Supporting information for:

Recycling Potentials of Precious Metals from End-of-Life Vehicle Parts by Selective Dismantling

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This document (22 pages, including 11 tables and 3 figures) stands as supporting information for the research article: "Recycling potentials of precious metals from end-of-life vehicle parts by selective dismantling" to *Environmental Science and Technology*.

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Acronyms and abbreviations

The acronyms and abbreviations are presented in alphabetical order.

Acronym and abbreviation	Description
ABS	Anti-lock braking system
ANS	Audio and navigation system
ASR	Automobile shredder residue
CD	Compact disc
CV	Conventional vehicle
ELV	End-of-life vehicle
ETC	Electronic toll collection
EV	Electric vehicle
HEV	Hybrid electric vehicle
LCD	Liquid-crystal display
LIB	Lithium-ion battery
MCV	Mini size conventional vehicle
NGVSP	Next-generation vehicle specific part
NiMH (battery)	Nickel metal hydride (battery)
PWB	Printed wiring board
PGM	Platinum group metal
PM	Precious metal
RPR	Recycling potential ratio
S1	Scenario 1
S2 (2a, 2b, 2c)	Scenario 2 (2a, 2b, 2c)
S3	Scenario 3
SFA	Substance flow analysis
SmCV	Small size conventional vehicle
StCV	Standard size conventional vehicle

Sections, tables, and figures

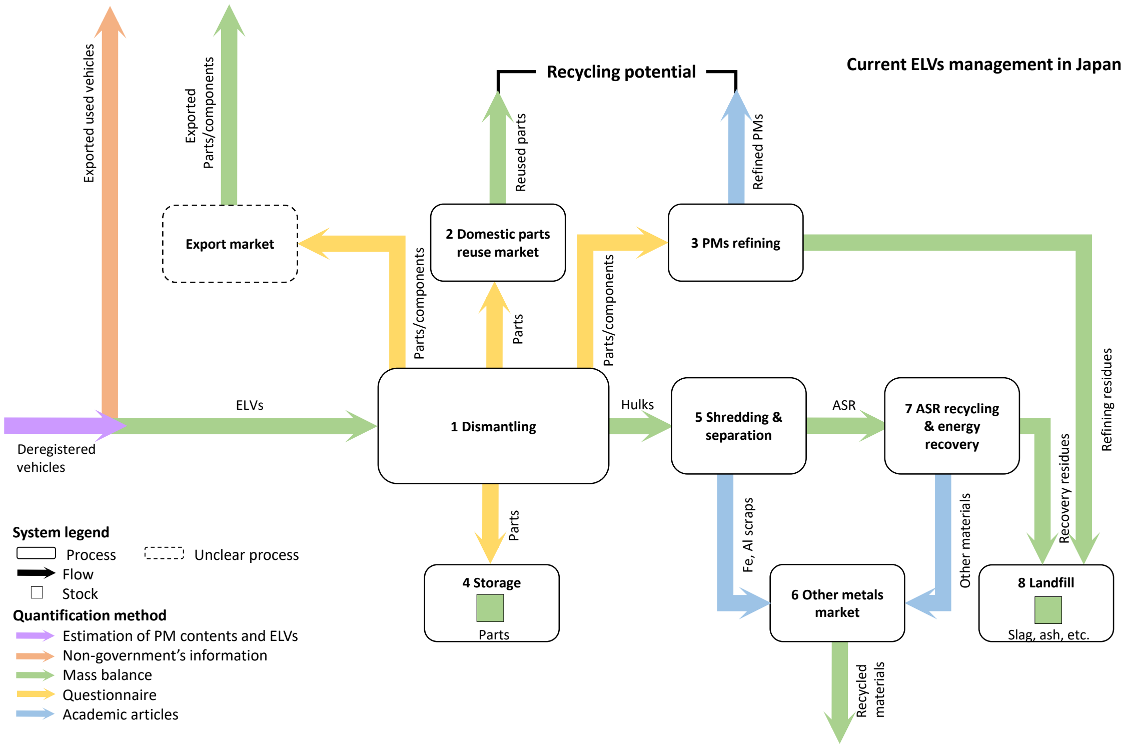

Figure S1. Processes, flows, and stocks of PMs in current ELVs management in Japan.[1,2] The emissions to the environment during ASR recycling and energy recovery are not considered. Detailed quantification methods for each PM flow can be found in Table S10.

