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ORIGINAL ARTICLE

Comparative assessment on greenhouse gas emissions of end-of-life vehicles recycling methods

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Abstract The ‘whole recycling method’, in which an end-of-life vehicle (ELV) is pressed and transferred to an electric furnace or converter, simultaneously recycles iron and treats automotive shredder residues. This contrasts with the usual practice of shredding ELVs to produce scrap. An advanced dismantling process is required to recycle pressed ELVs using a converter because the quality of scrap entering a converter is restricted (the copper content must be low). Here, life cycle assessments are performed to determine the amounts of greenhouse gases (GHGs) emitted recycling an ELV using the whole recycling method and using the shredding method. Recycling a pressed ELV in a converter was found to cause GHG emissions approximately 320 kg-CO_2e lower than caused by the recycling of the pressed ELV in an electric furnace. Approximately, 120 kg-CO_2e less GHGs were emitted when recycling in a converter than when using the shredding method. However, the amount of greenhouse gases reduced by a converter depends on the conditions used, such as the presence of a Linz–Donawitz converter gas recovery facility. It is hoped that incentives can be developed to improve scrap metal quality by encouraging automobile manufacturers to design for disassembly and recyclers to disassemble more ELV components.

Keywords Climate change · End-of-life vehicle (ELV) · Life cycle assessment (LCA) · Recycling · Waste management

Introduction

An end-of-life vehicle (ELV) contains hazardous objects (e.g., fuel and lubricant oil) and valuable resources (e.g., iron and copper), and the collection of both is regulated in many countries [1]. Typically, an ELV will be dismantled and the valuable and hazardous parts collected and recycled. The dismantled ELV will then be shredded and the iron and non-ferrous scrap collected. The remainder, consisting of plastics, glass, and other materials, is called automotive shredder residue (ASR). It is important to efficiently treat and recycle ASR from both economic and environmental points of view [2, 3]. Techniques have been developed for recovering and recycling heat and materials from ASR [4–6]. However, it has been reported that additional processes, such as advanced separation processes and hazardous gaseous emissions treatments, are required [7–11]. Further developing ASR treatments will require manufacturers to design vehicles to allow effective dismantling [12] and the dismantling process to be performed more rigorously than currently [13, 14].

Japanese dismantlers remove the valuable parts of an ELV and sell them to maximize their profits. The rest of the dismantled ELV is recycled in one of two ways. One method is to shred the dismantled ELV, separate the aluminum, copper, and iron scrap, then incinerate the remaining ASR or send it to a landfill site. The other method is called the ‘whole recycling method’, which involves pressing the dismantled ELV and transferring it directly to an electric furnace or converter to recycle the

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iron [15]. Even though the whole recycling method has the advantage of not producing ASR, it accounted for less than 10 % by number of the ELVs recycled in Japan in the 2013 financial year [16]. This method does not appear to be used in other countries. One reason the whole recycling method is used to recycle so few ELVs is that a dismantled ELV contains copper and plastics, both of which are regarded as unwelcome contaminants by the steel producers that may use the recycled metal [17]. It is difficult to remove copper from molten metal during the steel production process, and copper contamination negatively affects the quality of the steel produced. The copper content of the steel produced is managed by the producer by mixing high-quality (low copper content) scrap with low quality (high copper content) pressed ELV scrap. Plastics in pressed ELVs also cause problems. It is possible to recover heat from the plastics, but the energy-rich volatile matter produced by plastics is not used in most electric furnaces because of the large investment required to install facilities for recovering heat, treating the gases produced to meet emission standards, and other processes [18].

Blast furnace operators produce high-quality products, such as high-tensile steel, that require only virgin material or scrap with a copper content of less than 0.3 % to be used. To achieve this, certain parts need to be removed before an ELV is pressed [19] and transferred to a converter. Dismantling costs are, therefore, high when recycled iron is to be used to produce high-quality steel. Recyclers sell pressed ELV scrap with a copper content higher than 0.3 % to electric furnace companies. No statistical data are available on the proportions of pressed ELVs recycled in electric furnaces and in converters in Japan. It has been suggested that more pressed ELVs may be recycled in electric furnaces than converters because the latter involves higher dismantling costs and because a number of electric furnace operators use pressed ELVs [17]. However, at least two dismantlers sell pressed ELVs to blast furnace operators for recycling in converters [20].

Matsubae et al. [21] used a waste input and output material flow analysis model to assess the degree to which eliminating copper from ELV scrap will decrease CO_2 emissions. However, all the ELV scrap was recycled in electric furnaces in the scenarios they considered. In another study, automobile recycling inputs and outputs were analyzed to assess CO_2 emissions during the recycling of pressed ELV scrap in a converter and an electric furnace [22]. It was concluded that less CO_2 will be emitted using a converter than using an electric furnace. However, the different compositions of the pressed ELV materials recycled in converters and electric furnaces were not considered. In this study, we aimed to quantify the amounts of greenhouse gases (GHGs) emitted when recycling ELVs using the whole recycling method and the shredding method taking into account the different compositions of the materials recycled using the different methods.

