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Sustainability analysis of end of life vehicles recycling in the Japanese transportation sector
（日本の運輸部門における使用済み自動車リサイクルの持続可能性分析）

A dissertation submitted for the degree of Doctor of Philosophy (Engineering)

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Abstract

The transportation sector constitutes approximately 25% of the total energy consumption and CO_2 emissions worldwide. Therefore, in the last decades, several studies have been conducted to improve the energy efficiency of vehicles. A principal method to evaluate the total environmental effect of a vehicle is through the analysis of its life cycle. However, most of those analyses focused on the production and use phase, and little work has been performed to understand the material value of end-of-life vehicles (ELVs). Previous works have not comprehensively considered the benefits of the phase above that can provide a different perspective on the total vehicle life cycle. Firstly, our study clarifies how the materials obtained from scrapped vehicles are used, and we propose an analysis method to assess their benefits by defining the concepts of energy and CO_2 reductions. The Japanese ELV market is presented as a case study, and the material flow is elaborated. The energy and CO_2 reductions are calculated as 52.8 MJ and 2.80 kg CO_2 per kilogram of vehicle, demonstrating the importance of the analyzed phase in the entire life cycle. Finally, possible changes in ELV recycling to improve their benefits are discussed. Secondly, reductions in energy consumption and CO_2 emissions of vehicle lightweighting, considering the effects of the end of life vehicles (ELV) recycling is evaluated. For this propose, changes in the material composition of the body in white are assessed by an inventory analysis contemplating the entire life of the vehicles. The production phase is evaluated considering embodied energy and CO_2 values; the use phase through the mass induced energy consumption; and end of life vehicle recycling considers the part reusing, material recycling and energy recovery as possible destinations. Moreover, the use of aluminum, advanced high strength steel (AHSS) and carbon fiber reinforced plastic (CFRP) as alternative material are compared. Furthermore, users cost comparison is addressed as an additional assessment variable. Our results show that the effect from the standpoint of energy consumption and CO_2 emission of lightweighting materials on the production and end of life phase are essential as the benefits generated in its use phase. Moreover, material lightweight must be analyzed jointly with its possible recycling destination because when the first variable is considered individually maximum life cycle energy and CO_2 reduction of 23.8 MJ and 1.82 kg-CO_2 per kg of part to be lightweight can be expected; however, an adequate combination of both variables could almost double those benefits to 51.4 MJ and 3.34 kg-CO_2, but also incorrect combinations could be counter-productive guiding to an energy and CO_2 increment of 92.5 MJ and 6.71 kg-CO_2. Finally, a model to forecast the number of critical materials recovered from lithium-ion batteries (LiB) through the recycling of end of life electric vehicles (EV) and analyze the potential of a closed-loop supply in Japan is proposed. Compare to a typical internal combustion engine vehicle (ICEV) the dependency of the electric vehicle in its batteries have an important role. Efficient recycling of electric vehicle LiB to minimize its raw material supply risk but also the economic impact in its production process is going to be essential. Initially, this study forecast the vehicle fleet, sales, and end of life vehicles based on system dynamics modeling considering the growth of the vehicle ownership of the country and data of scrapping rates of vehicles by year of use. Then, the volume of the supplied critical materials (Li, Ni, Co, Mn) for LiB production and recovered from recycling are identified considering the power train of the scrapped vehicles, and variations in the size/type of its batteries. Moreover, economic analysis is conducted in conjunction with the identification of the current limitations to achieve a closed-loop in Japan. A timeframe of 2018 to 2035 was forecasted, and results indicate that 34% of the lithium, 50% of the cobalt, 28% of the nickel and 52% of manganese required in the production of new LiB could be supplied by batteries derives from end of life vehicles, however reduction of used electric vehicles exportation must be hardly diminished to achieve those objectives. This study, demonstrate the importance of clarifying the total benefits of the ELV in term of CO_2, energy and material supply. The total benefits of the phase are quantified numerically, allowing also the reader to understand the close relationship it has with the restart of the phases and the material composition of its parts. Results presented, allow automakers and parts producers to develop more sustainable vehicles assessing the environmental benefits of new technology or material correctly for the vehicle production. Vehicle users could understand the total effect on the society of the acquired product. Moreover, dismantlers. material recycling and part reusing companies could plan the adaptation of its facilities or evaluate new business models having in mind the limitations and benefits of the upcoming parts and materials from new generation of vehicles. Finally, public entities including the local governments are going to be able have a whole picture of the ELV market, allowing them to identifies technologies to be supported for development to achieve sustainable a sustainable society. Even the approaches conducted above develop as case study the Japanese vehicle market, the analysis methods proposed in this research can be applied universally for any country.

Keywords: ELV, recycling, material lightweighting, vehicle life cycle, energy, CO_2, cost, Lithium-ion batteries recycling, critical materials, forecasting

Abbreviations

AHSS	:	Advance high strength steel
ASR	:	Automotive shredder residue
BEV	:	Battery electric vehicles
$ASSY$	:	Assembly
Bus & trucks	:	Small trucks, standard trucks, small buses, large buses
CASE	:	Connected, Autonomous, Shared, Electric
Ca	:	Case aluminum
CFRP	:	Carbon fiber reinforced plastic
Co	:	Cobalt
Cp	:	Case plastic
Cs	:	Case steel
ELV	:	End of life vehicles
EV	:	Electric vehicles
EVB	:	Electric vehicle batteries
FCV	:	Fuel cell vehicles
GDP	:	Gross domestic product
HSS	:	High strength steel
HV	:	Hybrid vehicles
ICEV	:	Internal combustion engine vehicles
Li	:	Lithium
LiB	:	Lithium ion batteries
LMO	:	Lithium ion manages oxide
Mini	:	Mini passenger cars, mini trucks
Misc	:	Miscellaneous
Mn	:	Manganese
Ni	:	Nickel
NiMH	:	Nickel metal hybrid batteries
NMC	:	Lithium nickel manganese cobalt oxide
PHEV	:	Plug in hybrid vehicles
Small & standard	:	Standard passenger cars, small passenger cars

Nomenclatures

A	:	Front surface	[m^2]
Cw	:	Characteristic value	
CI	:	User's cost increment	[USD]
CO_2	:	CO_2 emission	[kg-CO_2 per vehicle]
CO_2R	:	CO_2 reduction	[kg-CO_2 per vehicle]
CO_2E	:	Embodied CO_2 for the automotive industry	[kg-CO_2/kg]
CO_2P	:	CO_2 emitted per kg of material produced	[kg-CO_2/kg]
E	:	Energy consumption	[kJ per vehicle]
ER	:	Energy reduction	[kJ per vehicle]
ED	:	Disposal energy	[kJ/kg]
EE	:	Embodied energy for the automotive industry	[kJ/kg]
EF	:	CO_2 emission factor per kg of material	[kg-CO_2 /kg]
EF'		CO_2 emission factor per kJ of energy	[kg-CO_2 /MJ]
EP	:	Energy consumed for the production of 1kg	[kJ/kg]

of materials
FE : Fuel economy [l/km]
G : Weight [kg]
GR : Weight ratio
HHV : Higher heating value [kJ/kg]
$LiBV$: Size of LiB of a vehicle [kwh/unit]
L_{Gear} : Energy lost in the gearbox
$Price$: Price [USD/l]
$Prof$: Profit
Psc : Probability of a vehicle to be scrapped
$RLiB$: Amount of recovered LiB [kwh]
$RMat$: Amount of recovered material from the LiBs [kg]
$Sales$: Sales [units]
$Scrapped$: Quantity of cars scrapped in the market [unit/year]
$SMat$: Amount of supplied material for the production of LiBs [kg]
Ss : Sale share of vehicle
U : Energy density [MJ/l]
V : Number of vehicles [units]
VO : Vehicle ownership [units per 1000 people]
$VLiB$: Rate of vehicles that use LiB for traction
VSa : Number of vehicles sold [units]
VSc : Number of vehicles scrapped [units]
W : Work required to move the part i during the analyzed drive cycle [J]
$WMat$: Weigh of material of a LiB from a vehicles [kg/kwh]
d : Total traveled distance [km]
g : Gravity [m/s^2]
r : Deceleration rate in the analyzed drive cycle
α : Parameter alpha related to the shape of the function.
β : Parameter beta related to the shape of the function.
γ : Saturation level of the number of vehicles [units per 1000 people]
ρ : Density [kg/l]
η_{Boil} : Efficiency of the incinerator-boiler [%]
η_{diff} : Differential efficiency of the engine
θ : Speed of effect between the variables ($0 < \theta < 1$)

Subscripts

AM : Automakers
ASR : Automobile shredder residues
D : Dealers
ELV : End of life vehicle phase
ERE : Energy recovery
$Ideal$: Ideal or maximum

JPN : Japan

M : Material

  1- Steel
  2- Iron
  3- Plastic
  4- Glass
  5- Rubber
  6- Aluminum
  7- Copper
  8- Fluid
  9- Misc.
  10- Foam
  11- Textile
  12- Wood
  13- Paper
  14- Wire harness
  15- Mix metal
  16- Cement slag, others

MR : Material recycling

L : Aerodynamic resistance

P : Production phase

PR : Part reusing

R : Rolling resistance

RM : Recyclable materials

Real : Real

SP : Spare parts

T : Total

U : Use phase

Veh : Vehicle

VM : Virgin materials

a : Acceleration resistance

ave : Average of the Japanese market

gas : Gasoline

i , j : Part

ker : Kerosene

m.i. : Mass induced

Other : Other

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1. Introduction

1.1 Background

Several global efforts to combat climate change have been performed in the last decades. To unify the goals and efforts, the Paris agreement on climate change was established in December 2015, where 195 nations agreed to maintain the temperature increase well below 2 °C (United Nations, 2015), demonstrating the global conscience and strong necessity to change the current measures regarding greenhouse gas emissions.

The transportation area constitutes approximately 25% of the total energy consumption (U.S. Energy Information Administration, 2016) and CO_2 emissions (International Energy Agency, 2009) worldwide. Therefore, over the past few decades, several studies have been conducted to improve the energy efficiency of vehicles. Moreover, in economic terms, the automotive industry accounts for a wide range of activities from material production, parts production, vehicle assembly, sales, transportation, and service. Only in Japanese territory, the number of people that work related to this sector includes 5.39 million people, representing 8.3% of the total Japanese workforce and being one of the main pillars of the local economy (Japan Automobile Manufacturers Association, 2018).

Nowadays, transportation means are essential for daily life of the human being and it is a necessity for the correct operation of the current society. Here, it is possible to mention the land, sea and air transport, where undoubtedly, the first one is the most important considering its constant use and accessibility.

Land vehicles can be divided roughly in route transport or railway. The first one includes passenger cars, trucks, buses and motorcycles. However, considering economic, energy and CO_2 point of view, this study does not consider the last type of vehicle in the analysis.

A typical passenger car is composed of 20,000 to 30,000 parts (Japan automobile manufacturers association, 2018) produced mainly by part makers and assembled in the automakers. The vehicle parts are designed mostly in the research and development centers of the second ones, considering a wide variety of materials as steel, iron, plastics, aluminum, rubbers, and others, to mentioning just a few of them.

Currently, the vehicles that are exclusively propelled by fossil fuel dominate the market; however, the automotive market is in an evolutive stage, where new technologies including alternative propulsion methods (electric vehicles, fuel cell vehicles, hybrid vehicles, and plug-in hybrid vehicles) are being introduced.

Another aspect, where resources have been dedicated to the improvement of the vehicles, is in the development and use of lightweight material. Those type of materials reduce the weight of the vehicles and improve the fuel consumption of its use phase. The predominant material in a vehicle is the Steel, representing approximately 64% of the total weight of a vehicle (Singh Harry, 2012). However, alternative materials as aluminum and carbon fiber reinforced plastic are being used more regularly for the production of structural parts.

To understand the total environmental impact of a product, this one must be assessed considering its entire life cycle, including the production, use, and end of life phases. The life cycle assessment is considered as an essential tool for different governments, and applied by important companies for environmental analysis of product and for the analysis of possible strategies (European Commission, 2019; Honda Motor Co., 2009; Toyota Motor Corporation, 2009). However, the three phases mentioned above are not analyzed equitably, being the last one left aside in different studies (Schweimer et al., 2000).

Even so, the concept of reusing and recycling has found strong support in the last years. This can be understood because the concept of cyclical economy implies not only gaseous emissions or energy consumption used in the disassembly or scrap processing phase, but also the harnessing of the materials obtained from the end of life products. This harnessing implies, environmental points but also economic benefits and the assurance of critical materials for the production of parts related to new technologies that help the society to be sustainable. A representative example is the case of critical materials needed for the production of lithium-ion batteries for the electrification of transportation.

Lastly, even the analysis methods proposed in this research can be applied universally for any country, our study focusses on Japan considering that it is the third-largest economy of the world (World Bank, 2018) but also it has one of the biggest vehicle markets and its technological contribution to the development of the vehicle industry is indispensable. Word wide-scale automakers have its central office here leading the research and development of a wide variety of new vehicle models.

1.2 Objectives

1.2.1 General objectives

- Clarify the importance of ELV recycling and reusing, and propose evaluation methods to assess its contribution to achieving sustainability in the automotive sector.

1.2.2 Specific objectives

- Numerically clarify the current benefits of the ELV phase proposing a simple evaluation method for it.
- Clarify the relationship between the different phases of the vehicle life cycle focusing on the benefits of the ELV phase.
- Understand the potential of ELV recycling considering the electrification of transportation.

1.3 Relevance of the research

This research contributes towards a more comprehensive assessment of the vehicle life cycle focusing on the environmental and economic value of the material recovered from the ELVs in order to reinforce the sustainability of the transportation sector.

On the first step, current material flow of the ELVs are elaborated evaluating the energy and CO_2 benefits of this phase (chapter 3). Then this effect is evaluated considering changes in the material composition of the vehicle and the entire life cycle (chapter 4). Finally, benefits of the batteries obtained from ELV are forecasted through dynamic approach (chapter 5).

The practical contribution of this work is the comprehensive analysis of the ELV phase. The total benefits of the phase are quantified numerically, allowing also the reader to understand the close relationship it has with the restart of the phases and the material composition of its parts. Results presented, allow automakers and parts producers to develop more sustainable vehicles assessing the environmental benefits of new technology or material correctly for the vehicle production. Vehicle users could understand the total effect on the society of the acquired product. Moreover, dismantlers. material recycling and part reusing companies could plan the adequation of its facilities or evaluate new business models having in mind the limitations and benefits of the upcoming parts and materials from new generation of vehicles. Finally, public entities including the local government, are going to be able have a whole picture of the ELV market, allowing them to identifies technologies to be supported for development to achieve sustainable a sustainable society. Additionally, compare the current situation of the country with other regions, and have a base scenario to verify the improvement considering future policies in the market are going to be possible.

1.4 Structure of the document

The aim of this study is to clarify the importance of the ELV phase and a comprehensive method to evaluate it. Even the analysis methods proposed in this research can be applied universally for any country, the Japanese vehicle market is analyzed as a case study. The rest of the document is structured as follows: In Chapter 2, the basic concepts regarding life cycle assessment are explained focusing on energy consumption and CO_2 emissions; following concepts and tendencies in circular economy are detailed. Moreover, in order to understand changes in the automotive industry, functional concepts of the different types of electric vehicles are described; finally, introduction to system dynamics modeling is presented in order to allow the readers obtain the basic concepts of the tool used in the forecasting section of this document. Chapter 3, describes the current material flow of the vehicles scrapped in Japan clarifying the amount of material of the vehicle destined to energy recovering, material recycling and part reusing. Analysis of the energy and CO_2 reduction are also carried in order to clarify the current benefits of this phase. Chapter 4 studies the relation between the benefits of lightweight materials with its possible recycling destinations. The body in white is analyzed considering alternative materials as AHSS, Aluminum, and CFRP. Here, as the previous section, effects in term of energy emission and energy consumption is analyzed but also economic point of view is added to verify possible limitations. Chapter 5 forecast the potential of battery recycling, which is the major and critical components for the fabrication of electric vehicles. System dynamic is considered for the modeling and variation of the material composition of the battery analyzed per powertrain, type of vehicle and variation in the technologies. The returning flow of ELV is calculated statistically dividing the vehicle fleet per year of life of the cars. Chapter 6 discussed integrally the aspects treated in chapters 3, 4 and 5. Finally, general conclusions are presented in Chapter 7.

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2. Theoretical framework

2.1 Life cycle assessment

The life cycle assessment is one of the most used techniques to evaluate the environmental effect of a determinate product. To achieve those objectives the following phases are conducted (The International Organization for Standardization, 1997):

- Clarifying relevant inputs and outputs of a product life
- Evaluate the potential environmental impact associated with them
- Interpretation of the results

Fig. 2.1 shows graphically the above concept. Moreover, the life of the product is generally divided into the following three sections.

- Production: Including the environmental impact of the material extraction, raw material production, manufacturing to distribution
- Use: consumption and emission related to the use of the evaluated product by the consumer or user. Here, the maintenance effect of the products is also included.
- End of life: Effect of the disposal of the product but also recycling and reusing process should be evaluated.

It is worth mentioning that the most representative aspects evaluated through this technique are energy consumption, green gas emissions, and water consumption. Define the boundary of the analysis and limitations is essential to conducting the assessment.

For specific cases of life cycle assessment of vehicles, Fig.2.2 and Fig 2.3 show the energy consumption and CO_2 emission evaluation proposed by previous studies (Kobayashi, 1997). Here, as other reviewed studies, as Schweime (2000) benefits of the ELV are not considered.

2.2 Circular economy

The concept of circular economy aims to change the current economic system based on the overconsumption of natural resources aspirating for sustainable growth of the society (Centre for European policy studies, 2017; European Commission, 2014). This transition is centered on reusing and recycling existing products and materials, turning the ‘waste’ of the take-make-dispose society into ‘resource’. The efficient use of materials but also environmental and economic benefits are expected. As an example, it is possible mentioning the case of Caterpillar, who, through the rebuilding of used parts reduces energy use 90% and the use of material 80% compared to parts made by virgin materials (National institute of science and technology policy, 2019). Moreover, Government of the European Commission has settled different guidelines oriented to different sector in order to boost this concept (National institute of science and technology policy, 2019), where not only reduction of waste as plastics are expected, but also assurance of critical raw material through closed-loop recycling can be expected for essential products as lithium-ion batteries.

2.3 Electric vehicles

Electric vehicles (EV) are the passenger or commercial vehicles that are propelled by electricity totally or partially. The following four types of EV (Un-Noor et al., 2017) are commercialized in the market depending on the level of electrification and energy source modes.

- Hybrid electric vehicles (HV): employ both internal combustion engine (ICE) and electrical power train. When the demanded power is low electric propulsion system is used, switching to ICE when higher speed is needed, also both drive trains can be used together for performance improvement. It uses batteries (Nickel hybrid batteries or Lithium-ion batteries) to store electric energy and standard tanks to storage fuel for propulsion. The motor turns to a generator when the vehicle is braking, charging the battery in the process.
- Plug-in hybrid electric vehicles (PHEV): As HV, this type of EV can be propelled by ICE or electrical powertrain. However, the PHEV can be charged its battery directly from the grid. Moreover, compare to HV, those vehicles use electric propulsion as the main driving train, and in this sense, it requires a bigger battery.
- Battery electric vehicles (BEV): utilize only electricity to propel its power train. They accumulate energy in the battery, charging them mainly by direct connection to the grid. The car runs between 100 to 500 km per charge depending model of the vehicles (Grunditz et al., 2016); moreover, the capacity of their batteries have also an essential role in it. The time necessary for charging its batteries, which is much more longer than the time necessary for refueling a conventional ICE vehicle, and the high economic and technological dependence of the vehicle in their batteries, are still some of the disadvantages of the BEV.
- Fuel cell electric vehicles (FCEV): As well as BEV, those vehicles are propelled only by electricity. However, they do not accumulate energy in batteries, been the hydrogen the source of energy, which 1are accumulated in high pressured tanks; fuel cells generate electricity and are used in the electric motor to drives the wheels. The vehicles are charged in hydrogen fuel stations which is still not frequently installed.

2.4 System dynamics

System dynamics is a computer modeling method that considers different variables in order to numerically simulate nonlinear behavior over time. It was developed by J. W. Forrester of the Massachusetts Institute of technology in the late 1950s (Kyoto University, 2010). It applies to problems arising in complex social, managerial, economic, or ecological systems (System Dynamics Society, 2019). Stocks, flows, and converters are used allowing the researcher clarifies the relation between the different variables considered in the model and predicts the change of state of elements and flows along a time scale. With representative and introductive aim, basic representation of a bathtub with system dynamics modeling is shown in Fig. 2.4. Here, the state of the bathtub (water volume) changes according the inflow rate controlled by the faucet and the outflow rate adjusted by the drain.

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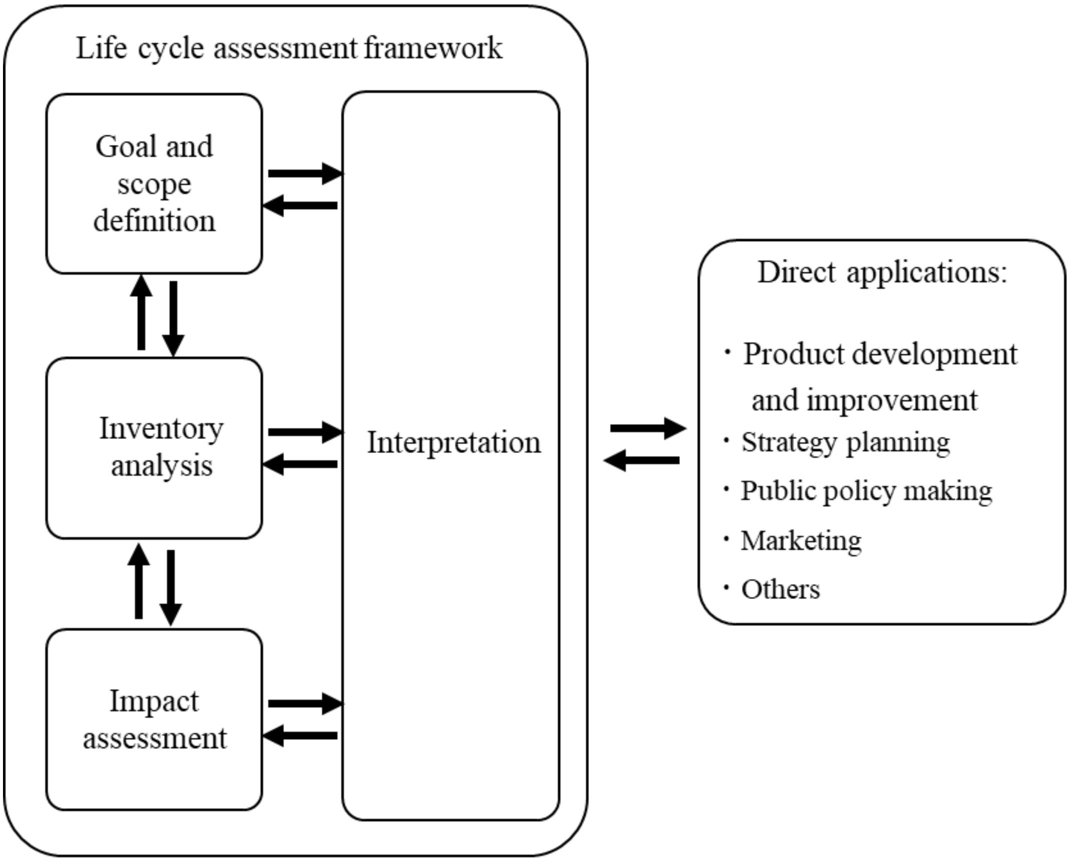

Reference: International Organization for Standarization, 1997

Fig. 2.1 Phases of an LCA

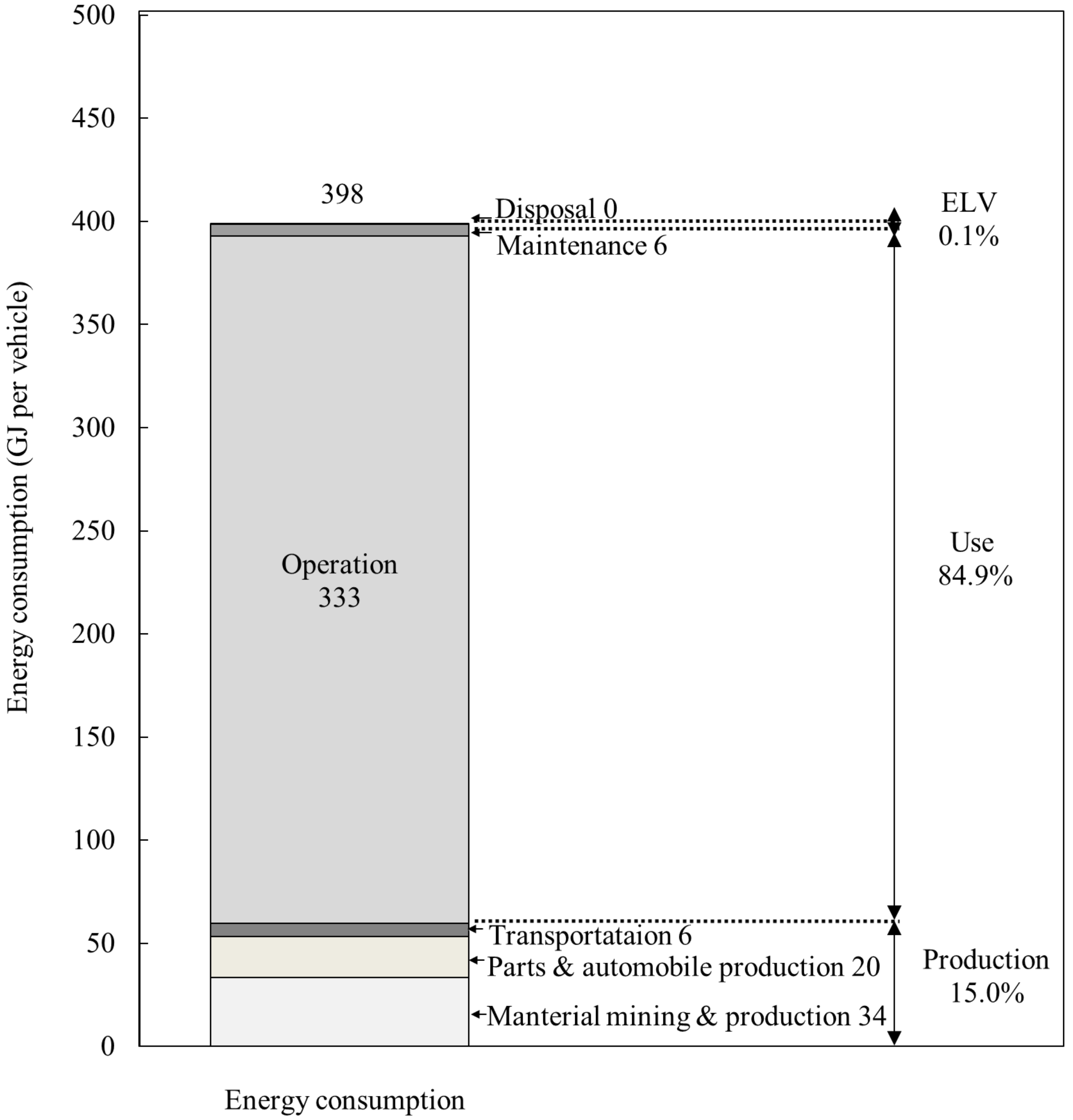

Fig. 2.2 Energy consumed in the vehicle life cycle proposed by previous studies

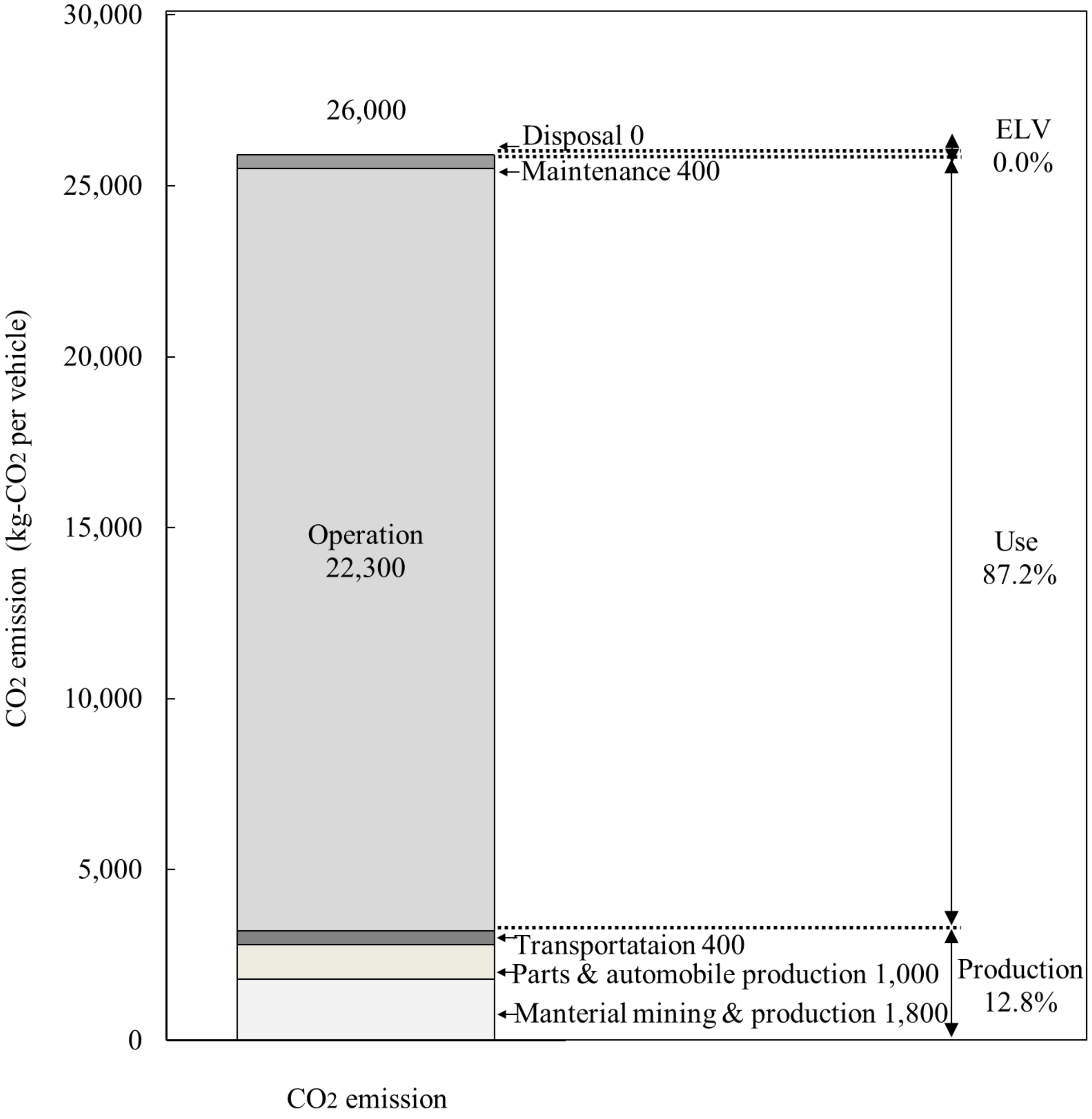

Fig. 2.3 CO_2 emitted in the vehicle Life cycle proposed by previous studies

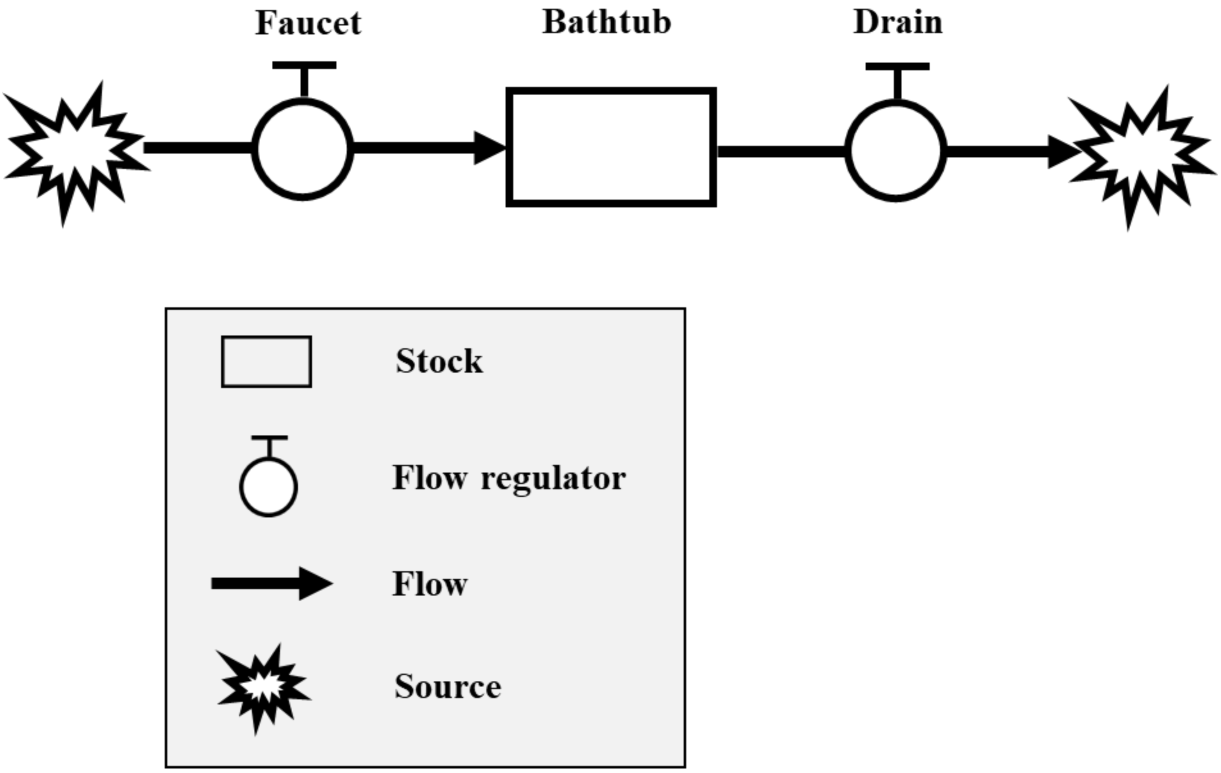

Fig. 2.4 Bathtub model in system dynamic

3. Energy and CO_2 reduction assessments for end-of-life vehicle recycling

3.1 Introduction

A typical method to evaluate the energy and CO_2 efficiency of a vehicle is through its life cycle, and many approaches have been proposed during the last few decades. Some studies estimated that the production phase constitutes 7–22%, and the use phase 79–93% of the energy consumed and CO_2 emitted of the entire cycle (Schweimer et al., 2000; Kobayashi, 1997; Nemry et al., 2008). However, only some of them studied end-of-life vehicles (ELVs), as they are considered to be insignificant with respect to energy consumption and CO_2 emission. Consequently, studies that evaluate the real benefits generated from ELVs are nonexistent.