Section S1. ELVs dismantling survey[3]

From 2012 to 2015, an ELVs dismantling survey funded by the Environment Research and Technology Development Fund, Ministry of the Environment, Japan, was conducted with the aim of identifying metal contents in ELVs. Cooperating with a commercial ELVs dismantler, six sample vehicles (Table S1) from Toyota, Suzuki, and Nissan were surveyed through two phases: (1) on-site sampling and (2) chemical analysis. In order to obtain the representative data of the resource contents in ELVs in 2012, we selected samples produced in 1997−1998, by considering the average lifespan of passenger vehicles to be around 13−14 years in Japan.[4] In total, 61 elements were included in this survey, but as this study focused on PMs, the following descriptions also focus on sampling and chemical analysis related to PMs.

During the (1) on-site sampling phase, sample vehicles were dismantled into the 26 types of targeted parts (Table S2) with assistance from professional dismantling engineers. Then, these parts were further manually dismantled into the eight types of targeted components (Table S2) and collected as sample components for later chemical analysis.

In the (2) chemical analysis phase, the sample components were weighted, then their PM concentrations were measured using inductively coupled plasma mass spectrometry. In total, we managed to measure the PM concentrations of 61 units of components including 47 PWBs, three NiMH battery cells, five catalysts, two LCDs, one ceramic, one earth electrode, one metal terminal, and one heating wire (ensuring at least one sample for one type of part). These concentrations were assumed to be representative, and to apply to components which considered but did not undergo chemical analysis.

Tables S3, S4, S5, S6, and S7 respectively show the estimated PM contents in components of StCVs, SmCVs, MCVs, HEVs, and EVs (without consideration of parts installation ratios).

Table S1. Sample vehicles in ELVs dismantling survey

Feature	StCV	SmCV	MCV		HEV	EV
Model	Crown	Corolla	Wagon R		Prius	Leaf
Manufacturer	Toyota	Toyota	Suzuki		Toyota	Nissan
Production year	1997	1997	1999	2009	1998	2011
Length (mm)	4820	4315	3395	3395	4310	4445
Width (mm)	1760	1690	1475	1475	1695	1770
Height (mm)	1425	1380	1685	1675	1490	1550
Displacement (cc)	2997	1498	658	658	1496	—
Weight (kg)	1490	1100	760	810	1240	1520
—: no related feature						

Table S2. Targeted parts and components in this study

Component	Part		Vehicle		
			CV	HEV	EV
PWB	PWB-containing ANSs	Navigation system	○	○	○
		Audio system	●*	●	●
	PWB-containing Controllers	Engine controller	●	●	–
		Steering controller	○	○	○
		ABS controller	○	○	○
		Air-bag controller	●	●	●
		Speedometer	●	●	●
		ETC controller	○	○	○
	PWB-containing NGVSPs	NiMH battery unit	–	●	–
		LIB unit	–	–	●
		Hybrid computer	–	●	–
		Electric motor computer	–	–	●
		Inverter	–	●	●
	Other PWB-containing parts	Shift lock	●	●	●
		Glove compartment (switch)	●	●	●
		Mirror (adjustment switch)	●	●	●
		Door (switch)	●	●	●
		Door lock (receiver)	●	●	●
		Wiring harness	●	●	●
		Unidentified parts	●	●	●
Battery cell	NGVSPs	NiMH battery	–	●	–
Catalyst	Catalytic converter		●	●	–
LCD	ANSs	Center console monitor	○	○	○
Ceramic	O_2 sensor		●	●	–
Metal terminal	Rear window		●	●	●
Heating wire			●	●	●
Earth electrode	Igniter		●	●	–

●: installed

○: partially installed with parts installation ratios

–: no installation

* Sub-part CD changer of audio system is an old technology, and we considered it only be installed in StCVs partially.