Materials and methods

Scope of the study

This study is focused on ELV recycling using the whole recycling method and the shredding method. We classed the dismantling methods as conventional or advanced. Conventional dismantling meets the requirements of Japanese automobile recycling laws, but only valuable and easily disassembled parts and parts specified by law (air bags and fluorocarbons) are removed and collected. An ELV will have a copper content of approximately 0.7 %. When the whole recycling method is used, scrap with such a copper content can only be accepted by electric furnaces. In an advanced dismantling process, parts with higher copper contents (e.g., windshield wiper motors and motors and cable harnesses in doors) are also collected and recycled. Glass remaining in a pressed ELV will decrease the heat efficiency of the process, so the front and rear windshields and side windows are also removed before an ELV is pressed. This glass can be recycled to produce glass fiber. These extra dismantling stages mean that a pressed ELV will have a copper content of less than 0.3 % and can be used in a converter to produce iron for use in high-quality steel.

The lifecycle assessment method [23] was used to evaluate GHG emissions during the recycling activities. We performed this study because recycling metals can cause large amounts of GHGs to be emitted and because climate change is one of the most important environmental issues. The lifecycle assessment method allowed the total amounts of GHGs emitted to be estimated. Geographical aspects of a source of emissions and the concentrations of the gases emitted should be considered when evaluating other environmental factors such as effects on human health. Emissions of hazardous substances (e.g., NOx) are regulated and managed at each site, so this study was focused on the potential effects of recycling ELVs on climate change. GHG emissions were evaluated in terms of net CO_2 equivalent (CO_2e) units accruing from emissions of gases including CO_2, CH_4, and N_2O. As characterization factors for GHGs, global warming potentials based on a 100-year timeframe [24] were used. The recycling of one ELV was used as the functional unit, in accordance with Japanese automobile recycling law.

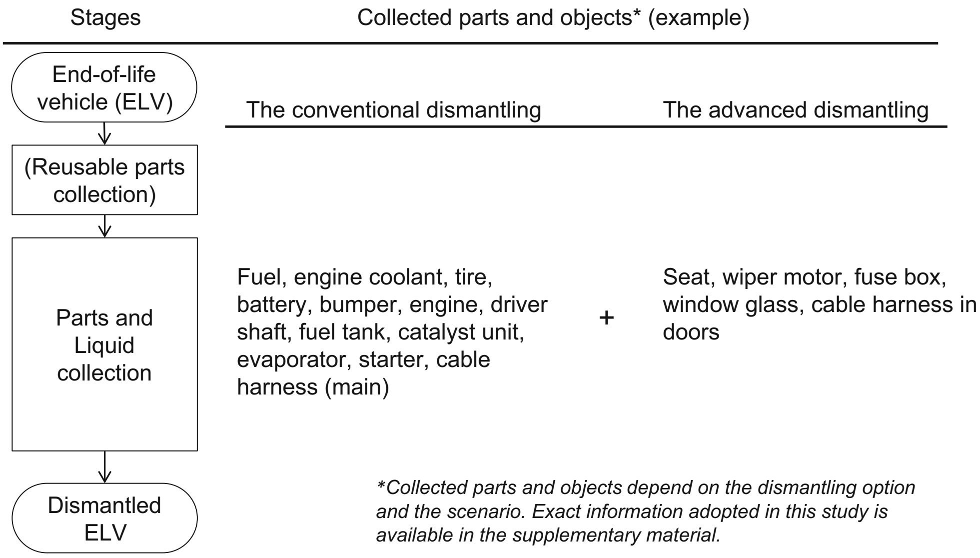


Fig. 1 Outline of the dismantling processes, adapted from [24]

Recycling process

An overview of the dismantling processes is shown in Fig. 1. First, reusable parts are removed from an ELV. The market for spare parts determines the components that are removed. Parts that are easily damaged in accidents, such as bumpers, fenders, headlights, and doors, are kept for reuse. We assumed, in our default scenario, that not all parts will be removed for reuse because market conditions vary. Liquids, plastics, and functional parts (e.g., fuel and engine coolant, seats, and tires, respectively) are then removed. Heaters, evaporators, condensers, and cable harnesses are then removed, and, if the doors are not reused, the advanced dismantling process also involves removing cable harnesses and motors from the doors to decrease the copper content of the dismantled ELV. The dismantled ELV is then pressed to give a block approximately 500 mm × 600 mm × 700 mm. The pressed ELV is then recycled in an electric furnace or converter to produce iron.

The whole recycling method does not produce ASR because any remaining plastic parts are incinerated in the furnace or converter. Plastics incinerated in a converter have to be pressed within the ELV block to avoid the plastic burning too rapidly and to increase the heat efficiency of the process. Plastic parts that are not reused are, therefore, placed within an ELV before the ELV is pressed.

System boundary

The system boundary used in the study is shown in Fig. 2. Dismantled parts that are reused were excluded from the system because these are not end-of-life parts. All of the parts collected for disposal or for their materials to be recycled were included in the system. GHG emissions during the recycling and disposal processes and decreases in GHG emissions (called credits) caused by recycling materials (compared with producing new materials) were included in the assessment. Credits were quantified from the total mass of material recycled, and recovered heat was defined as the decrease in heat that needed to be added. A substitution rate of 100 % was used. For example, we assumed that scrap iron from an ELV was recycled to make crude steel, decreasing the amount of crude steel needing to be produced from virgin material by the amount of crude steel produced from the scrap iron supplied. GHG emissions associated with the amount of virgin material not required were therefore subtracted when producing a net assessment of the impact of recycling. We did not include transportation in the analysis because the distances materials are transported and the transportation methods used are independent of the recycling method used.

Data collection

Outline

The data collection and calculation stages are shown in Fig. 3. The mass and material type of each ELV part were first modeled. Lists were then drawn of the parts collected in the conventional and advanced dismantling processes and of the recycling and disposal methods used for the parts. GHG emission data were then acquired for the recycling and disposal methods used for the parts, for recycling the pressed ELV in an electric furnace or converter, and for producing steel from virgin material.