It is well known that large quantities of materials are destined to vehicle production. However, conscience regarding the waste generated at their disposal is low.

From 2009 to 2013, an average of 3,474,000 units of ELVs have been scrapped in the Japanese vehicle market (Yano Research Institute Ltd., 2015); this value represents approximately 4.6 Mt of waste (Yano Research Institute Ltd., 2015; MOE, 2015b) and approximately 10% of the nonindustrial waste generated annually throughout Japan (SBJ, 2016).

The processing of an ELV involves dismantling the vehicle through the steps detailed below. Initially, the discarded vehicles are sent to dismantling companies. Next, their fluids, batteries, tires, and airbags are removed as a preventive measure. Subsequently, based on the vehicle model and considering the market demand, specific automotive parts are selected and extracted to be resold as second-hand spare parts. At this stage of the procedure, other parts are also separated to be recycled as alternative raw materials. The remaining dismantled vehicles are pressed and sent to shredding companies, where they are ground, and metals are primarily separated magnetically. Finally, the automobile shredder residues (ASRs) that are composed primarily of plastics, foam, and textiles are obtained as remainders.

Moreover, reports from the Japanese government (METI, 2014a) indicate that 20–30% of the weight of each scrapped vehicle is reused as spare parts, 50–60% is separated as recyclable material, and the remaining 17% is processed as ASRs.

As mentioned previously, the conventional life cycle studies focused on the analysis of the first two phases, and the end-of-life phase was typically neglected (Schweimer et al., 2000). Studies that included the indicated phase in their analyses, such as those of Bauer et al. (2015), Mitropoulos et al. (2015), and Lewis et al. (2014), based the calculation of the end-of-life stage on external databases without clarifying the contents of the proposed values or the calculation method. Wang et al. (2013), Mijailović (2013) and Zamel et al. (2006) approximated the ELV values using constants that depend only on the disposed vehicle mass. Meanwhile, representative databases and constants include the energy or emission required for dismantling vehicles for disposal, but do not include the material recycling or the energy recovery process (Burnham et al., 2006). Few studies that included energy recovery, such as that of Viñoles-Cebolla at al. (2015), did not analyze the recycling of vehicle parts and materials. Moreover, the most important factor of those approaches was that only the energy consumption and CO_2 emission associated with the disposal process were considered, and the important benefits obtained from the vehicle recycling itself were not evaluated.

Studies that analyzed the end-of-life stage specifically were centered in part of the vehicle recycling process, such as ASR processing (Kim et al., 2004; Passarini et al., 2012), the dismantling process (Che et al., 2011; El Halabi et al., 2015), material recycling (Ohno et al., 2014, 2015, 2017), those three processes together (Belboom et al., 2016), part reusing (Sato et al., 2018), or dismantling process and part reusing (Tian et al., 2016). Only a few studies, such as that of Sakai et al. (2014), analyzed the whole end-of-life phase; however, the benefits were assessed qualitatively instead of quantitatively.

Meanwhile, the end-of-life stage is important for the vehicle lightweighting and life cycle optimization, and studies such as those of González et al. (2016) and O'reilly et al. (2016) recommended the analysis of the disposal process in future investigations.

This study considers the above-mentioned shortcomings of previous studies and analyze the ELV phase considering each recycling process, the total benefit obtained from them and proposes a quantitative assessment method through an inventory analysis of the ELV market.

By understanding and considering the benefits of the ELV phase, we can assess the environmental benefits of a new technology or material correctly for the vehicle production, thus evaluating its possible effects comprehensively.

The aim of this study is to demonstrate the importance of ELVs and propose a simple evaluation method to assess their current benefits numerically in terms of energy consumption and CO_2 emission. Furthermore, possible changes in ELV recycling are discussed, and the Japanese market is presented as a case study.

Finally, it is noteworthy that our study clarifies the material flow and destination of a disposed vehicle, which has not been described hitherto.

3.2 Methodology

Figure 3.1 shows a basic flowchart of the ELV recycling system described in this study. Compared to previous conventional life cycle approaches, our analysis focuses on the recycling of an ELV parts and materials.

The reuse of parts benefits the use phase of the vehicle life cycle, considering that the energy and CO_2 necessary to produce brand-new spare parts for the vehicle maintenance will be reduced. Meanwhile, the ASR is subjected primarily to the energy recovery and thermal energy obtained. Additionally, recyclable materials are separated to be recycled as alternative raw materials.

The total energy and CO_2 from ELV recycling are evaluated through the elaboration of its material flow. Hence, the concept of energy reduction is defined as the "energy conserved or energy generated owing to the correct use of ELVs," and the CO_2 reduction as the "CO_2 not emitted owing to the correct use of ELVs."

Expanding the definition indicated above, the total benefits from ELV recycling can be calculated using (1) and (2).

$$ER_T = ER_{ASR} + ER_{RM} + ER_{SP} \tag{1}$$

ER_T : Total energy reduction [kJ per vehicle].

ER_{ASR} : Energy reduction because of the ASR [kJ per vehicle].

ER_{RM} : Energy reduction because of the recyclable materials (materials separated for recycling obtained from disarmament and shredder companies) [kJ per vehicle].

ER_{SP} : Energy reduction because of the spare parts (parts extracted in dismantling companies
to be reused) [kJ per vehicle].

$$CO_2R_T = CO_2R_{ASR} + CO_2R_{RM} + CO_2R_{SP} \tag{2}$$

CO_2R_T : Total CO_2 reduction [kg-CO_2 per vehicle].

CO_2R_{ASR}: CO_2 reduction because of the ASR [kg-CO_2 per vehicle].

CO_2R_{RM} : CO_2 reduction because of the recyclable materials [kg-CO_2 per vehicle].

CO_2R_{SP} : CO_2 reduction because of the spare parts [kg-CO_2 per vehicle].

It is noteworthy that in this study, the ASRs, recyclable materials, and spare parts are referred to the destination flow of the materials, instead of to the recycling methods where the materials are subjected to. Those methods are defined as material recycling, energy recovery, and part reusing.

3.2.1 Material flow of the ELVs

To better understand the destinations of the materials obtained from the ELVs, a material flowchart is elaborated. Hence, the material structure of a representative vehicle studied by Singh (2012) (Honda Accord 2011; 1,481 kg), shown in Fig. 3.2 (a), was considered.

As mentioned previously, the material of an ELV contains three types of destinations: the spare parts (extracted in the dismantling companies), the recyclable materials (obtained from dismantling and shredder companies), and the ASRs (leftovers). Based on the report indicated earlier (METI, 2014a.), we conservatively selected 23% of the total weight of a vehicle destined to spare parts, 60% of the material separated as recyclable materials, and 17% as ASRs.

The total weight of the material (m) in the studied vehicle can be expressed as follows:

$$G_{veh,m} = G_{veh} * GR_{veh,m} \tag{3}$$

$G_{veh,m}$: Weight of the material (m) of the studied vehicle [kg per vehicle].

G_{veh} : Weight of the studied vehicle.

$GR_{veh,m}$: Weight ratio of the material (m) in the vehicle, shown in Fig. 3.2 (a).

(a) Material composition of the ASRs

The ASRs are the leftovers rejected from the processing of an ELV. Because most of the metals are previously separated in the shredder company, the ASRs are composed primarily of plastics, rubbers, foam, and textiles.

Figure 3.2 (b) shows the material composition of the Japanese ASRs based on reports of the Japanese government (MOE, 2015a; METI, 2014b), and The Japan Machinery Federation (The Japan Machinery Federation, 2004).

The weight of the material (m) of the ASRs can be obtained using (4).

$$G_{ASR,m} = G_{veh} * GR_{veh,ASR} * GR_{ASR,m} \tag{4}$$

$G_{ASR,m}$: Weight of the material (m) of the ASRs [kg per vehicle].

$GR_{veh,ASR}$: Weight ratio of a vehicle destined to the ASR flow, 0.17 (METI, 2014a.).

$GR_{ASR,m}$: Weight ratio of the material (m) in the ASRs, shown in Fig. 3.2 (b).

The ASRs are subjected to different recycling methods depending on the treatment factory to which they are destined. The factories can be divided into two types: first, the energy recovery facilities that use the ASRs as fuel (i.e., smelting facilities, gasification melting facilities, incinerators, fluidized bed furnaces, carbonization furnaces, and cement factories); and second, the ones centered in material separation.

As reported previously, 77.3 % (MOE, 2015a) of the ASRs are destined to the first one, where the ASRs are incinerated in boilers as fuel or used as raw material for the production of secondary products. In both cases, their burnable parts contribute to systems with thermal energy. Moreover, products such as cement, slag, mixed metals, and steel are obtained.

Meanwhile, 22.2% (MOE, 2015a) of the ASRs are destined to material separation facilities. Here, in contrast to the energy recovery facilities, recyclable materials such as plastics, steel, aluminum, copper, and glass are initially separated before being subjected to the energy recovery process. It is assumed that the metals are primarily separated in these factories, and that recyclable glasses are obtained.

Finally, the remaining 0.5 % (MOE, 2015a) of the ASR is destined to landfills.

Figure 3.2 (c) shows the final destination of the ASR by weight percent (MOE, 2015a).

(b) Material composition of the spare parts

The material composition of the spare part flow was estimated through the evaluation in terms of material composition, sales, and weights of 42 representative reused parts. Table 3.1 lists the analyzed parts by weight and sales based on studies conducted by Singh (2012), and data from NGP Japan Automobile Recycling Business Cooperative Association (NGP, 2016). It is noteworthy that the mentioned association controls approximately 30% of the Japanese second-hand spare part market share, and the column "sales" of the table indicates the total parts sold by them between September 2014 and August 2016. The 42 selected parts represent nearly 75% of the total weight of the studied vehicle (without considering the weight of the vehicle body, which is recycled as alternative raw materials, and airbags and fluids, which cannot be reused as spare parts).

The generic "various parts" indicated at the bottom of the table, was calculated to reflect the effect of the remaining 280 reused parts (NGP, 2016) that are not included in our list. Their material composition was calculated as the material composition of an entire vehicle minus the composition of the 42 studied parts and the composition of the nonreusable parts.

To calculate the material composition of the studied flow, the following equations are proposed.

First, the sales of each part are reflected as the weight ratios:

$$GR_{SP,i} = \frac{G_i * Sales_i}{\sum_j G_j * Sales_j} \tag{5}$$

$GR_{SP,i}$: Weight ratio of part (*i*) on the total spare parts flow.

G_i : Weight of a unitary part (*i*) [kg per vehicle], shown in Table 3.1.

$Sales_i$: Sales of parts (*i*) in the studied period (September 2014 to August 2016) [units], shown in Table 3.1.

Next, the obtained ratios are separated by the material composition of each part (6).

$$GR_{SP,i,m} = GR_{SP,i} * GR_{i,m} \tag{6}$$

$GR_{SP,i,m}$: Weight ratio of the material (m) of the part (i) on the spare parts.

$GR_{i,m}$: Weight ratio of the material (m) of the part (i), shown in Table 3.1.

The calculated weight percent by materials of the spare part flow is shown in Fig. 3.2 (d).

To transform the obtained relative weights into concrete weight values of a vehicle, this ratio is multiplied by the weight of the studied vehicle and the weight ratio of the vehicle reused as spare parts (7).

$$G_{SP,i,m} = G_{veh} * GR_{veh,SP} * GR_{SP,i,m} \tag{7}$$

$G_{SP,i,m}$: Weight of the material (m) of the part (i) as spare parts [kg per vehicle].

$GR_{veh,SP}$: Weight ratio of a vehicle destined to the spare parts flow, 0.23 (METI, 2014a.).

(c) Material composition of the recyclable materials

Finally, the material composition of the recyclable material flow can be approximated easily by equation (8).

$$G_{RM,m} = G_{veh,m} - G_{ASR,m} - \sum_i G_{SP,i,m} \tag{8}$$

$G_{RM,m}$: Weight of the material (m) on the recyclable materials [kg per vehicle].

Figure 3.2 (e) shows the calculated weight percent by material of the recyclable material flow.

It is noteworthy that, in its majority, the material collected in this stage returns to the production phase as an alternative raw material. However, approximately 80% (JATMA, 2017) of the tires, which are the primary components of the rubber flow, are subjected to energy recovery, and the fuel is reused primarily for self-consumption.

3.2.2 Energy reduction by the recycling of ELVs

In this subsection, energy reductions from ELVs are calculated depending on the recycling methods to which they are subjected (energy recovery, part reusing, or material recycling).

(a) Energy reduction by energy recovery

As mentioned previously, most of the materials obtained from the ASRs are used as alternative fuel. Thermal energy is obtained from its combustible part through incineration (9).

$$ER^{ERE} = \eta_{Boil} \sum_m HHV_m G_m^{ERE} = ER_{ASR}^{ERE} + ER_{RM}^{ERE} \tag{9}$$

ER^{ERE} : Energy reduction by energy recovery [kJ per vehicle].

G_m^{ERE} : Weight of the material (*m*) recycled by energy recovery [kg].

HHV_m : Highest heating value of the combustible material (*m*) [kJ/kg], shown in Table 3.2.

η_{Boil} : Efficiency of the incinerator-boiler, which has been adopted as 63% (Tchobanoglous et al., 1993).

ER_{ASR}^{ERE} : Energy reduction through the energy recovery of the materials obtained from the ASR [kJ per vehicle].

ER_{RM}^{ERE} : Energy reduction through the energy recovery of the materials obtained from the recyclable materials [kJ per vehicle].

(b) Energy reduction by part reusing

The reuse of vehicle parts implies that the energy consumed to produce new components for vehicle repairing/maintenance will be reduced. Das et al. (1995) defined the concept of embodied energy as "the energy contained in a fabricated material part, reflecting the energy required to process the material from raw material to finished product." For example, in the vehicle roof, the mentioned value includes the energy spent in ore mining, smelting, steel rolling, and the final press processes. This study proposes specific values for automobile part production, and the energy reduction by the reuse of parts can be calculated using (10).

$$ER^{PR} = \sum_i \sum_m EE_m * G_{i,m}^{PR} = ER_{SP}^{PR} \tag{10}$$

ER^{PR} : Energy reduction by part reuse [kJ per vehicle].

$G_{i,m}^{PR}$: Weight of the material (*m*) of the part (*i*) recycled by part reuse [kg].

EE_m : Embodied energy for the material (*m*) for the automotive industry [kJ/kg], shown in Table 3.2.

ER_{SP}^{PR} : Energy reduction through part reusing of the spare parts [kJ per vehicle].

(c) Energy reduction by material recycling

Part of the material obtained from an ELV are recycled as alternative raw material and destined to produce different products, including vehicle parts.

A product created from recycled materials requires less energy than a product created using virgin materials. This benefit can be calculated using (11).

$$ER^{MR} = \sum_m (EP_{VM_m} - EP_{RM_m}) G_m^{MR} = ER_{ASR}^{MR} + ER_{RM}^{MR} \tag{11}$$

ER^{MR} : Energy reduction by material recycling [kJ per vehicle].

G_m^{MR} : Weight of the material (m) recycled by material recycling [kg].

EP_{VM_m} : Energy consumed in producing 1 kg of raw material through virgin materials [kJ/kg], show in Table 3.2.

EP_{RM_m} : Energy consumed in producing 1 kg of raw material through recycled materials [kJ/kg], show in Table 3.2.

ER_{ASR}^{MR} : Energy reduction through material recycling of the material obtained from the ASRs [kJ per vehicle].

ER_{RM}^{MR} : Energy reduction through material recycling of the material obtained from recyclable materials [kJ per vehicle].

(d) Energy reduction by each material flow

The proposed energy reductions are subjected specifically to the recycling method analyzed. To calculate the energy reduction per destination flow and the total energy reduction per ELV, those values are reflected in the equation (1) as follows.

$$ER_{ASR} = ER_{ASR}^{ERE} + ER_{ASR}^{MR} \tag{12}$$

$$ER_{RM} = ER_{RM}^{ERE} + ER_{RM}^{MR} \tag{13}$$

$$ER_{SP} = ER_{SP}^{PR} \tag{14}$$

3.2.3 CO_2 reduction by recycling ELVs

Similar to energy reduction, CO_2 reduction depends on the recycling method to which the ELV is subjected. The calculation methods by each recycling process are proposed below.

(a) CO_2 reduction by energy recovery

The boilers installed in Japan are fed primarily by kerosene, natural gas, or heavy oil. Energy production by the incineration of ASRs implies that the kerosene, natural gas, or heavy oil necessary to produce the same amount of energy is reduced. Similarly, CO_2 emitted using traditional fuels is replaced by the emission generated by the incineration of ASRs.

Meanwhile, considering that the energy recovery emits CO_2 to the environment, the CO_2 reduction in this process can present a negative impact depending on the emission factor of the incinerated material. Considering the emission value of kerosene as generic, the total CO_2 reduction from energy recovery can be calculated by

$$CO_2R^{ERE} = EF'_{ker}(ER^{ERE}/\eta_{Boil}) - \sum_m EF_m G_m^{ERE} = CO_2R_{ASR}^{ERE} + CO_2R_{RM}^{ERE} \qquad (15)$$

CO_2R^{ERE} : CO_2 reduction by energy recovery [kg-CO_2 per vehicle].

EF_m : Emission factor of the material (m) [kg-CO_2 /kg], shown in Table 3.3.

EF'_{ker} : Emission factor of kerosene [0.07127 kg-CO_2 /MJ] (EPA, 2014).

$CO_2R_{ASR}^{ERE}$: CO_2 reduction through the energy recovery of the materials obtained from the ASRs [kg-CO_2 per vehicle].

$CO_2R_{RM}^{ERE}$: CO_2 reduction through the energy recovery of the materials obtained from the recyclable materials [kg-CO_2 per vehicle].

(b) CO_2 reduction by part reusing

Similar to energy reduction, the reuse of vehicle parts implies that the CO_2 emitted to produce new components for vehicle repairing/maintenance will be reduced.

Nishimura et al. (2001 and 1997) calculated the embodied carbon for different productive sectors, including the values for the Japanese passenger car industry. The CO_2 reduction by reusing parts can be calculated using (16).

$$CO_2R^{PR} = \sum_m \sum_i CO_2E_m * G_{i,m}^{PR} = CO_2R_{SP}^{PR} \tag{16}$$

CO_2R^{PR}: CO_2 reduction by part reusing [kg-CO_2 per vehicle].

CO_2E_m : Embodied CO_2 for the material (*m*) for the automotive industry [kg-CO_2/kg], shown in Table 3.3.

$CO_2R_{SP}^{PR}$: CO_2 reduction through the part reusing of spare parts [kg-CO_2 per vehicle].

(c) CO_2 reduction by material recycling

As mentioned earlier, the materials obtained from ELVs are recycled as alternative raw materials. CO_2 is reduced in the production phase, and the related benefits can be calculated using (17).

$$CO_2R^{MR} = \sum_m (CO_2P_{VM_m} - CO_2P_{RM_m})G_m^{MR} = CO_2R_{ASR}^{MR} + CO_2R_{RM}^{MR} \tag{17}$$

CO_2R^{MR} : CO_2 reduction by material recycling [kg-CO_2 per vehicle].

$CO_2P_{VM_m}$: CO_2 emitted in producing 1 kg of materials through virgin materials [kg-CO_2/kg], shown in Table 3.3.

$CO_2P_{RM_m}$: CO_2 emitted in producing 1 kg of materials through recycled materials [kg-CO_2/kg], shown in Table 3.3.

$CO_2R_{ASR}^{MR}$: CO_2 reduction through material recycling of the materials obtained from the ASRs [kg-CO_2 per vehicle].

$CO_2R_{RM}^{MR}$: CO_2 reduction through material recycling of the materials obtained from the recyclable materials [kg-CO_2 per vehicle].

(d) CO_2 reduction by each material flow

The proposed CO_2 reductions are subjected to the recycling methods analyzed. To calculate the CO_2 reduction per destination flow and the total CO_2 reduction per ELV, those values are reflected in equation (2) as follows.

$$CO_2R_{ASR} = CO_2R_{ASR}^{ERE} + CO_2R_{ASR}^{MR} \tag{18}$$

$$CO_2R_{RM} = CO_2R_{RM}^{ERE} + CO_2R_{RM}^{MR} \tag{19}$$

$$CO_2R_{PFR} = CO_2R_{SP}^{PR} \tag{20}$$

3.2.4 Primary assumption and limitations

First, we analyze the ELV phase by presenting a case study of the Japanese market; moreover, energy and CO_2 effects of vehicle recycling were calculated. However, those benefits do not impact the Japanese society exclusively, considering that part of the recyclable materials, as well as spare parts, are exported to other countries.

Next, because the data used in the recycling process analysis are general for the entire market, the material composition of a Honda Accord was selected as generic considering that it does not represent a strong limitation for the calculation of the percentage values.

Subsequently, the distances between dismantlers and reused part users were not included in the analysis considering that new parts were also transported from factories. Moreover, several factors such as durability, compatibility, and the safety of reused parts would be additional factors to be adjusted in future analysis.

Finally, it is noteworthy that the recycling of rare metals were not considered in this study.

3.3 Results and discussion

3.3.1 Material flow of ELVs

Figure 3.3 shows the obtained material flow, where the ASRs, recyclable materials, and spare parts are subjected to different recycling methods. The methods are energy recovery, material recycling, and part reusing.

It is noteworthy that, in the proposed figure, wood, paper, wire harness, and textile are included in miscellaneous, whereas foam is classified under plastic.

As shown, in terms of the material weight, the vehicles are made primarily of steel, plastic, and aluminum. Meanwhile, most of the steel and aluminum are recycled as raw materials; however, the plastics are subjected primarily to energy recovery.

3.3.2 Energy reduction by the recycling of ELVs

The ELV material flow is used in equations (9) to (14) to calculate energy reductions. Table 3.4 (a) summarizes the calculated reduction values per recycling method and destination flow. The total energy reduction was calculated as 78.3 GJ per vehicle, where 3.9 GJ corresponded to the energy reduction by the ASR, 34.4 GJ by the recyclable materials, and 39.9 GJ by the spare parts.

Figure 3.4 (a) is elaborated considering the energy reduction per vehicle by each material and destination. As shown, the primary energy contributor in the ASRs is plastic, making up 64% of the energy reduction by this destination flow. Similarly, in cases of recyclable materials and spare parts, the primary contributor is aluminum, making up 68% and 47% of the respective reductions.

Figure 3.4 (b) shows the energy reductions per unit (kg) of the material. As the diagram indicates, in all the destinations, the major energy contributor per kilogram of material is aluminum; however, steel, which is the dominant material in a vehicle, has one of the lowest reduction values. Moreover, plastic has an acceptable level of energy reduction as being recycled ASR; however, it still presents an important energy reduction opportunity if it is separated as recyclable materials or spare parts.

Meanwhile, as shown in the last column of Fig. 3.4 (b), the flow with the highest reduction values per unit of material recycled is that of the spare parts, followed by those of the recyclable materials and ASRs.

3.3.3 CO_2 reduction by recycling ELVs

Table 3.4 (b) summarizes the CO_2 reductions calculated from equations (15) to (20). The total CO_2 reduction by recycling an ELV was calculated as 4,160 kg-CO_2, where -20 kg-CO_2 corresponds to the CO_2 emitted by the incineration of ASRs, 1,960 kg-CO_2 corresponds to the CO_2 reduced by the recyclable materials, and 2,220 kg-CO_2 reduced by the spare parts.

Figure 3.5 (a) shows the CO_2 reductions of each material and destination per vehicle. As shown, the ASRs contribute negatively to the CO_2 reduction as their incineration causes more pollution than the typically used fuel (kerosene). Plastics are the major contributors of this negative value, not only owing to their relatively high emission factor but also because they comprise the primary component of ASRs.

Steel and aluminum are the major contributors in the recyclable material and spare part flows, making up 82% and 57% of the reductions of each destination flow. However, it is noteworthy that the reason for the highly beneficial effect of steel is not its emission factor, but rather the large amount of steel that forms a vehicle.

Figure 3.5 (b) shows the CO_2 reduction per unit (kg) of material. Similar to the energy analysis, aluminum is the major CO_2 contributor per kilogram of material in the recyclable material flow. However, the CO_2 reduction difference is little between the materials in the spare part flow. As was expected, the plastics in the ASRs exhibit a negative CO_2 reduction value; further, similar to energy, they present an important CO_2 reduction opportunity if they are recycled as recyclable materials or spare parts. Finally, as shown in the last column of Fig. 3.5 (b), the flow with the highest CO_2 reduction per unit of material is that of the spare parts, followed by those of the recyclable materials and ASRs.

3.3.4 Energy and CO_2 reductions for the entire Japanese market

The results obtained above are only for a unit vehicle. To estimate the total benefit for the Japanese ELV market, its two representative aspects were considered: the average weight of a vehicle, and the number of vehicles scrapped annually. Both values were estimated based on the data between year 2009 to 2013, obtained from reports published by the Japanese government (Yano Research Institute Ltd., 2015; MOE, 2015b).

First, the total amount of waste generated by the scrapping of ELVs is calculated as follows.

$$G_{JPN} = Scrapped * G_{veh,ave} \tag{21}$$

G_{JPN} : Total weight of ELVs processed in the Japanese market [kg/year].

$Scrapped$: Number of cars scrapped in the Japanese market [unit/year].

$G_{veh,ave}$: Average weight of the vehicles in the Japanese market [kg/unit].

Next, the total energy reduced in the Japanese market by the recycling of ELV is estimated using (22).

$$ER_{JPN} = ER_T * \frac{G_{JPN}}{G_{veh}} \tag{22}$$

ER_{JPN}: Total energy reduction by the recycling of ELVs in the Japanese market [kJ/year].

Similarly, the total CO_2 reduction by the recycling of ELVs in the Japanese market is estimated using (23).

$$CO_2R_{JPN} = CO_2R_T * \frac{G_{JPN}}{G_{veh}} \tag{23}$$

$CO_2R_{T\,JPN}$: Total CO_2 reduction by the recycling of ELVs in the Japanese vehicle market [CO_2-kg/year].

The average weight of the Japanese vehicles was calculated as 1,345 kg/unit, and the number of vehicles scrapped annually as 3,474,000 units/year. Table 3.4 (c) lists the estimated weight, energy reduction, and CO_2 reduction by ELV recycling for the entire market. Moreover, Fig. 3.6 shows the comparisons between the obtained reduction values and the total energy consumption, and the CO_2 emissions for different sectors in Japan (Takita et al., 2015). These results highlight the significant effect of ELV recycling even when the energy and CO_2 values of an entire country are analyzed, reducing 2.2% of the energy consumption and 1.1% of the CO_2 emission of the country. This also indicates that a wrong decision or policy making through an insufficient analysis of this phase could generate a national level energy and CO_2 inconvenient effecting the current reduction values.

3.3.5 Sensitivity analysis

(a) Specific benefits expected by the modification of the recycling destination.

Figures 3.4 (b) and 3.5 (b) indicate that the amount of energy and CO_2 reduced per kilogram of the same material can vary widely among the recycling destinations (ASR, recyclable materials, and spare parts) to which the parts/materials are subjected. This section clarifies how these benefits vary when the recycling destinations of the primary materials of a vehicle (plastics, steel, and aluminum) are modified. Figure 3.7 shows the current recycling destination of the materials, and the following cases are analyzed.

- Case plastic (Cp): One unit (kg) of plastic changes the recycling destination from ASRs to recyclable materials (Cp^{ASR-RM}), from recyclable materials to spare parts (Cp^{RM-SP}), or from ASRs to spare parts (Cp^{ASR-SP}).

- Case steel (Cs): One unit (kg) of steel changes the recycling destination from ASRs to recyclable materials (Cs^{ASR-RM}), from recyclable materials to spare parts (Cs^{RM-SP}), or from ASRs to spare parts (Cs^{ASR-SP}).
- Case aluminum (Ca): One unit (kg) of aluminum changes the recycling destination from ASRs to recyclable materials (Ca^{ASR-RM}), from recyclable materials to spare parts (Ca^{RM-SP}), or from ASRs to spare parts (Ca^{ASR-SP}).

Figure 3.8 (a–c) and Fig. 3.9 (a–c) show the comparisons between the cases and indicate that, in terms of energy and CO_2, the differences between the recycling destinations to which steel is subjected are relatively low (a maximum of 57.1 MJ and 4.35 kg-CO_2 per kg of steel). This is because the steel included in the ASR flow is also recycled as raw material through magnetic separation or by melting it to become a mixed metal. Meanwhile, the manufacturing/forming of steel parts do not consume as much energy compared to aluminum.

Moreover, changing the recycling method of one unit of aluminum can yield a higher energy reduction (a maximum of 302 MJ per kg of aluminum); however, CO_2 reduction is barely affected because of the high utilization of gas in its forming processes.

(b) Total benefits expected by the modification of the recycling destinations

This section clarifies the total potential and benefits by modifying the current recycling destination of plastics, steel, and aluminum. Similar to the approach presented above, the following cases are proposed.

- Case total plastic (Cp_T): All the plastics of the ASRs change the recycling destination to recyclable materials (Cp_T^{ASR-RM}), all the plastic of recyclable materials change the recycling destination to spare parts ($Cp_T^{RM\text{-}SP}$), or all the plastics of the ASRs change the recycling destination to spare parts ($Cp_T^{ASR\text{-}SP}$).

- Case total steel (Cs_T): All the steel of the ASRs change the recycling destination to recyclable materials ($Cs_T^{ASR\text{-}RM}$), all the steel of the recyclable materials change the recycling destination to spare parts ($Cs_T^{RM\text{-}SP}$), or all the steel of the ASRs change the recycling destination to spare parts ($Cs_T^{ASR\text{-}SP}$).
- Case total aluminum (Ca_T): All the aluminum of the ASRs change the recycling destination to recyclable materials ($Ca_T^{ASR\text{-}RM}$), all the aluminum of the recyclable materials change the recycling destination to spare parts ($Ca_T^{RM\text{-}SP}$), or all the aluminum of the ASRs change the recycling destination to spare parts ($Ca_T^{ASR\text{-}SP}$).

Figure 3.8 (d) and Fig. 3.9 (d) show the potential energy and CO_2 reduction per vehicle if all the aluminum, steel, or plastics of the ASRs are recycled as recyclable materials. These increments are possible through improvements in the separation process of the materials. As shown, the benefits of changing the recycling destination of 1 kg of plastic from the ASRs to recyclable materials are low; however, considering the total plastic content of the ASRs (123 kg), its beneficial potential of 3,070 MJ and 146 kg-CO_2 per vehicle is much higher than that of the other materials.

Figure 3.8 (e) and Fig. 3.9 (e) show the potential energy and CO_2 reduction per vehicle if the recyclable materials are reused as spare parts. As shown, the total beneficial potential of steel and aluminum is much higher than the total potential calculated for plastics in the ASRs. This reduction potential was estimated as 28,200 MJ and 1,990 kg-CO_2 per vehicle for steel and 21,100 MJ and 271 kg-CO_2 per vehicle. However, the increased quantity of the materials/parts reused as spare parts depends on the market demand and changing the recycling process does not yield a significant effect. Additionally, the recycled steel is obtained primarily from the vehicle body that is not reused as a part.

Finally, Fig. 3.8 (f) and Fig. 3.9 (f) show the high potential by reusing plastic as a spare part owing to its high quantity in the ASRs. This reduction potential was estimated as 3,070 MJ and 1,040 kg-CO_2 per vehicle. However, the limitation of the market demand mentioned previously is also applied here.

3.3.6 Comparisons and the total impact in the entire life cycle

To evaluate the obtained values, different life cycle comparisons are proposed in this study.

First, our results and those of previous studies performed by Schweimer et al. (2000) are compared. Here, the total energy consumption and CO_2 emission in the life cycle of a Volkswagen Golf A4's (1,059 kg) are calculated, and the ELV phase is considered negligible.

Next, our results are compared with the values calculated through a classic life cycle approach. Hence, a rough simulation of the energy consumption and CO_2 emission in the life cycle of the studied vehicle is proposed. Here, the environmental effect of its production phase is approximately equal to the total energy necessary for the production of its vehicle parts (24).

$$E_P = \sum_m EE_m * G_{veh,m} \qquad (24)$$

E_P: Energy consumed in the production phase [kJ per vehicle].

Meanwhile, the energy consumption in the use phase can be calculated using (25).

$$E_U = FE * d * \rho_{gas} * HHV_{gas} \qquad (25)$$

E_U : Energy consumed in the use phase [kJ per vehicle].

FE : Fuel economy, e.g., Honda Accord, 2011, 9.046 l/ 100 km (U.S. Department of Energy, 2011).

d : Total traveled distance, 100,000 km.

HHV_{gas} : Higher heating value of gasoline, 46.4 MJ/kg (Demirel, 2012).

ρ_{gas} : Density of gasoline, 0.75 kg/l (Demirel, 2012).

The energy consumed in the disposal process of the ELV can be obtained using (26).

$$E_{ELV} = ED * G_{veh} \tag{26}$$

E_{ELV} : Energy consumed in the ELV disposal process [kJ per vehicle].

ED : Disposal energy, 602 kJ/kg (Schuckert et al., 1996).

It is noteworthy that the ELV recycling benefits calculated in this research correspond to the energy reduced, and do not include the process calculated by (26) that corresponds exclusively to the consumptions.

In terms of CO_2 emissions, the following equations are proposed. First, the CO_2 emission in the production phase is calculated as follows.

$$CO_{2_P} = \sum_m CO_2E_m * G_{veh,m} \tag{27}$$

CO_{2_P}: CO_2 emitted in the production phase [kg-CO_2 per vehicle]

Moreover, the CO_2 emission in the use phase is obtained as follows.

$$CO_{2_U} = FE * d * \rho_{gas} * EF_{gas} \tag{28}$$

CO_{2_U}: CO_2 emission in the vehicle use phase [kg-CO_2 per vehicle].

EF_{gas} : Emission factor from the combustion of 1 kg of gasoline, 3.3 kg-CO_2/ kg (Demirel, 2012).

Finally, the CO_2 emission in the disposal process is neglected owing to its low value (Wang et al., 2013; Zamel et al., 2006).

Figure 3.10 (a) shows a comparison between the obtained energy consumption values expressed in GJ per kg of vehicle. The superior values of the first column are calculated through the classical approach, and the inferior values of the same column are proposed herein as the current energy reductions by ELV recycling. These benefits represent approximately 16% of energy reduction in the entire vehicle life cycle. The second column, indicated as “improved,” is added to demonstrate the effect in the life cycle when the plastics in the ASRs are totally separated and recycled as raw material (Cp^{ASR-RM}). The third column, indicated as “maximized,” demonstrates the effect when all the plastic, steel, and aluminum recycled as ASRs and recyclable materials are reused as spare parts ($Cp_T^{RM-SP}+Cs_T^{RM-SP}+Ca_T^{RM-SP}+Cp_T^{ASR-SP}+Cs_T^{ASR-SP}+Ca_T^{ASR-SP}$). Finally, the third column indicates the values proposed by Schweimer et al. (2000).

