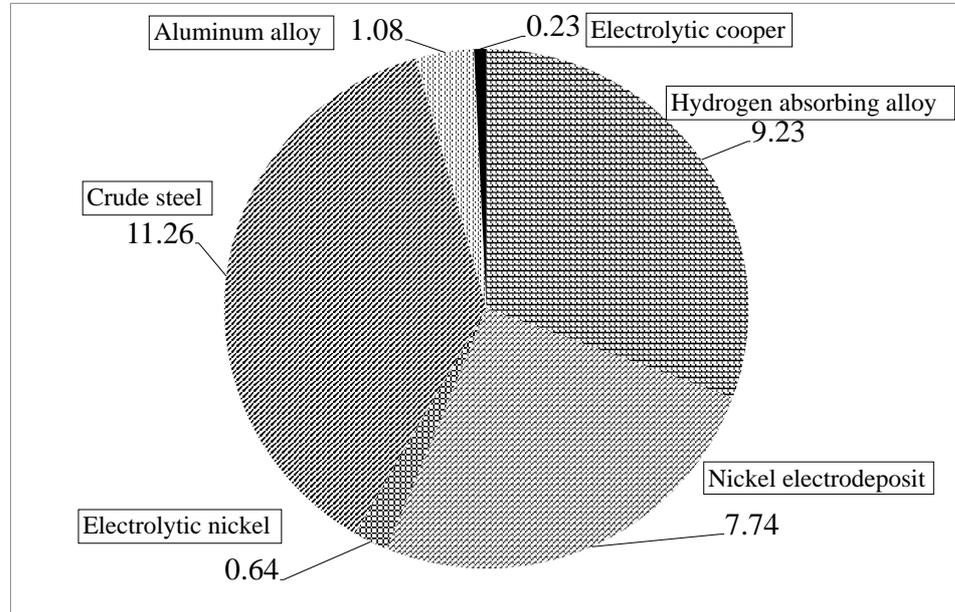
## 6 The Reuse of NiMH Battery and Resource Savings

In this section, resource savings and waste reduction effect of regenerating a waste NiMH battery will be analyzed. First, as for resource savings, metal resources (including hydrogen-absorbing alloy, nickel electrodeposit, electrolytic cobalt, crude steel, aluminum alloy and electrolytic copper) which have been largely used in NiMH will be the main research object<sup>2</sup>.

As Fig. 6 shows, by making a repairing battery out of 1.7 waste battery rather than raw materials, 30kg metal resources will be saved. Among all these metals, nickel is about 7.7kg, cobalt is 0.6kg, these metals can satisfy 55% nickel and cobalt demand for one HV (Yano et al. 2016). On the other hand, as for the waste reduction effect of regenerate one NiMH battery, when assuming reuse rate for battery case is the same to NiMH battery modules (60%)<sup>3</sup>, 23kg waste will be reduced.

<sup>2</sup> PP, ABS and PTFE are all classified as “Plastic”

<sup>3</sup> on average, to manufacture one regenerated NiMH, 1.7 waste NiMH will be used. Therefore, the reuse rate for battery case is 1/1.7 and is around 60%



*Fig 6: Metal resource consumption during new NiMH battery production  
Figure 6 was created by the author*

## **7 Comparison in the Usage of HV: Focusing on CO<sub>2</sub> Emission**

In this research, repairing NiMH battery is assumed to be used in a 5-year old HVs, which is also the warranty time offered by the vehicle maker. In this section, ordinary gasoline vehicle<sup>4</sup>, HV without a repairing battery, HV with a regenerated repairing battery<sup>5</sup> and HV with a new repairing battery will be compared based on their CO<sub>2</sub> emission from years 6-10. Based on JC-08 mode (Japan Automobile Federation 2013)<sup>6</sup>, fuel consumption for a HV is around 32.6km/L (E-fuel) and 16.4km/L for an ordinary gasoline vehicle according to Toyota. This means that by using NiMH battery with 100% capacity, vehicles' performance will be upgraded for 0.99 times. On the other hand, time-related deterioration for NiMH battery and engine is needed to be known.