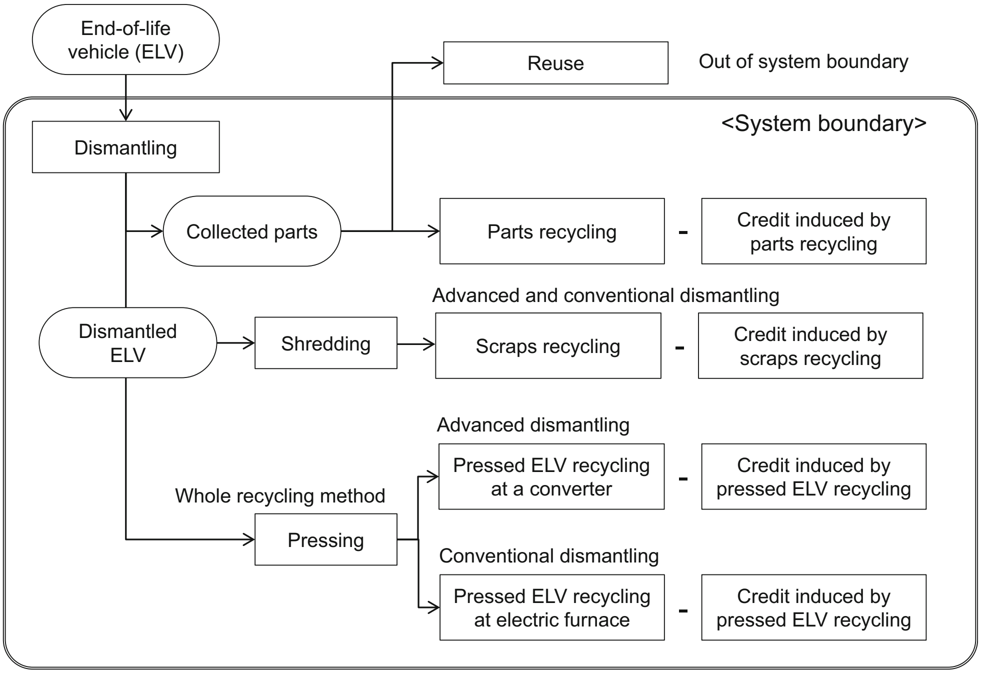


Fig. 2 Schematic of the recycling methods and the system boundary used

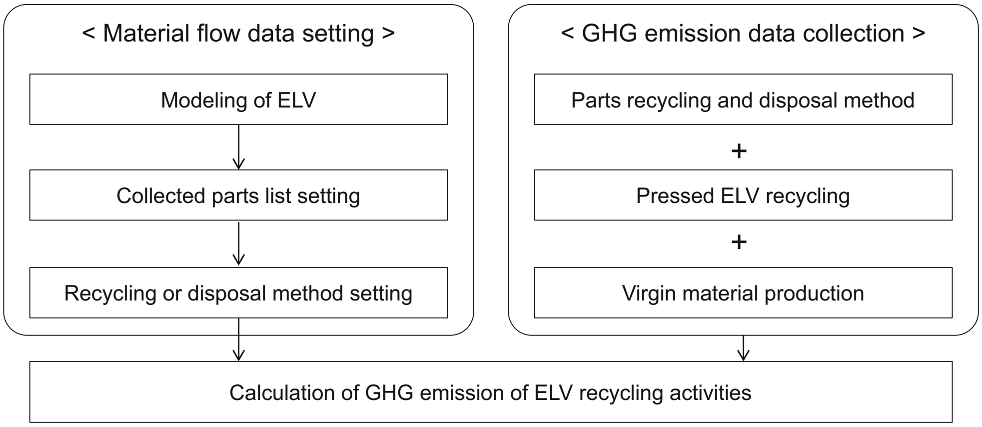


Fig. 3 Data collection and calculation flow

Model ELV

A new automobile becomes an ELV after approximately 13.3 years [25]. Most of the material in an automobile is iron, but the proportion of plastics in automobiles was higher in the 1990s and early 2000s than in the 1970s [26]. The proportion of aluminum in automobiles was also slightly higher in the 1990s and early 2000s than in the 1970s [26, 27], whereas the proportion of lead in automobiles was lower in the 1990s and early 2000s than in the 1970s [28]. The material compositions of automobiles did not fluctuate significantly in the 1990s and early 2000s [26].

Given these trends, model data for an automobile with a 1500 cc engine manufactured in 1997 [29] were used as the base data, and component mass data for the same type of automobile but manufactured in 2002 [30] were used to update the dataset. The material composition of the model ELV is summarized in Table 1 (detailed data are available as supplementary material). The plastic fraction is mainly polypropylene [26], so all of the plastics were treated as polypropylene. We note that hybrid vehicles, which have different material compositions to the model ELV used here [31], will become increasingly common ELVs in the future, but such vehicles were not included in our model.