Figure 3.10 (b) shows a comparison between the obtained CO_2 emission values. Similar to energy, the superior part of the first column indicates the values calculated through the classical approach, and the inferior part of the same column the values proposed herein as the current CO_2 reductions by ELV recycling. The recycling benefits represent approximately 13% of CO_2 reduction in the entire vehicle life cycle. A second column is added to indicate the improved life cycle through the increase in plastic separation, and a third column to indicate the life cycle with the maximized utilization of the plastic, steel, and aluminum of the ELV. Finally, the fourth column indicates the values proposed by Schweimer et al. (2000).

The proposed comparisons demonstrate not only the compatibility of the obtained results but also emphasizes the importance of the ELV phase in the entire vehicle life cycle.

Wang et al. (2013) and Zamel et al. (2006) estimated the energy consumption of vehicle scrapping as 307 to 370 kJ per kilogram of vehicle; however, we calculated that the studied phase generates a positive 52 MJ of energy reduction. Additionally, considering the data used by Viñoles-Cebolla et al. (2015), and that 17% of the vehicle weight is destined as ASR, the CO_2 emission of the ELV phase can be calculated as 0.261 kg-CO_2 per kilogram of vehicle; our study shows a positive 2.80 kg-CO_2 of CO_2 reduction.

In contrast to the classic life cycle approaches where only direct consumption and emission are considered, our results assess the cycle comprehensively in that the demerits and benefits of the phases are evaluated.

3.3.7 Possible changes in ELV recycling

The ELVs are recycled efficiently in terms of energy and CO_2. However, it still presents an important reduction potential.

The increased quantity of reused vehicle parts exhibits the highest effect in terms of energy and CO_2 reductions. However, this opportunity is limited by the demand of the aftermarket and vehicle models, and possible measures in terms of improving the restricted recycling process.

The diminution of the material recycled as ASRs can also improve the reduction benefits of the ELVs considerably. Hence, improvements in plastic separation and recycling are the key factors. As an example, the unification of plastics used in vehicle production (PP, ABS, and others) to facilitate the related recycling process can be studied.

In terms of the recyclable materials, aluminum exhibits the highest energy and CO_2 reduction values per kilogram of material owing to the significant difference between the energy and CO_2 necessary for the production of virgin and recycled aluminum. This implies that the initial energy and CO_2 "investments" necessary for the production of virgin aluminum can be compensated by the energy and CO_2 reduced in its recycling and by its lightweighting benefits.

Finally, steel, which is the principal material of a vehicle, exhibits a low reduction level per unit of material recycled and can be substituted by alternative lightweight materials with high recyclability benefits.

Future studies should target either cost or probabilistic analysis to numerically assess the percentage of energy reduction and CO_2 reduction that are actually feasible through the proposed changes.

Compared with previous studies, our study concludes the vehicle life cycle through a recycling assessment. The results provided insights into the proposal of new approaches for life cycle analysis including the introduction of alternative lightweight materials during vehicle design. Hence, limitations in vehicle design should be considered. The results of this research will be important as a basis for the analysis of cyclical resource strategies of high quantities of rare metals used in the production of electric vehicles.

The results of our study indicate that currently, ELVs represent 16% and 13% of energy and CO_2 reductions in the vehicle life cycle, respectively, highlighting the importance of the study phase. These values were calculated for the Japanese vehicle market and can vary depending on the country being analyzed. However, the high energy and CO_2 reduction potential expected by correct recycling and the proposed evaluation method can be applied without considering this limitation.

3.4 Conclusion

A principal method to assess the environmental effect of a vehicle is through the analysis of its life cycle; nevertheless, according to the author’s knowledge, no comprehensive work has been dedicated to understand the total benefits of ELV recycling.

This paper highlighted the importance of the aforementioned phase, providing a new framework to assess vehicle life environmentally, and also showed that a wrong decision or policy making through the insufficient analysis of this phase could generate a national level energy and CO_2 inconvenient affecting the current reduction values. The recycling process of ELVs was clarified and their material flow elaborated. The scrapped vehicles were dismantled in three flows (ASR, recyclable materials, and spare parts), and recycled through three different methods (energy recovery, material recycling, and part reusing).

The primary conclusions of the study are listed below:

- The energy reduction by ELV recycling was estimated as 52 MJ per kilogram of vehicle (16% of energy reduction in the life cycle), and the benefits for the entire Japanese market as 247 PJ/ year.
- The CO_2 reduction by ELV recycling was estimated as 2.80 kg-CO_2 per kilogram of vehicle (13% of the CO_2 reduction in the life cycle), and the benefits for the entire Japanese market as 13.1 Mt-CO_2/ year.
- The flow with the highest level of contribution in terms of energy and CO_2 was that of the spare parts, followed by those of the recyclable materials and ASRs.
- In general, the ELVs were recycled efficiently, however, it still presented an important reduction potential. The increased use of reused spare parts presented significant effects in terms of energy and CO_2 reductions. Additionally, these benefits could be improved through the reduction in the recycled materials as ASRs. Hence, improvements in plastic separation and recycling were shown to be vital.
- The metals were primarily separated as recyclable materials. Here, aluminum was the primary contributor in terms of energy and CO_2 reductions. Steel demonstrated low reduction levels per unit of material recycled, and the substitution of steel with alternative lightweight materials with high recycling potential should be evaluated.

Finally, we conclude that the correct evaluation of the ELV could be important for future vehicle life cycle improvement strategies, where not only the first two phases should be considered but also the benefits generated through its recycling process.

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Table 3.1 Weight, sales and material composition of the studied 42 reused parts

Part name	Weight (kg)	Sales (units)	Material composition									
			Steel	Iron	Plastic	Foam	Glass	Rubber	Alum	Copper	Misc.	Source
Exterior parts												
Front bumper ASSY	13.86	142,646	57.43%		42.57%							c)
Rear bumper ASSY	12.34	119,059	63.21%		36.79%							c)
Right fender	4.03	116,786	100.00%									c)
Left fender	4.03	121,557	100.00%									c)
Front right door ASSY	28.18	70,588	63.96%		9.55%		9.85%	3.83%			12.81%	c)
Front Left door ASSY	28.18	84,269	63.96%		9.55%		9.85%	3.83%			12.81%	c)
Rear right door ASSY	23.73	56,094	62.31%		9.54%		13.06%	4.07%			11.02%	c)
Rear Left door ASSY	23.73	104,220	62.31%		9.54%		13.06%	4.07%			11.02%	c)
Windshield	13.94	5,471					100.00%					b)
Right door mirror	1.32	99,152			65.00%		25.00%		2.00%	2.00%	6.00%	a)
Left door mirror	1.32	114,313			65.00%		25.00%		2.00%	2.00%	6.00%	a)
Right headlight ASSY	3.43	159,516			85.00%			8.00%		2.00%	5.00%	a)
Left headlight ASSY	3.43	158,654			85.00%			8.00%		2.00%	5.00%	a)
Bonnet hood	17.90	108,469	84.92%								15.08%	c)
Trunk lid	12.37	11,136	80.44%								19.56%	c)
Rear right taillight	1.27	133,780			85.00%			8.00%		2.00%	5.00%	a)
Rear left tail light	1.27	125,928			85.00%			8.00%		2.00%	5.00%	a)
Rear window glass	7.44	8,342					100.00%					b)
Interior parts												
Front seat (driver)	22.87	7,614	69.96%		9.01%	12.02%					9.01%	c)
Front seat (assistant)	22.87	1,787	69.96%		9.01%	12.02%					9.01%	c)
Rear seat	21.03	1,850	37.80%		2.95%	33.86%					25.39%	c)
Engine parts												
Engine ASSY	169.90	135,853	46.13%						21.68%		32.19%	c)
Muffler ASSY	14.29	831	99.99%								0.02%	b)
Fuel tank	12.00	11,133			100.00%							a) c)
Starter motor / cell motor	1.50	143,790	36.10%						36.10%	27.80%		a) b)
Alternator / dynamo	1.50	177,027	36.10%						36.10%	27.80%		a) b)
Radiator	4.42	65,265	5.00%						85.00%		10.00%	a)
Underbody parts												
Transmission	96.70	58,820	30.00%	30.00%	5.00%			5.00%	30.00%			b)
Steering rack & pinion	8.24	58,394	30.00%		5.00%				53.00%		12.00%	a) c)
Right front drive shaft	7.60	64,079	100.00%									b)
Left front drive shaft	7.60	79,251	100.00%									b)
Right front strut ASSY	7.40	47,709	100.00%									b)
Left front strut ASSY	7.40	54,637	100.00%									b)
Tire	43.44	226,505						100.00%				a) c)
Wheel	46.96	70,369	100.00%									b)
Right rear strut ASSY	5.10	7,673	100.00%									b)
Left rear strut ASSY	5.10	8,208	100.00%									b)
Right front knuckle ASSY	21.45	17,150		69.70%					26.18%		4.13%	a) c)
Left front knuckle ASSY	21.45	20,385		69.70%					26.18%		4.13%	a) c)
Electrical parts												
Cooler compressor	5.74	108,303	10.00%	35.00%					35.00%		20.00%	a)
Cooler condenser	4.20	38,580							90.00%		10.00%	a)
Battery	12.40	15,089			6.10%						93.90%	b)
Various parts (280 parts)	0.97	2,988,408	0.93%	5.58%	42.94%		0.08%	2.26%	35.08%	7.00%	6.14%	

a) Authors estimation

b) Data from Burnham et al., 2006, 2012

c) Data from Singh, 2012

Table 3.2 Energy reduction coefficients for each proposed method

[kJ/kg]

Material	Energy recovery		Part reusing		Material recycling		
	Heating value		Embodied energy		Material production 100% virgin	100% recycled	
		Ref.		Ref.			Ref.
Steel	n/a		63,965	c)	40,000	30,000	d),e),f)
Iron	n/a		63,965	c)	40,000	30,000	d),e),f)
Plastic	38,016	a)	108,651	c),g)	90,000	45,000	d),e),f)
Glass	n/a		55,126	c)	30,000	15,000	d),e),f)
Rubber	23,121	a)	153,749	c)	70,000	43,600	d),e),f)
Aluminum	n/a		341,924	c)	220,000	40,000	d),e),f)
Copper	n/a		126,768	c)	100,000	45,000	d),e),f)
Fluid	43,400	b), g)	46,985	c)	46,985	0	c),g)
Misc.	n/a		63,965	c),g)	40,000	30,000	d),e),f),g)
Foam	18,962	a)	n/a		n/a	n/a	
Textile	17,041	a)	n/a		n/a	n/a	
Wood	15,719	a)	n/a		n/a	n/a	
Paper	16,916	a)	n/a		n/a	n/a	
Wire harness	20,711	a)	n/a		n/a	n/a	
Mix metal	n/a		n/a		40,000	30,000	d),e),f),g)
Cement, slag, others	n/a		n/a		0	0	g)*

a) Kim et al., 2004

b) DUKES, 2017

c) Das et al., 1995

d) Weiss et al., 2000

e) Schuckert et al., 1996

f) Wang et al., 2013

g) Author estimation

*Considered as sub-product of the recycling process

Table 3.3 CO_2 reduction coefficients for each proposed method

[kg-CO_2/kg]

Material	Energy recovery		Part reusing		Material recycling		
	Emission factor	Ref.	Embodied CO_2	Ref.	CO_2 emitted 100% virgin	100% recycled	Ref.
Steel	n/a		5.510	c)	2.100	0.400	d)
Iron	n/a		7.710	c)	2.100	0.400	d),g)
Plastic	2.652	a)	8.070	c)	2.100	1.300	e)
Glass	n/a		1.468	c)	0.380	0.230	d)
Rubber	2.652	a)	13.579	c)	3.040	1.893	f),g)
Aluminum	n/a		7.648	f),g)	6.660	1.100	f)
Copper	n/a		6.239	c)	2.580	1.161	f),g)
Fluid	2.222	b)	8.441	c)	7.380	0	c),g)
Misc.	n/a		5.510	c),g)	2.100	0.400	d),e),f),g)
Foam	2.652	a)	n/a		n/a	n/a	
Textile	1.280	a)	n/a		n/a	n/a	
Wood	0.568	a)	n/a		n/a	n/a	
Paper	1.279	a)	n/a		n/a	n/a	
Wire harness	0.884	a),g)	n/a		n/a	n/a	
Mix metal	n/a		n/a		2.100	0.400	d),g)
Cement, slag, others	n/a		n/a		0	0	g)*

a) McDougall et al., 2001

b) EPA, 2014

c) Nishimura et al., 2001 and 1997

d) CEPA, 2011

e) Hillman et al., 2015

f) GREET, 2015

g) Author estimation

*Considered as sub-product of the recycling process

Table 3.4 End-of-life vehicle recycling benefits in Japan

a) Energy reduction per vehicle by recycling methods and material destinations

[GJ per vehicle]

	Energy recovery ER^{ERE}	Material recycle ER^{MR}	Part reuse ER^{PR}	Total ER
ASR	3.4	0.5		3.9
Recyclable materials	1.7	32.8		34.4
Spare parts			39.9	39.9
Total	5.1	33.3	39.9	78.3

b) CO_2 reduction per vehicle by recycling methods and material destinations

[kg-CO_2 per vehicle]

	Energy recovery CO_2R^{ERE}	Material recycle CO_2R^{MR}	Part reuse CO_2R^{PR}	Total CO_2R
ASR	-60	30		-20
Recyclable materials	20	1,940		1,960
Spare parts			2,220	2,220
Total	-40	1,970	2,220	4,160

c) Waste generated and benefits for the entire Japanese vehicle market

Analyzed item		Waste and benefits		Share [*)]	
Scrapped material	G_{JPN}	4.67	Mt/year	10	%
Energy reduction	ER_{JPN}	247	PJ/year	2.2	%
CO_2 reduction	CO_2R_{JPN}	13.1	Mt-CO_2/year	1.1	%

[*)] Considering the total nonindustrial waste generated in Japan as 44.87 Mt/year (SBJ, 2016), total energy consumption as 11.33 EJ/year (Takita et al., 2015), and total CO_2 emitted as 1,246 Mt-CO_2/year (Takita et al., 2015)

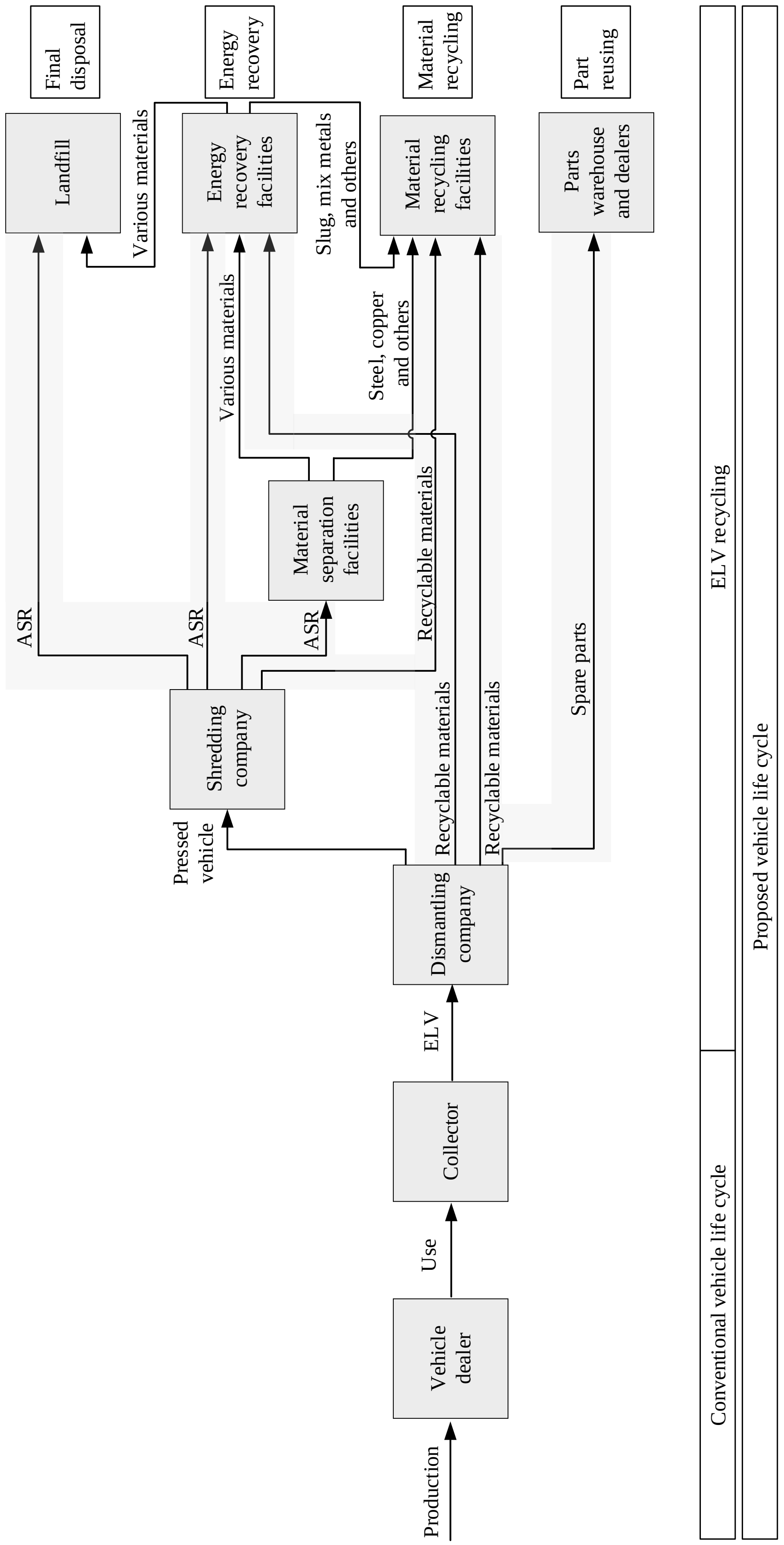
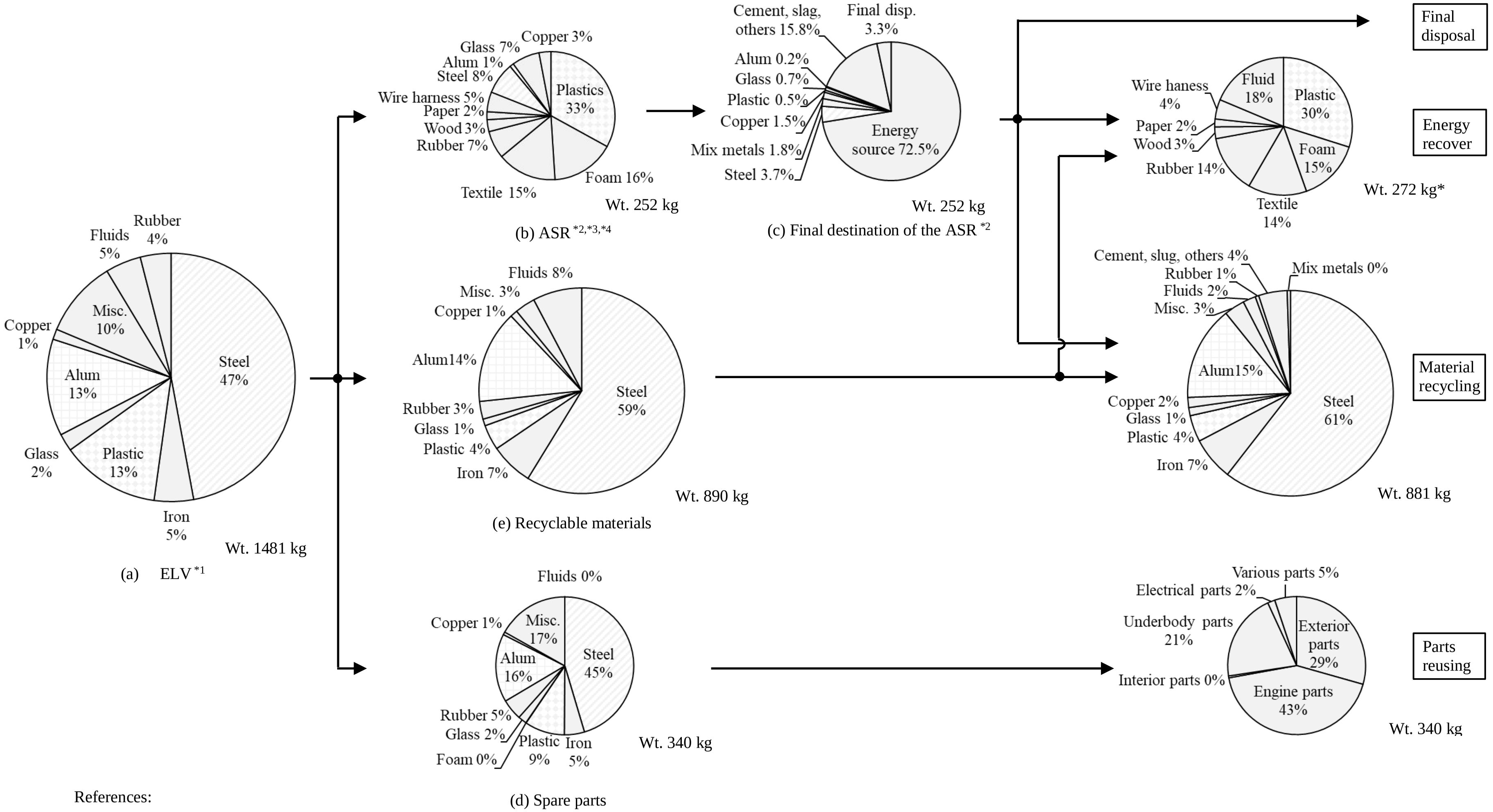


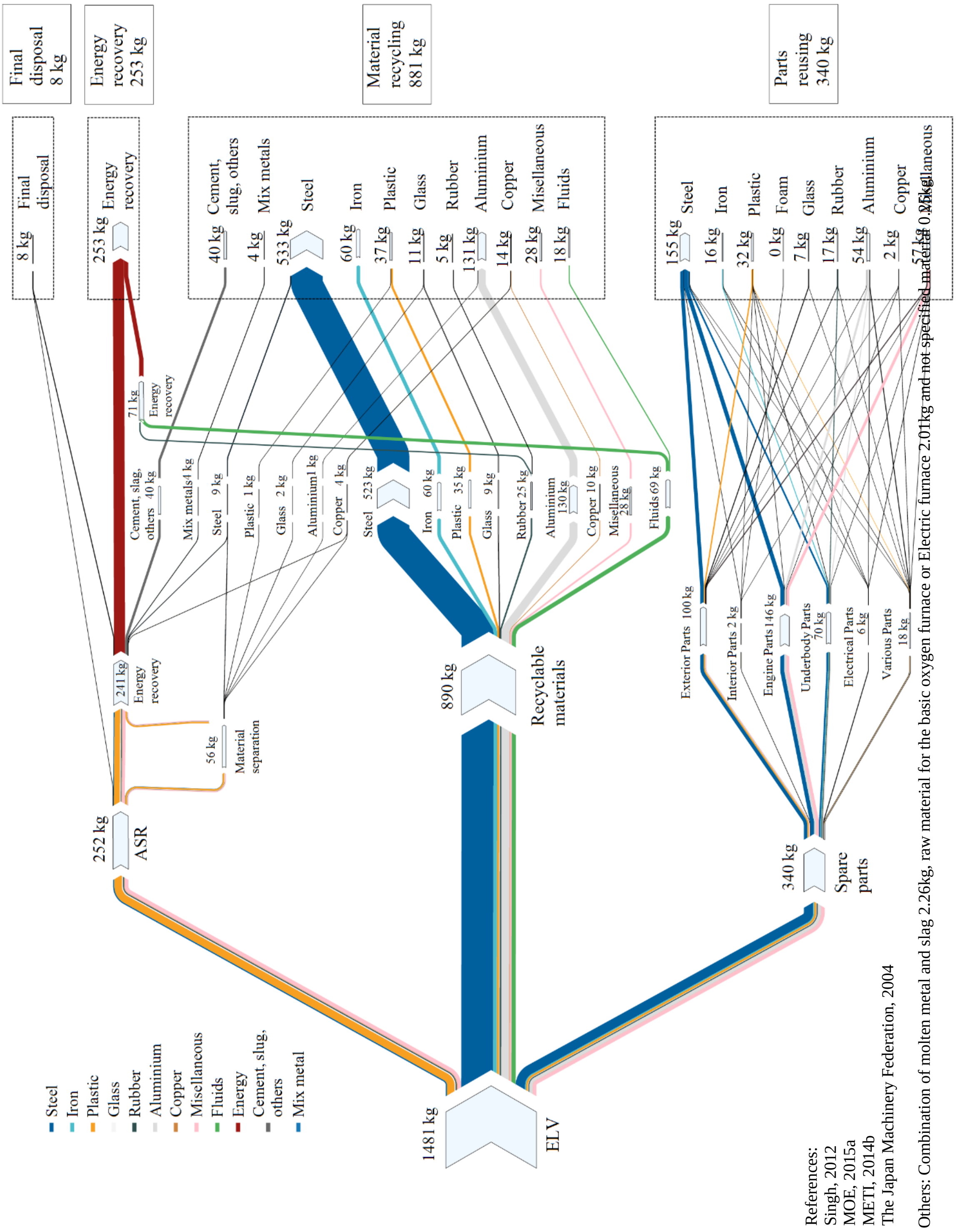
Fig. 3.1 Current vehicle life cycle and recycling system



*Indicates the weight of the burnable input of the energy recovery system differing from output indicated in the material flow.

References:
*1 Singh, 2012
*2 MOE, 2015a
*3 METI, 2014b
*4 The Japan Machinery Federation, 2004

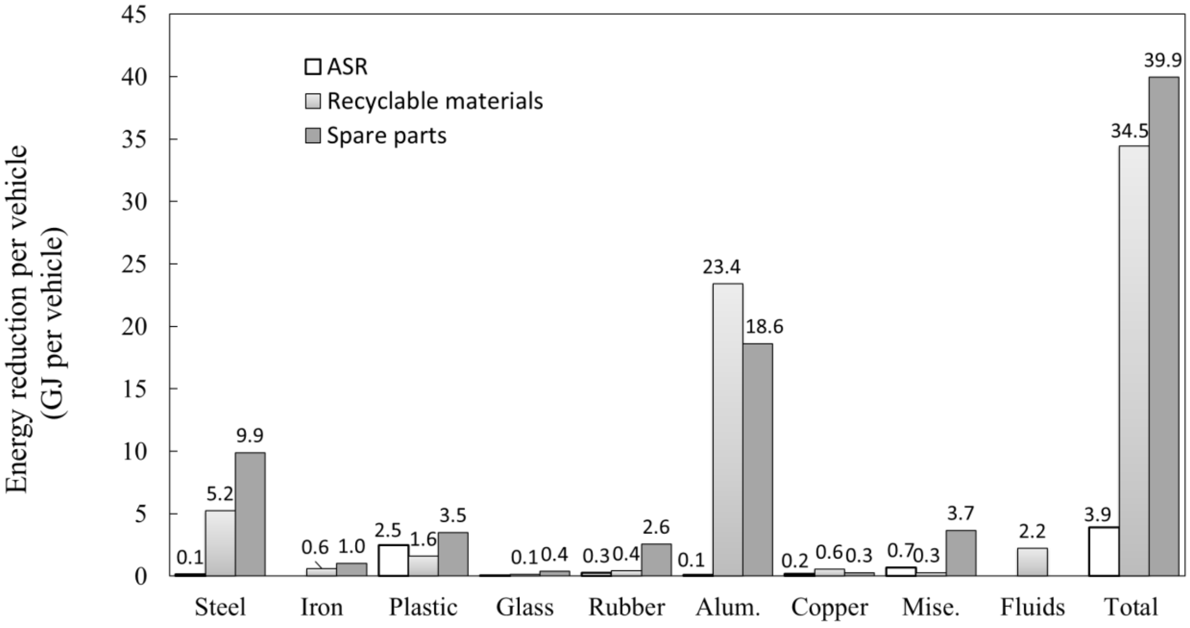
Fig. 3.2 Weight percent of ASR, recyclable materials and spare parts



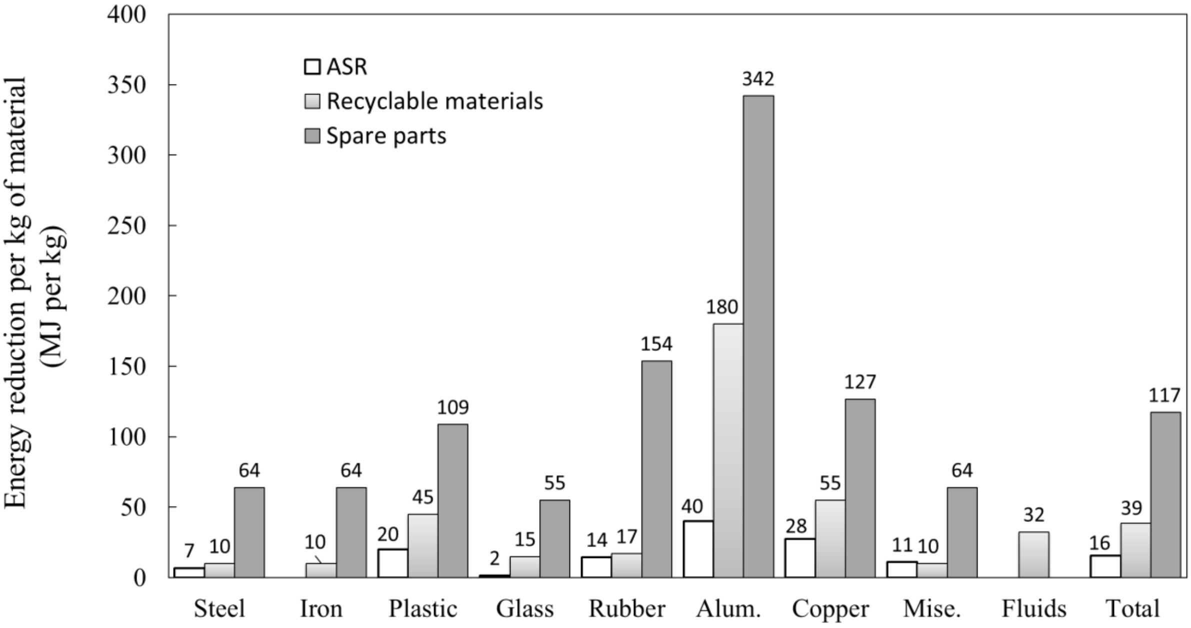
References:
Singh, 2012
MOE, 2015a
METI, 2014b
The Japan Machinery Federation, 2004

Others: Combination of molten metal and slag 2.26kg, raw material for the basic oxygen furnace or Electric furnace 2.01kg and not specified material 0.25kg