Table S3. Estimated PM contents in components of StCVs. Note that in this table and following Tables S4, S5, S6, and S7, weight refers to a set of components; parts installation ratios are not considered; in addition, the heating wire was sampled and analyzed together with the rear window glass; thus, their total weight is shown.

Component (part)	**Weight**	**PMs**					
		Ag	**Rh**	**Pd**	**Pt**	**Au**	**Total**
PWBs (ANSs: audio system* and navigation system)	2785	0.28	0.00	0.70	0.00	0.53	1.52
PWBs (controllers: Engine controller, Steering controller, ABS controller, air-bag controller, speedometer, ETC controller)	1486	0.12	0.00	0.18	0.00	0.14	0.44
PWBs (NGVSPs: NiMH battery unit, LIB unit, hybrid computer, electric motor computer, inverter)	–	–	–	–	–	–	–
PWBs (other parts)	398	0.15	0.00	0.06	0.02	0.04	0.27
Battery cell (NiMH battery)	–	–	–	–	–	–	–
Catalyst (catalytic converter)	1068	0.02	0.28	1.98	0.21	0.00	2.48
LCD (center console monitor)	102	0.00	0.00	0.00	0.00	0.00	0.01
Ceramic (O_2 sensor)	5	0.00	0.00	0.00	0.01	0.00	0.01
Earth electrode (igniter)	2	0.00	0.00	0.00	0.00	0.00	0.00
Metal terminal (rear window)	12	0.00	0.00	0.00	0.00	0.00	0.00
Heating wire (rear window)	7486	1.95	0.00	0.00	0.00	0.00	1.95

Unit (g)

–: no related weight or content

* Sub-part CD changer of audio system is considered to be only installed in StCVs partially.

Table S4. Estimated PM contents in components of SmCVs

Component (part)	Weight	PMs					
		Ag	Rh	Pd	Pt	Au	Total
PWBs (ANSs: audio system and navigation system)	1173	0.06	0.00	0.18	0.00	0.20	0.45
PWBs (controllers: Engine controller, Steering controller, ABS controller, air-bag controller, speedometer, ETC controller)	1109	0.09	0.00	0.13	0.00	0.11	0.33
PWBs (NGVSPs: NiMH battery unit, LIB unit, hybrid computer, electric motor computer, inverter)	–	–	–	–	–	–	–
PWBs (other parts)	294	0.11	0.00	0.05	0.01	0.03	0.20
Battery cell (NiMH battery)	–	–	–	–	–	–	–
Catalyst (catalytic converter)	766	0.01	0.20	1.42	0.15	0.00	1.78
LCD (center console monitor)	75	0.00	0.00	0.00	0.00	0.00	0.01
Ceramic (O_2 sensor)	4	0.00	0.00	0.00	0.01	0.00	0.01
Earth electrode (igniter)	1	0.00	0.00	0.00	0.00	0.00	0.00
Metal terminal (rear window)	9	0.00	0.00	0.00	0.00	0.00	0.00
Heating wire (rear window)	5527	1.44	0.00	0.00	0.00	0.00	1.44

Unit (g)

–: no related weight or content

Table S5. Estimated PM contents in components of MCVs. Values are the average values of two MCV samples.

Component (part)	Weight	PMs					
		Ag	Rh	Pd	Pt	Au	Total
PWBs (ANSs: audio system and navigation system)	837	0.04	0.00	0.13	0.00	0.15	0.32
PWBs (controllers: Engine controller, Steering controller, ABS controller, air-bag controller, speedometer, ETC controller)	805	0.06	0.00	0.10	0.00	0.08	0.25
PWBs (NGVSPs: NiMH battery unit, LIB unit, hybrid computer, electric motor computer, inverter)	–	–	–	–	–	–	–
PWBs (other parts)	210	0.08	0.00	0.03	0.01	0.02	0.14
Battery cell (NiMH battery)	–	–	–	–	–	–	–
Catalyst (catalytic converter)	299	0.00	0.08	0.55	0.06	0.00	0.69
LCD (center console monitor)	54	0.00	0.00	0.00	0.00	0.00	0.00
Ceramic (O_2 sensor)	3	0.00	0.00	0.00	0.01	0.00	0.01
Earth electrode (igniter)	1	0.00	0.00	0.00	0.00	0.00	0.00
Metal terminal (rear window)	6	0.00	0.00	0.00	0.00	0.00	0.00
Heating wire (rear window)	3944	1.03	0.00	0.00	0.00	0.00	1.03