Collection and recycling of parts

The parts of an ELV that are removed and recycled depend on the business policy of the recycling company

Table 1 Material compositions of the model end-of-life vehicle and the dismantled end-of-life vehicle [Unit: kg]

	ELV before dismantling[a]	Dismantled ELV			
		Without reuse		With reuse[b]	
		Conventional	Advanced	Conventional	Advanced
Iron	743.5	418.9	366.6	291.1	239.8
Aluminum	79.2	18.0	18.0	18.0	18.0
Copper	11.6	4.1	1.3	3.5	1.0
Lead	5.9	0.0	0.0	0.0	0.0
Plastics	170.0	125.3	96.9	107.6	79.3
Glass	31.1	31.1	0.6	12.5	0.3
Liquids	35.8	0.0	0.0	0.0	0.0
Others	1.7	0.3	0.0	0.3	0.0
Total	1,078.8	597.9	483.5	433.1	338.6

[a] The ELV composition data were modeled from [29, 30]

[b] The ELV composition with reuse was only used for the uncertainty analysis

Table 2 Recycling and disposal methods for the major components

Name	Mass (kg)	Recycling or disposal method (if collected)
Engine unit	180.0	Electric furnace (iron); nonferrous refining (the rest)
Tire	52.5	Electric furnace (iron); heat recovery (plastics)
Front strut	42.7	Electric furnace
Rear chassis component	40.5	Electric furnace
Fuel	25.2	Heat recovery
Driver's seat	19.5	Electric furnace (iron); landfilled (plastics)
Passenger's seat	18.5	Electric furnace (iron); landfilled (plastics)
Cable harness	14.8	Shredded and nonferrous refining (copper); landfilled (plastics)
Rear sheet (right)	13.0	Electric furnace (iron); landfilled (plastics)
Windshield glass	13.0	Recycling to glass fiber
Rear sheet (left)	12.5	Electric furnace (iron); landfilled (plastics)
Drive shaft	12.2	Electric furnace

performing the work, the businesses the recycling company trades with, the states of the scrap and spare parts markets, and a number of other factors. The Toyotsu Recycle Corporation, which recycles ELVs produced by Toyota, Honda, and other brands owned by these companies (later called the 'TH team'), has three standards stipulating the parts that should be removed from an ELV to ensure that the copper content of the pressed ELV will be less than 0.7, 0.5, or 0.3 % [19]. The TH team pays incentives to ELV treatment companies to ensure that high-quality pressed ELVs are produced. For a medium-sized car, the incentive for a pressed ELV containing less than 0.3 % copper is 4000 JPY and the incentive for a pressed ELV containing less than 0.7 % copper is of 2500 JPY [19]. In our model, conventional dismantling processes were assumed to meet the 0.7 % copper standard and advanced dismantling processes were assumed to meet the 0.3 % copper standard. The conditions used by the West-Japan Auto Recycle Company [32] were used for parts not mentioned in the TH team standards. The West-Japan Auto Recycle Company can recycle 1000 ELVs per month and is one of the main companies currently using the whole recycling method. The material composition of a dismantled ELV is summarized in Table 1, and the parts removed during each type of dismantling process are listed in the supplementary material. In the default scenario, we assumed that all of the parts are recycled rather than reused. However, the reuse of parts was taken into account in the uncertainty analysis described in the "Results and discussion" section.

The recycling and disposal methods used for major ELV parts are summarized in Table 2, and further details are available as supplementary material. Parts made of a single plastic and that could easily be collected were assumed to be mechanically recycled, but other plastics were assumed to be incinerated (to recover heat) or landfilled. Iron was assumed to be recycled in an electric furnace except for pressed ELVs dismantled using the advanced process. Aluminum was assumed to be melted to produce secondary aluminum for use in processes such as die-casting. Copper was assumed to be recycled in a copper smelter to give electrolytic copper.

GHG emission factors

The utilities consumed during the dismantling and pressing processes shown in Table 3 were determined using actual West-Japan Auto Recycle Company data collected between April 2014 and March 2015 [32]. The data included utility consumption not directly related to the dismantling and pressing processes, but this consumption was small and did not significantly affect our results.

The main GHG emission factors used in the study are summarized in Table 4. The GHG emission factors for the generation of electricity and the production of materials were mainly obtained from the Japanese process-based lifecycle assessment database IDEA v.1.1 [33], but a few special cases required modifications, as described below.

– *Recycling pressed ELV scrap in an electric furnace or converter* Inventory data from a previous study were used [34]. Carbon-rich molten pig iron is oxidized in an exothermic process in a converter. Scrap iron is added, and the excess energy is collected as Linz–Donawitz converter gas (LDG). The heat balance in the converter was modeled using the aluminum and plastic contents to evaluate the heat input (modeled as Al to Al_2O_3 and C to CO_2) and heat loss (caused by adding glass). For example, glass will be heated to the same temperature as the molten iron (1600 °C), and the heat required was calculated from the specific heat of glass. Plastics in a

Table 3 Consumptions of utilities per end-of-life vehicle in the dismantling and pressing processes

Recycling process	Utility (unit)	Amount	GHG emission factor[b] (kg-CO_2e/unit)	GHG emission (kg-CO_2e)
Dismantling and pressing process	Electricity (kW h)	4.66×10^1	5.68×10^{-1}	2.65×10^1
	LPG[a] (kg)	4.37×10^{-1}	3.73	1.63
	Diesel oil (L)	5.58	2.90	1.65×10^1
	Water (m^3)	3.31×10^{-1}	1.34×10^{-1}	4.44×10^{-2}
	Total			4.46×10^1
Dismantling process for shredding	Electricity (kW h)	2.93×10^1	5.68×10^{-1}	1.66×10^1
	Diesel oil (L)	9.70	2.90	2.81×10^1
	Total			4.48×10^1

[a] Liquefied petroleum gas

[b] Greenhouse gas emission factors were taken from the lifecycle assessment inventory database IDEA v.1.1 [33]