Fig. 3.3 Current material flow of an ELV

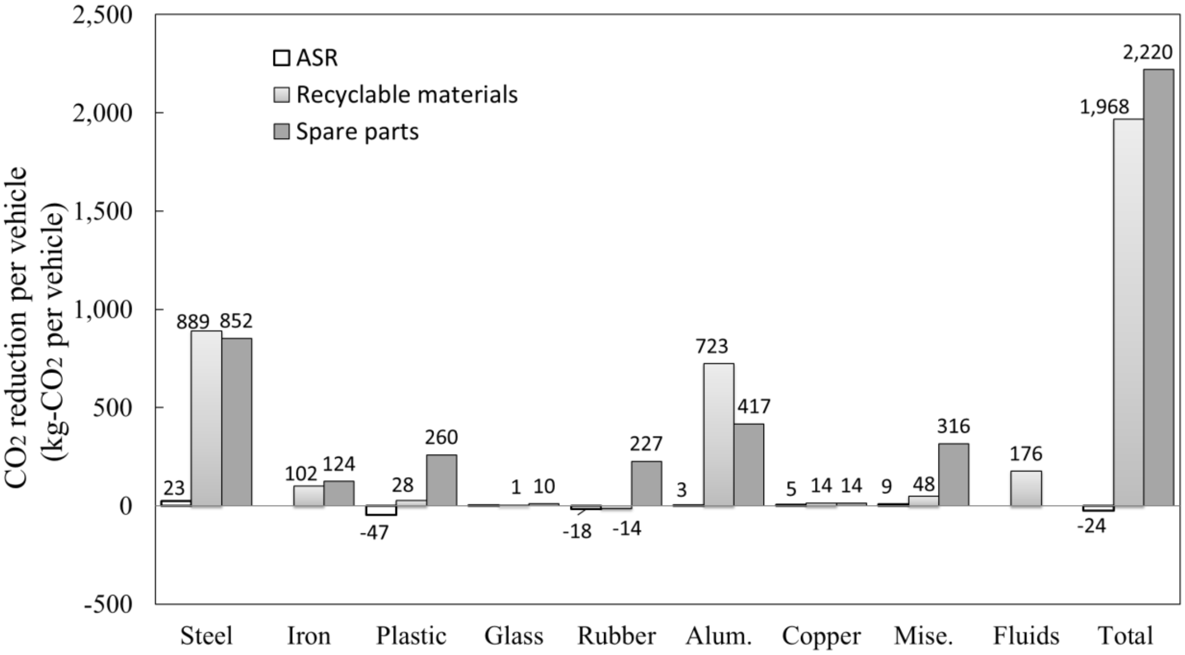


(a) Per vehicle and destination

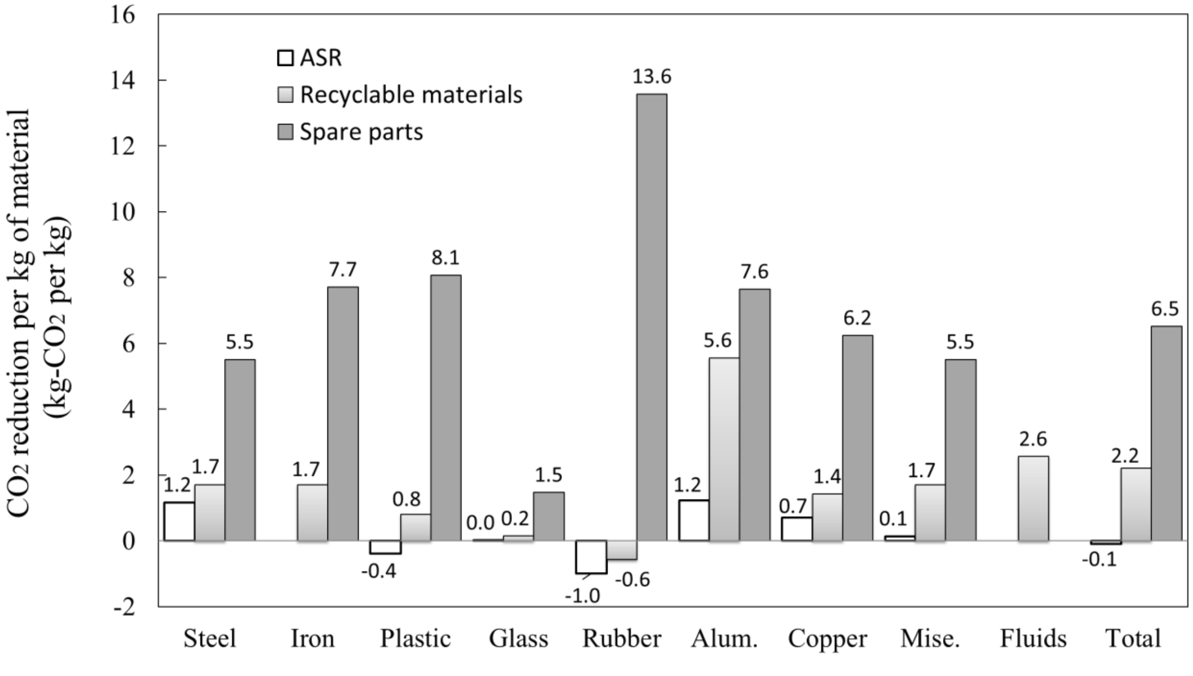


(b) Per unit of material and destination

Fig. 3.4 Energy reductions

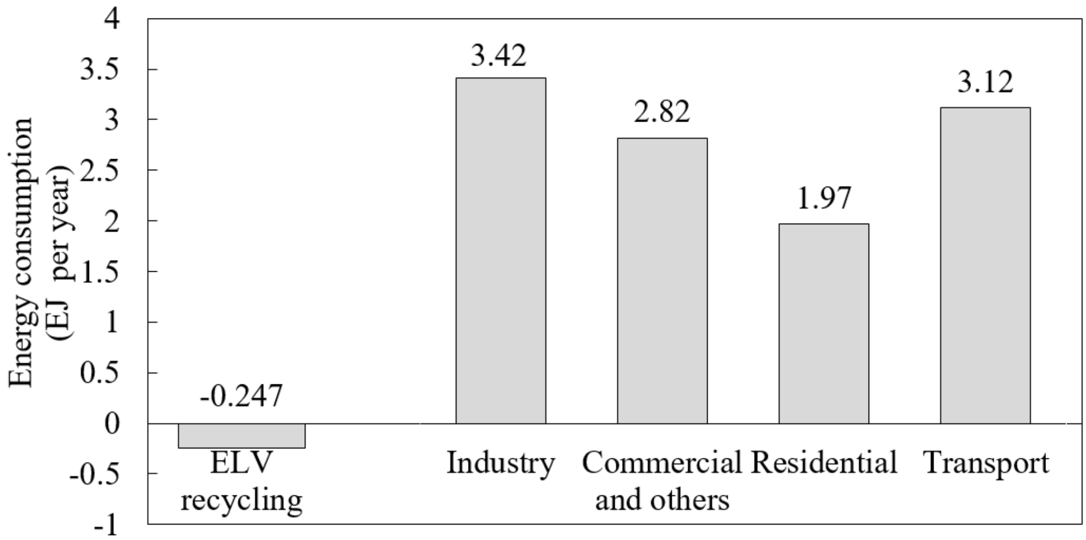


(a) Per vehicle and destination



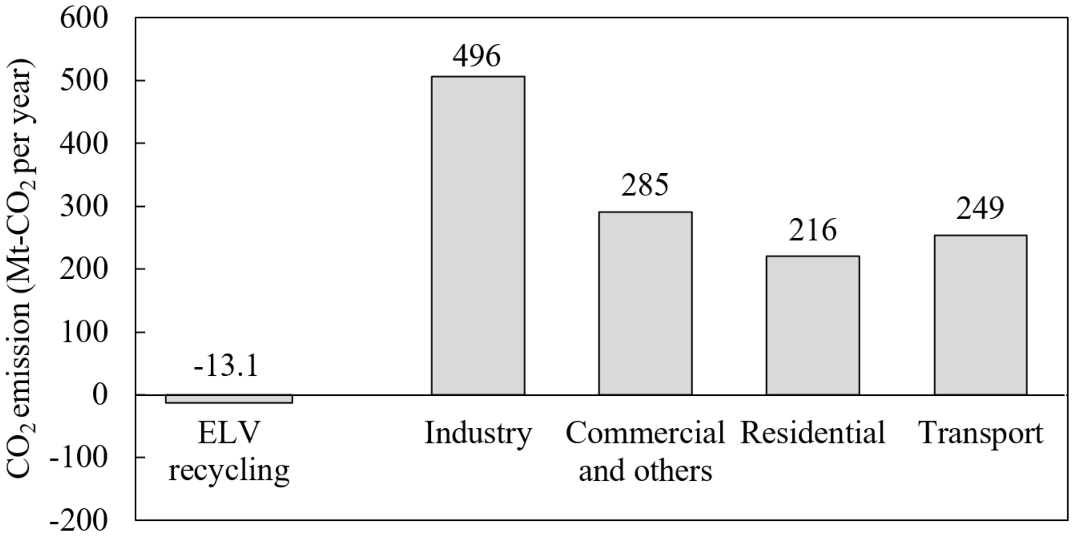
(b) Per kg of material and destination

Fig. 3.5 CO_2 reductions



References: Takita et al., 2015

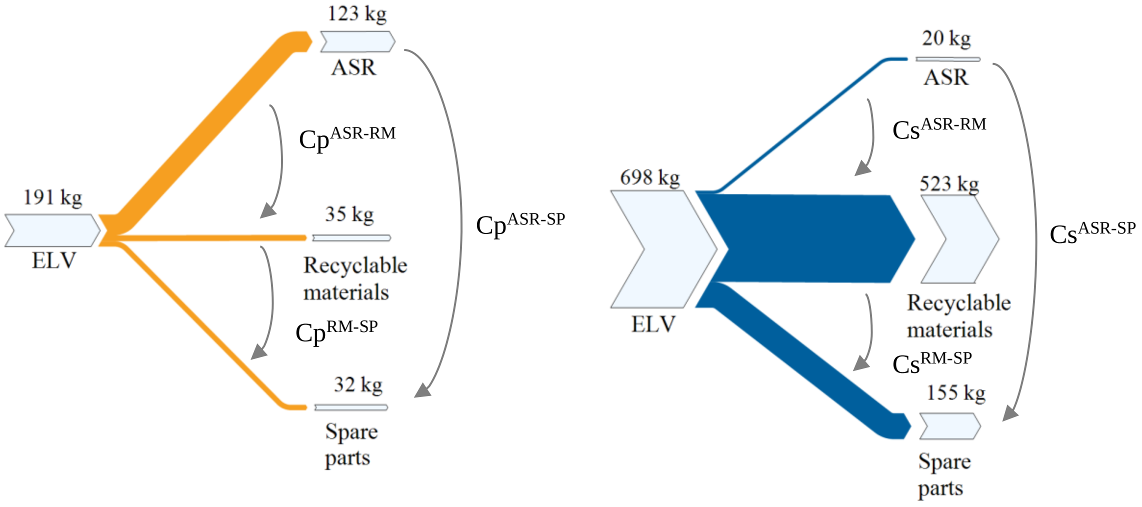
a) Energy demand by sector



References: Takita et al., 2015

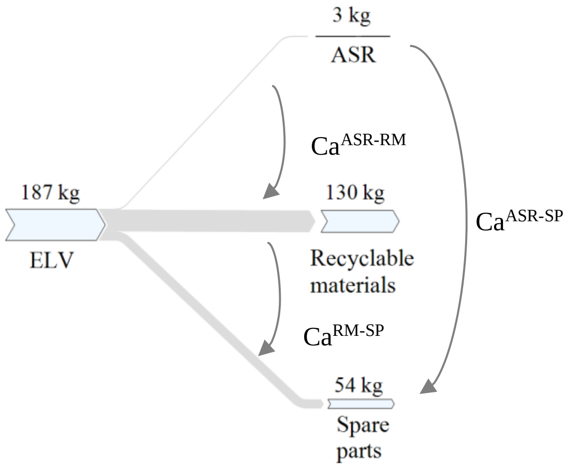
b) CO_2 emission by sector

Fig. 3.6 Effects of the ELV recycling on energy consumption and CO_2 emission



a) Plastic

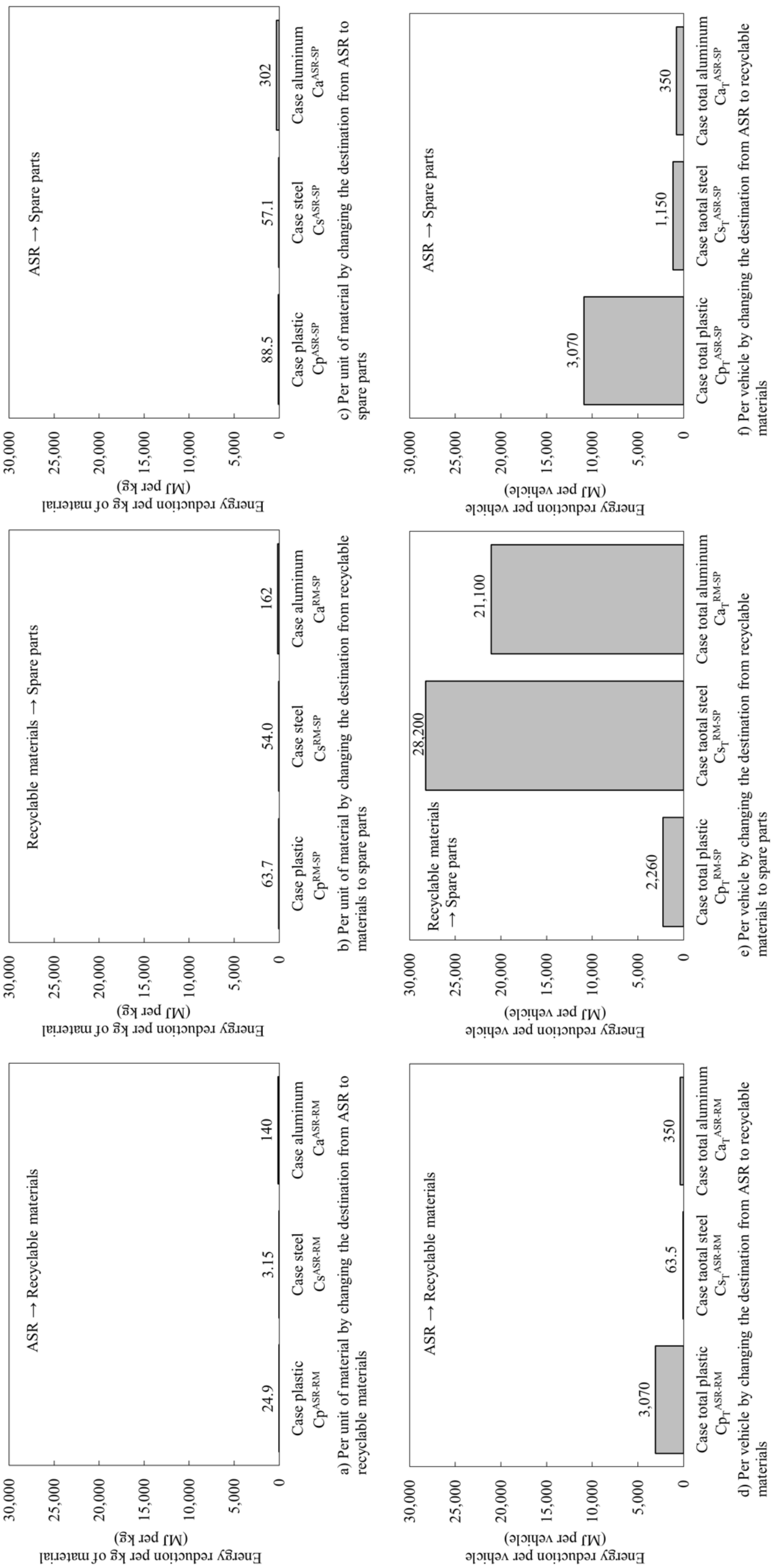
b) Steel



c) Aluminum

[kg/vehicle]

Fig. 3.7 Destination of the plastic, steel and aluminum of an ELV, and case settings for the sensitivity analysis



a) Per unit of material by changing the destination from ASR to recyclable materials

b) Per unit of material by changing the destination from recyclable materials to spare parts

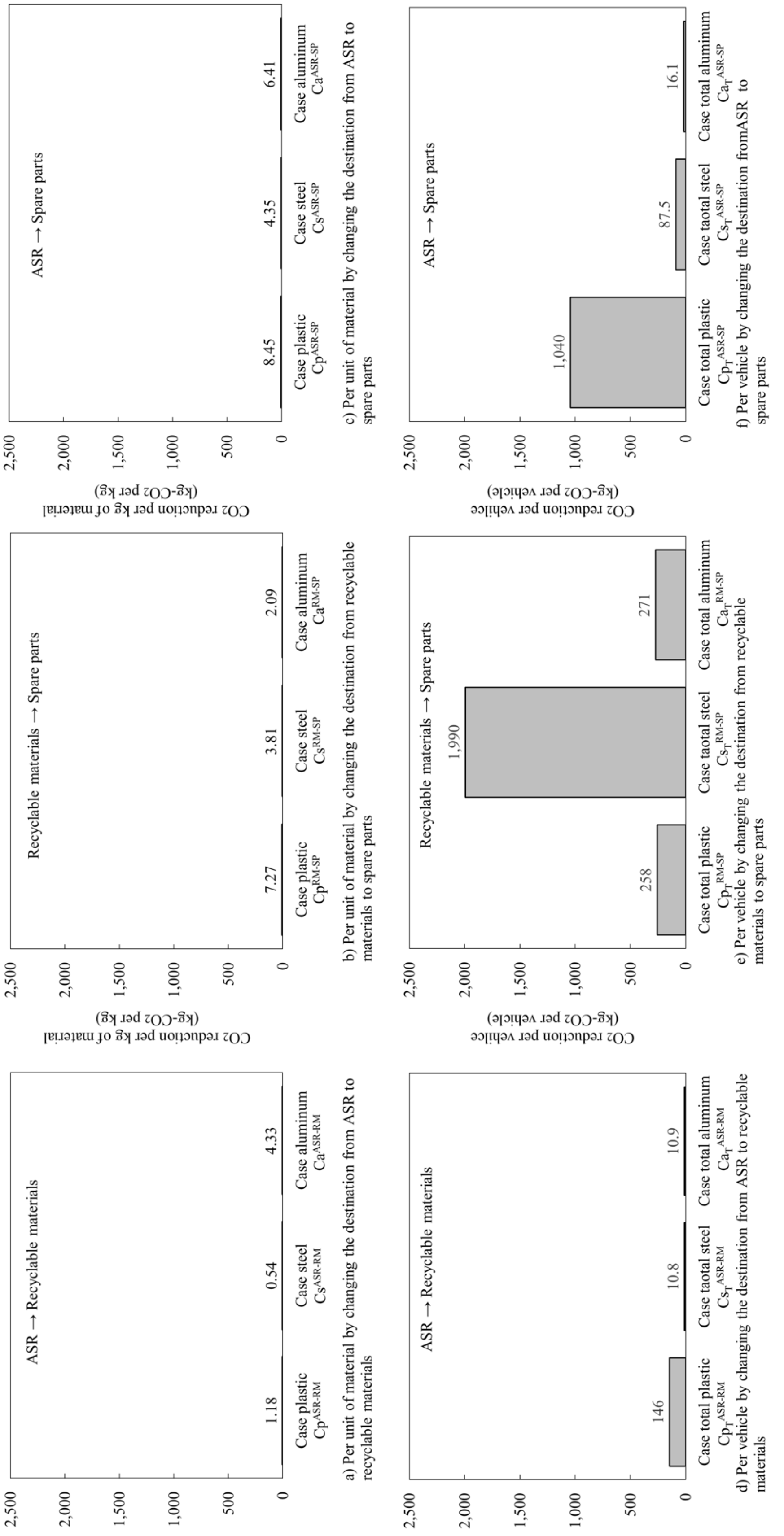
c) Per unit of material by changing the destination from ASR to spare parts

d) Per vehicle by changing the destination from ASR to recyclable materials

e) Per vehicle by changing the destination from recyclable materials to spare parts

f) Per vehicle by changing the destination from ASR to recyclable materials

Fig. 3.8 Potential energy reduction by changing the recycling destination of ELV



a) Per unit of material by changing the destination from ASR to recyclable materials

b) Per unit of material by changing the destination from recyclable materials to spare parts

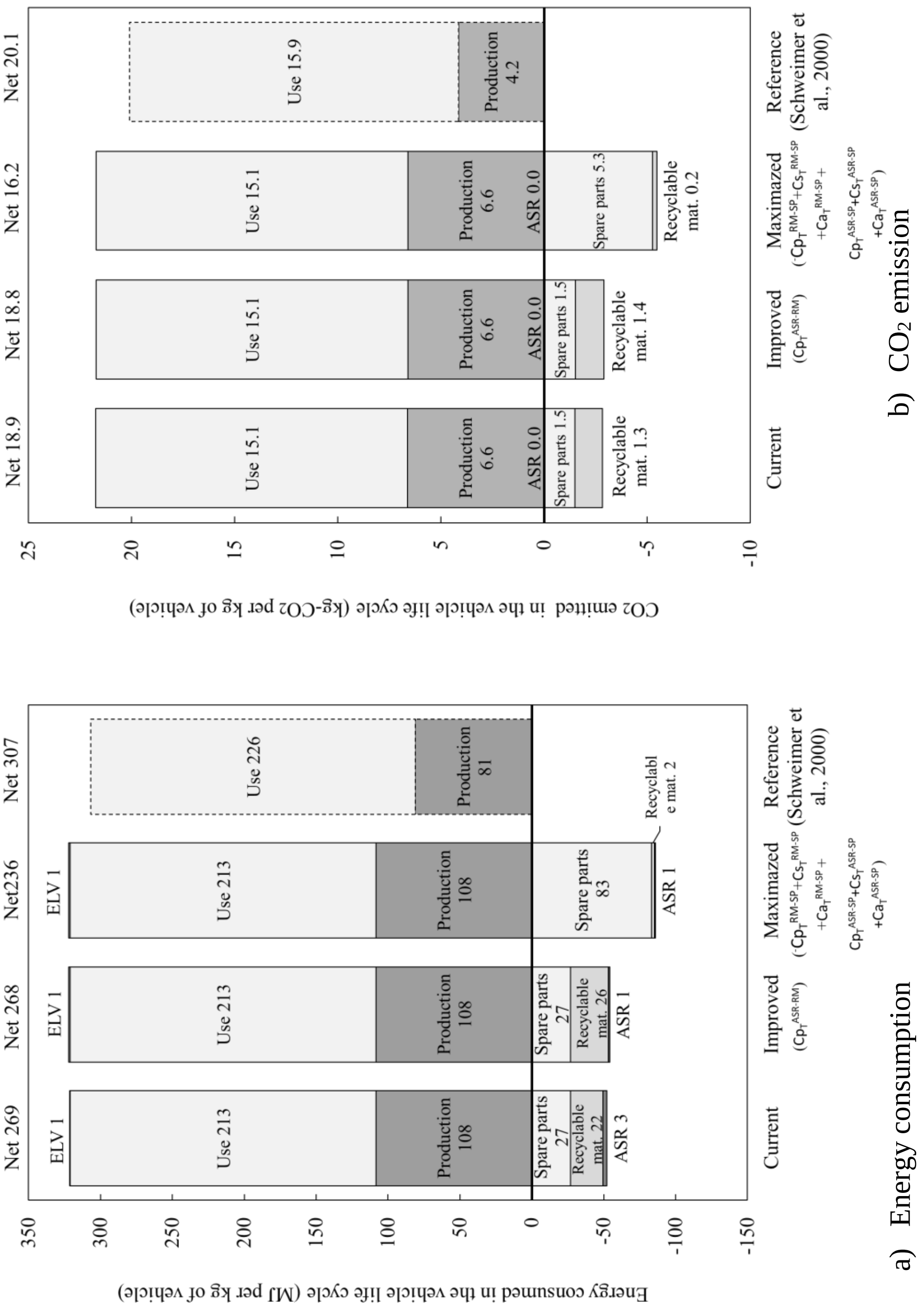
c) Per unit of material by changing the destination from ASR to spare parts

d) Per vehicle by changing the destination from ASR to recyclable materials

e) Per vehicle by changing the destination from recyclable materials to spare parts

f) Per vehicle by changing the destination fromASR to spare parts

Fig. 3.9 Potential CO_2 reduction by changing the recycling destination of ELV



a) Energy consumption

b) CO_2 emission

Fig. 3.10 Comparative between life cycle studies

4. Assessment of vehicle lightweighting on recycling benefits considering life cycle energy and CO_2 reductions

4.1 Introduction

A typical method of evaluating the energy and CO_2 efficiency of a vehicle is through the analysis of its life cycle, and many approaches of it have been proposed during the last decades. Some studies estimated that the production phase constitutes 7–22% and the use phase 79–93% of the energy consumed and CO_2 emitted of the entire cycle (Schweimer et al., 2000; Kobayashi Osamu, 1997; Nemry et al., 2008). Moreover, previous studies performed by most of the authors considered the end-of-life vehicles (ELVs) insignificant, representing at the most 1% of the energy consumption and CO_2 emission of the vehicle life cycle.

At present, approximately 50%–60% of the end of life vehicle weight is separated as recyclable material, 20%–30% reused as second-hand spare parts and 17% processed as automotive shredder residue (ASR) (METI, 2014 (a)). Moreover, those material are subjected to three recycling methods; material recycling, parts reusing, and energy recovery. Previous studies (Sato et al., 2018, 2019) highlight the importance of this phase indicating that the ELV phase represents 16% and 13% of energy and CO_2 reduction of the entire vehicle life cycle, but also emphasized that the benefits of recycling depend strongly on the material composition of the vehicle and the recycling method they are subjected.

A vehicle is made by more than 20,000 parts, and the materials used in its production are selected from the standpoint of security, environment, functional, productivity, as well as, economic perspective. Moreover, it is well known that steel and iron accounts for the majority of vehicle weight and represent approximately the 64% of the total weight of a vehicle (Singh Harry, 2012).

Various studies about the environmental effects of lightweighting have been carried out focusing the attention on the production and/or use phase of the vehicle without considering the ELV phase

(González Palencia et al. 2014, 2015; Das et al., 2016; Luk et al., 2017; Koffler et al., 2009); and it is said that 100 kg of mass reduction in an automobile results in a fuel saving of 0.1 l to 0.32 l per 100 km driven (Cheah et al., 2007; Pagerit et al., 2006; Carlson et al., 2013; Kim et al., 2016) . Few studies as Das (2000, 2005, 2011) and Modaresi et al. (2014) include the ELV benefits in their study. However, those studies analyze one type of alternative material and comparison with other lightweight materials are not conducted. Mayyas et al. (2012) and Lewis et al. (2014), Dhingra et al. (2014) and Kim et al. (2013) analyze different types of lightweight materials but they consider fictitious scenarios where only material recycling is contemplated and other possible destinations as part reusing and energy recovery are disregarded. Other studies as O'Reilly et al. (2016) emphasize the importance of ELV phase in lightweight scenarios; however, numerical analysis is not conducted.

In this sense and according to the author’s knowledge, no comprehensive work has been dedicated to understanding the total effect of material lightweighting in the vehicles including the effect of the possible recycling destinations of its parts.

Currently, steel from ELVs are efficiently separated through magnetic segregation; non-ferrous metals as aluminum and copper partially separated by operators (Toyota Metal Corp., 2019); and plastics mainly subjected to energy recovery (Sato et al., 2019). Future massive migration from vehicle parts made of steel to lightweight materials will drastically change the current benefits of the ELV phase. Our study analyzes those possible scenarios numerically clarifying the life cycle energy and CO_2 emission effects of new materials cases for the upcoming vehicles.

New technologies and materials for vehicle production can be correctly assessed when the ELV phase is also considered. Carmakers, part-makers, and governments should define strategies and policies to achieve a sustainable transportation sector understanding the environmental limitations of each material to reach a circular economy. In this sense our approach can help to identify recycling and material separation process to be prioritized for development.

Finally, vehicle users are going to be able to comprehend the total environmental effect of the selected vehicles if results of the proposed assessment are placed at the disposal of the clients, promoting in this way a more socially responsible purchase.

This section aims to quantitively evaluate the reductions in energy consumption and CO_2 emissions of vehicles by the introduction of lightweight materials considering also the possible effects of its recycling system. For this propose, the entire life cycle of the vehicle is assessed for the Japanese market. Here, lightweighting of the body in white through the use of aluminum, advanced high strength steel and carbon fiber reinforced plastic is analyzed as a case study.

4.2 Methodology

Fig. 4.1 shows the concept of this research, where the total energy consumption and CO_2 emission of a vehicle vary depending on the material composition of its parts and the recycling method they are subjected to. Moreover, Fig. 4.2 shows the analysis flow of this research.

Here, the total life cycle energy consumption and CO_2 emission of the vehicle (i.e., production, use and ELV phase) is calculated as the sum of the consumptions and emissions of its parts and components (1)(2).

$$E_{LC_{vehicle}} = \sum_i E_{LC_i} \tag{1}$$

$E_{LC_{Vehicle}}$: Energy consumed in the vehicle life cycle [MJ].

E_{LC_i} : Energy consumed in the vehicle life cycle related to part *i* [MJ].

$$CO_{2\,LC_{vehicle}} = \sum_i CO_{2\,LC_i} \tag{2}$$

$CO_{2\,LC_{Vehicle}}$: CO2 emitted in the vehicle life cycle [kg-CO2].

$CO_{2\,LC_i}$: CO2 emitted in the vehicle life cycle related to part *i* [kg-CO2].

4.2.1 Energy consumption assessment for vehicle parts

The energy consumption in the vehicle life cycle related to a specific part can be calculated as the sum of the energy consumed of its phases (3).

$$E_{LC_i} = E_{P_i} + E_{U_i} + E_{ELV_i} \tag{3}$$

E_{P_i} : Energy consumed in the production phase related to vehicle part *i*. [MJ].

E_{U_i} : Energy consumed in the use phase related to part *i* [MJ].

E_{ELV_i} : Energy consumed in the ELV phase related to part *i* [MJ].

Das et al. (1995) defined the embodied energy as "The energy contained in a fabricated material part, reflecting the energy required to process the material from raw material to finished product". The energy consumed in the production phase of a part is calculated considering those values and the weight of the materials utilized in its production (4).

$$E_{P_i} = \sum_m EE_m * G_{i,m} \tag{4}$$

EE_m: Embodied energy of the material *m* for vehicle part production [MJ/kg].

$G_{i,m}$: Weight of the material *m* of a part *i* [kg].

The energy consumption in the use phase of a part can be divided into two; the "mass induced energy consumptions" and "other energy consumptions" (5).

$$E_{U_i} = E_{U(m.i.)_i} + E_{U(other)_i} \tag{5}$$

$E_{U(m.i.)_i}$: Mass induced energy consumption in the use phase related to vehicle part i. [MJ].

$E_{U(other)_i}$: Other energy consumption in the use phase related to vehicle part i. [MJ].

Here, the mass induced energy consumption is defined as the consumption in the use phase of the vehicle related to the analyzed part that varies depending on the weight of it. This value is calculated base on previous studies of Koffler et al. (2010) and O'reilly et al. (2016) (6).

$$E_{U(m.i.)_i} = \frac{d}{d_{DC}} * W_{T_i} * (1 + L_{Gear}) * \eta_{diff} * U_{gas} \tag{6}$$

W_{T_i} : Total work required to move the part *i* during the analyzed drive cycle. [J].

d : Distance travelled by the vehicle, 100,000 km.

d_{DC} : Distance of the analyzed drive cycle [km].

η_{diff} : Differential efficiency of the engine, adopted as 0.0731 l/MJ (Koffler et al., 2009).

L_{Gear} : Energy lost in the gearbox, adopted as 0.02 (Koffler et al., 2009).

U_{gas} : Energy density of the gasoline, adopted as 32 MJ/l.

It should be made clear that this value represents the energy needed to transport the parts, and that engines, h-vac, and electric components are subjected to additional energy consumption explicitly related to its functionalities. Those values are included in other energy consumptions.

Reducing the mass of the vehicle part, the acceleration and the roll resistance of the vehicle will also decrease. On the other hand, the part shape affects the aerodynamic resistance. Total work required to move the part derives from the mentioned three types of resistances and its relation can be represented by the equations (7).

$$W_{T_i} = (1 - r)\, W_{R_i} + W_{L_i} + W_{a_i} \qquad (7)$$

W_{R_i} : Work needed to overcome the rolling resistance of the part i. [J]

W_{L_i} : Work needed to overcome the aerodynamic resistance of the part *i* [J].

W_{a_i} : Work needed to overcome the acceleration resistance of the part *i* [J].

r : Deceleration rate in the analyzed drive cycle

The values of each work are calculated by the following equations (8)(9)(10) (Koffler et al., 2010; O'reilly et al., 2016).

$$W_{R_i} = G_i * g * f_R * C_{WR} \tag{8}$$

$$W_{L_i} = \left(\frac{\rho}{2}\right) * c_w * A * C_{WL} \tag{9}$$

$$W_{a_i} = G_i * C_{Wa} \tag{10}$$

C_{WR} : Characteristic values related to rolling resistance, 4,165 m (Koffler et al., 2010)

C_{WL} : Characteristic values related to aerodynamic resistance, 699,767 m^3/s^2 (Koffler et al., 2010)

C_{Wa} : Characteristic values related to acceleration resistance, 687 m^2/s^2 (Koffler et al., 2010)

G_i : Weight of the part *i* [kg]

g : Gravity [m/s^2]

f_R : Rolling resistance, 0.01 (Koffler et al., 2010)

ρ : Air density [kg/m^3]

c_w : Air drag coefficient

A : Front surface [m^2]

The above characteristic values depend on the analyzed driving cycle. Here, they are subjected to the Japanese 10-15 mode.

Finally, the energy consumption in the ELV phase is analyzed based on the approaches of Sato et al. (2018, 2019) considering that the reuse and recycle of vehicle parts have a beneficial impact on the total vehicle life cycle. Here, the total effect is calculated as the difference of the energy consumed in the dismantling process and the energy saving by the recycling of its parts and materials (11). As previously stated, ELVs are recycled through three methods; energy recovery, material recycling, and part reusing. Firstly, the reuse of vehicle parts implies that the energy consumed to produce new components is saved and it can be calculated considering the embodied energy used in the analysis of the production phase (12). Secondly, make a product from recycled materials requires less energy than making the same product using virgin materials (13). Finally, the energy reduction by energy recovery is the thermal energy generated by the incineration of the materials as an alternative fuel.

$$E_{ELV_i} = E_{dis} * G_i - (ER_{PR,i} + ER_{MR,i} + ER_{ER,i}) \tag{11}$$

$$ER_{PR,i} = \sum_m EE_m * G_{PR,m,i} \tag{12}$$

$$ER_{MR,i} = \sum_m EP_{\Delta M_m} * G_{MR,m,i} \tag{13}$$

$$ER_{ERE,i} = \eta_{Boil} \sum_m HHV_m * G_{ER,m,i} + \sum_m EP_{\Delta M_m} * G'_{ER,m,i} \tag{14}$$

E_{dis}	: Energy consumed for the disposal of vehicle parts [MJ/kg]
$ER_{PR,i}$	: Energy reduction by the reusing of part *i* [kJ].
$ER_{MR,i}$	: Energy reduction by material recycling of part *i* [kJ].
$ER_{ERE,i}$	: Energy reduction by energy recovery of part *i* [kJ].

$G_{PR,m,i}$: Weight of the material *m* of the part *i* subjected to part reusing [kg].

$G_{MR,m,i}$: Weight of the material *m* of part *i* destined to material recycling [kg].

$G_{ER,m,i}$: Weight of the material *m* of part *i* destined to energy recovery [kg].

$G'_{ER,m,i}$: Weight of the material *m* of part *i* recovered after energy recovery [kg].

$EP_{\Delta M_m}$: Difference between the energy consumed in producing 1 kg of material *m* through virgin and recycled resources [kJ/kg].

HHV_m : Highest heating value of the combustible material *m*) [kJ/kg], shown in Table 3.2 a).

η_{Boil} : Efficiency of the incinerator-boiler, which has been adopted as 63% (Tchobanoglous et al., 1993).

Its worthily to mention that the ASR obtained from the scrapped vehicle is subjected to energy recovery, and materials such as cement, slag, mixed metals, and steel are recovered. Moreover, it has been estimated considering previous studies of Sato et al. (2019) and report of the Ministry of Environment (MOE, 2015) that 38% of the metals subjected to this process are recovered as recycled raw material. The related energy and CO_2 benefits were calculated considering that the values of the recovered metals are similar to steel.

4.2.2 CO_2 emission assessment for vehicle parts

Similar to energy consumption, the CO_2 emission related to the life cycle of a specific part can be calculated as the sum of the emissions on its phases (15).

$$CO_{2\,LC_i} = CO_{2_{P_i}} + CO_{2_{U_i}} + CO_{2_{ELV_i}} \tag{15}$$

$CO_{2\,P_i}$: CO_2 emitted in the production phase related to vehicle part *i* [kg-CO_2].

$CO_{2\,U_i}$: CO_2 emitted in the use phase related to vehicle part *i* [kg-CO_2].

$CO_{2\,R_i}$: CO_2 emitted in the ELV phase related to vehicle part *i* [kg-CO_2].

Nishimura et al. (1997, 2001) calculated different embodied CO_2 including values for the Japanese car industry. The CO_2 emission for the production of a vehicle part can be evaluated using (16).

$$CO_{2_{P_i}} = \sum_m ECO_{2_m} * G_{i,m} \qquad (16)$$

ECO_{2_m} : Embodied CO_2 of the material *m* for vehicle part production [kg-CO_2/kg].

The CO_2 emission in the use phase of a part can also be divided into two parts (17).

$$CO_{2_{U_i}} = CO_{2_{U(m.i.)_i}} + CO_{2_{U(other)_i}} \qquad (17)$$

Here, the mass induced CO_2 emissions in the use phase of the part can be calculated considering the related energy consumptions and emissions of the gasoline combusted in the vehicle engine (18).

$$CO_{2U(m.i.)_i} = \frac{E_{U(mass\,ind)i} * EF_{gas}}{HHV_{gas}} \tag{18}$$

HHV_{gas} : High heating value of the gasoline, 46.4 MJ/kg (Demirel, 2012).