In fact, NiMH batteries' capacity will degrade for 50% after being charged for 1800 times (Ikeya et al. 2002), and vehicle use frequency in Japan is five days per week in 2015 (Japan Automobile Manufacturers

<sup>4</sup> Axio of TOYOTA, 2WD, 1.8L, and the weight is assumed to be around 1,230kg to 1,505kg

<sup>5</sup> 3rd generation of Prius, 2WD, 1.8L with the motor, the weight is assumed to be 1,310kg

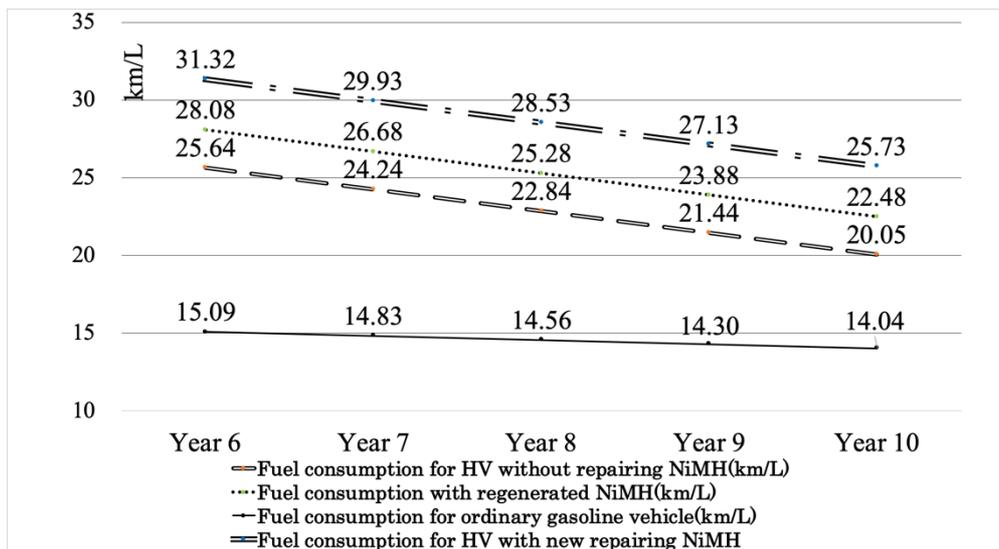
<sup>6</sup> JC-08 mode means the vehicle emission will be tested when the vehicle engine is started in low temperature and will consider speed variation

Association 2016), and 260 days per year. If each time the vehicle was being used, the NiMH battery will be fully charged for one time, it will cost 7 years before the battery capacity degrades to 50% (degradation rate of 7% per year). As for the degradation rate for the engine, it is 1.6% per year (WU 2015).

According to these results, when vehicles' weight is all the same, fuel consumption for vehicles without a repairing battery will be 25.6km/L from the 6th year and is 28.8km/L for vehicles with a regenerated repairing battery, 15.09km/L for an ordinary gasoline vehicle. CO<sub>2</sub> emission during vehicles' running process was calculated when assuming the annual running distance is 8,085km (Ministry of Land, Infrastructure, Transport and Tourism 2016b; Automobile Inspection & Registration Information Association 2017). CO<sub>2</sub> emission during vehicles' running stage is calculated by Eq. (4) (Ministry of the Environment Government of Japan 2012). In Eq. (4),  $E_{CO_2}$  is CO<sub>2</sub> emission (kg),  $C_g$  is gasoline consumption (L),  $I_{CO_2}$  means the CO<sub>2</sub> emission intensity during fuel combustion in Japan and is around 2.32kg-CO<sub>2</sub>/L.

$$E_{CO_2} = C_g * I_{CO_2} \quad (4)$$

Moreover, when the voltage for NiMH battery is extremely low, the engine will burn some fuel to charge the battery. However, since it is hard to know the frequency or the fuel consumption during this process, NiMH battery is assumed to be charged only by recovered energy from braking process. Transition of fuel consumption of each kind of vehicle from year 6-10 is also shown in Fig7.



*Fig 7: Fuel consumption for vehicles and its transition  
Figure 7 was created by the author*

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As for CO<sub>2</sub> emission during the vehicles' running process as shown in Fig. 8, in five years, ordinary gasoline vehicle will produce 6,444kg CO<sub>2</sub> during the running process and is about 2,114kg~2,754kg more than HVs, even when considering the CO<sub>2</sub> emission during the battery manufacturing process. On the other hand, HV without a repairing battery will produce 4,330kg CO<sub>2</sub>, HV with a regenerated repairing battery is 376kg less than this (3,954kg CO<sub>2</sub>). This means that even if the NiMH battery is a regenerated one, vehicle emission during the running process can still be reduced. Also, CO<sub>2</sub> emission for HV with a regenerated repairing battery is only 264kg larger than HV with a new repairing battery. This result is enlightening for not only advanced countries but also developing countries such as Mongolia. It is because Mongolia is importing plenty of secondhand vehicles from Japan and most of these secondhand vehicles have been used for over 15 years. Under this scenario, the NiMH battery in these vehicles may be unfunctional already. This means that unless old NiMH battery in exported vehicles is replaced, these vehicles should not be considered as an "eco-friendly HV". For these countries, replacing unfunctional NiMH battery with a regenerated one could be an environmental countermeasure.