Unit (g)

–: no related weight or content

Table S6. Estimated PM contents in components of HEVs

Component (part)	Weight	PMs					
		Ag	Rh	Pd	Pt	Au	Total
PWBs (ANSs: audio system and navigation system)	1323	0.07	0.00	0.21	0.00	0.23	0.51
PWBs (controllers: Engine controller, Steering controller, ABS controller, air-bag controller, speedometer, ETC controller)	1352	0.04	0.00	0.23	0.00	0.14	0.41
PWBs (NGVSPs: NiMH battery unit, LIB unit, hybrid computer, electric motor computer, inverter)	1459	0.24	0.00	0.27	0.01	0.06	0.54
PWBs (other parts)	534	0.12	0.00	0.02	0.02	0.02	0.18
Battery cell (NiMH battery)	43300	0.03	0.02	0.04	0.02	0.02	0.11
Catalyst (catalytic converter)	880	0.01	0.23	1.63	0.17	0.00	2.05
LCD (center console monitor)	71	0.00	0.00	0.00	0.01	0.00	0.01
Ceramic (O_2 sensor)	4	0.00	0.00	0.00	0.01	0.00	0.01
Earth electrode (igniter)	2	0.00	0.00	0.00	0.00	0.00	0.00
Metal terminal (rear window)	10	0.00	0.00	0.00	0.00	0.00	0.00
Heating wire (rear window)	6230	1.62	0.00	0.00	0.00	0.00	1.62

Unit (g)

─: no related weight or content

Table S7. Estimated PM contents in components of EVs

Component (part)	Weight	PMs					
		Ag	Rh	Pd	Pt	Au	Total
PWBs (ANSs: audio system and navigation system)	1429	0.07	0.00	0.22	0.00	0.25	0.55
PWBs (controllers: Engine controller, Steering controller, ABS controller, air-bag controller, speedometer, ETC controller)	1136	0.04	0.00	0.24	0.00	0.10	0.39
PWBs (NGVSPs: NiMH battery unit, LIB unit, hybrid computer, electric motor computer, inverter)	428	0.65	0.00	0.01	0.00	0.01	0.68
PWBs (other parts)	577	0.13	0.00	0.02	0.02	0.02	0.20
Battery cell (NiMH battery)	–	–	–	–	–	–	–
Catalyst (catalytic converter)	–	–	–	–	–	–	–
LCD (center console monitor)	77	0.00	0.00	0.00	0.01	0.00	0.01
Ceramic (O_2 sensor)	–	–	–	–	–	–	–
Earth electrode (igniter)	–	–	–	–	–	–	–
Metal terminal (rear window)	11	0.00	0.00	0.00	0.00	0.00	0.00
Heating wire (rear window)	6730	1.75	0.00	0.00	0.00	0.00	1.75

Unit (g)