EF_{gas} : Emission factor from the combustion of one kg of gasoline, 3.3 kg-CO_2/ kg (Demirel, 2012)

Finally, similar to energy consumption, previous studies of Sato et al. (2019) was contemplated and the CO_2 emissions in the ELV phase calculated considering the CO_2 reductions by each recycling methods the parts are subjected (19)(20)(21)(22).

$$CO_{2ELV_i} = -(CO_2R_{PR_i} + CO_2R_{MR_i} + CO_2R_{ER_i}) \tag{19}$$

$$CO_2R_{PR_i} = \sum_m ECO_{2_m} * G_{PR,m,i} \tag{20}$$

$$CO_2R_{MR,i} = \sum_m CO_2P_{\Delta M_m} * G_{MR,m,i} \tag{21}$$

$$CO_2R_{ERE,i} = EF'_{ker} \sum_m HHV_m * G_{ER,m,i} - \sum_m EF_m G_{ER,m,i} + \sum_m CO_2P_{\Delta M_m} * G'_{ER,m,i} \tag{22}$$

EF_m : Emission factor of the material (*m*) [kg-CO_2 /kg], shown in Table 3.3.

EF'_{ker} : Emission factor of kerosene [0.07127 kg-CO_2 /MJ] (EPA, 2014).

$CO_2R_{PR,i}$: CO_2 reduction by the reusing of part *i* [kg-CO_2].

$CO_2R_{MR,i}$: CO_2 reduction by material recycling of part *i* [kg-CO_2].

$CO_2R_{ERE,i}$: CO_2 reduction by energy recovery of part *i* [kg-CO_2].

$CO_2P_{\Delta M_m}$: Difference between the CO_2 emitted in producing 1 kg of material m through virgin and recycled resources [kg-CO_2/kg].

4.2.3 Energy and CO_2 reduction assessment for vehicle parts

To assess the comprehensive benefits of the introduction of lightweight material in vehicle parts, energy consumption and CO_2 emission reductions are calculated bearing in mind the potential changes in its recycling system. Here, possible combinations of lightweight materials and recycling process are denominated as “scenarios”, and the energy and CO_2 reduction compared with a part made by conventional material and subjected to conventional recycling calculated using (23) (24).

$$ER_{LC_i}^{Scenario_s} = E_{LC_i}^{Conv} - E_{LC_i}^{Scenario_s} \qquad (23)$$

$ER_{LC_i}^{Scenario_s}$: Energy reduction in the vehicle life cycle related to part *i* for scenario *s* [MJ].

$E_{LC_i}^{Conv}$: Energy consumption in the vehicle life cycle related to part *i* made by conventional material and subjected to conventional recycling [MJ].

$E_{LC_i}^{Scenario_s}$: Energy consumption in the vehicle life cycle related to part *i* for a scenario *s* [MJ].

$$CO_2R_{LC_i}^{Scenario_s} = CO_{2}{}_{LC_i}^{Conv} - CO_{2}{}_{LC_i}^{Scenario_s} \qquad (24)$$

$CO_2R_{LC_i}^{Scenario_s}$: CO_2 reduction in the vehicle life cycle related to part *i* for scenario *s* [kg-CO$_2$].

$CO_{2}{}_{LC_i}^{Conv}$: CO$_2$ emission in the vehicle life cycle related to part i made by

conventional

material and subjected to conventional recycling [kg-CO$_2$].

$CO_{2}{}_{LC_i}^{Scenario_s}$: CO$_2$ emission in the vehicle life cycle related to part i for scenario s

[kg-CO$_2$].

4.2.4 Sub-optimization of the material choice

To find the best combination of parts to be lightweight, material to be use and recycling method to be prioritized, the following material choice procedures have been carried. Equation (25) propose the best combination to reduce the life cycle energy consumption of the vehicle, equation (26) to reduce the life cycle CO$_2$ emission, and equation (27) to reduce the user's life cycle cost increment.

$$max\, ER_{LC} = \sum_i (E_{LC_i}^{Conv} - min\, E_{LC_i}^{Scenario_s}) \tag{25}$$

$$max\, CO_2R_{LC} = \sum_i (CO_{2}{}_{LC_i}^{Conv} - min\, CO_{2}{}_{LC_i}^{Scenario_s}) \tag{26}$$

$$min\, CI_{LC} = \sum_i min\, CI_{LC_i}^{Scenario_s} \tag{27}$$

ER_{LC} : Energy reduction in the vehicle life cycle [MJ].

CO_2R_{LC} : CO$_2$ reduction in the vehicle life cycle [kg-CO$_2$].

CI_{LC} : User’s cost increment in the vehicle life cycle [USD].

$CI_{LC_i}^{Scenario_s}$: User’s cost increment in the life cycle related to the part *i* for a case *c* [USD].

Here, the user’s life cycle cost is defined as the extra cost the user must pay for the use of alternative lightweight material in the vehicle parts (28)(29). The recycling fee pay by the users is supposed to be the same in all the proposed cases.

$$CI_{LC_i}^{Scenario_s} = CI_{Prod_i}^{Scenario_s} * Prof_{AM} * Prof_D + CI_{Use_i}^{Scenario_s} \tag{28}$$

$$CI_{Use_i}^{Scenario_s} = \left(E_{U(m.i.)_i}^{Conv} - E_{U(m.i.)_i}^{Scenario_s} \right) * \frac{Price_{gas}}{U_{gas}} \tag{29}$$

$CI_{Prod_i}^{Scenario_s}$: User’s cost increment in the production phase of the vehicle related to the part *i* for scenario *s* [USD], shown in Table 4.1.

$Prof_{AM}$: Profit of the automakers, considered in this study as 10% of the vehicle production cost.

$Prof_D$: Profit of the dealers, considered in this study as 10% of the vehicle cost.

$CI_{Use_i}^{Scenario_s}$: User’s cost increment in the use phase of the vehicle related to the part i for scenario *s* [USD].

$E_{U(m.i.)_i}^{Conv}$: Mass induced energy consumption in the use phase related to vehicle part *i* made by conventional material and subjected to conventional recycling [MJ].

$E_{U(m.i.)_i}^{Scenario_s}$: Mass induced energy consumption in the use phase related to vehicle part i for scenario s [MJ].

$Price_{gas}$: Price of gasoline in Japan, adopted as 1.30 USD/l (Trading economics, 2019).

4.3 Body in white lightweighting as a case study

Considering the total weight of its parts in the vehicles and the material homogeneity of them, our study analyzes the body in white as a case study.

Fig. 4.3 shows the eight parts that compose a body in white of a vehicle. Moreover, Table 4.1 lists those parts with its weights and production cost increment depending on the lightweight material used in its production. Here, the body in white of a Honda Accord (weight: 1,481kg) is analyzed as a generic vehicle, and AHSS, aluminum, and CFRP considered as alternative materials.

Fig. 4.4 shows the current material flow of the body in white elaborated considering previous studies of Sato et al. (2018, 2019). Here, 87% of its weight is destined to material recycle, 13% reused as spare part, and the low percentage of metals processes as ASR (METI, 2014(b)) was considered negligible.

Table 4.2 a) and b) shows the coefficients for the calculation of the energy consumption and CO_2 emission in the vehicle production and recycling of the body in white parts. Embodied energy and embodied CO_2 values indicated in the first column of both tables were estimated considering average values for the production of the body in white parts. The second columns indicate the difference between the energy consumed and CO_2 emitted for producing 1 kg of material through virgin and recycled resources. Here, it has been considered that the carbon fiber recycled as raw material accounts 29% of the mass of the CFRP and 98% of it is recovered through pyrolysis process (Das, 2011). Meanwhile, the third columns indicate the highest heating value and the emission factor of the materials.

Finally, Table 4.3 indicates the twenty scenarios analyzed in this study where the material composition and recycling method of the parts are modified to calculate the possible energy and CO_2 reductions. It is noteworthy that the scenario indicated in the first column and the first row (A-1) represents the current material flow of the body in white shown in Fig. 4.4.

4.3.1 Primary assumption and limitations

First, the relation between vehicle lightweighting and recycling is analyzed considering as a case study the body in white part in the Japanese market. Here, the vehicle life cycle energy, CO_2 and cost reductions were calculated. However, those benefits do not affect the Japanese society exclusively, considering that part of the raw materials and component of the vehicle are produced and imported from foreigner suppliers; and the dismantled ELVs exported as second-hand part, recyclable material and ASR.

Secondly, some approximations, such as constant engine efficiency and constant energy lost, have been set to simplify the calculations. On the other hand, there is a considerable dependence of the equations proposed for the analysis of the benefits in the production and ELV phases on the embodied energy and embodied CO_2. Changes in those values can guide us to different numerical results, and the combination of parts and material for minimizing the life cycle energy consumption and CO_2 emission can also moderately vary, however, the main conclusions of this study remain unchanged.

Next, cost analysis has been conducted in general terms considering that the aim of this study is centered on the analysis of the energy consumption and CO_2 emission effects of the lightweight materials.

Finally, secondary mass reductions from lightweighting, which include the additional effect in the power train reducing its components and the engine friction is going to be analyzed in future studies.

4.4 Analytical results

Fig. 4.5 a) and b) shows the material flows of each twenty proposed scenarios in Table 4.3. The last row of Fig. 4.5 b) shows the scenarios where the life cycle energy consumption and CO_2 emission of the parts are prioritized by the sub-optimization of the material choice presented in the previous section. Here, it can be observed that, environmentally, the best combination of parts and materials depends on the recycling method they are going to be subjected. When the body in white is mainly subjected to material recycling (scenarios A-5 and C-5), its parts should be made mainly by aluminum. However, when the parts are frequently reused (scenarios B-5), the use of CFRP should be prioritized because of the high fuel consumption reduction in its use phase. Finally, if the parts are mainly subjected to energy recovery (scenarios D-5), AHSS is the best material choice considering the low energy consumption in its production phase.

4.4.1 Energy and CO_2 reductions considering conventional recycling method

In this section, the effect of lightweight materials is analyzed considering invariable the current recycling and reusing percentage of the body in white parts (i.e., scenarios A-2, A-3, A-4, A-5).

Fig. 4.6 a) and b) show the life cycle energy and CO_2 reduction of the analyzed vehicle when its body in white is lightweight. Here, it can be observed that the effects of the production and end of life phase are essential as the benefits generated in its use phase. For example, results indicate that the use of CFRP is highly beneficial from the use phase point of view; however, the total benefit is much lower if the production and ELV phases are considered. Moreover, average reduction values indicate that while the use phase represents 6.4 GJ and 477 kg-CO_2 of the total life cycle energy and CO_2 reduction per vehicle, the production represent -26.9 GJ and -1,508 kg-CO_2, and the ELV phase 27.1 GJ and 1,383 kg-CO_2 of it. In other words, the energy effect of the production and ELV phase is 4.2 times higher, and the CO_2 reduction effects approximately 3 times higher than the effect of the use phase. In this sense, the combination of parts and material to lightweight a vehicle must be selected considering the entire life cycle, reinforcing again the importance of considering the recycling system in a lightweighting analysis.

Fig. 4.6 c) shows the user's life cycle cost reduction by case. It can be noted that the cost increments in the production phase through the introduction of alternative materials are higher than the cost reduction in the use phase by the improvement of the vehicle's fuel consumptions. Moreover, lightweight the body in white using CFRP is not efficient from the standpoint of user's cost, and the prioritized cost scenario consists mainly of parts made by conventional materials, where only the bumpers and fenders are modified to AHSS. This can be explained by the significant cost increment on the introduction of alternative materials in the production phase, which cannot be absorbed through the benefits generated in its use phase.

Table 4.4 summaries the user's cost increment per unit of energy and CO_2 expected to be reduced in the vehicle life cycle through the introduction of lightweight materials. The point to observe is that the most expensive choice to meet the above objective is through the use of CFRP, where USD 733 is needed to reduce 1 MJ of energy and even USD 53 is paid the CO_2 emission would increase 1 kg-CO_2. On the contrary, the use of AHSS is the most favorable choice, where a combination of parts made with them and conventional material could guide us to a unit of energy and CO_2 reduction in conjunction with a cost saving of USD 27 and USD 0.4. However, it is noteworthy that the total energy and CO_2 reductions expected in the lightweight of the body in white varies widely depending on the material, and effects of low-cost options are limited when considerable differentiation with conventional material is required.

4.4.2 Energy and CO_2 reductions considering variations in the recycling methods

Fig. 4.7 a) and b) summarize the life cycle energy and CO_2 reduction potential of the twenty scenarios proposed in Table 4.3. Compared to section 4.1, where lightweighting is analyzed considering the percentage of material destined to recycling unchanged, here, scenarios wherein the body in white is entirely reused, recycled as material and subjected to energy recovery are also assessed. The point to observe is that even considering the use of the same lightweight material, the total energy and CO_2 reduction in the life cycle can vary drastically depending on the recycling method the body in white is subjected. Results indicates that, if the body in white is mainly subjected to material recycling its parts should be made mainly by aluminum; However, when the parts are frequently reused, the use of CFRP should be prioritized, and if the parts are mainly subjected to energy recovery AHSS is the best material choice.

Representative energy and CO_2 reduction values of the above figure divided by the weight of the analyzed parts produced with conventional material are summarized in Table 4.5 a) and b). The first rows indicate that when only material lightweighting is considered (subjected to conventional recycling) maximum energy and CO_2 reduction of 23.8 MJ/kg of part and 1.82 kg-CO_2/kg of part can be expected when the body in white is made mainly by aluminum. The second rows, where only variations of the recycling system are considered (made by conventional material), indicate that an increment of 10.8 MJ/kg of part and 1.29 kg-CO_2/kg of part can be expected if the parts are subjected to energy recovery. Finally, the last rows show that an adequate combination of both variables could almost double the energy and CO_2 benefits to 51.4 MJ/kg and 3.34 kg-CO_2/kg considering the use of CFRP and reusing the parts. On the other hand, the second columns of the tables indicate that if both variables are not jointly assessed the introduction of lightweight materials could be highly counterproductive reaching an energy and CO_2 increment of 92.5 MJ/kg of part and 6.71 kg-CO_2/kg of part when use of CFRP/Aluminum are combined with energy recovery.

4.4.3 Comparisons with previous studies and total impact on the entire life cycle

Previous studies indicate that 100 kg of mass reduction in an automobile results in a fuel saving between 3.2 GJ to 10.24 GJ per 100,000 km driven in its use phase (Cheah et al., 2007; Pagerit et al., 2006; Carlson et al., 2013; Kim et al., 2016). Table 4.6 summarizes comparable energy reduction values calculated in this study analyzing the lightweighting of the body in white. The third column of the table shows that, when 100kg of mass is reduced, 0.4 GJ of energy reduction can be expected in the use phase. The material considered in the production of the part does not impact here, showing compatibility with previous studies mentioned above. Here, an important point to emphasize is that even though the impact per kg of mass reduction in the use phase remains unchanged, the energy reduction effect in the production and recycling vary widely on the selected lightweight material. 100 kg of mass reduction in an automobile can result in a total life cycle energy reduction between -23.0 (All aluminum and energy reduction) to 18.5 GJ (All AHSS and part reusing); reconfirming the importance of considering the production and ELV phase in the lightweight analysis of the vehicle.

Next, our energy and CO_2 reduction results presented in section 4.1 and 4.2 are reflected on the life cycle of the vehicle to clarify the effect in it. Here, only a conventional recycling scenario has been considered and the total energy consumption of the vehicle life cycle is calculated using (30).

$$E_{LC_{vehicle}} = E_P + E_U + E_{ELV} \tag{30}$$

Here, the environmental effect of its production phase is calculated as follows (31).

$$E_P = \sum_m EE_m * G_{veh,m} \tag{31}$$

E_P : Energy consumed in the production phase of the vehicle [kJ per vehicle].

$G_{veh,m}$: Weight of the material (m) of the studied vehicle [kg per vehicle].

Meanwhile, energy consumption in the use phase can be calculated using (32).

$$E_U = d * \rho_{gas} * HHV_{gas} \,/\, FE \tag{32}$$

E_U : Energy consumed in the use phase [kJ per vehicle].

FE : Fuel economy, Honda Accord 2011, 14.4 km/l (Honda Motor co., 2013)

ρ_{gas} : Density of gasoline, 0.75 kg/l (Demirel, 2012).

Finally, results of Sato et al. (2019), which this study is based for the analysis of the recycling system and considers the same generic vehicle, are used to represent the total energy reduced/consumed in the ELV phase.

In terms of CO_2 emissions, the following equations are proposed, and the life cycle CO_2 emission of the vehicle is calculated using (33).

$$CO_{2\,LC_{vehicle}} = CO_{2_P} + CO_{2_U} + CO_{2_{ELV}} \tag{33}$$

First, the CO_2 emission in the production phase is calculated as follows (34).

$$CO_{2_P} = \sum_m CO_2E_m * G_{veh,m} \tag{34}$$

CO_{2_P} : CO_2 emitted in the production phase of the vehicle [kg-CO_2 per vehicle]

Moreover, the CO_2 emission in the use phase is obtained as follows (35).

$$CO_{2_U} = FE * d * \rho_{gas} * EF_{gas} \tag{35}$$

CO_{2_U} : CO_2 emission in the vehicle use phase [kg-CO_2 per vehicle].

Finally, as well as energy reduction, results of Sato et al. (2019) are used to represent the total CO_2

emitted/reduced in the ELV phase.

Fig. 4.8 shows the life cycle energy consumption and CO_2 emission of the vehicle where different materials are considered for the lightweighting of the body in white. Here, it was calculated the total energy consumption and CO_2 emission of a vehicle made by conventional materials and subjected to conventional recycling as 324 GJ and 22.8 t-CO_2, showings also the possibility of decreasing those values 3.19% and 3.85% depending on the substitute lightweight material. Moreover, when results which consider different recycling scenarios shown in Fig. 4.7 are additionally contemplated, the total life cycle energy consumption and CO_2 emission of the vehicle life cycle could decrease 6.90% and 6.39%, but also increase 11.82% and 12.69% depending on the respective scenario.

4.5 Discussion

Results presented in this study indicate that the recycling phase of the vehicle must always be considered when the introduction of alternative lightweight material is analyzed.

Even our analysis focus on the environmental analysis of lightweight material is worthy of mentioning that the aim of using that material in the vehicles are not always to improve its fuel efficiency, but also for improving the acceleration performance of the high-end cars and sports cars.

Currently, one of the principal characteristics considered in the purchasing process of a vehicle is its fuel economy. Moreover, the users tend to associate directly “low fuel consumption vehicle” with the concept of “environmentally friendly vehicle”. This study refuses this misconception showing that lower fuel consumption in the use phase does not imply an environmentally friendly vehicle if the effect of the production and ELV phase is not taken into account in the assessment. The above concept will be crucial considering proposal of the European Commission (2017) which urge to make available to authorities, entities and operators the life cycle costing of the vehicles, including the cost of greenhouse gas emission and other pollutant emissions, in order to support their procurement process.

The vehicle life cycle is subjected to an open loop recycling where the steel obtained from the end of life vehicle is mainly reused for construction, and the recovered aluminum is cascaded into cast aluminum (Modaresi et al., 2014). Meanwhile, CFRP is not a mature technology, and the scraped material is mainly subjected to energy recovery. A drastic modification of the material composition of the vehicles, such as the case of the body in white, will obligate the vehicle recycling companies to review its installations and disassembly process. In that sense, the current ELV recycling benefits of 52.8 MJ and 2.8 kg CO_2 per kg of the vehicle (Sato et al., 2019) would probably drastically decrease considering that the current shredder factories are technologically focused on steel scrap recycling through magnetic separation. In the same way, the government could define policies to support those investments and develop essential recycling process for achieving sustainable lightweight materials. The representative case in this study is the CFRP which low-cost separation and recycling technologies are the keys to reducing its actual life cycle environmental impact. It also worthily to mention that approximately 28% of the ELV is currently exported (MOE, 2015), and leverages the recycling benefits inside Japan is not always possible. In this sense, recycling technologies should also be introduced into the countries where the vehicles expend its final years.

On the other hand, the results of this study are essential for assessing the advantages and disadvantages of different material for vehicle production, considering the entire life cycle. This assessment methodology could guide Automakers to understand, design, and produce a more environmentally friendly vehicle, but also allow the government to identify material and technology that is worth to support for its development.

The proposed methodology was applied to assess alternative materials for the body in white parts but also the rest of vehicle parts could be environmentally evaluated considering the same approach. Moreover, the same approach of analyzing the entire life cycle of parts is applicable to assess materials of other means of transport as motorcycles, train, ships, and airplanes but also to evaluate other products where the lightweighting materials play an essential role in its use phase as agriculture machinery, elevators and mechanical stairs.

4.6 Conclusions

A material based environmental assessment of vehicle parts considering the entire life cycle of the vehicles was proposed. As a case study, lightweighting and recycling of body in white parts have been analyzed. Here, studies of Singh (2012) and Wheatley et al. (2013) have been considered for the estimation of the weight and cost of the lightweight parts; embodied energy and CO_2 for the calculation of the lightweighting effects in the production phase; the use phase analyzed base on studies of Koffler et al. (2010) and O 'reilly et al. (2016); and the recycling phase has been assessed considering previous studies of Sato et al. (2018, 2019).

This study proposes a simple methodology in order to analyze the impact of lightweighting materials in the entire life cycle. Compare to previous studies, possible alterations in the ELV recycling system were also assessed.

The main conclusions of the study are listed below.

・The effect from the standpoint of energy consumption and CO_2 emission of lightweighting materials on the production and end of life phase is essential as the benefits generated in its use phase. Energy effect of production and ELV phases by the introduction of lightweight material could be 4.2 times higher, and the CO_2 reduction effects approximately 3 times higher than the effect of the use phase.

・Cost increments in the production phase through the introduction of lightweight materials are higher than the cost reduction in the use phase by the improvement of the vehicle's fuel consumptions.

・Material lightweight must be analyzed jointly with its possible recycling system because when the first variable is considered individually maximum life cycle energy and CO_2 reduction of 23.8 MJ and 1.82 kg-CO_2 per kg of part to be lightweight can be expected; however, an adequate combination of both variables could almost double those benefits to 51.4 MJ and 3.34 kg-CO_2, but also incorrect combination of them could be counter-productive guiding us to an energy and CO_2 increment of 92.5 MJ and 6.71 kg-CO_2.

・If the body in white is mainly subjected to material recycling its parts should be made mainly by aluminum; however, when the parts are frequently reused, the use of CFRP should be prioritized; finally, if the parts are mainly subjected to energy recovery, AHSS is the best material choice.

・Lower fuel consumption of the vehicles in the use phase does not imply a lower environmental effect in the life cycle of the vehicle. For example, our results indicated that CFRP is not an environmentally favorable material considering the entire life cycle if they continue to be subject to energy recovery.

・100 kg of mass reduction in an automobile can results in a total life cycle energy reduction between -23.0 to 18.5 GJ depending on the material used for lightweighting and the recycling process it is subjected.

Finally, what needs to be emphasized is that the introduction of lightweight materials for vehicles must always consider the effect in its production phase and the possible recycling scenarios. The proposed assessment method could guide the governments and automakers to achieve a sustainable circular economy through a better understanding of the effects of lightweight materials and its recycling.

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Table 4.1 Weights and production cost increment by each lightweighting material for the body in white parts

Part		Conventional			Lightweighted								
					Aluminum			AHSS			CFRP		
		Material	Mass [kg]	Ref.	Mass [kg]	Production cost increment [USD]	Ref.	Mass [kg]	Production cost increment [USD]	Ref.	Mass [kg]	Production cost increment [USD]	Ref.
A	Body structure	HSS	328	a)	213.2	720.0	a)	255.2	147.0	a)	164.0	1,708.9	a),b),c)
B	Front bumpers	Steel	7.96	a)	5.2	17.5	a)	4.4	-0.9	a)	3.6	97.8	a),b),c)
C	Rear bumpers	Steel	7.84	a)	5.1	17.2	a)	4.3	2.1	a)	3.5	96.3	a),b),c)
D	Decklid (frame)	Steel	9.95	a)	4.7	17.0	a)	8.5	3.1	a)	5.0	51.8	a),b),c)
E	Fenders	Steel	7.3	a)	4.0	12.6	a)	6.2	1.4	a)	3.7	38.0	a),b),c)
F	Front doors (frame)	Steel	32.8	a)	16.9	49.6	a)	27.9	10.2	a)	16.4	170.9	a),b),c)
G	Hood (frame)	Steel	15.2	a)	7.5	21.3	a)	12.9	4.7	a)	7.6	79.2	a),b),c)
H	Rear doors (frame)	Steel	26.8	a)	14.9	53.2	a)	22.8	8.4	a)	13.4	139.6	a),b),c)
Total			435.9		271.5	908.4		342.1	176.1			217.1	2,382.5

a) Singh, 2012.

b) Wheatley et al., 2013.

c) Author estimation.

Table 4.2 Energy and CO_2 coefficients for vehicle production and each recycling method of the body in white parts

a) Energy consumption and reduction coefficients [MJ/kg]

Material	Embodied energy	Ref.	Diff. energy consumption virgin & recycled resources	Ref.	Heating value	Ref.
Steel/HSS	45.9	a),b),c),g)	10.0	c),g)	n/a	
AHSS	46.2	a),b),c),g)	10.0	c),g)	n/a	
CFRP	303.7	a),e),g)	200.1	e),g)	38.0	f),g)
Aluminum	217.4	a),b),c),d),g)	176.0	d),e),g)	n/a	

a) Mayyas et al., 2012

b) Sullivan et al., 2010

c) Weiss et al., 2000

d) Das, 2000

e) Das, 2011

f) Kim et al., 2004

g) Author estimation

b) CO_2 emission and reduction coefficients [kg-CO_2/kg]

Material	Embodied CO_2	Ref.	Diff. CO_2 emission virgin & recycled resources	Ref.	Emission factor	Ref.
Steel/HSS	3.8	a),b),c),h)	1.7	c),d),h)	n/a	
AHSS	4.3	a),b),c),h)	1.7	c),d),h)	n/a	
CFRP	16.7	a),e),h)	8.8	e),h)	2.65	g),h)
Aluminum	16.1	a),d),h)	14.0	d),f),h)	n/a	

a) Mayyas et al., 2012

b) Sullivan et al., 2010

c) CEPA, 2011

d) Das, 2000

e) Das, 2011

f) Ding et al., 2012

g) McDougall et al., 2001

h) Author estimation

Table 4.3 Scenarios analyzed for the body in white parts

		(II) Recycling system			
		A- Conventional recycling	B- Part reusing	C- Material recycling	D- Energy recovery
(I) Material lightweighting	1- Conventional material	A-1	B-1	C-1	D-1
	2- All aluminum	A-2	B-2	C-2	D-2
	3- All AHSS	A-3	B-3	C-3	D-3
	4- All CFRP	A-4	B-4	C-4	D-4
	5- Minimum energy and CO_2	A-5	B-5	C-5	D-5

Table 4.4 Energy and CO_2 reduction cost by material in conventional recycling scenarios

	All aluminum	All AHSS	All CFRP	Minimum energy and CO_2	Minimum Cost
Energy reduction cost [USD per MJ]	62	3	733	67	-27
CO_2 reduction cost [USD per kg-CO_2]	0.81	0.08	-53.09	0.89	-0.40

Table 4.5 Representative energy and CO_2 reduction values by mass of analyzed part

a) Energy reduction

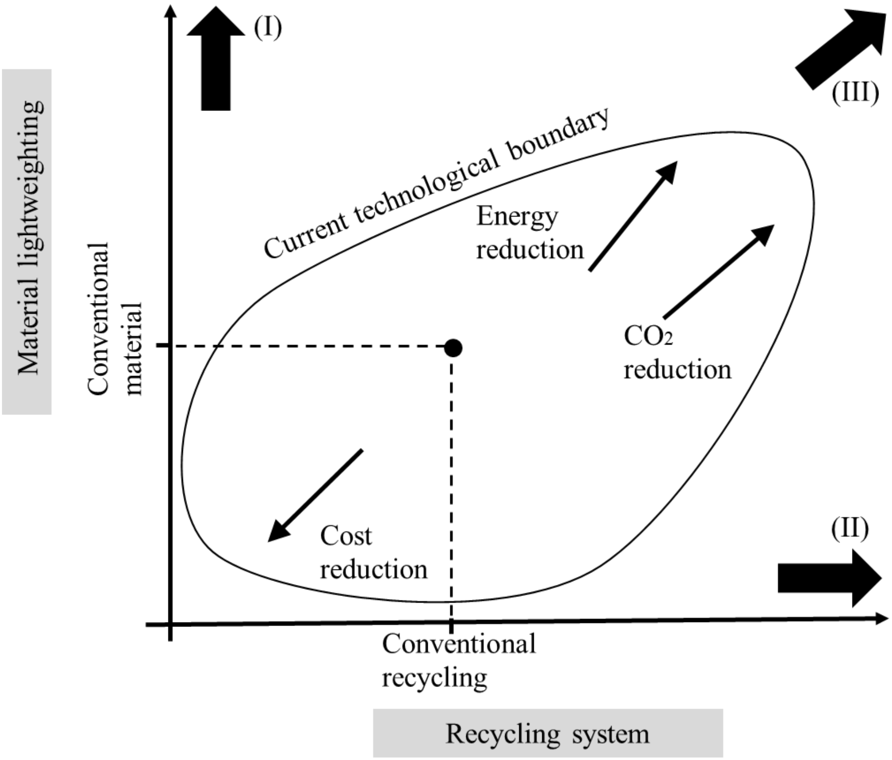
Analysis parameter	Energy reduction [MJ/kg of part]	
	Minimum	Maximum
(I) Material lightweighting	0.00 (Conventional material)	23.76 (Aluminum)
(II) Recycling system	-10.84 (Energy recovery)	31.25 (Part reusing)
(III) Material lightweighting & recycling system	-92.49 (CFRP and energy recovery)	51.36 (CFRP and part reusing)

b) CO_2 reduction

Analysis parameter	CO_2 reduction [kg-CO_2/kg of part]	
	Minimum	Maximum
(I) Material lightweighting	0.00 (Conventional material)	1.82 (Alum)
(II) Recycling system	-1.29 (Energy recovery)	1.83 (Part reusing)
(III) Material lightweighting & recycling system	-6.71 (Aluminum and energy recovery)	3.34 (CFRP and part reusing)

Table 4.6 Life cycle energy reduction per 100kg of mass reduced

Material	Energy reduction per 100 kg of mass reduced [GJ per 100,000km traveled]					
	Production	Use	ELV			
			A-Conventional recycling	B-Part reusing	C- Material recycling	D-Energy recovery
2- All aluminum	-23.7	4.0	26.0	32.0	25.2	-3.3
3- All AHSS	4.5	4.0	-1.5	10.0	-3.2	-5.4
4- All CFRP	-21.0	4.0	18.3	27.2	16.9	-2.3
5-Minimum energy and CO_2	-22.8	4.0	25.0	-	-	-
	-20.4	4.0	-	26.6	-	-
	-22.4	4.0	-	-	23.9	-
	4.5	4.0	-	-	-	-5.4



(I) Energy and CO_2 reduction considering only material lightweighting
*Most of previous studies
(II) Energy and CO_2 reduction considering only recycling system
*Sato et al. 2018 & 2019
(III) Energy and CO_2 reduction considering lightweighting and recycling system
*This research

Fig. 4.1 Concept of energy and CO_2 reduction

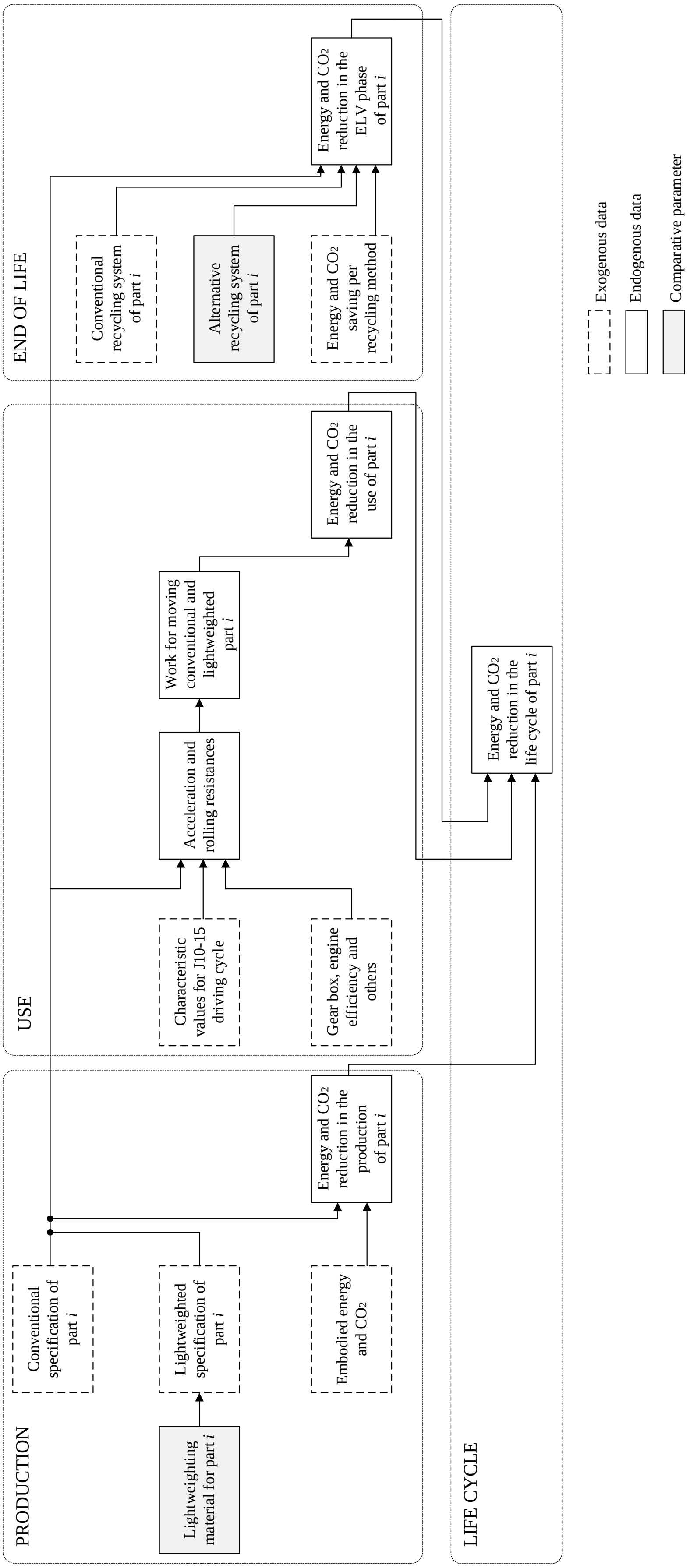
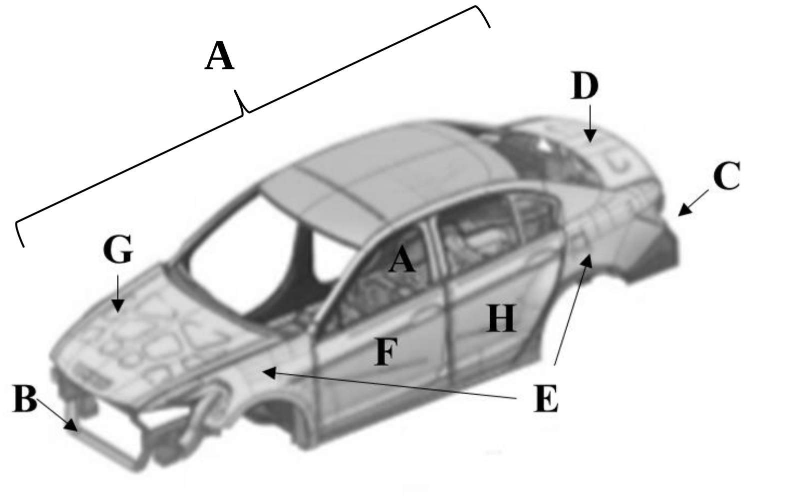