Table 4 Main greenhouse gas emission data used in the study

Class	Process	GHG emission factor (kg-CO_2e/unit)	Unit	Ref.
Recycling process	Electric furnace (iron)	6.03×10^{-1}	kg	[33]
	Converter (pressed ELV)	2.96×10^{-2}	kg	[34]
	Electric furnace (pressed ELV)	3.80×10^{-1}	kg	[34]
	Secondary aluminum production (aluminum)	3.55×10^{-1}	kg	[33]
	Copper refining	1.84×10^{-1}	kg	[33]
	Mechanical recycling (plastics)	9.20×10^{-2}	kg	[33]
	Shredding of cable harness	5.04×10^{-2}	kg	[37]
	Shredding of dismantled ELV	3.57×10^{-2}	kg	[29]
	Incineration (plastics)	3.14	kg	[33]
	Recycling to glass fiber	1.93	kg	[33]
Credit (virgin material/energy production)	Crude steel	1.66	kg	[33]
	Primary aluminum	1.03×10^1	kg	[33]
	Electrolytic copper	2.94	kg	[33]
	Polypropylene	1.84	kg	[33]
	Heat energy (coal)	9.48×10^{-2}	MJ	[33]
	Glass fiber	2.34	kg	[33]

pressed ELV were assumed to be converted to LDG in the converter using the heat value of the plastic. Every blast furnace in Japan has a gas recovery facility [35]. The energy in the plastic was estimated to be converted into heat at an efficiency of 70 % [18], and an uncertainty analysis was performed on this parameter. Gases produced from plastics are not used in electric furnaces [18]. Recycling a pressed ELV increases the amount of electricity consumed in an electric furnace because of the gas emission treatments and other processes that are required [18], so the GHG emission factor will be larger for an electric furnace than for a converter when a pressed ELV is recycled.

- *Shredding a dismantled ELV* Dismantling one ELV uses 29.3 kW h electricity and 9.7 L diesel oil and shredding one ELV uses 0.0628 (kW h)/kg electricity [29]. After shredding, 99.5 % of iron and 80 % of non-ferrous scrap are collected [29], then ASR is incinerated in a power generation system. The electricity generation efficiency was assumed to be 17 %, which is the best electricity generation efficiency that has been achieved using industrial waste in Japan [36].
- *Recycling copper scrap in a copper smelter* Cold scrap is added to a copper smelter, so we included GHG emissions for the processes involved in changing crude copper into electrolytic copper. These data were taken from IDEA v.1.1 [33].
- *Recycling cable harnesses* Shredding process data were obtained from the JLCA-LCA database [37].
- *Recycling glass* Glass is recycled and turned into glass fiber. The GHG emissions for this were calculated by subtracting data for the input material (silica sand) from data for the glass fiber production process (from IDEA v.1.1) [33].

Results and discussion

Results

The contributions of the four recycling options to the GHG emissions are shown in Table 5. GHG emissions were found to be approximately 320 kg-CO_2e lower using the whole recycling method with advanced dismantling than using the whole recycling method with the conventional recycling and approximately 120 kg-CO_2e lower than using the shredding method. The use of gases produced from the plastics included in the pressed ELV in the converter (i.e., heat recovery) contributed to the lower GHG emissions in the whole recycling method with advanced dismantling. Removing the glass also decreased the GHG emissions by increasing the parts recycling credit and avoiding heat loss during the ELV recycling process. As shown Table 1, more than 28 kg more plastic was removed in the advanced dismantling process than in the conventional dismantling, and this decreased GHG emissions using the advanced dismantling process. The GHG credit of iron in dismantled ELV recycling process was higher for conventional dismantling than for advanced dismantling because more iron is retained in conventional dismantling when compared with the advanced dismantling, as shown in Table 1.

Almost the same amounts of GHG emissions were found for both dismantling methods used with the shredding method. Even using conventional dismantling, incinerating the ASR at a high heat recovery efficiency (17 %) was found to lead to GHG emissions similar to emissions during advanced recycling.

Less GHGs were found to be emitted using the shredding method than using the whole recycling method when an ELV is dismantled using the conventional processes. This was because a different amount of GHG will be emitted during the recycling of non-ferrous metals. Non-ferrous metals remaining in the dismantled ELV were collected and treated as scrap in the shredding method but were not recycled in the whole recycling method. Aluminum contributed most of the remaining non-ferrous metals, as shown in Table 1. Heat energy from plastics in the pressed ELV was assumed not to be used in the electric converter, unlike in the shredding method.

The whole recycling method with advanced dismantling was found to emit less GHGs than the other options. The plastics remaining in the pressed ELV were assumed to be used very efficiently (70 %), and the heat recovered in the converter was assumed to decrease the amount of coal required to provide heat. More CO_2 per unit of heat was found to be emitted using coal than using other energy sources, such as the energy supplied to the electric furnace. Additionally, increasing the amounts of parts recycled would also decrease the amounts of GHGs emitted because non-ferrous metals and glass in a pressed ELV will decrease the heat efficiency of processing the pressed ELV in an electric furnace or converter and cause inert pellets to form.

Uncertainty analysis

Uncertainty analysis was performed on the parameters that may have affected the results. The effects of the parameters on the results in the scenarios described below were evaluated.