–: no related weight or content

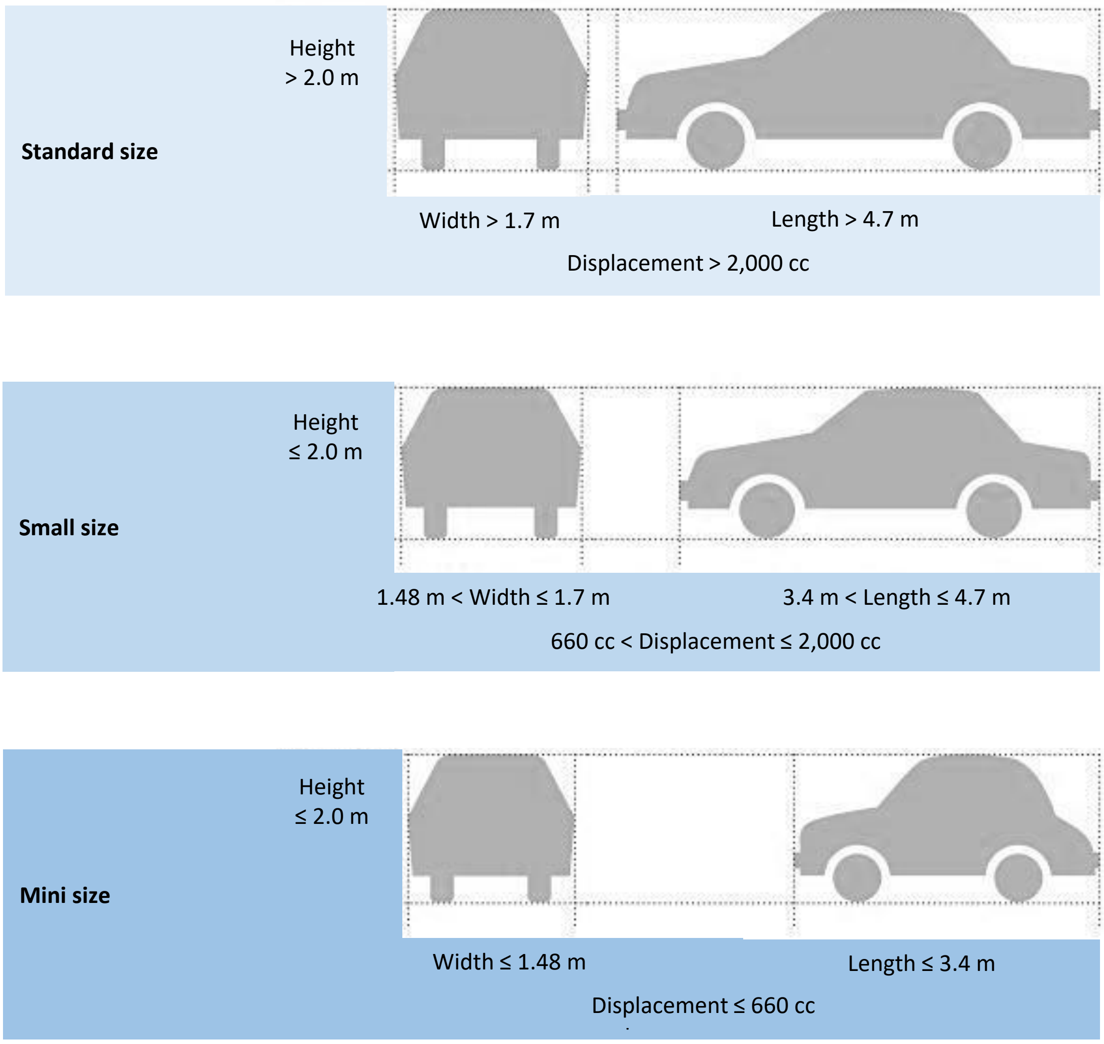

Figure S2. Size classification of passenger vehicles in Japan.[5] This classification is used for registration and inspection in Japan. If a vehicle exceeds any one of the stipulations in a size, that vehicle is automatically classified into the larger size.

Table S8. Parts installation ratios in ELVs in Japan. The ratios for steering controllers and ABS controllers were assumed from our previous study;[6] the ratios of ETC controllers, navigation systems and center console monitors were assumed from the study of Restrepo et al.;[7] CD changers in audio systems are mostly installed in StCVs; thus, these were considered only for StCVs.

Part	Installation ratio		
	2015	2030	2040
Navigation system	30%	60%*	80%
CD changer in audio system	30%	12%*	0%
Center console monitor	30%	60%*	80%
ETC controller	30%	60%*	80%
Steering controller	30%	66%*	90%
ABS controller	30%	66%*	90%
* Values were calculated linearly using ratios between 2015 and 2040.			

Section S2. Estimation of ELV generations

ELVs generation in Japan, between 2015 and 2040 was estimated by a population balance model that describes the mass balance between inputs, stocks, and outputs of a product or material with a certain lifespan.[8,9] To estimate the ELVs generation (equivalent to the output), three key factors are required: (1) the number of newly registered vehicles (equivalent to the input), (2) the remaining ratio of vehicles (equivalent to the lifespan), and (3) the exported used vehicles (equivalent to a part of the output).