Fig. 4.2 Analysis flow of the research



A	Body structure	E	Fenders
B	Front bumpers	F	Front doors
C	Rear bumpers	G	Hood
D	Decklid	H	Rear doors

Fig. 4.3 Analyzed part for the body in white lightweighting

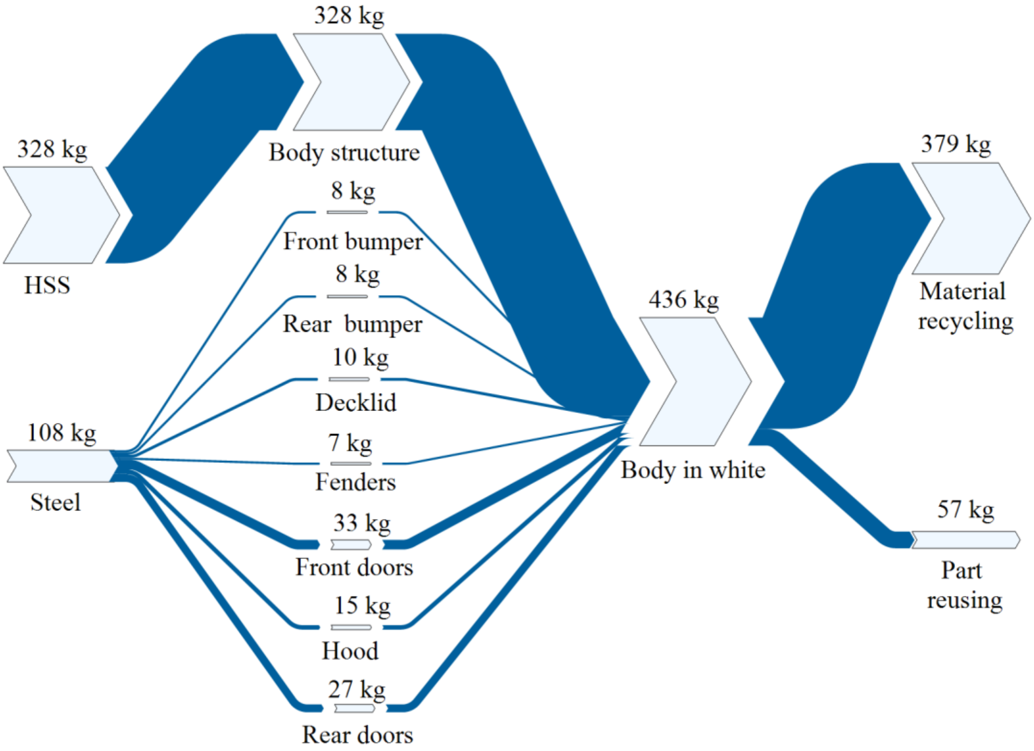
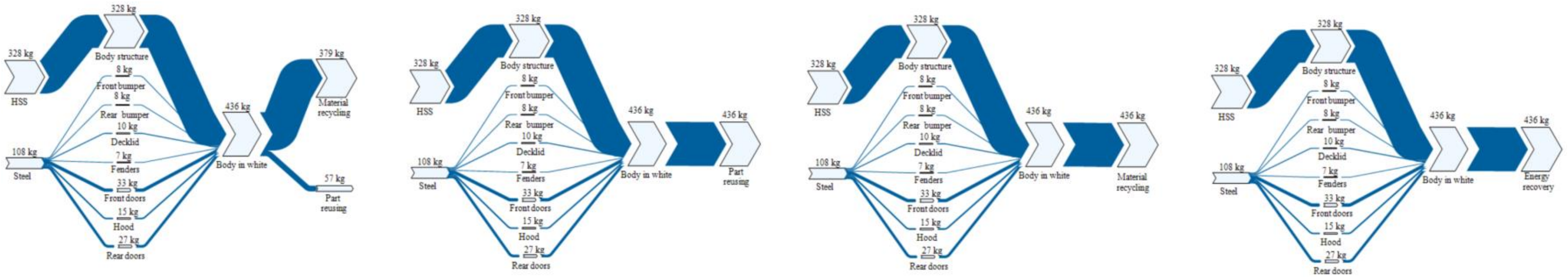


Fig. 4.4 Conventional material flow of the body in white

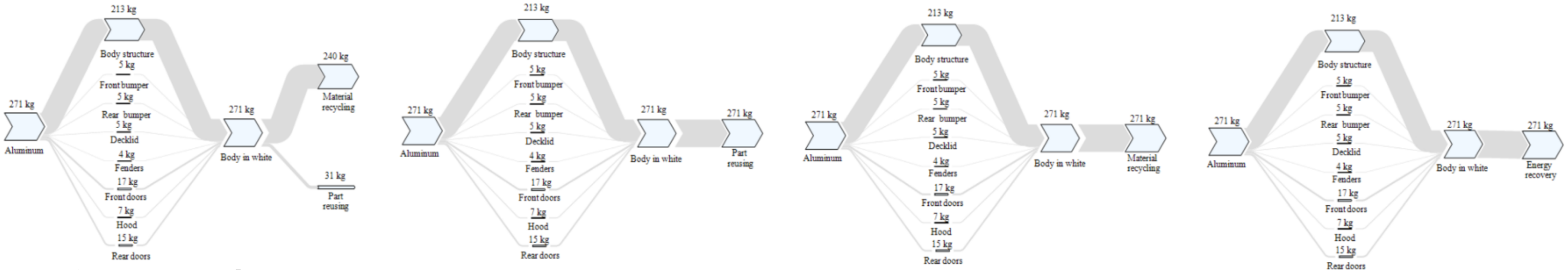


A-1) Conventional

B-1) All part reusing & conv. material

C-1) All material recycling & conv. material

D-1) All energy recovery & conv. material

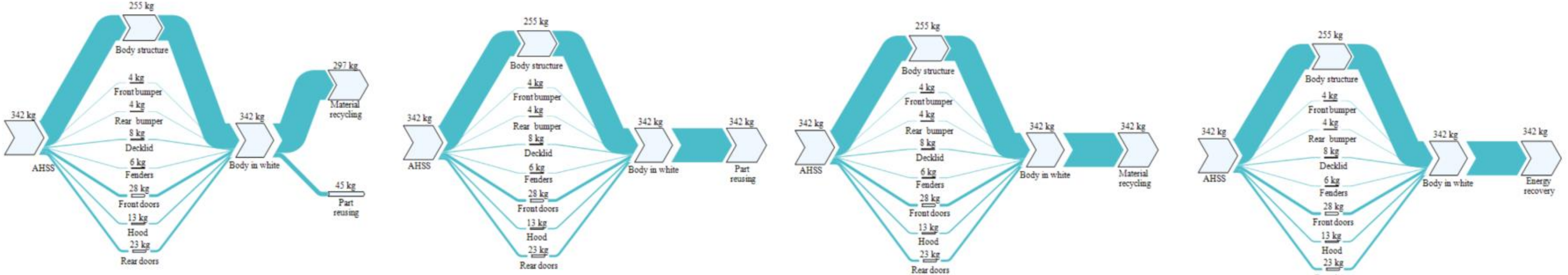


A-2) Conv. recycling & all aluminum

B-2) All part reusing & all aluminum

C-2) All material recycling & all aluminum

D-2) All energy recovery & all aluminum



A-3) Conv. recycling & all AHSS

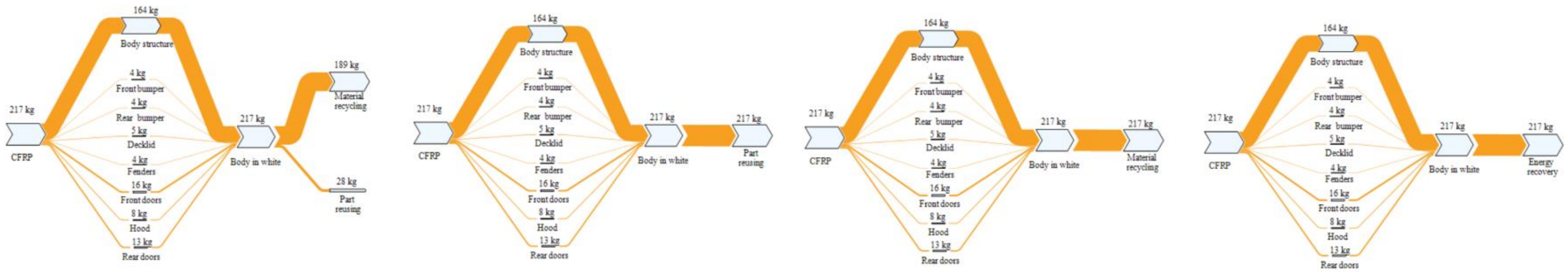
B-3) All part reusing & all AHSS

C-3) All material recycling & all AHSS

D-3) All energy recovery & all AHSS

a) Part 1

Fig. 4.5 Material flow of different scenarios of the body in white



A-4) Conv. recycling

& all CFRP

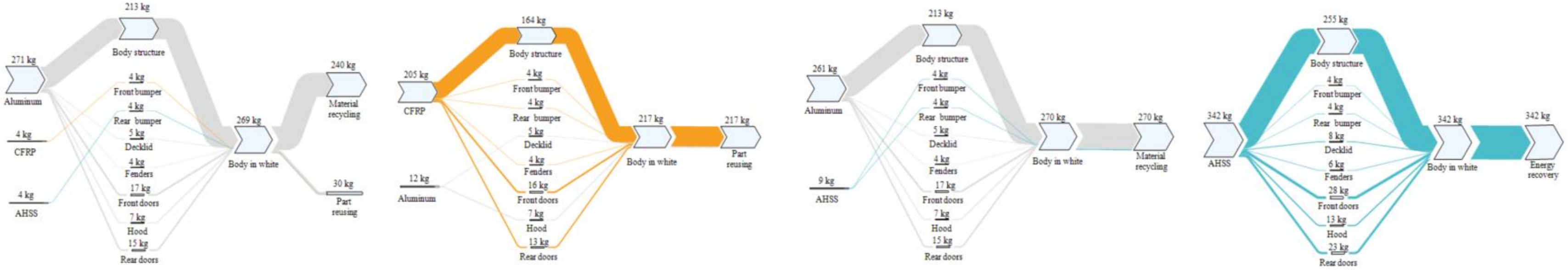
B-4) All Part reusing

& all CFRP

C-4) All material recycling

& all CFRP

D-4) All energy recovery
& all CFRP



A-5) Conv. recycling

& minimum energy-CO_2

B-5) All Part reusing

& minimum energy-CO_2

C-5) All material recycling

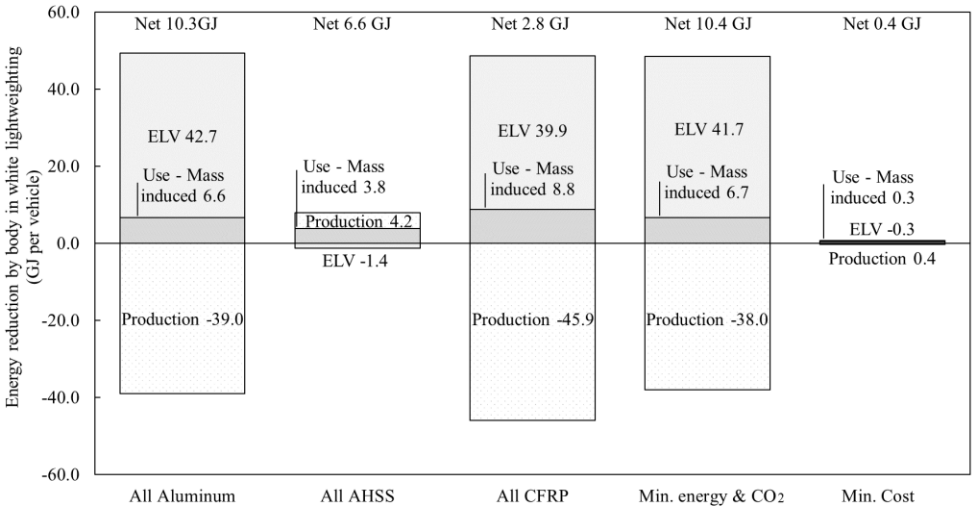
& minimum energy-CO_2

D-5) All energy recovery &

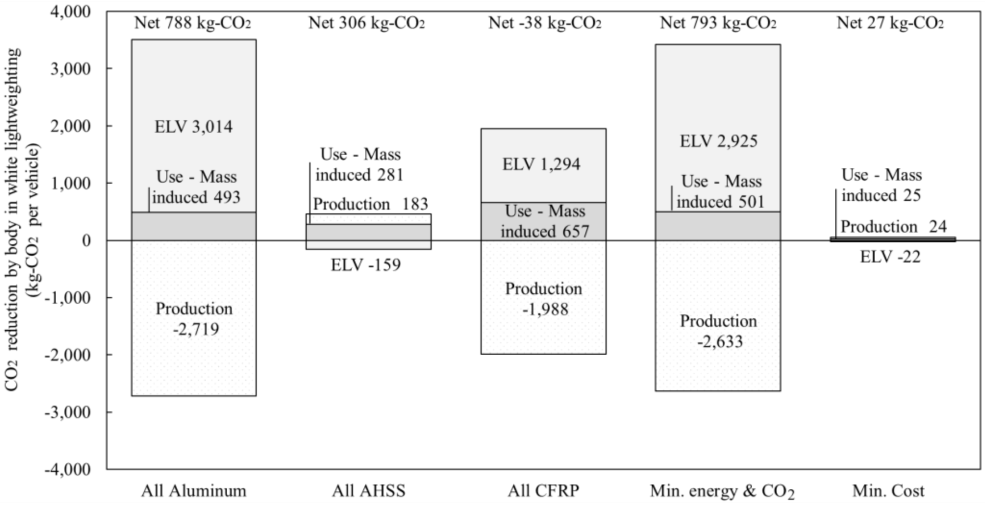
minimum energy-CO_2

b) Part 2

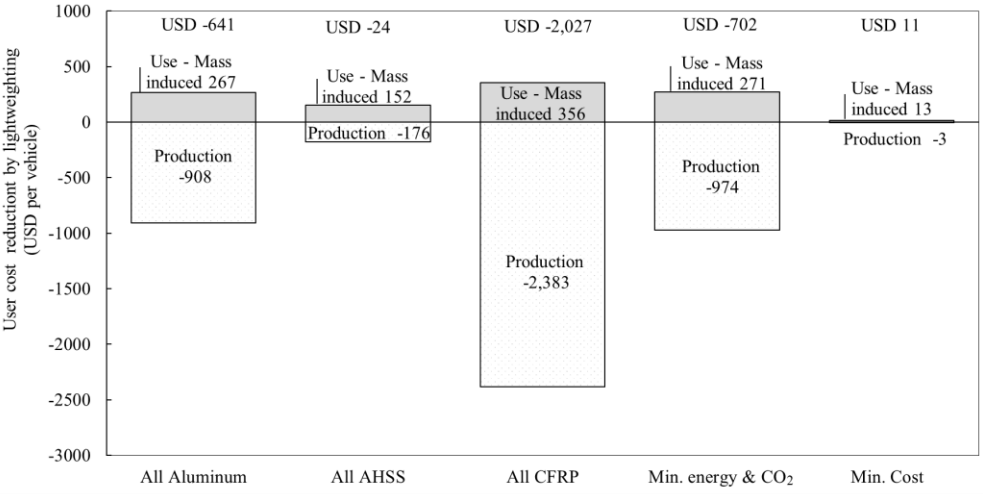
Fig. 4.5 Material flow of different scenarios of the body in white



a) Energy reduction

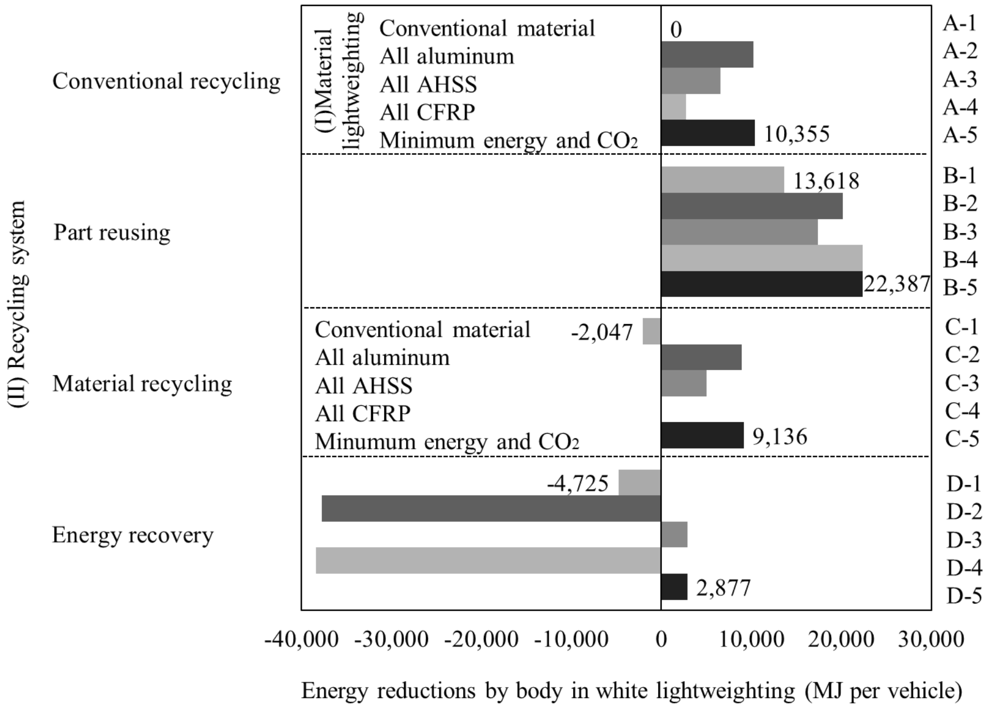


b) CO_2 reduction

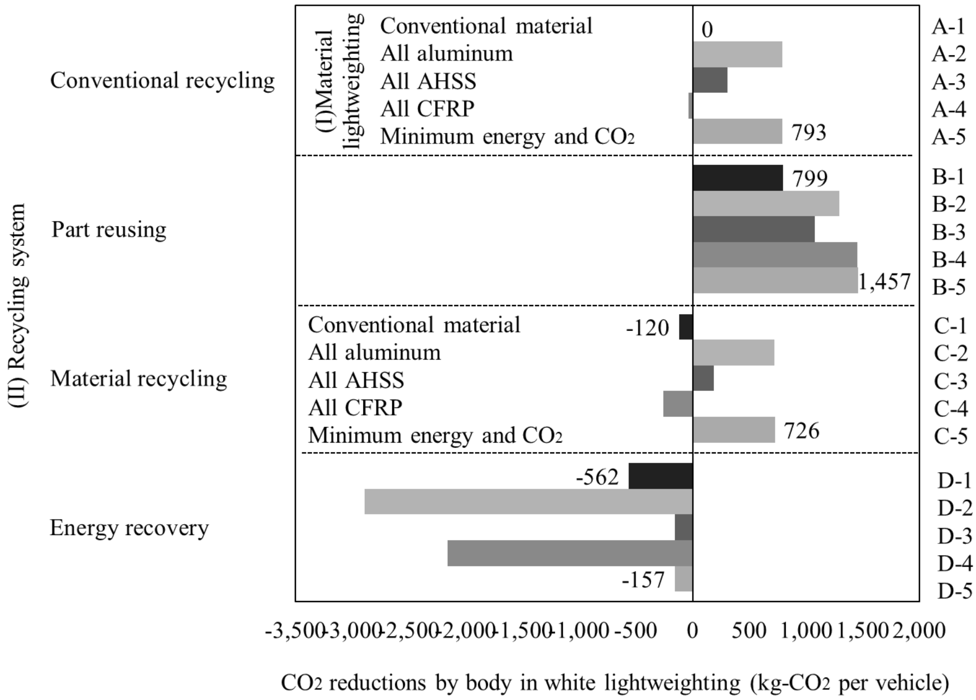


c) User cost reduction

Fig. 4.6 Life cycle energy, CO_2 and user cost reductions by the body in white lightweighting in a conventional recycling system

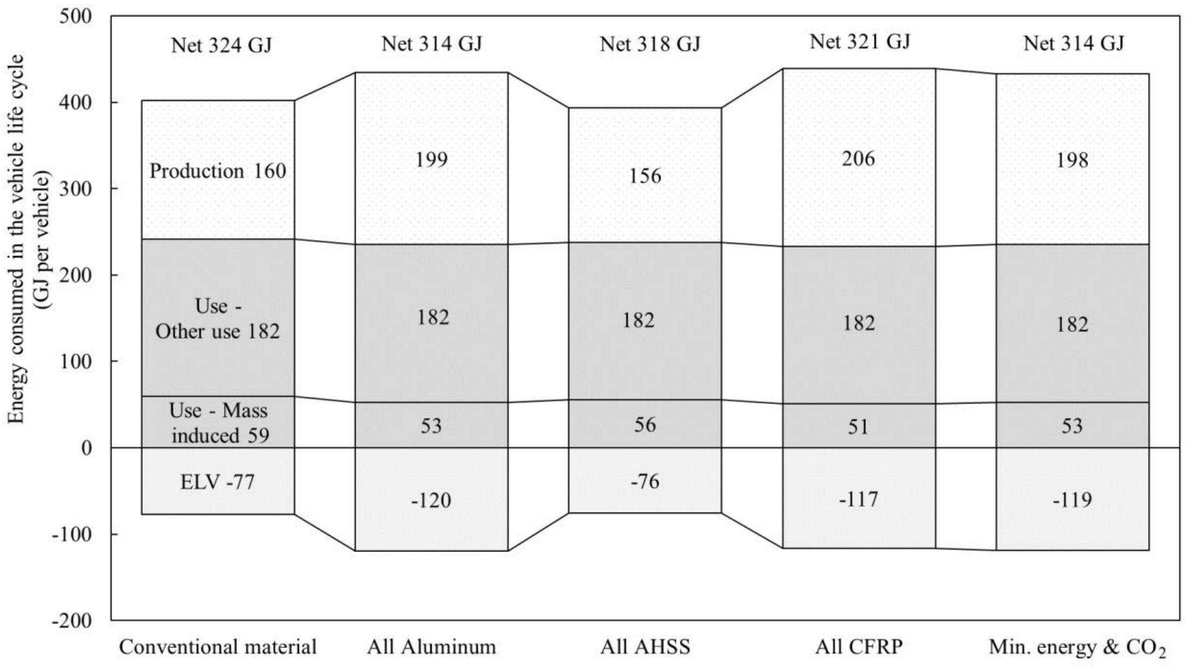


a) Energy reduction potential by improvement in lightweighting and recycling system

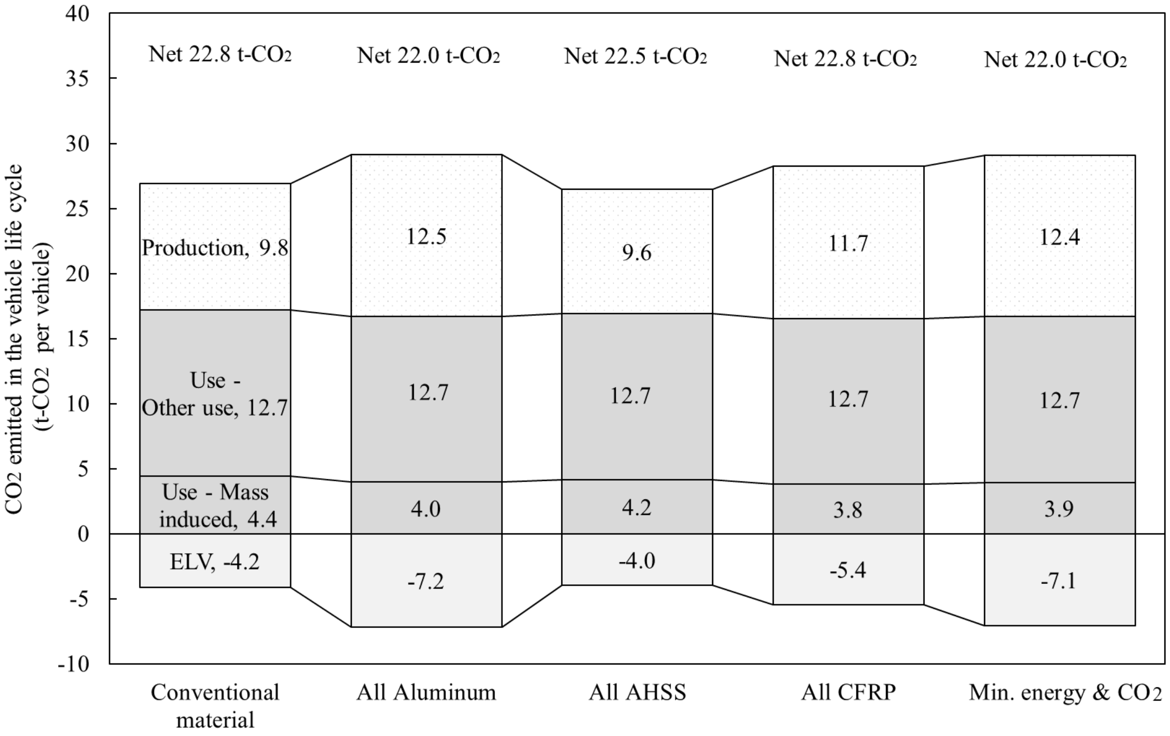


b) CO_2 reduction potential by improvement in lightweighting and recycling system

Fig. 4.7 Energy and CO_2 effects and scenarios considering the lightweighting and recycling system



a) Energy consumptions



b) CO_2 emissions

Fig. 4.8 Life cycle energy consumption and CO_2 emissions of vehicles with lightweighted body in white

5. Recoverability assessment of critical materials from electric vehicle lithium ion batteries

5.1 Introduction

Japan is the third more representative vehicle market when worldwide production and sales volume of vehicle is considered (International Organization of Motor vehicle Manufacturers, 2018a; International Organization of Motor vehicle Manufacturers, 2018b), but also are ones of the countries that lead the development of new electrical technologies in the transportation area, including the development of hybrid electric vehicles and fuel cell vehicles.

Internal combustion engine vehicles depend to fossil fuels; however, the electric vehicles which include hybrid electric vehicles (HV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV) and fuel cell vehicle (FCV) depends partially or totally on electricity. Currently, the EVs account for 32.9% of vehicle sales in Japan (Next Generation Vehicle Promotion Center, 2018), and it is expected a rapid increase in its share in the following years. Here, the size and weight of the electric vehicle batteries (EVB) vary depending on the electrification level, driving range of vehicle and its technology. Most of those vehicles use Lithium ion batteries (LiB) to store the energy needed for traction due to its higher energy density and more extended life compared with other available technologies. Additionally, considering the use of LiB in consumer electronics and grid energy storage, the increment of the dependency of the transportation sector but also of the society on those technologies in the middle and long term seems to be inevitable.

Sustainable production of the LiB in the upstream of the supply chain is indispensable; however, an adequate collection, treatment, recycling and reusing of those batteries in the downstream stage is also necessary. Firstly, considering the electrical, fire-explosion, and chemical hazard potential of the LiB (Diekmann et. al. 2018). Secondly, the high carbon intensity of the cell's production and the significant potential of its cascade use to minimize its life cycle environmental impact (Ager-Wick et al., 2013; Ahmadi et al., 2017). Third, considering that valuable and critical metals such as Co and Ni can be recovered with an adequate recycling process (Olivetti et al.,2017). Moreover, collected LiB can be reused in second life stationary applications as storage of wind power, peak shaving, EV charging, electrical trading, backup, and so on, significantly reducing the production cost of them. Finally, the high processing and transportation cost of scrapped LiB need to be reduced, which is approximately 10 to 15 thousand yens per unit of battery for HV in Japan (Honda Motor Co., 2017); a critical factor when the total weight of future scrapped electric vehicles batteries (EVB) are considered. In this sense, directives by governments have been settled to promote the efficient collection and recycling of batteries.

Many studies have analyzed the importance of the recycling of the spent LiB (Zheng at. al, 2018; Gaines, 2014; Winslow et. al, 2018); however, only few of them assessed its real potential when those concepts are put into practice, for this propose two variables are indispensable to be analyzed, the recovery volume and time of the batteries. Few studies have proposed dynamic approaches to forecast used traction battery flow, however one of the key factors for the modeling which is the returning timing of the EV and batteries are modeled considering the life span of the vehicle as a constant by a single point estimation (Pehlken et. al, Ziemann et. al, 2018) or a truncated lifespan distribution (Bobba et.al 2019, Richa at.al). Moreover, changed on the battery technologies through the time which impact directly in the material composition of them are also not considered. The proposed model forecast the volume of end of life vehicles base on the scrapping rate by year of use calculated considering past data of the Japanese vehicle market. Possible changes in the material composition of the recovered and supplied batteries are calculated based on open data of different LiB specifications. Additionally, for the author knowledge, previous studies are centered on European or North

American and there are no studies that analyze the japan market; on the other hand, cost comparative is also carried including in the consideration the upstream and downstream of the battery life cycle.

The criticality of the different materials could vary depending on the country, the time when the material is suppled and also has a strong dependence on the risk factors considered in its calculation. However, when criticality related to the production of the LiBs is analyzed Li, Ni, Co and Mn are usually highlighted as the representative ones (Helbig et al. 2018, Song et al. 2019, International energy agency, 2018).

The aim of this study is to propose a model to forecast the number of critical materials recovered from LiB through the recycling of end of life electric vehicles (EV) and analyze the potential of a closed-loop supply in Japan. System dynamics modeling has been utilized for this propose.

5.2 Methodology

5.2.1 Analysis of vehicle sales, fleet size, and scrapping

Fig. 5.1 shows the concept of our forecasting model, where the entire vehicle market is analyzed dividing the vehicle market into three parts: sales, fleet/aging, and scrap. The different power trains (ICEV, HV, PHEV, BEV) sold by type of vehicle (mini passenger cars, mini trucks, standard passenger cars, small passenger cars, standard trucks, small trucks & large buses and small buses) are also considered.

The total number of vehicles in a region (fleet size) is annually updated considering the number of vehicles sold and scrapped in a year (1). Here, the term vehicle scrapped includes the ELV that are dismantled but also the ones that spent its second life in foreign countries.

$$VSa_{t+1} = V_{t+1} - V_t + VSc_{t+1} \tag{1}$$

V_t : Number of vehicles at the end of the year t in the fleet[units].

V_{t+1} : Number of vehicles at the end of the year $t+1$ in the fleet [units].

VSa_{t+1} : Number of vehicles sold during the year $t+1$ [units].

VSc_{t+1} : Number of vehicles scrapped during the year $t+1$ [units].

The above flow is separately analyzed considering the type and power train of the vehicles (2)-(5).

$$V_t = \sum_i \sum_p \sum_l V_{i,p,l,t} \tag{2}$$

$$V_{t+1} = \sum_i \sum_p \sum_l V_{i,p,l,t+1} \tag{3}$$

$$VSc_{t+1} = \sum_i \sum_p \sum_l VSc_{i,p,l,t+1} \tag{4}$$

$$VSa_{t+1} = \sum_i \sum_p VSa_{i,p,t+1} \tag{5}$$

$V_{i,p,l,t}$: Number of vehicles of type i, power train p and year of life l at the end of the year t in the fleet [units].

$V_{t+1,i,p,l}$: Number of vehicles of type *i*, power train *p* and year of life *l* at the end of the year *t+1* in the fleet [units].

$VSc_{i,p,l,t+1}$: Number of vehicles scrapped of type *i*, power train *p* and year of life *l* during the year *t+1* [units].

$VSa_{i,p,t+1}$: Number of vehicles sold of type *i*, power train *p* during the year *t+1* [units].

The number of vehicles (fleet size) is forecasted considering previous studies of Dargay et. al.(1999; 2007), who proposes an s-shape function to represent the relation between the vehicle ownership per capita and the GDP growth of a country (6).

$$VO_{t+1} = \gamma * \theta * e^{\alpha * e^{\beta \, \mathrm{GDP}}} + (1 - \theta) * VO_t \tag{6}$$

VO_{t+1} : Vehicle ownership at the end of the year *t+1* [units per 1000 people]

VO_t : Vehicle ownership at the end of the year *t* [units per 1000 people]

γ : Saturation level of the number of vehicles [units per 1000 people].

α : Parameter alpha related to the shape of the function.

β : Parameter beta related to the shape of the function.

θ : Speed of effect between the variables ($0 < \theta < 1$).

Moreover, the number of vehicles scrapped during a year depends on the number of vehicles available and the probabilities of the vehicles to be scrapped which vary depending on the type, power train, and year of life of them (7).

$$VSc_{i,p,l,t+1} = \sum_i \sum_p \sum_l V_{i,p,l,t} * Psc_{i,p,l,t+1} \qquad (7)$$

$Psc_{i,p,l,t+1}$: Probability of a vehicle type *i*, powertrain *p* and year of life *l* to be scrapped during the year *t+1*.

Finally, the total sales of vehicles per year can be divided by type and powertrain, considering future share predictions (8).

$$VSa_{i,p,t+1} = VSa_{t+1} * \sum_p \sum_l Ss_{i,t+1} * Ss_{p\in i,t+1} \qquad (8)$$

$Ss_{i,t+1}$: Sale share of vehicle type *i* during the year *t+1*.

$Ss_{p\in i,t+1}$: Sale share of vehicles with powertrain *p* in the market of the vehicle type *i* during the year *t+1*.

5.2.2 Analysis of the possible critical material supply from LiB recovered from the end of life EV.

Firstly, it is worthy of clarifying that this study considers two types of EVB technologies in the forecast, Nickel-metal hybrid batteries (NiMH) and LiB. However, the analysis of recovered and supplied critical materials focus only on the second one considering that NiMH are still used in some HV, but LiB are more attractive for PHEV and BEV due to their much higher energy density, longer cycle life, lightweight and ability to provide deep discharges (Olivetti et al., 2017). Supplied and recovered amounts of critical metals (Ni, Co, Mn, Li) used in the production of the LiB and possible to recover from scrapped vehicles are forecasted.