Scenario 1 In the default analysis, we assumed that not all parts would be reused, but some would be recycled or disposed of, and some reused (depending on the state of the spare parts market). Therefore, parts that are easily

Table 5 Greenhouse gas emissions during the recycling of an end-of-life vehicle [Unit: kg-CO_2e]

	Whole recycling		Shredding	
	Conventional dismantling	Advanced dismantling	Conventional dismantling	Advanced dismantling
ELV dismantling and pressing or shredding	45	45	66	62
Parts recycling process				
Iron	192	224	192	224
Aluminum	22	22	22	22
Plastics	106	187	106	187
Glass	0	59	0	59
Others	29	29	29	29
Parts recycling credit				
Iron	−502	−584	−502	−584
Aluminum	-88	−88	-88	-88
Plastics	−116	−128	−116	−128
Glass	0	−71	0	−71
Others	−35	−43	−35	−43
Dismantled ELV recycling process				
Iron	159	11	251	220
Non-ferrous metals	7	7	6	5
Plastics	394	305	394	305
Glass	7	0	0	0
Others	0	0	0	0
Dismantled ELV recycling credit				
Iron	−661	−578	−657	−575
Non-ferrous metals	0	0	−158	−152
Heat recovery	0	−160	−155	−120
Total	−442	−766	−649	−650

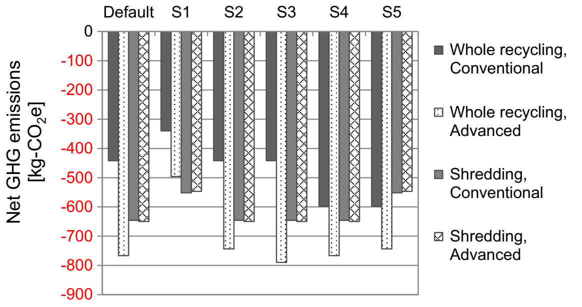
damaged in accidents, such as bumpers, fenders, headlights, and doors were assumed to be reused and were treated as being outside the system boundary. The material composition data are summarized in Table 1.

Scenarios 2 and 3 Plastics added to the converter were assumed to be used to produce heat at an efficiency of 70 % in the default analysis. The heat production efficiency was set at 60 % in the worse-case scenario 2 and 80 % in the better-case scenario 3.

Scenario 4 Energy from plastic was assumed not to be used in the electric furnace in the default analysis, but some energy could be recovered before the volatile products are exhausted. Therefore, the potential for energy released from plastic through the conversion of C to CO decreasing the consumption of electricity was estimated.

Scenario 5 Scenarios 2 and 4 were combined to give a particularly poor whole recycling method with advanced dismantling scenario.

As shown in Fig. 4, the uncertainty analysis showed that less GHGs would be emitted using the advanced dismantling option than using the conventional option in all of the scenarios that were tested using the whole recycling method. It should be noted that the baseline (zero) in Fig. 4



S1: Major parts were reused
S2: Heat efficiency of plastics use was 60 % in the converter
S3: Heat efficiency of plastics use was 80 % in the converter
S4: Plastics' energy from C to CO was recovered in an electric furnace
S5: Combination of S2 and S4

Fig. 4 Uncertainty analysis results for greenhouse gas emissions in different scenario is the point at which a vehicle first becomes an ELV; therefore, all recycling options in all scenarios reduced GHG emissions. In scenario 4, less GHGs (−156 kg-CO_2e) were found to be emitted when the whole recycling method involved conventional dismantling than in the default scenario because of the use of energy released from plastic (only from the conversion of C into CO), but the amount of GHGs emitted using advanced dismantling was not affected. The conversion of CO into CO_2 releases 283 kJ/mol, and the conversion of C into CO releases 111 kJ/mol. Therefore, recovering energy (C into CO_2) in a converter will significantly decrease GHG emissions.

In scenario 1, less GHGs were found to be emitted using the shredding method than the whole recycling method. Reusing parts decreased the advantage of using a converter. This was because the plastic content in the dismantled ELV had been reduced by the reuse and the effect of high-efficient heat recovery, a characteristic of a converter use, was reduced. The aluminum in the dismantled ELV was assumed not to be recycled in the whole recycling method, and this removed the advantage offered by the whole recycling method. The model dismantled ELV contained more than 10 kg of aluminum, as is shown in Table 1, and it is recommended that the whole recycling method should include the removal of parts containing aluminum.

Discussion

Less GHGs were found to be emitted by the whole recycling method with advanced dismantling than by the other options that were evaluated. This was because the whole recycling method with advanced dismantling involved very efficiently using energy in the plastic material, because all blast furnaces in Japan are equipped with LDG recovery facilities. However, blast furnaces in other countries are not always equipped with LDG recovery facilities. For example, blast furnaces responsible for less than 20 % of the total steel production capacities of China, the EU, India, and the US were equipped with LDG recovery facilities in 2000 [35]. The whole recycling method using a converter was found only to improve performance using a converter equipped with a LDG recovery facility, so the availability of such facilities should be taken into account when studies are performed for regions other than Japan. Note that using an electric furnace with an energy recovery facility will decrease the difference between the results for the different processes.

When major parts were assumed to be reused (Scenario 1 in the uncertainty analysis), the shredding method was found to offer a slight advantage over the whole recycling method with advanced dismantling. We assumed an ASR heat recovery power generation efficiency of 17 % for the shredding method using both conventional and advanced dismantling, but this is the best case that occurs in Japan. It should be noted that a low generation efficiency will cause this advantage to disappear.

Almost the same GHG emission rates were found for the different shredding methods because we assumed that valuable scrap would be collected during the shredding process even when parts were not removed. However, recently produced automobiles, such as hybrid cars, contain materials that are difficult to remove separately during the shredding process. Therefore, it is not recommended that ELVs that have undergone simplified dismantling processes are shredded.