(1) The numbers of newly registered vehicles between 2020 and 2040 were assumed to be constant at 3.96 million annually, based on forecasts from Japan Automobile Dealers Association.[10] The proportions of newly registered conventional vehicles and next-generation vehicles were estimated from government's targets.[11] Note that these targets state that the shares of new HEVs and EVs amongst all newly registered vehicles should reach 15–30% and 5–20%, respectively by 2020, and 30–40% and 20–30%, respectively, by 2030. Accordingly, we applied the target and assumed that the shares of HEVs and EVs amongst all newly registered vehicles will reach 35% and 25% (mean values of the targets), respectively, by 2030, and 40% and 30% (maximum values of the targets), respectively, by 2040.

(2) Two sets of remaining ratios were estimated based on statistics[12] using Weibull distribution, one for conventional vehicles (i.e. StCVs, SmCVs, and MCVs), and another for next-generation vehicles (HEVs and EVs). More detailed estimation methods can be found in our previous study.[6] The shape and scale parameters for conventional vehicles and next-generation vehicles were estimated as 2.75 and 12.80, and 2.20 and 15.69 respectively. The average lifespan for conventional vehicles and next-generation vehicles were estimated as 11.2 and 13.3 years respectively.

(3) The numbers of exported used vehicles between 2016 and 2040 were assumed to be constant at 0.63 million annually by using the average value of recent years (from 2010 to 2015).[13] Additionally, we also assumed that the shares of each type of vehicle in exported used vehicles are proportional to the shares of each type of vehicle in deregistered vehicles.

Finally, by putting these key factors into the population balance model, the ELVs generation which is the output of the model was estimated (number of ELVs is equal to number of deregistered vehicles minus number of exported used vehicles). Figure S3 show the estimated numbers of newly registered vehicles, vehicles in use, exported used vehicles, and ELVs generation in Japan during this period.