The amount of the LiB supplied to the automotive industry is calculated through equation (9).

$$SLib_t = \sum_i \sum_p VSa_{i,p,t} * LibV_{i,p,t} * VLiB_{i,p,l} \tag{9}$$

$SLib_{t,l}$: Amount of supplied LiB during the year *t* [kwh]

$LibV_{i,p,t}$: Size of LiB of a vehicle type *I* and power train *p* in the year *t* [kwh/unit]

$VLib_{i,p,t}$: Rate of vehicles of type *i*, power train *p* in the year *t* that use LiB for traction

Moreover, the material supplied for the production of the LiB depends on the technology of the battery (10).

$$SMat_{m,t} = \sum_i \sum_p VSa_{t,i,p} * LiBV_{i,p,t} * VLiB_{i,p,t} * WMat_{m,i,p,t} \tag{10}$$

$SMat_{m,t}$: Amount of supplied material *m* for the production of LiB during the year *t* [kg]

$WMat_{m,i,p,t}$: Weigh of material m of a LiB from a vehicle of type i, power train p in the year [kg/kwh]

The size of the LiBs recovered from scrapped varies depending on the type, power train, and year of life of the vehicle (11).

$$RLib_t = \sum_l \sum_i \sum_p VSc_{i,p,l,t} * LiBV_{i,p,l,t} * VLiB_{i,p,l,t} \tag{11}$$

$RLib_t$: Amount of recovered LiB during the year *t* [kwh].

$LiBV_{i,p,l,t}$: Size of LiB of a vehicle type *i*, power train *p* and year of life *l* in the year t [kwh/unit]

$VLiB_{i,p,l,t}$: Rate of vehicles of type *i*, power train *p* and year of life *l* in the year *t* that use LiB for traction

The material recovered from the scrapped LiBs depends on the technology and material composition of its cells which varies through the evolution of its technologies (12).

$$RMat_{m,t} = \sum_l \sum_i \sum_p VSc_{i,p,l,t} * LiBV_{i,p,l,t} * VLiB_{i,p,l,t} * WMat_{m,i,p,l,t} \tag{12}$$

$RMat_{t,m}$: Amount of recovered material *m* from the LiBs during the year *t* [kg]

$WMat_{m,i,p,l,t}$:Weigh of material m of a LiB from a vehicle of type i, power train p and year of life l in the year t [kg/kwh]

5.3 Analysis of the Japanese vehicle market

As the third-largest economy of the world (World Bank, 2018), Japan has one of the biggest vehicle markets, and its technological contribution to the electrification of vehicles is indispensable. Word wide-scale automakers and battery makers lead the local automotive industry been them pioneers in the development of electric vehicles.

Fig. 5.2 shows the analysis flow of this approach. To assess the effect of the LiB recovering through the methodology proposed above, here main characteristics of the Japanese vehicle market and manufacturing were analyzed and listed below in order to use them as input data for our model. It is worth to mentioning that part of the input data is based on the Japanese fiscal year (April to March).

・Vehicle fleet size: Fig. 5.3 a) shows the forecast of the Japanese GDP presented by the OECD (2018) which was used to in the equation (6) to calculate the growth of the vehicle ownership shown in Fig. 5.3 b). Fig. 5.3 c) indicates the population growth forecast of the country estimated by The world bank (2019). Finally, Fig. 5.3 d) shows estimation of the size of future Japanese vehicle fleet. Moreover, the initial composition of the vehicle fleet by type and powertrain was broadly estimated based on reports from the Next Generation Vehicle Promotion Center (2019b) and Automobile Inspection & Registration Information Association (2019).

・Sale share of vehicles: Fig. 5.4 shows the share of the future vehicle sales in Japan by type and power train estimated considering data from the Ministry of the Environment (2010) Japan Automotive Manufacturers Association (2019) and Next Generation Vehicle Promotion Center (2019 a). Moreover, it is worthy of mentioning that the share from 2009 to 2017 represents historical records of the market (Japan Automotive Manufacturers Association, 2019; Next Generation Vehicle Promotion Center, 2019 a; Next Generation Vehicle Promotion Center, 2017).

・Probability of vehicle to be scrapped: Vehicle scrapping rates were calculated as the percentage of vehicles that are scrapped annually per year of use base on reports of the Automobile Inspection & Registration Information Association (2019). Here, average data of standard/small passenger cars and trucks been utilized, and scrapping rate from 2018 to 2050 estimated by linear least squares regression. Fig. 5.5 shows the historical and forecasting of the vehicle scrapping rate considered in this model. It is worthy of clarifying that the scrapping rate of passenger cars varies shapely every two years due to the impact of the automobile inspection requirement of the Japanese government.

・Size of LiBs: Size of the LiB vary widely depending on the type, power train, and specifications of the vehicle. In this study, the capacities of the batteries of Mini Passenger cars & Mini Trucks, Standard/small Passenger cars have been considered 2 kWh for HV, 9kWh for PHEV, and 28 kWh for BEV (Dunn et/ al, 2012) ; Moreover, batteries for Standard/small Trucks & large/small buses have been considered 3.9 kwh for HV (Isuzu motor limited, 2017) and 304 kwh for BEV (Gao et al., 2017).

・Battery technologies: Material compositions of the batteries are modified considering core LiB technology used in electric vehicles at the moment. Fig. 5.6 shows the evolution scenario adopted in this study. To forecast future changes, representative LiB technologies during the past years have been estimated base on Nissan motor corporation (2019) and Blue Energy Co. (2016), and possible new technologies for the following years forecasted considering reports from International energy agency (2018), Argus media Ltd. (2019) and Lebedeva et. al. (2016). Moreover, Table 5.1 shows the material composition of the mentioned LiB technologies.

・Cost of the materials and batteries: Table 5.2 shows the price of the material used for the production of the cathodes and production. Here, data of the report of the International energy agency (2018) have been considered.

5.4 Results and discussions

The proposed forecasting model was simulated through System dynamics and the software Vensim PLP x32 (2019) used for this propose.

5.4.1 Forecast of vehicle fleet size, sales and scrapping

Fig. 5.7 a) shows the forecast for vehicle sales by power train in the market. Here, it can be observed that the total sales of vehicles will decrease moderately in the following years due to the changes in the Japanese vehicle fleet size. However, sales of electric vehicles will increase considerably, and it is expected to reach a peak in 2040 with 4.17 million units sold per year. This value represents 2.2 times the EV sales of 2018 considering that it is not expected drastic changes in the HV demand. However, if sales of BEV are analyzed separately, it can be observed that the related sales will reach 1.94 million units in the same period, increasing 11.6 times the sales of 2018.

Fig. 5.7 b) shows the forecast of the Japanese vehicle market size. Here, it is possible to observe that even an increase in the GDP per capita and vehicle ownership is expected, the Japanese vehicle fleet could reach a peak in 2029 with 84.1 million units of vehicles in the market due to the possible decrease of the population. Moreover, compared to sales, where it can be observed the domination of electric vehicles in the following years, the vehicle fleet itself will be still predominated by ICEV until 2032.

Fig. 5.7 c) shows the forecast for the number of vehicles scrapped in the market. Here, it can be observed that the number of ELV will vary slightly in the following years. Moreover, ICEV will dominate the ELV market until 2038 reaching 2.58 million units scrapped per year compared to the 2.45 million units of EV. Moreover, even a substantial quantity of HV are reaching its end on life in the coming years; the amount of BEV and PHEV expected to be collected until 2025 seems to be minimal, being less than 2% of the total ELV generated in a year.

Finally, it worthily to mention that grey parts on the left side of each figure indicate historical records of vehicle sales [Japan Automotive Manufacturers Association, 2019; Next Generation Vehicle Promotion Center , 2019a; Next Generation Vehicle Promotion Center, 2017], fleet [Japan Automotive Manufacturers Association, 2015], and scrapping [Ministry of Environment, Government of Japan, 2015], which are compatible with the values forecasted in this model.

5.4.2 Forecast of EVB supply and recovery

Fig. 5.8 a) shows the forecast of the EVB supply simulated by this model, here, it can be noted that even though, in term of vehicles sales, HV play an essential role, the demand of EVB for BEV is going to dominate the market considering its higher energy capacity. EVB demand is going to increase rapidly in the following years; however, it is expected to reach maturity near 2030, considerably decreasing after that its growth rate. It is expected that the supply of EVB reaches 78 GWh per year in 2050, increasing 8.4 times from 2018 but 1.37 times from 2030. Moreover, electric buses and trucks will importantly affect the demand for future EVB.

Fig. 5.8 b) shows the forecast for the number of EVB that can be recovered from the ELV. The quantity of EVB for recycling and reusing is expected to be predominated by batteries from HV in the first years, but after this period, batteries recovered from BEV will represent the majority of the returning volume drastically increasing the size of the entire market from that time on. The recovered number of recovered EBV reaches 61 GWh in 2050 representing an increment of 55 times compared to 2018.

Fig. 5.9 show the forecast of the relation in term of energy capacity between the total EVB supplied for new vehicles and expected to be recovered from ELV. It can be noted that in 2025, the recoverability will be still less than 10% of the supply, but also, the rapid growth of those values can be expected in the following years, reaching 31% in 2035. Moreover, a complete close-loop could be expected nearly 2050 if only the energy capacity of batteries is considered.

5.4.3 Forecast of critical material supply and recovery for LiB

This section includes in the analysis different LiB technologies from 2010 to 2035 considering the composition of its critical materials.

Fig. 5.10 a) and b) show the forecasting of supplied and recovered LiB in terms of energy capacity by technologies. It can be observed that the LiB supplied until 2035 is going to be recovered gradually, and the mode of the returning flow is going to be nearly 2044. The grey section of the chart illustratively indicates the possible supplied and recovered volume of unknowable batteries technology.

Fig. 5.10 c) and d) show the weight of each critical material supplied for the LiB production and recovered from the market. Here, it is possible to observe that the demand of Ni is going to increase concisely in the following years, been the most representative critical material required for the LiB production. However, even the production of LiB increases, the demand for Mn, Co and Li seems not to change. Similarly, the most representative critical material, in terms of recovered mass, is also the Ni and 15,7 tons of is expected to return from ELV in 2035. Moreover, the supplied and recovered weigh of Mn, Co, and Li seem to be similar. This can be explained by the expected increment of Ni concentration on LiB, which increases the energy content of the batteries in exchange for stability (Olivetti et al, 2017).

Fig. 5.11 indicates that 34% of the lithium, 50% of the cobalt, 28% of the nickel, and 52% of manganese required in the production of new LiB could be supplied by batteries derives from end of life vehicles in 2035. Compared to Fig. 5.9, where the possible closed loop is analyzed in terms of energy capacity, and the recovered batteries represent 31% of the volume supplied, here, the recovered material is assessed, also considering the material weighs. It can be observed that, when changes in the battery technologies are taken into consideration, results are different, highlighting the importance of analyzing the potential of a close-loop including the material composition of them.

5.4.4 Economic analysis of the recovered materials

Fig. 10 e) and f) show the value of each critical material supplied for production and recovered from LiB. Compare to the analysis base on the material weights, here, it is possible to observe that the value of Co and Li supplied and recovered are as important as Ni. However, it is seen that the value of the Mn seen to be considerably lower. The total value of critical material required in japan for vehicle production of LiB reach 936 million US dollars in 2035, where 325 million dollars of it could be recovered by materials from ELV. The secondary axis of Fig. 11 shows the above relation, where 35% of the value of critical materials could be supplied locally by scrapped LiB in Japan, considerably reducing the dependency of those materials from foreign countries.

5.4.5 Limitations in the practice

In order to recover the forecasted quantity of critical materials from scrapped LiB, the following obstacle must be overcome.

Firstly, battery recycling facilities in Japan are Pyrometallurgical (Elibama, 2014; Mayyas et al., 2018), recovering the Co and Ni as molten metal alloy and the Li and Mn as slag (Cusensa et al., 2019). Shift to hydrometallurgical technologies must be carried in order to obtain high-grade materials possible to use in the production of new batteries. The recycling efficiencies of the analyzed materials in those facilities are close to 100% (Tytgat, 2013).

Secondly, the exportation of used vehicles in Japan represents approximately 28% of the total ELV (Ministry of Environment, Government of Japan, 2015).. Here, the demand for used HV are notorious, wherein 2017 approximately 84% of them were sent overseas to spent their second life (Japan Automobile Recycling Promotion Center, 2017). In the case of BEV this value exceeds 96% (Japan Automobile Recycling Promotion Center, 2017), having an important effect in the current LiB collection volumes. The exportation of end of life EV are centered in underdeveloped Asian countries; however, it can be expected in the middle and long term a natural decreasing of those values jointly with the saturation of electric vehicles in those market.

Thirdly, the results of recovered LiB proposed in this approach could be used for recycling as well as reusing proposes. However, reusing of LiB could delay the returning time of the spent batteries. In this sense, future studies could be carried to elevate the accuracy of the forecasting assuming alternative scenarios.

Fourthly, this study proposed a model to forecast the Japanese vehicles market based on open data. Different approximations in the inventory analysis for the Japanese vehicle market has been carried in order to conduct the simulation. Moreover, external analysis, such as the forecasting of the Japanese population, GDP, and vehicle sales share has been considered. Change on those values could guide us to different results; however, the proposed forecasting model and main conclusions are not going to change.

Finally, the price of the critical metals varies constantly and unpredictably depending on changes in the global market. This study has considered constant prices for the calculation of the values of the supplied and recovered critical materials. In this sense, the analysis methodology proposed in this approach can be easily adjusted to updated values.recycling facilities:

5.4.6 Implications and utilization in the practice

The results presented in this study give a whole picture of the ELV market but also perspectives of the scrapped EVB possible to recover from them. The proposed forecasting model can be applied by automakers and related companies to propose and verify the economic feasibility of different battery reusing and recycling business strategies clarifying the quantity and variety of "resources" available for its production process in the short, middle, and long term.

Even the supplied of critical materials for LiB production will considerably increase due to the diffusion of EV in the immediate years, the quantity of returning batteries of BEV and PHEV seems to be minimal until 2025. In this sense, new business and development of LiB reusing and recycling technologies should be center, in the short term, in batteries of HV considering the total returning volume of them.

Dismantlers and material recycling companies are going to be able to define optimal plans for the adaptation of its facilities, knowing the time and quantity of EV and LiB returning from the market. Moreover, the development of new recycling technologies should be centered on the recovering of Ni if the total available mass of material is prioritized but focused on Ni. Co, Li, when material value is put in front. On the other hand, an efficient reverse logistics network for spent batteries could be planned considering the forecasting values of this research.

This study also demonstrated that more than 50% ELV would be ICEV until 2038, in this sense, development of new technologies and new reusing and recycling project of them should not play second fiddle considering its room for improvement.

Due to the lifetime of the EV, the recovered LiB will no be significant source of material for the production of new ones in a short term; however, when longer time horizon is considered, and principal limitation clarified in this study overcame, the recovered batteries will play an essential role in the automotive industry and a total closed-loop feasible for EVB.

Finally, it worthy of mentioning that the proposed model can be easily adapted to other countries but also for different products such as electrical household appliance that needs to be recycled after its use as was proposed by the approach of Baldé et al. (2017).

Even a few entities and consultants forecasted supply or recover volume of critical material for EVB (Argus media Ltd, 2019; The Center for European Policy studies, 2018; Avicenne energy, 2017) details of the model implemented for the analysis is never open or available for utilization. In the same way, accuracy and premises considered in the forecasting are unknown. In this sense, the proposed model can be adopted and modified depending on the necessity allowing possible changes in premises be reflected.

5.5 Conclusions

This study proposes a model to forecast the number of LiB and critical materials possible to be recovered from the recycling of ELV. System dynamic concepts and open data are used to simulate the Japanese vehicle market. Compare to previous studies, this approach forecasts the number of end of life vehicles bases on the scrapping rate by year of life, calculated considering past data of the Japanese vehicle market. The main conclusions of this approach, where vehicle fleet and sales were additionally analyzed, are listed below.

・The total sales of vehicles in Japan seem to decrease moderately in the following years due to the decreasing Japanese population. However, sales of electric vehicles will increase considerably, and it is expected to reach a peak in 2040 with 4.17 million units sold per year. In this sense, EVB demand is going to increase rapidly in the following years; however, it is expected to reach maturity near 2030, considerably decreasing after that its growth rate.

・More than the 50% of the ELV will be ICEV until 2038, in this sense, development of new technologies and new reusing and recycling project of them should not play second fiddle.

・The amount of scrapped EVB will increase 55 times from 2018 reaches 61 GWh recovered per year in 2050. Moreover, the number of recovered EVB is expected to be predominated by batteries from HV in the first 5 years, clarifying the need to center reusing and recycling projects in them in the short term.

・Closed loop in EVB production could be expected in 2050 if only the energy capacity of batteries is considered. However, changes in batteries technologies play an essential role and the volume of critical material supplied for the production and possible to recover from ELV vary widely depending on the material composition of the LiB. Results indicate that 34% of the lithium, 50% of the cobalt, 28% of the nickel and 52% of manganese required in the production of new LiB could be supplied by batteries derives from end of life vehicles in 2035.

・Development of new recycling technologies should be centered in the recovering of Ni if the total available mass of material is prioritized but focused in Ni. Co, Li, when material value is put in front.

・The total value of critical material required in japan for EV’s LiB production reach 936 million US dollars in 2035, where 325 million dollars of it could be recovered by the material recovered from ELVs considerably reducing the dependency of those materials from foreign countries

- Considering that the quantity of returning batteries of BEV and PHEV seems to be minimal until 2025, new business and development of LiB reusing and recycling technologies should be center, in the short term, in batteries of HV.
- Exportation of used EV has a substantial impact on the current LiB processing/recycling market. Moreover, local LiB recycling facilities should shift to hydrometallurgical process if closed loop of batteries wants to be achieved.

Finally, the forecasting model proposed in this study could be adjusted to different situations and market premises considering that open data are used for the calculation, and the methodology used explained in detail.

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Table 5.1 Cathode active material composition of lithium ion battery technology

[kg/kwh]

	LMO	NMC 111	NMC 622	NMC 811
Li	0.10 [a),b),c),e)]	0.15 [d)]	0.13 [d)]	0.11 [d)]
Co	0.00 [a),b),c),e)]	0.4 [d)]	0.19 [d)]	0.09 [d)]
Ni	0.00 [a),b),c),e)]	0.4 [d)]	0.61 [d)]	0.75 [d)]
Mn	1.56 [a),b),c),e)]	0.37 [d)]	0.2 [d)]	0.09 [d)]

LMO, Lithium ion manganese oxide; NMC, Lithium nickel manganese cobalt oxide

a) Macquarie research, 2017 [45]

b)Argonne National Laboratory, 2018 [46]

c) Dai et. al, 2018 [47]

d) International Energy Agency, 2018 [18]

e) Author estimation

Table 5.2 Price of critical materials

Price of raw materials	$ per kg	Ref.
Lithium Carbonate	8.00	a)
Cobalt	30.00	a)
Nickel	9.00	a)
Manganese	2.00	a)

a) International Energy Agency, 2018 [18]

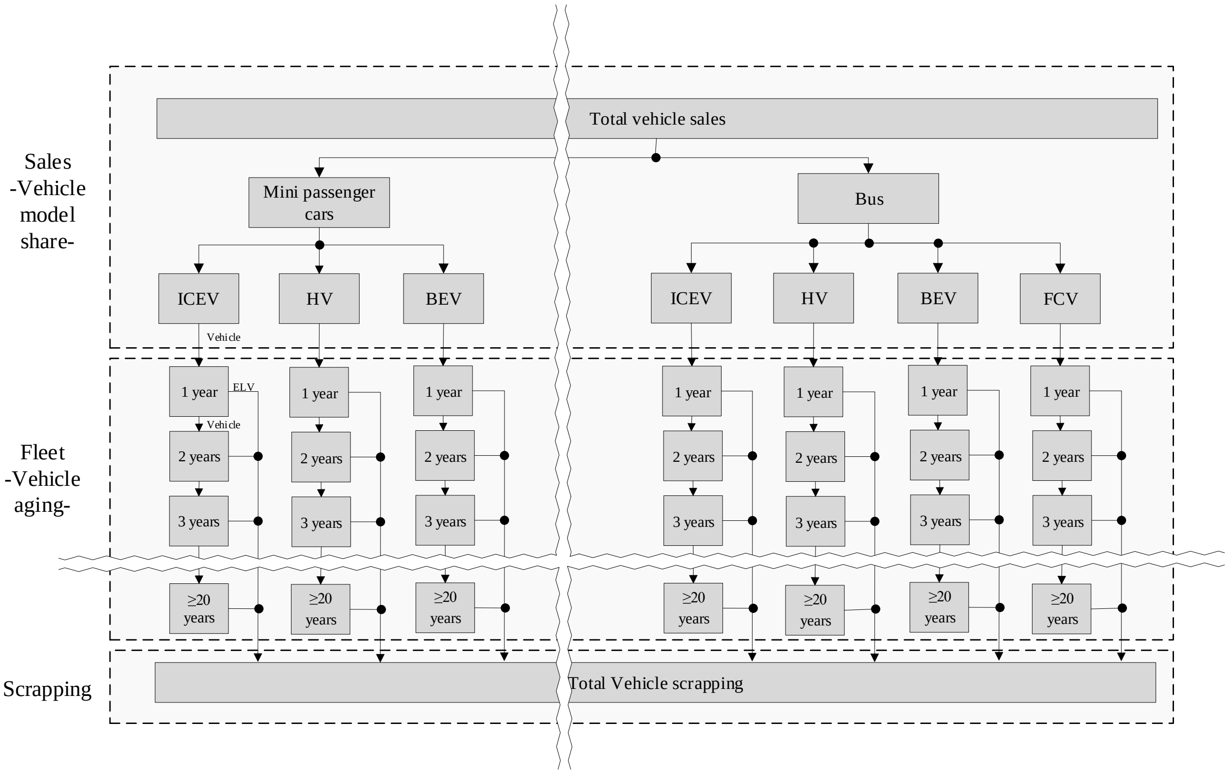


Fig. 5.1 Concept of the dynamic forecasting model

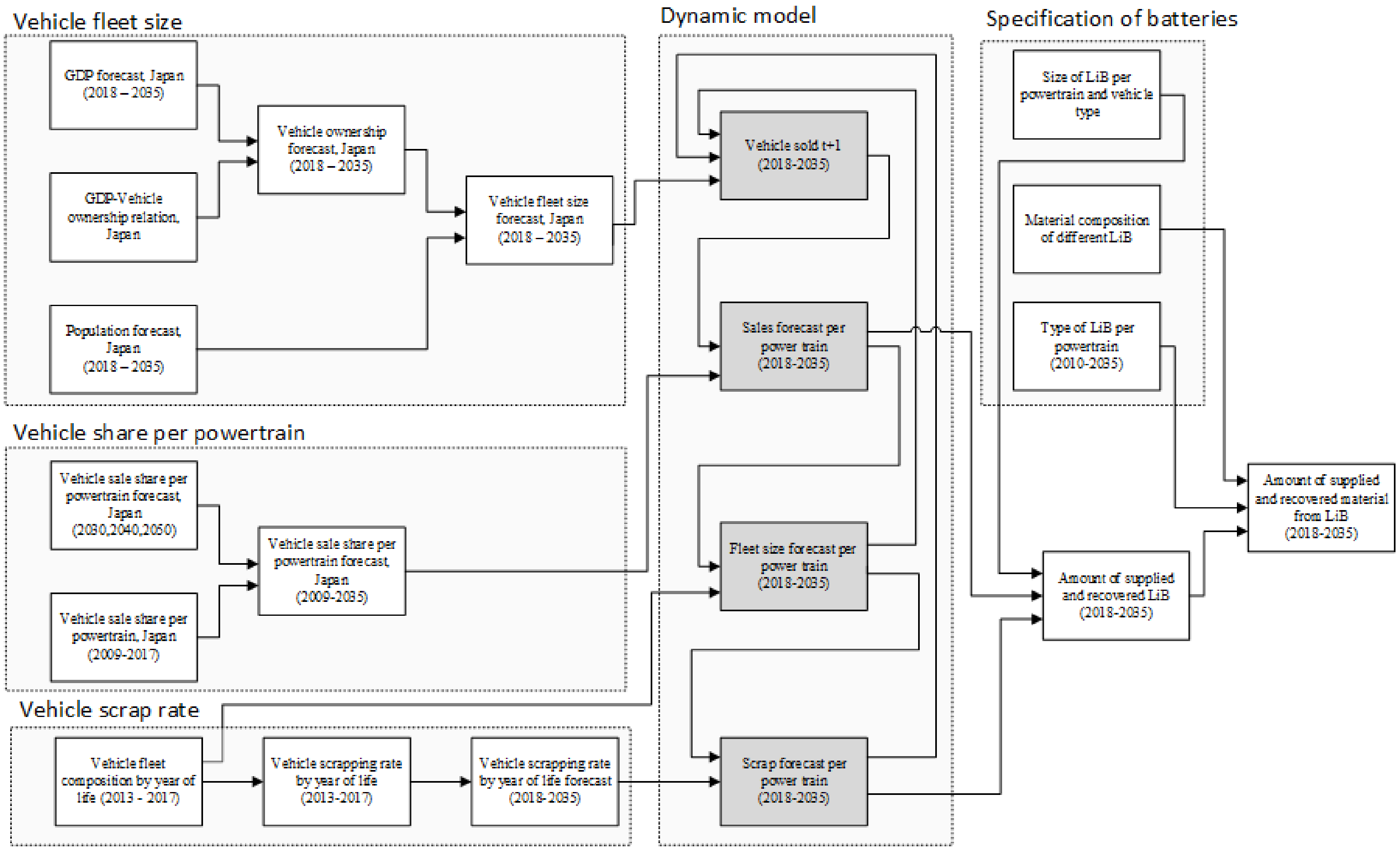
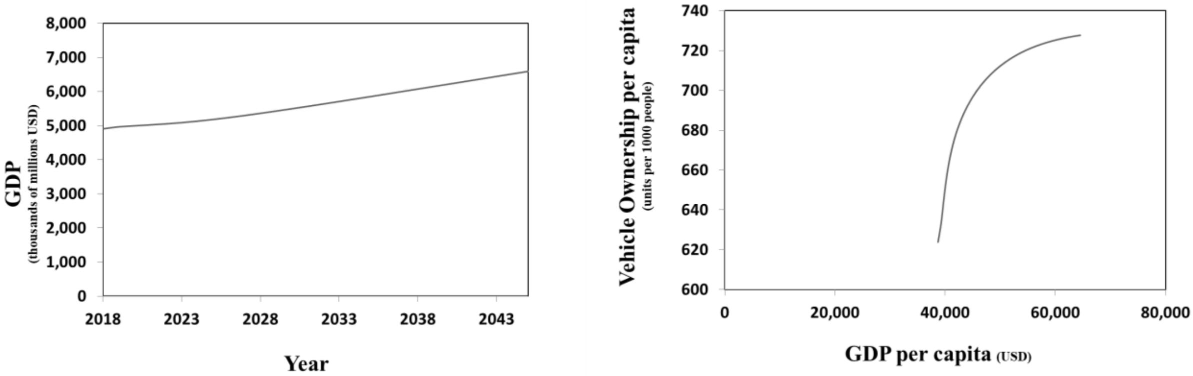
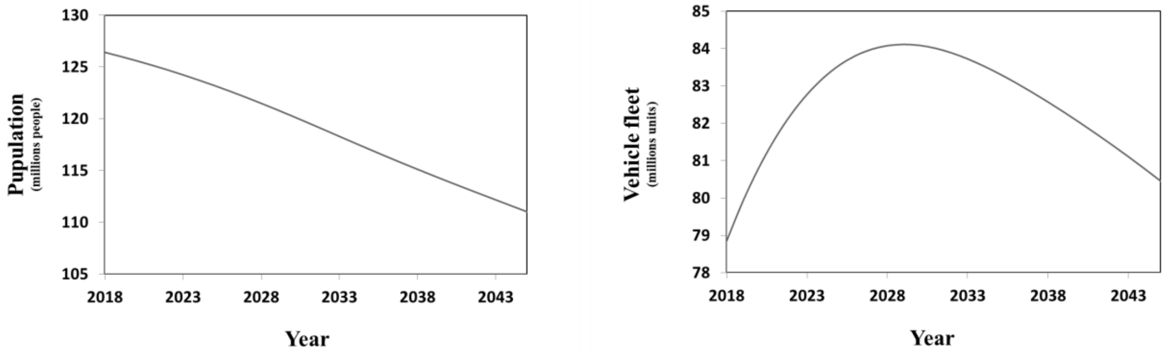


Fig. 5.2 Analysis flow of the model



a) GDP b) Vehicle ownership



c) Vehicle ownership d) Vehicle fleet

Fig. 5.3 Forecast of the Japanese GDP, population, vehicle ownership and vehicle fleet

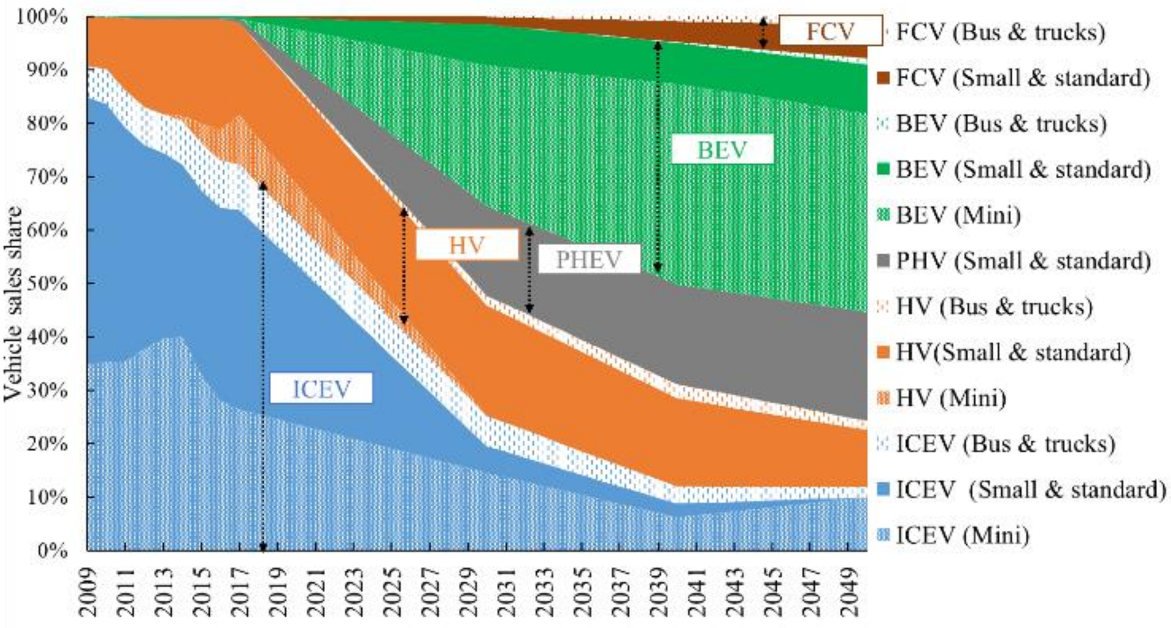
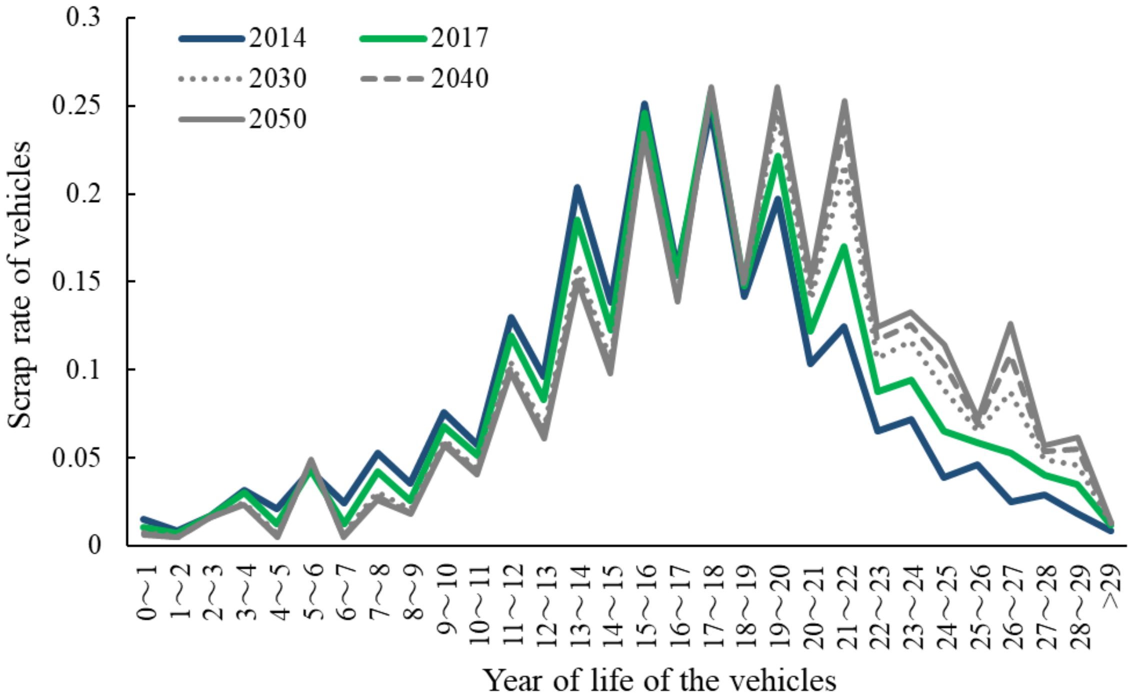
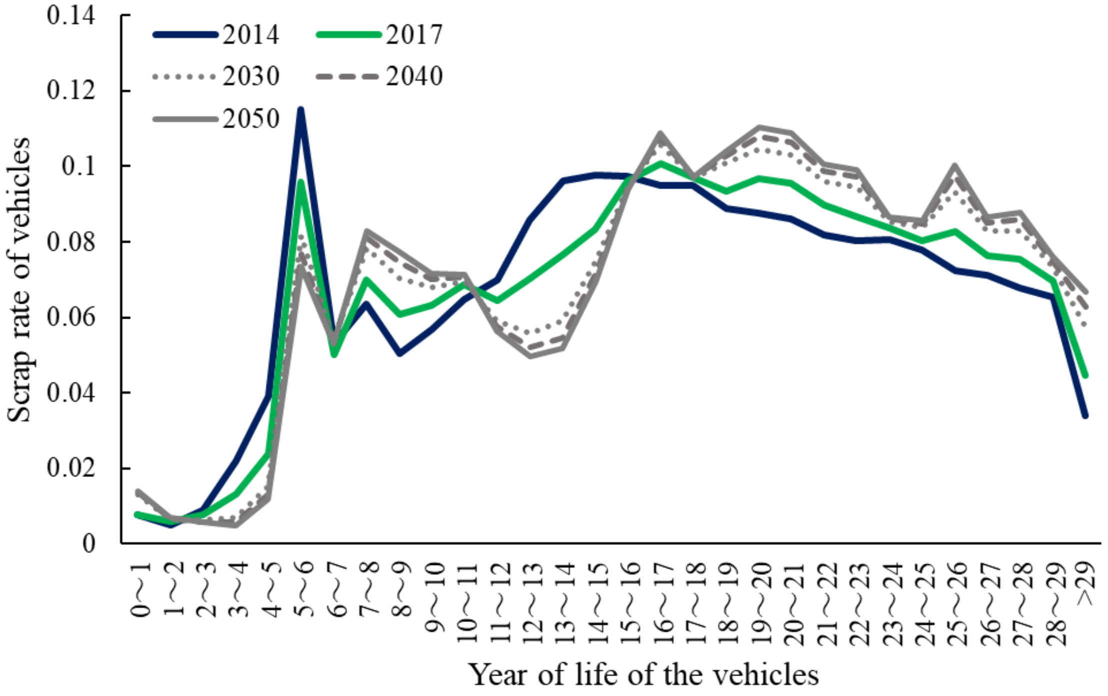