A converter producing high-quality steel requires scrap with a low copper content, and it is recommended that parts containing aluminum are removed so that less GHGs are emitted than when the shredding method is used. More effort will, therefore, be required to decrease the copper and aluminum contents of scrap if the demand for scrap with low copper and aluminum contents for use in converters increases. The parts that contain copper and aluminum and that remain in an ELV are either of little economic value or are difficult to remove. The profit margin is smaller using the whole recycling option than using the conventional option [20]. Therefore, it is necessary that automobiles are better designed for being disassembled and that the operational efficiencies of recycling companies are improved. Offering incentives to automobile manufacturers to better design automobiles for disassembly and to recyclers to remove more parts may lead to the wider use of the whole recycling method. An existing example of such an incentive is that Toyotsu Recycle Corporation pays higher treatment fees to recyclers that can provide pressed ELVs with low copper contents than to those that cannot [19].

Conclusions

Emissions of GHGs when recycling an ELV in different ways were quantified taking into account the different materials in the ELV when dismantled in different ways. Recycling a pressed ELV in a converter (which requires more extensive removal of parts than do other methods) was found to cause GHG emissions approximately 320 kg-CO_2e lower than caused by conventional recycling (in which only major parts are removed and an electric furnace is used). Approximately 120 kg-CO_2e less GHGs was found to be emitted when recycling in a converter than when using the shredding method. However, the GHG emissions were found to be dependent on a number of conditions, including whether the converter is equipped with a LDG recovery facility and the amount of parts removed for reuse. Increasing the proportion of parts recycled was found to decrease the amount of GHGs emitted because non-ferrous metals and glass in a pressed ELV will negatively affect the heat efficiency of an electric furnace or converter and form inert pellets. It is hoped that incentives can be developed to improve scrap metal quality by encouraging automobile manufacturers to design automobiles for disassembly and recyclers to remove more parts than currently.

Compliance with ethical standards

Conflict of interest Part of this study was funded by the West-Japan Auto Recycle Co., Ltd, but the company had no control over the interpretation, writing, or publication of this work.