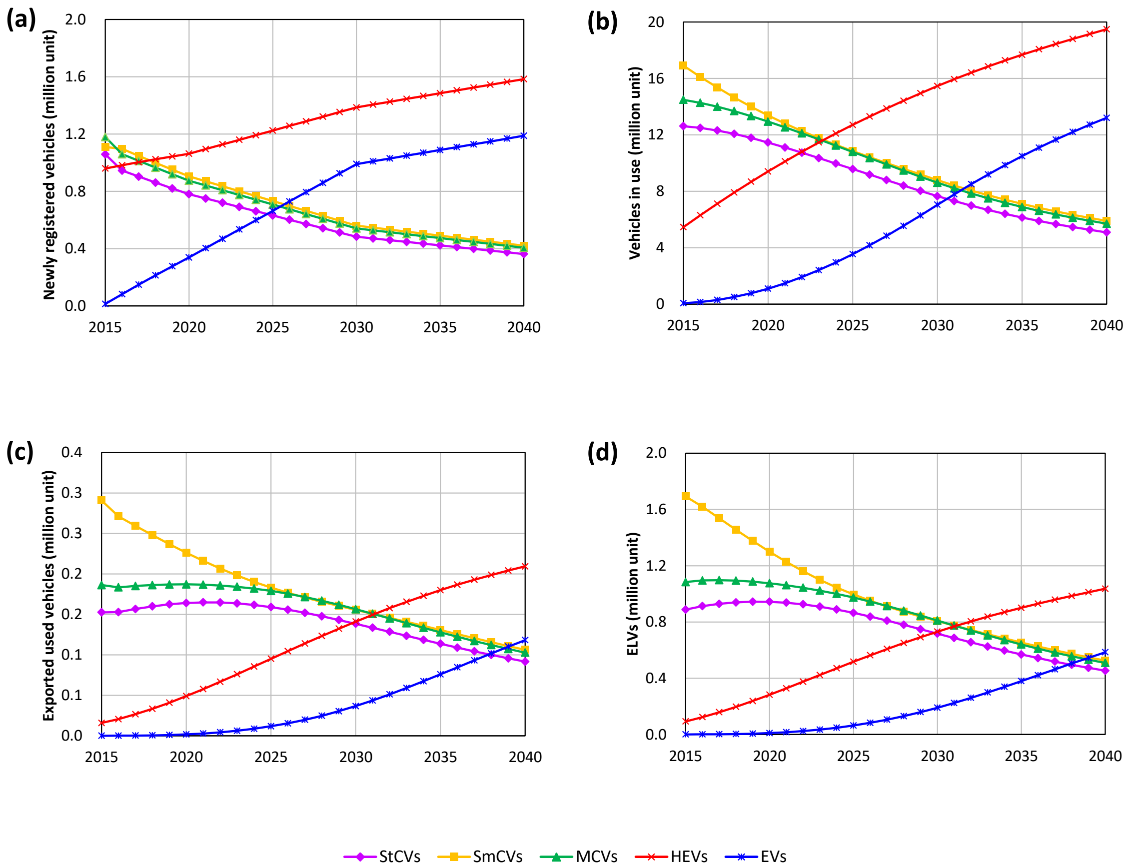

Figure S3. Estimated newly registered vehicles (a), vehicles in use (b), exported used vehicles (c), and ELV generations (d) in Japan between 2015 and 2040. Total number of ELVs in 2015, 2030, and 2040 is 3.8 million, 3.3 million, and 3.1 million, respectively.

Section S3. Automotive components collection questionnaire

In 2015, an automotive PM-containing components collection questionnaire funded by the Environment Research and Technology Development Fund, Ministry of the Environment, Japan, was conducted with the aim of identifying the situation of removal of the PM-containing components during dismantling.

The commercial ELV dismantler (with an 11000 unit per year capacity) with whom we collaborated in the ELVs dismantling survey was queried. The targeted 26 parts and eight components in the layered ELV model were included in this questionnaire. According to advice from the dismantler, we set a five collection levels questionnaire: 0% (i.e. no collection), 1–24%, 25–49%, 50–74%, and 75–100%. In the meantime, four fates after collection: export market for parts reuse and PMs refining purposes (hereafter, for short all references to export market mean this process), domestic parts reuse market, PMs refining, and storage for the parts/components were considered. All the questions in the questionnaire were answered by experts in the dismantler, based on annual situation.

Summarized component collection and fate ratios can be found in Table S9.

Table S9. Collection ratios of components and their fates following dismantling. Components can be collected as individual components or contained in their original parts.

Component (part)	**Collection ratio**		**Fate ratio**			
	Min	**Max**	**Export market**	**Reuse part market**	**PMs refining**	**Storage**
PWBs (ANSs, controllers, and NGVSPs)	25%	49%	25%	25%	50%	–
PWBs (other parts)	0%	0%	–	–	–	–
Battery cells (NiMH batteries)	75%	100%	–	5%	–	95%
Catalysts (catalytic converters)	75%	100%	–	10%	90%	–
LCDs (center console monitors)	50%	74%	–	95%	5%	–
Ceramic (O_2 sensors)	75%	100%	–	5%	95%	–
Earth electrodes (igniters)	0%	0%	–	–	–	–
Metal terminals (rear windows)	1%	24%	–	–	100%	–
Heating wires (rear windows)	1%	24%	–	–	100%	–

0%: components were considered, but no commercial collection.