Japan owns NiMH battery regeneration technology but it failed to collect waste NiMH battery. One of the reasons is most NiMH batteries have been exported abroad along with old HV. Consequently, waste NiMH battery will emerge massively in secondhand HV exportation destination. However, since these countries have no reuse/recycling technology, waste NiMH battery will be thrown away and treated inappropriately. It is recommended that Japan, who owns most HV, should put more effort into collecting, reusing and recycling waste NiMH battery on an international scale.

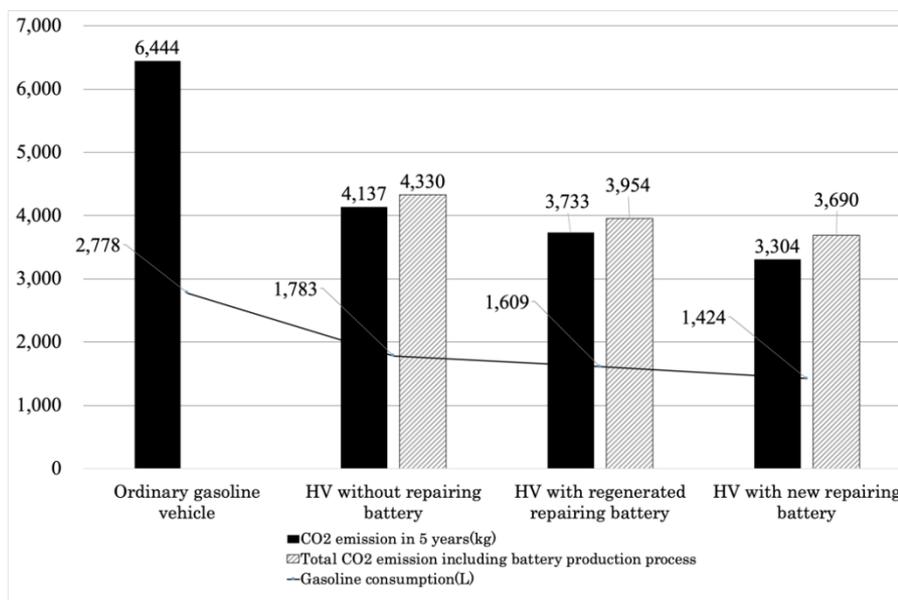


Fig 8: Vehicle Fuel Consumption and CO<sub>2</sub> emission  
Figure 8 was created by the author

## 8 Sensitivity Analysis of Recycling Rate on Resources Saving and Waste Occurrence

In this section, Japanese end-of-life HV and NiMH battery recycling rate, as well as secondhand HV exportation situation in 2013, which have been published and with high dependability will be used for sensitivity analysis.

About 12,500 HV were sold in Japan in 2000 (TOYOTA 2017) and since the lifespan of a vehicle in Japan is around 13 years (Automobile Inspection & Registration Information Association 2016), in 2013, there should be around 12,500 end-of-life HVs. However, there are only 6,000 end-of-life HV being dismantled in 2013 (Yano research institute 2015) which was half of the predicted number. The other half could be exported as secondhand vehicles. Moreover, only 3,000 waste NiMH batteries are collected in Japan at the same time (Japan Automobile Manufacturers Association 2018), which means that collection rate for used NiMH from domestic end-of-life HV in Japan is around 50%. Uncollected NiMH batteries could be exported as secondhand parts. Moreover, in 2013, about 33,000 secondhand HV were exported (Yano research institute 2015). That is to say, nearly 19% (0.65/3.3) of exported HVs may be end-of-life HV.

In this section, two scenarios (all these old NiMH will be recycled or regenerated) and their sensitivity analysis will be discussed. As the premise for sensitivity analysis, the recycling rate for nickel and cobalt (the main target metal for recycling) is set to be 98.5% and 95.5% (Tenmaya 2008), respectively. Under this scenario, 7.6kg nickel and 0.6kg cobalt (total amount around 8kg) can be recycled from one waste NiMH battery. Resource-saving and waste reduction effect by NiMH reusing/recycling are shown in Fig. 9.