References

1. Sakai S, Yoshida H, Hiratsuka J, Vandecasteele C, Kohlmeyer R, Rotter VS, Passarini F, Santini A, Peeler M, Li J, Oh GJ, Chi NK, Bastian L, Moore S, Kajiwara N, Takigami H, Itai T, Takahashi S, Tanabe S, Tomoda K, Hirakawa T, Hirai Y, Asari M, Yano J (2013) An international comparative study of end-of-life vehicle (ELV) recycling systems. J Mater Cycles Waste Manage 16:1–20. doi:10.1007/s10163-013-0173-2
2. Castro MBG, Remmerswaal JAM, Reuter MA (2003) Life cycle impact assessment of the average passenger vehicle in the Netherlands. Int J Life Cycle Assess 8:297–304. doi:10.1007/BF02978922
3. Joung HT, Cho SJ, Seo YC, Kim WH (2007) Status of recycling end-of-life vehicles and efforts to reduce automobile shredder residues in Korea. J Mater Cycles Waste Manage 9:159–166. doi:10.1007/s10163-007-0181-1
4. Nourreddine M (2007) Recycling of auto shredder residue. J Hazard Mater 139:481–490. doi:10.1016/j.jhazmat.2006.02.054
5. Santini A, Passarini F, Vassura I, Serrano D, Dufour J, Morselli L (2012) Auto shredder residue recycling: mechanical separation and pyrolysis. Waste Manage 32:852–858. doi:10.1016/j.wasman.2011.10.030
6. Taylor R, Ray R, Chapman C (2013) Advanced thermal treatment of auto shredder residue and refuse derived fuel. Fuel 106:401–409. doi:10.1016/j.fuel.2012.11.071
7. Endoh S, Takahashi K, Lee JR, Ohya H (2006) Mechanical treatment of automobile shredder residue for its application as a fuel. J Mater Cycles Waste Manage 8:88–94. doi:10.1007/s10163-005-0140-7
8. Sakai SI, Noma Y, Kida A (2007) End-of-life vehicle recycling and automobile shredder residue management in Japan. J Mater Cycles Waste Manage 9:151–158. doi:10.1007/s10163-007-0180-2
9. Vermeulen I, Van Caneghem J, Block C, Baeyens J, Vandecasteele C (2011) Automotive shredder residue (ASR): reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals' valorisation. J Hazard Mater 190:8–27. doi:10.1016/j.jhazmat.2011.02.088
10. Mancini G, Viotti P, Luciano A, Fino D (2014) On the ASR and ASR thermal residues characterization of full scale treatment plant. Waste Manage 34:448–457. doi:10.1016/j.wasman.2013.11.002
11. Boughton B (2007) Evaluation of shredder residue as cement manufacturing feedstock. Resour Conserv Recycl 51:621–642. doi:10.1016/j.resconrec.2006.11.006
12. Tian J, Chen M (2014) Sustainable design for automotive products: dismantling and recycling of end-of-life vehicles. Waste Manage 34:458–467. doi:10.1016/j.wasman.2013.11.005
13. Santini A, Morselli L, Passarini F, Vassura I, Di Carlo S, Bonino F (2011) End-of-Life Vehicles management: italian material and energy recovery efficiency. Waste Manage 31:489–494. doi:10.1016/j.wasman.2010.09.015
14. Tasala Gradin K, Luttropp C, Björklund A (2013) Investigating improved vehicle dismantling and fragmentation technology. J Cleaner Prod 54:23–29. doi:10.1016/j.jclepro.2013.05.023
15. Hiratsuka J, Sato N, Yoshida H (2014) Current status and future perspectives in end-of-life vehicle recycling in Japan. J Mater Cycles Waste Manag 16:21–30. doi:10.1007/s10163-013-0168-z
16. Ministry of Environment Japan (2015) Implementation status of automotive recycling: transfer report (in Japanese). Ministry of Environment of Japan. http://www.env.go.jp/recycle/car/pdfs/kouhyou_25d.pdf. Accessed 15 May 2015
17. The Mechanical Social Systems Foundation (2005) Study on optimized-dismantling system of automobile recycling (in Japanese). The Japan Research and development Center for Metals web. http://www.jrcm.or.jp/works_reports/16R11.pdf. Accessed 15 May 2015
18. JFE Techno-Research (2013) Survey of unutilized heat energy use and energy saving in steel industry (in Japanese). Ministry of Economy, Trade and Industry of Japan. http://www.meti.go.jp/meti_lib/report/2013fy/E003116.pdf. Accessed 15 May 2015
19. Toyotsu recycle Corporation (2015) Whole recycling: TH team standard (in Japanese). Toyotsu recycle web. http://www.toyotsurecycle.co.jp/ASR/all-th.html. Accessed 3 Jun 2015
20. Interview to an anonymous ELV dismantler. Interviewed 24 Sep 2015
21. Matsubae K, Nakajima K, Nakamura S, Nagasaka T (2011) Impact of the recovery of secondary ferrous materials from alternative ELV treatment methods on CO_2 Emission: a waste input output analysis. ISIJ Int 51:151–157. doi:10.2355/isijinternational.51.151
22. Fuse M, Kashima S, Yagita H (2006) Input-output analysis of automobile recycling (in Japanese). J Life Cycle Assess, Jpn 2:65–72. doi:10.3370/lca.2.65
23. ISO (2006) ISO 14040. environmental management—life cycle assessment—principles and framework. International Organization for Standardization, Geneva
24. IPCC (2007) Climate Change 2007—the physical science basis: working group I contribution to the fourth assessment report of the IPCC (Climate Change 2007). Cambridge University Press, Cambridge
25. Oguchi M, Fuse M (2015) Regional and longitudinal estimation of product lifespan distribution: a case study for automobiles and a simplified estimation method. Environ Sci Technol 49:1738–1743. doi:10.1021/es505245q
26. Nikkan Jidosha Shimbun and Automobile Business Association of Japan (2003) Automotive Years Hand Book (in Japanese). Tokyo
27. Passarini F, Ciacci L, Santini A, Vassura I, Morselli L (2014) Aluminium flows in vehicles: enhancing the recovery at end-of-life. J Mater Cycles Waste Manage 16:39–45. doi:10.1007/s10163-013-0175-0
28. Yano J, Hirai Y, Okamoto K, Sakai S (2014) Dynamic flow analysis of current and future end-of-life vehicles generation and lead content in automobile shredder residue. J Mater Cycles Waste Manage 16:52–61. doi:10.1007/s10163-013-0166-1
29. Japan Environmental Management Association for Industry (2006) Development of technology to assess and verify product life cycle carbon dioxide emissions: development of life cycle assessment (LCA) method in relation to venous process (in

Japanese). New Energy and Industrial Technology Development Organization (NEDO), Kawasaki

30. Mitsubishi UFJ Research and Consulting (2015) Experimental project on dismantling and shredding of end-of life vehicles (ELV) for reducing the content of inhibitor elements in automotive shredder reside (ASR), and for improving resource efficiency in automobile recycling system in Japan (in Japanese). Ministry of Environment of Japan. http://www.env.go.jp/recycle/car/pdfs/h26_report01_mat02.pdf. Accessed 15 May 2015
31. Yano J, Muroi T, Sakai S (2015) Rare earth element recovery potentials from end-of-life hybrid electric vehicle components in 2010–2030. J Mater Cycles Waste Manage. doi:10.1007/s10163-015-0360-4
32. West-Japan Auto Recycle (2015) Company profile. http://www.warc.co.jp/english/english.html. Accessed 29 Jun 2015
33. Tahara K, Onoye T, Kobayashi K, Yamagishi K, Tsuruta S, Nakano K (2010) Development of inventory database for environmental analysis (IDEA). In: Proceedings of the 9th International Conference Ecobalance. Tokyo, p 119
34. Nakano K, Narita N, Aoki R, Funazaki A, Yagita H (2006) Specification of environmental impact reduction processes on end of life vehicle through down-stream LCA (in Japanese). J Life Cycle Assess, Jpn 2:159–165. doi:10.3370/lca.2.159
35. Oda J, Akimoto K, Sano F, Tomoda T (2007) Diffusion of energy efficient technologies and CO_2 emission reductions in iron and steel sector. Energ Econ 29:868–888. doi:10.1016/j.eneco.2007.01.003
36. Morihiro O, Manako K, Hirai Y, Sakai S (2012) Life cycle assessment for treatment and recycling of automobile shredder residue (ASR) (in Japanese). J Jpn Soc Mater Cycles Waste Manage 23:264–278. doi:10.3985/jjsmcwm.1101201
37. LCA forum of Japan (2013) JLCA database, 2013/3 ed. JLCA. http://lca-forum.org/. Accessed 29 Jun 2015