–: no related fate

Table S10. Calculation methods of PM flows and stocks in SFA. In the equations, r is the type of PM (e.g. Au); p is the type of vehicle (e.g. HEV); j is the type of component (e.g. PWBs); $C_{veh.}$ and $C_{com.}$ are the PM content in a vehicle and a component respectively; N_{der}, $N_{exp.}$[13], and $N_{E.}$ are the number of deregistered vehicles, exported used vehicles and ELVs; O is the collection ratio of component; $F_{exp.}$, $F_{reu.}$, $F_{ref.}$, and $F_{sto.}$ are the fates (i.e. export market, domestic parts reuse market, PMs refining, and storage); $R_{ref.}$ is the refining ratio in PM refining; $S_{shr.}$ and $S_{rec.}$ are the separate ratios of PMs in shredding and separation, ASR recycling and energy recovery to other metals market. For example, $C_{veh.}(r.p)$ is the content of PM type r in vehicle type p, $N_E(p)$ is the number of ELVs type p, O(j) is the collection ratio of component type j, $F_{exp.}(j)$ is the fate of component type j after collection, $R_{ref.}(r)$ is the refining ratio of PM type r in PM recycling, $S_{shr.}(r)$ is the separate ratio of PM type r in shredding and separation to other metals market, f1_4(r) is the type of PM r contained in the flow f1_4. $R_{ref.}(r)$, $S_{shr.}(r)$, and $S_{rec.}(r)$ were estimated from previous studies, of which $R_{ref.}(r)$ is 70% for Rh, 95% for Ag, Au, Pd, and Pt;[14,15] $S_{shr.}(r)$ is 87% for Ag, 99% for Au, 95% for PGMs;[16] $S_{rec.}(r)$ is assumed as 92% for each PM.[17]

Flow/stock	Quantification method	Calculation equation
–	PM contents and ELVs generation	f_deregistered vehicles = $\sum C_{veh.}(r,p) \times N_{der}(p)$
–	Association statistics	f_exported used vehicles = $\sum C_{veh.}(r,p) \times N_{exp.}(p)$
–	Questionnaire	f_parts/components to export market $= \sum C_{com.}(r,j) \times N_{E.}(p) \times O(j) \times F_{exp.}(j)$
f1_2		f1_2 = $\sum C_{com.}(r,j) \times N_{E.}(p) \times O(j) \times F_{reu.}(j)$
f1_3		f1_3 = $\sum C_{com.}(r,j) \times N_{E.}(p) \times O(j) \times F_{ref.}(j)$
f1_4		f1_4 = $\sum C_{com.}(r,j) \times N_{E.}(p) \times O(j) \times F_{sto.}(j)$
f3_0	Academic articles	f3_0 = $\sum f1\_3(r) \times R_{ref.}(r)$
f5_6		f5_6 = $\sum f1\_5(r) \times S_{shr.}(r)$
f7_6		f7_6 = $\sum f5\_7(r) \times S_{rec.}(r)$
–	Mass balance	f_exported used parts/components = f_parts/components to export market
f0_1		f0_1 = f_deregistered veh. - f_exported used veh.
f2_0		f2_0 = f1_2
f3_8		f3_8 = f1_3 - f3_0
f1_5		f1_5 = f0_1 - (f1_2 + f1_3 + f1_4 + f_parts/components to export market)
f5_7		f5_7 = f1_5 - f5_6
f7_8		f7_8 = f5_7 - f7_6
f6_0		f6_0 = f5_6 + f7_6

Flow/stock	**Quantification method**	**Calculation equation**
s4	Mass balance	*s4 = f1_4*
s8		*s8 = f7_8 + f3_8*
—: no related symbol		

Table S11. Sensitivities to the recycling potential amounts of selected parameters. The closer the sensitivity is to one, the greater the sensitivity is.

Parameter, *x*		**Sensitivity, *S(x)***	
		When parameter +10%	**When parameter -10%**
1 Component weight	All components	1.10	0.90
	Components in NGVSPs	1.01	0.99
2 PM concentration	Pd in PWBs	1.01	0.99
	PGMs in catalysts	1.04	0.96
3 Part installation ratio		1.01	0.99
4 Newly registered vehicle number		1.12	0.88
5 Next-generation vehicle target		0.99	1.01
6 Exported used vehicle number		0.98	1.02
7 Component collection ratio*		1.06	0.90
8 PM flow of export (parts/components) market^		1.01	–

* Collection ratio has an upper limit of 100%, therefore, when the collection level has reached 75–100%, it can only increase to 83–100%.

^ We conservatively assumed that exported parts/components are neither reused nor refined overseas, because their final fates and recycling efficiencies are largely unclear; the default value is 0, thus only +10% is effective in the case that 10% of PM in parts/components can be recycled overseas.

–: no related situation

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