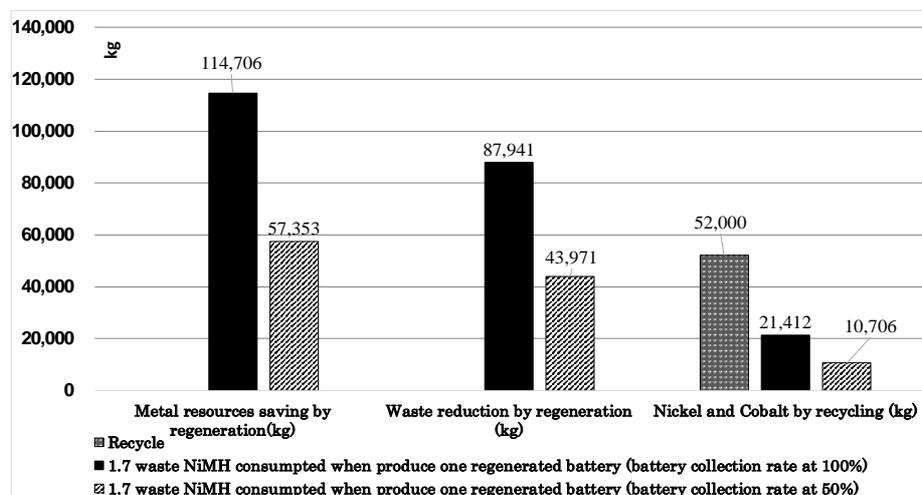


Fig 9: Result of sensitivity analysis for resource saving and waste

*reduction<sup>7</sup>*  
*Figure 9 was created by the author*

If 19% of exported secondhand HV are end-of-life HVs and all the NiMH batteries in these HVs are recycled, 52,000kg nickel and cobalt will be recovered, and could be enough to make 3,444 HVs. On the other hand, by regenerating waste NiMH batteries, 43,971~87,941kg waste will be reduced, and 57,353kg ~ 114,706kg metal resources (nickel and cobalt range 16,059kg to 32,118kg) will be saved. At the same time, from unregenerable batteries, 10,706kg ~ 21,412kg nickel and cobalt will be recycled. Therefore, when considering nickel and cobalt, 26,765kg ~ 53,530kg of these resources will be recycled. These resources are enough for making 1,773~3,545 HVs.

Based on the previous result, in 2013, about 52,000kg nickel and cobalt were not being used efficiently since they were exported abroad from Japan and treated inappropriately at exportation destination.

Secondhand HV will emerge at a faster speed as the sales of HVs grows in the future. To guarantee enough resource for HV production, it is important to collect waste NiMH battery from exported HV and reuse/recycle these batteries appropriately. Also, since the demand for regenerated NiMH could raise in the future, for advanced countries, proper treatment for exported HV and NiMH batteries should also be discussed. Since it is hard to install advanced recycling technology in developing countries within a short time, NiMH battery regeneration technology should be developed. Therefore, international scheme and cooperation on NiMH battery regeneration and reuse is essential.

## **9 Summary**

Based on the result of this research, it is plain to see that regenerating and reusing waste NiMH battery will reduce massive CO<sub>2</sub> emission and metal consumption.

Moreover, the result shows that using a regenerated NiMH battery, improves the environmental performance of an HV (6th year to 10th year). That is to say, other than reusing these NiMH batteries as stationary battery or recycle them directly, regenerating waste NiMH batteries and reusing them into a HV should also be considered as another option.

However, it is also true that the End-of-Life NiMH battery collected in Japan are mainly being recycled other than being reused in vehicles. That is because Japanese vehicle makers are aiming at selling new batteries

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<sup>7</sup>The nickel and cobalt from recycling is not included in the metal resource saving from remanufacture process

instead of old batteries for profit and safety reasons. This manner of dealing with waste NiMH battery is clearly against the principle of waste hierarchy which advocates reuse before recycling. Even if the Japanese government and vehicle maker try to enhance waste NiMH battery recycling rate in Japan, collected NiMH battery remains small. Reason is that many developing countries are also starting to value the environment and are trying to improve air pollution by importing secondhand HV vehicles from Japan.

As the HV exportation number became bigger, the need for secondhand NiMH battery is also increasing, and thus, many of these batteries are being exported abroad. Japanese vehicle makers are also helpless to collect and recycle these NiMH batteries once they are exported. The reason is that it is hard to trace these batteries in developing countries, and even if Japanese vehicle makers are willing to bring these waste NiMH batteries back to Japan to recycle, they still face waste customs clearance as well as cost-performance problems.

Therefore, large quantity of waste NiMH battery will emerge in the secondhand HV recipient countries soon, where appropriate recycling technology and policy are generally lagging behind. It is fair to assume that metal resources may not be recycled with efficiency and under some circumstances, pollution problem may also emerge during the battery recycling process.

To avoid such situation, Japanese vehicle makers and the government may consider paying more to the vehicle dismantlers to ensure a higher recycling rate. Japanese battery remanufacturers may offer more high-quality remanufactured NiMH battery for secondhand HV importing countries. As these batteries will still emerge as End-of-Life battery in developing countries eventually, the possibility and validity for utilization of end-of-life NiMH in these countries should be considered in the future along with safeguards to ensure the environmental worthiness of these items.

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