Fig. 5.4 Share prediction of the vehicle sales for the Japanese market



a) Forecast of the passenger cars scrapping rate



b) Forecast of trucks and buses scrapping rate

Fig. 5.5 Scrapping rate forecast of the Japanese vehicles

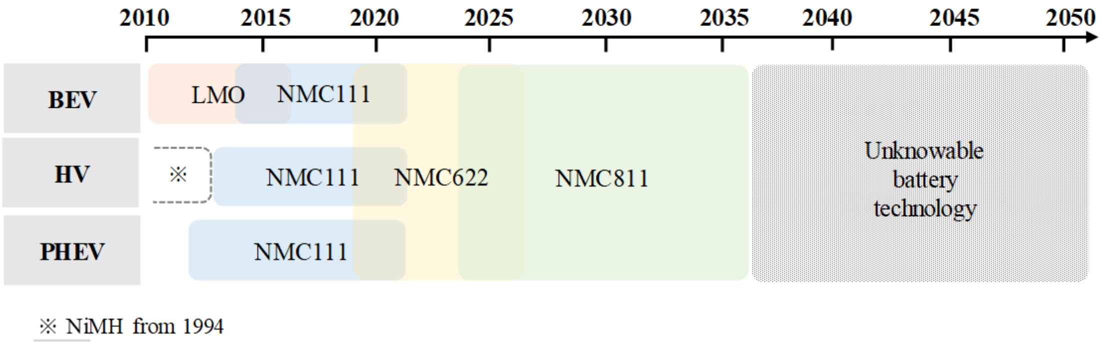
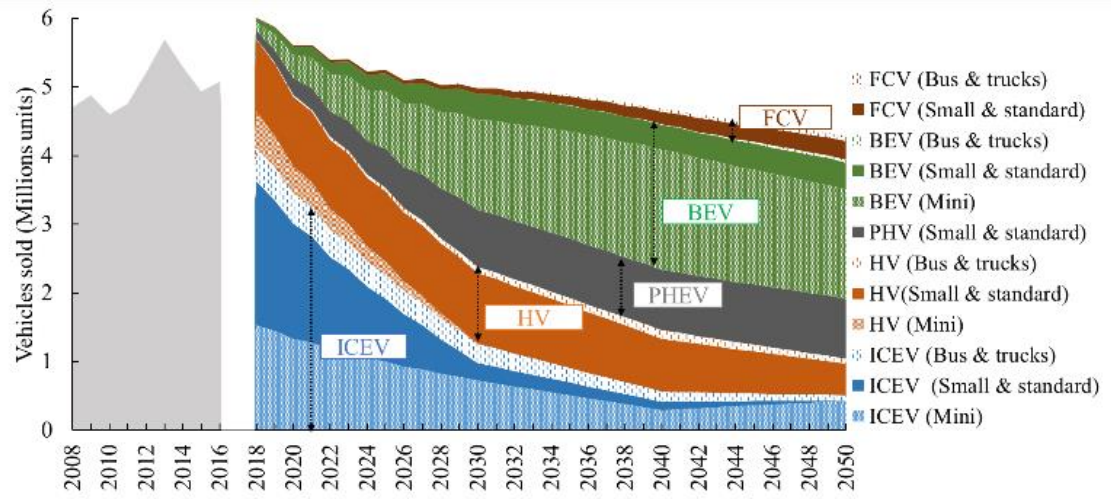
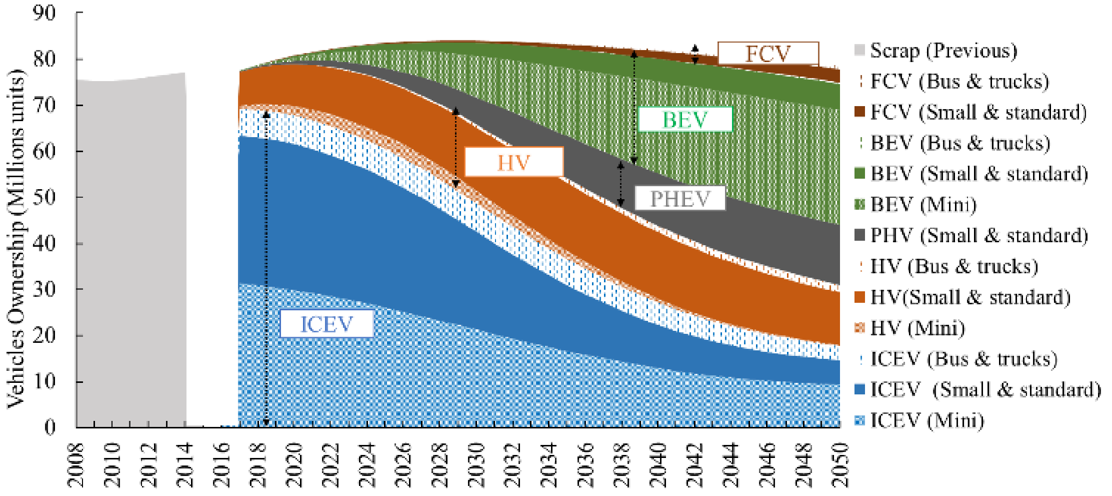


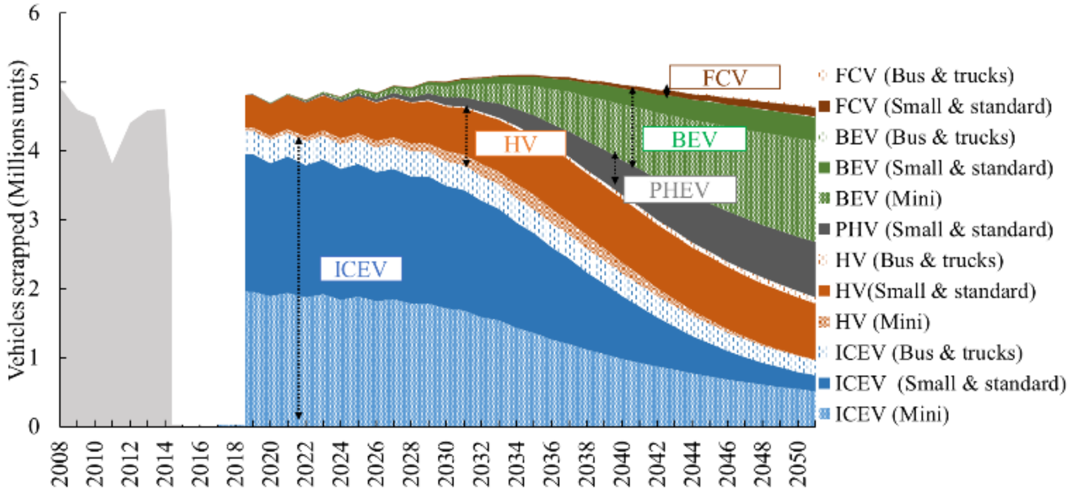
Fig. 5.6 Changes in the EVB technologies by years



a) Forecast of vehicle sales by power train

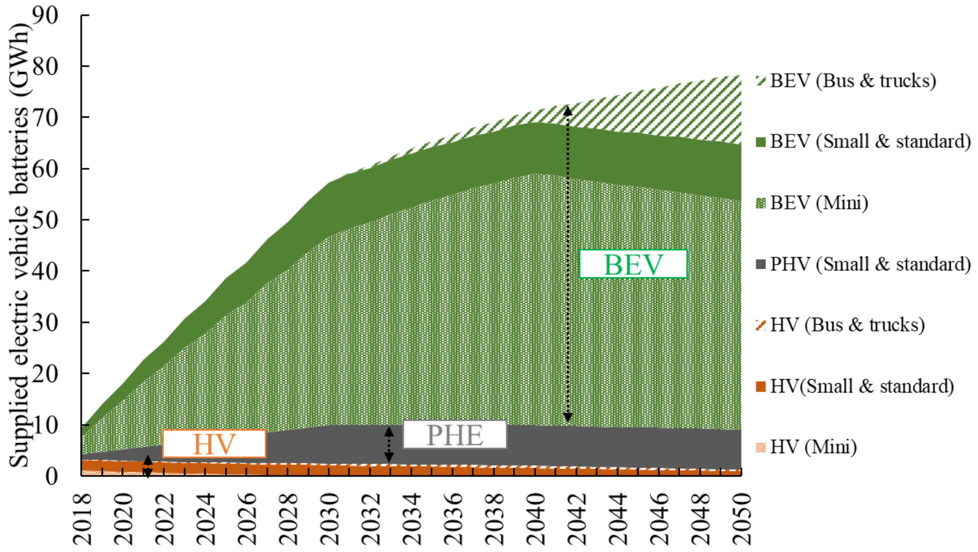


b) Forecast of the vehicle ownership by power train

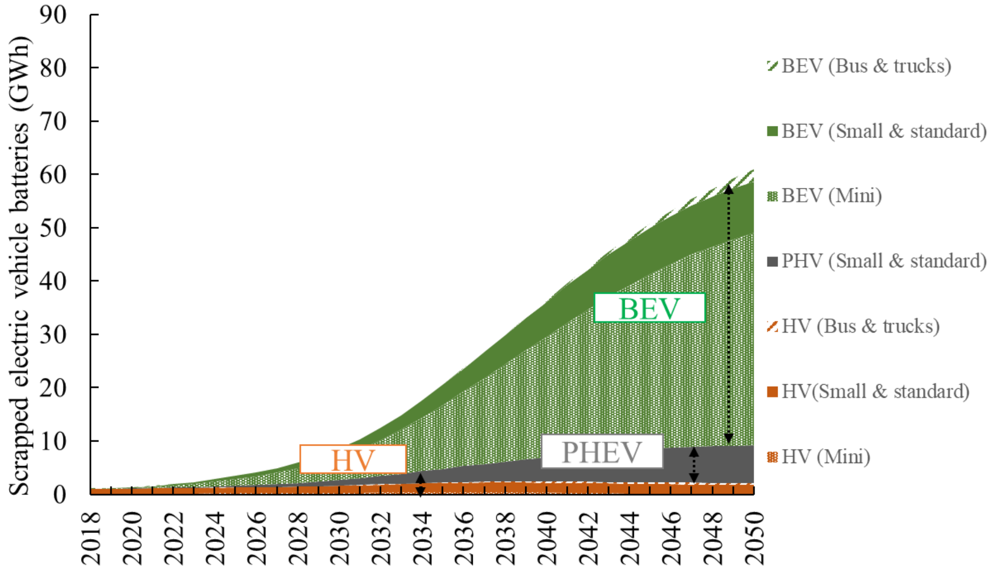


c) Forecast of the vehicle scrap by power train

Fig 5.7 Forecast of the Japanese vehicle market by vehicle type and power train



a) Forecast of EVB supply for the automotive industry



b) Forecast of EVB scrapped and recovered from the ELV

Fig. 5.8 Forecast of EVB supply and recovery for the Japanese vehicle market

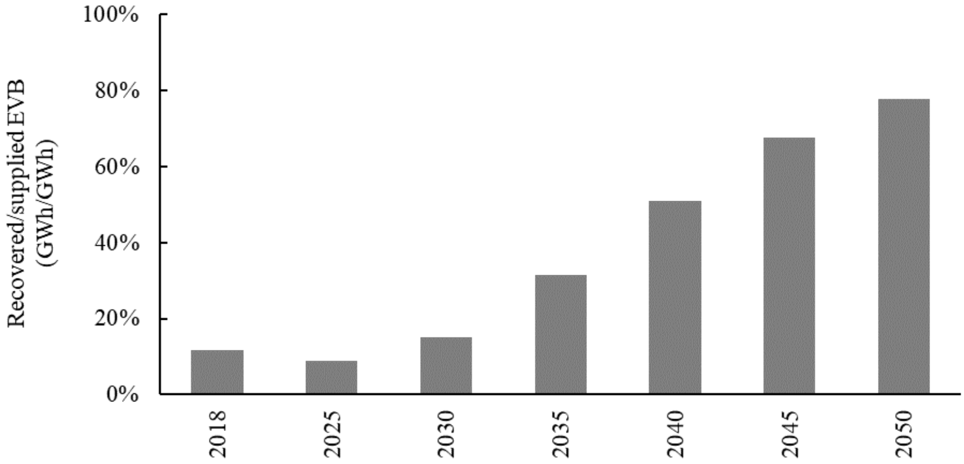
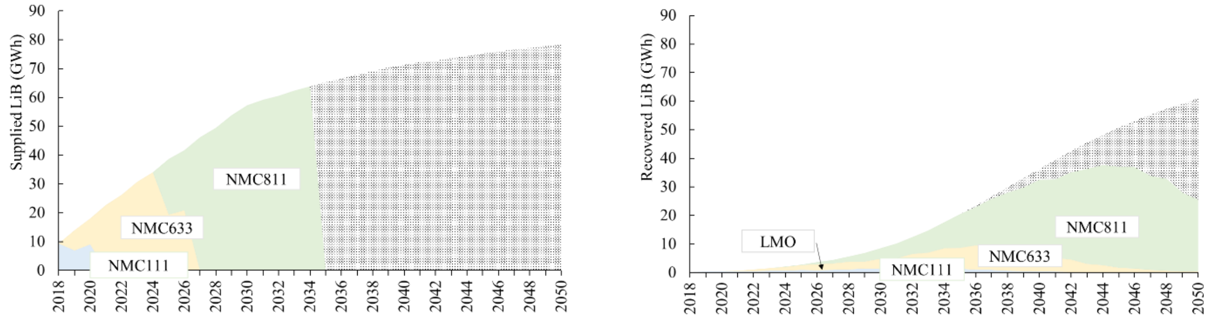
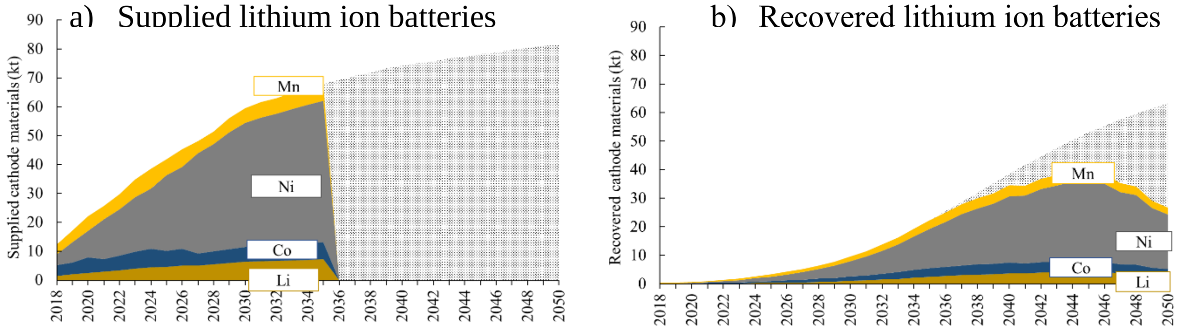


Fig. 5.9 Precentral relation between the EVB supplied and recovered



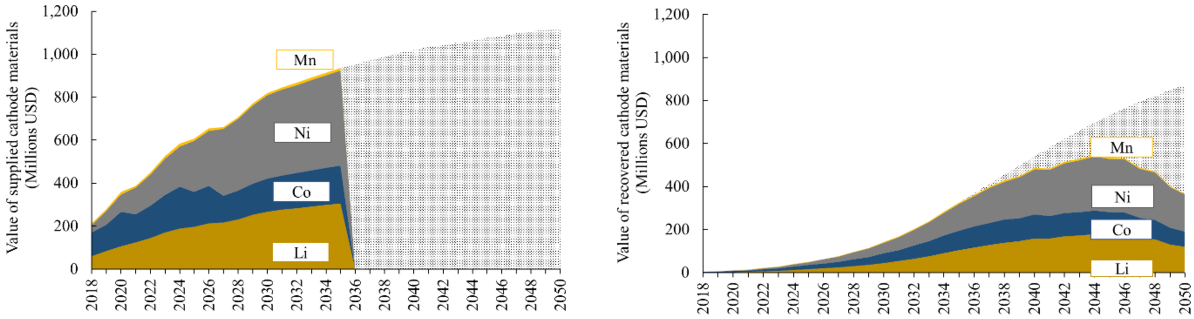
a) Supplied lithium ion batteries

b) Recovered lithium ion batteries



c) Weight of supplied material

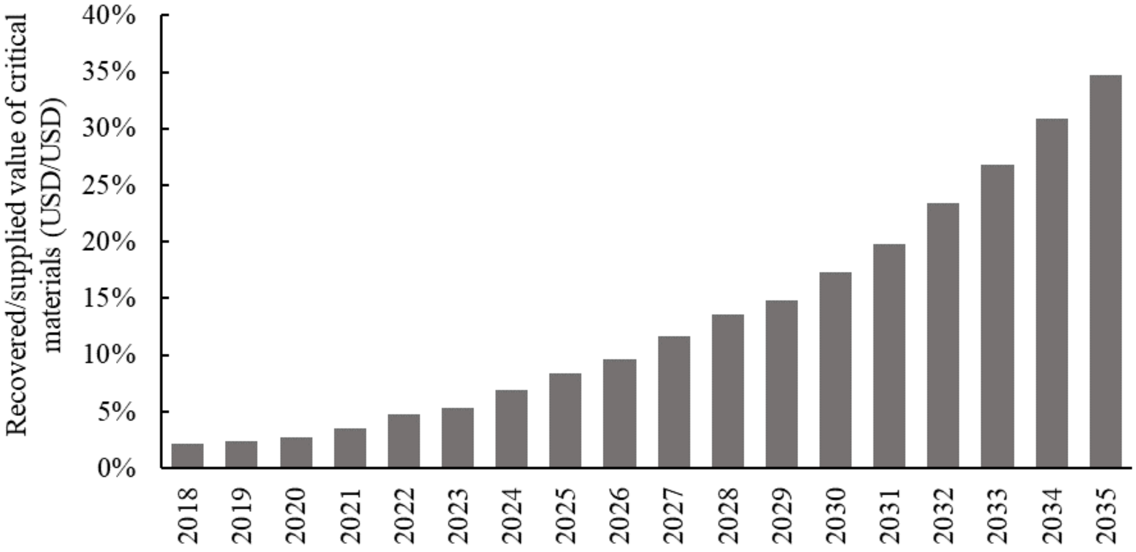
d) Weight of recovered material



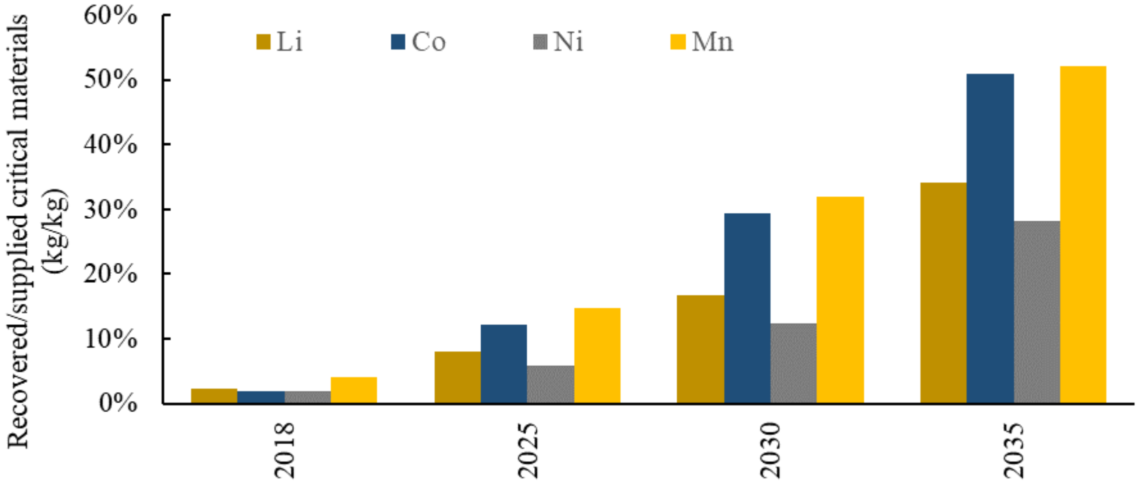
e) Cost of supplied material

f) Cost of recovered material

Fig. 5.10 Forecast of LiB and critical material supplied and recovered



a) Material value



b) Material weight

Fig. 5.11 Percentual relation between the weight and value of supplied and recovered critical materials

6. Discussion

6.1 Theorical and practical implementations of the study

It is going to be able to apply the following point in theorical approaches.

Evaluate quantitatively the impact of the ELV recycling considering the material composition of its parts and components, contributing towards a more comprehensive environmental and economic assessment of a vehicle life cycle. Moreover, materials and vehicle parts to be prioritized for recycling and recycling method to be developed can be identified through the assessment methods proposed in this study having in mind the whole picture of the current ELV material flow.

Environmentally assess the benefits and limitation of new or currently available lighweighted materials for the automotive industry depending on the development stage of its recycling process. Also, allow understanding the close relationship the ELV phase has with the rest of the phases.

Even a few entities and consultants forecasted supply or recover volume of critical material for EVB, details of the model implemented for the analysis is never open or available for utilization. In this sense, the proposed model can be adopted and modified depending on the necessity of the researcher and be applied in their own researches. Results obtained in this study give also a whole picture of the upcoming EVB market and its critical material possible to be recovered from ELV, this allow researchers to identify future recycling technologies to be prioritized for development, but also to identify the critical material that should be improved in its production and utilization phase.

Practical implementations are listed below.

Though the comprehensive analysis of the vehicle life cycle including the ELV phase, automakers and parts producers are going to be able to develop more sustainable vehicles assessing the environmental benefits of new technology or material correctly for the vehicle production. The above concept will be crucial considering proposal of the European Commisssion urge to make available to authorities, entities and operators the life cycle costing of the vehicles, including the cost of greenhouse gas emission and other pollutant emissions, in order to support their procurement process. Vehicle users could understand the total effect on the society of the acquired product. Moreover, dismantlers. material recycling and part reusing companies could plan the adaptation of its facilities or evaluate new business models having in mind the limitations and benefits of the upcoming parts and materials from new generation of vehicles. For example, a drastic modification of the material composition of the vehicles, such as the case of the body in white, will obligate the vehicle recycling companies to review its installations and disassembly process. Finally, public entities including the local government, are going to be able have a whole picture of the ELV market, allowing them to identifies materials and recycling technologies to be prioritized for development to achieve a sustainable society. In the same way, the government could define policies to support those initiatives, and financial incentives, not only for the development of technologies but also for the purchasing of sustainable product are going to be an important key for the society.

The proposed scrapped EVB forecasting model can be applied by automakers and related companies to propose and verify the economic feasibility of different battery reusing and recycling business strategies clarifying the quantity and variety of “resources” available for its production process in the short, middle, and long term. Dismantlers and material recycling companies are going to be able to define optimal plans for the adaptation of its facilities, knowing the time and quantity of EV and LiB returning from the market. Moreover, government will be able to define plans to ensure the supply of critical material for the production of batteries which currently have a high dependency on foreign country.

6.2 Secondary materials as source for vehicle production

As it has been explained throughout this document, the ELV recycling has an important role in the sustainability of the entire life cycle of the vehicle. Here, energy consumption, CO_2 emissions and economic point of view have been assessed. Three main recycling flow has been identified, ASR, which are mainly subjected to energy recovery, material recycling, and part reusing. As it is already known the material that is subjected to the last flow goes back to the vehicle as alternative spare parts. However, material destination of the first and second flow varies widely depending to the disassembly company or recycling factory where are destined.

The vehicle is elaborated with high spec materials and even the same steel, plastic or aluminum; those materials have a different grade in order to fulfill the functional or visual specification the parts are requested. An easy to identify example is the case of the aluminum used in the engine block and the ones used in the production of wheels. Even the first one needs to fulfill thermal requirement, the second one needs additional visual and mechanical resistance. In that sense, considering that the main part of the ELV enters to the shredding machine and the materials are separated after been grinded, mixed grade materials are obtained as output. This means that the material obtained from the ELV is not separated by grade, and currently, it is difficult to return them to the production of the same part. Specifically speaking, in the case of steel, which is the main material component of the vehicle, the recovered material finish in an electric furnace. Here, metals from different origins are mixed, obtaining lower-grade steel mainly used in the construction sector. In the case of aluminum and iron, recycled materials that lose their initial grade can be smelted and destined to casting vehicle parts. The mentioned kind of recycling, where the initial product finishes in to lower grade products is known as cascade recycling. A few examples of horizontal recycling in the automotive industry can be mentioned, one example is the recycling of bumpers that are recycled and used in the production of the same part. This can be carried because the bumper is easy to be dismantled manually before enter the entire vehicle to the shredding and that they use same grade of plastic (polypropylene). However, many issues in order to apply this recycling flow on a larger scale are pending to be solved. The main one is the transportation cost of scrapped bumpers, which its volume is not negligible.

Considering the above-mentioned limitations, it is correct to say that in order to reach a closed-loop recycling or horizontal recycling, not only improvement in technologies to separate different material by grade should be developed, but also decreasing the requirements in the material used in new part production should be also considered. Moreover, propose an efficient reverse logistics network for recyclable materials could help to achieve cost objectives in order to boost the cyclical economy.

Finally, it is worth discussing the concept of car to car recycling, which is appointed several times in the automotive industry. This concept is of interest in order to assure critical materials inside the industry to not depend on external factors. However, for generally used materials, the mentioned goal has low effect in the society considering that range of possible horizontal recycling is wider, including the use of recycled material from other industries in the automotive one. In this sense, future works should be analyzing the optimization of the use of recycled materials in order to boost even more the environmental and economic potential of the ELV phase.

6.3 Applicability of this approach to other durable goods

The waste electric and electronic equipment (WEEE) recycling has been in the eye of different governments considering the material consumed for the production and the volume of recycled waste generated in its end of life. As well as the ELV recycling, the WEEE are subjected to recycling objective settled by the Japanese government and its recycling process consist of an initial dismantling, following by the shredding process.

As it was explained in Chapter 3, understand the current effect of the end of life phase of the vehicle is of interest to understand the total environmental effect of the product. In the same way, benefits and material flow of WEEE recycling should be clarified in order to clarify the current strengths and weaknesses of the system to define the dismantling technologies to be prioritized for improving. Compare to our study, where separation of plastic has been pointed out for the ELV, this objective could vary in the case of WEEE considering that even the recycling process is similar, the material composition of the home appliances are totally different to the vehicles.

In Chapter 4, our study analyzed the use of lightweight material and the relation with the ELV phase. In the case of WEEE, this concept can not be applied directly considering that the benefits of lightweight materials are directly involved with the use of fuel consumption in the use of the vehicles. Here, rolling resistance, acceleration resistance, and aerodynamic resistance have an important role. has an important role; however, in the case of home appliance which is mostly immobile, the necessity of this technology is limited. One possible part where this analysis could be carried, in the case of internal mobile part, as the compressor of the refrigerators, however, the effect seems to be low.

Finally, in chapter 5, this study proposes a model to forecast the upcoming scrapped flow of batteries from EV. The dynamic model developed here can be adjusted to any type of product if input data as the relation between the GDP and the ownership and, the life expectancy of the product are previously calculated. For the case of WEEE, in addition to critical materials from LiB, returning flow of materials of importance as gold from electronic parts can be also forecasted.

6.4 Possible scenarios of the ELV market due to the implementation of CASE

An important concern for the automakers is the correct adaptation of its technologies and business to the changes in the mobility industry known as CASE (connected autonomous shared electric). The circular economy of the vehicles is going to be also affected, and the following tendency can be expected.

Due to the diffusion of connected vehicles. Automaker are going to be able to share and receive information from the users constantly. In this sense, new businesses could be stablished between them including a buying-selling system of reused parts. Moreover, recyclers and automakers will have the opportunity to implement a real time monitoring of different vehicle parts, including the status of the EVB, allowing them predict the time and place where those parts are coming back for reusing or recycling propose.

Autonomous vehicles will decrease the human errors in the vehicle driving. In this sense, accidents and vehicle crushes could be avoided on a large scale, eliminating the necessity of high resistant vehicle bodies. This possible scenario, will allow automakers to chose more environmentally friendly materials for the vehicle production considering also the recyclability of them.

Shearing means that the vehicles will be constantly operating. In that sense, even the life of a vehicle would not change in term of traveled distance, the time necessary for achieving its end of life will be much shorter. ELV, including its batteries, will return from the market faster and a dynamic close loop of them can be expected. New business such as the reusing of body parts for the production of new vehicles could be proposed considering the high durability of them.

Through the electrification of vehicles, the batteries and its critical materials are going to play an important role in the industry, as it was analyzed in chapter 5. Moreover, other parts as motors, inverters and wires are going also to gain ground. Quite the opposite, parts such as the engines, which are currently highly reuses, will lose importance. Achieve the current recycling level of the ICEV in the EV is going to be vital. On the other hand, EV are composed by lower quantity of parts, and the unification of common parts between vehicle models could be a fact in a future. In this sense, electrification of vehicle could boost the interchange of its parts (reusing).

Considering the points mentioned above CASE could be highly favorable for improving the circularity of the automotive industry.

7. Conclusions

The objective of this research is to clarify the importance of ELV recycling and reusing, and propose evaluation methods to assess its contribution to achieving sustainability in the automotive sector. For this propose, this document analyzes comprehensively the ELV phase considering economic and environmental benefits taking into consideration the entire life cycle of the vehicles.

The Japanese vehicle market has been analyzed as a case study considering that it is the third-largest economy of the world but also it has one of the biggest vehicle markets and its technological contribution to the development of the vehicle industry is indispensable. However, the analysis methods proposed in this research can be applied universally for any country.

Firstly, Chapter 1 describes the relevance of the automotive industry and the transportation sector, highlighting the necessity of selecting adequately the material used in its development. The research objectives are presented, as well as the relevance of the approach and its contribution.

Secondly, considering that this study analyzes the ELV considering the entire life cycle of the vehicles, fundamental concepts of life cycle assessment of vehicles and cyclical economy, including recycling and reusing, are presented in Chapter 2. Moreover, in order to understand the differences between the current and upcoming technologies in the automotive market, basic explanation of the functionality of the different electric vehicles has been presented. Moreover, introduction to system dynamics was carried to acquire basic knowledge to understand the forecasting modeling proposed in last part of this study.

Thirdly, the recycling process of ELVs was clarified and their material flow elaborated in Chapter 3. The scrapped vehicles were dismantled in three flows (ASR, recyclable materials, and spare parts), and recycled through three different methods (energy recovery, material recycling, and part reusing). Here, the flow with the highest level of contribution in terms of energy and CO_2 was that of the spare parts, followed by those of the recyclable materials and ASRs. The total energy reduction by ELV recycling was estimated as 52 MJ per kilogram of a vehicle (16% of energy reduction in the life cycle), and the benefits for the entire Japanese market as 247 PJ/ year. Moreover, the CO_2 reduction by ELV recycling was estimated as 2.80 kg-CO_2 per kilogram of vehicle (13% of the CO_2 reduction in the life cycle), and the benefits for the entire Japanese market as 13.1 Mt-CO_2/ year. In this sense, the ELVs were recycled efficiently, however, it still presented an important reduction potential improving the current reusing and recycling percentage of parts.

Fourthly, a simple methodology in order to analyze the impact of the ELV recycling system in the selection of lightweighting materials is proposed in Chapter 4. The lightweight of the body in white with AHSS, aluminum, and CFRP has been analyzed as case study. The effect from the standpoint of energy consumption and CO_2 emission of lightweighting materials on the production and end of life phase is essential as the benefits generated in its use phase. In that sense, material lightweight must be analyzed jointly with its possible recycling system because when the first variable is considered individually maximum life cycle energy and CO_2 reduction of 23.8 MJ and 1.82 kg-CO_2 per kg of part to be lightweight can be expected; however, an adequate combination of both variables could almost double those benefits to 51.4 MJ and 3.34 kg-CO_2, but also incorrect combination of them could be counter-productive guiding us to an energy and CO_2 increment of 92.5 MJ and 6.71 kg-CO_2. If the body in white is mainly subjected to material recycling its parts should be made mainly by aluminum; however, when the parts are frequently reused, the use of CFRP should be prioritized; finally, if the parts are mainly subjected to energy recovery, AHSS is the best material choice.

Next, a dynamic fleet model for assessing the upcoming flow of used EVB has been proposed in chapter 5. Results indicate that 34% of the lithium, 50% of the cobalt, 28% of the nickel and 52% of manganese required in the production of new LiB could be supplied by batteries derives from end of life vehicles in 2035 Our study has clarified the important potential of the material recovering from scrapped EVB in order to decrease the dependence of exported critical material for the production of new batteries.

Chapter 6 discussed integrally the aspects treated in chapters 3, 4 and 5. Finally, general conclusions are presented in Chapter 7.

This study, demonstrate the importance of clarifying the total benefits of the ELV in term of CO_2, energy and material supply. The total benefits of the phase are quantified numerically, allowing also the reader to understand the close relationship it has with the restart of the phases and the material composition of its parts. Results presented, allow automakers and parts producers to develop more sustainable vehicles assessing the environmental benefits of new technology or material correctly for the vehicle production. Vehicle users could understand the total effect on the society of the acquired product. Moreover, dismantlers. material recycling and part reusing companies could plan the adaptation of its facilities or evaluate new business models having in mind the limitations and benefits of the upcoming parts and materials from new generation of vehicles. Finally, public entities including the local government, are going to be able have a whole picture of the ELV market, allowing them to identifies technologies to be supported for development to achieve sustainable a sustainable society.

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