Article

Methodological Study of Evaluating Future Lightweight Vehicle Scenarios and CO₂ Reduction Based on Life Cycle Assessment

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Abstract: Changing the material composition of vehicles from steel to alternative materials, such as aluminum and magnesium, is being explored to reduce the weight of vehicles. Further, this change could lead to a significant reduction in vehicular CO₂ emissions. To analyze this relationship and estimate the CO₂ reduction effect over the life cycle, it is important to create potential scenarios by considering the logistics balance from material production to recycling. Therefore, this study aims to quantitatively predict the amount of renewable energy employed in vehicles, along with the various alternative materials used; further, the demand for aluminum and magnesium is predicted. These predictions are made via several multivariate analyses and a dynamic substance flow analysis (SFA) to explore future scenarios. It is estimated that 65% of rolled aluminum can be obtained from a secondary alloy via closed-loop recycling of rolled products in a sustainable development scenario. However, 510 kt/year of end of life scrap aluminum must be imported from overseas to provide 90% of the secondary alloy required in cast and die cast parts. The overall CO₂ reduction amount is predicted to be 3920 kt/year in the 2040 sustainable development scenario. This study successfully demonstrated that combining SFA and life cycle assessment is efficient for quantitatively estimating the synergies of renewable energy implementation, vehicular weight reduction, and recycling.

Keywords: Sustainability; aluminum; magnesium; substance flow analysis; LCA; material recycling

1. Introduction

As the focus on global warming has increased worldwide, the reduction of CO₂ emissions from the transportation sector has become an important issue. Since the 2015 Paris Agreement [1], this issue has garnered steady traction. Particularly in recent years, spearheaded by the introduction of hybrid electric vehicles, plug-in hybrid electric vehicles, electric vehicles, and fuel cell vehicles, efforts to reduce vehicular CO₂ emissions are being promoted aggressively worldwide [2]. Moreover, the automotive industry is continuously and rapidly developing on a large scale, and according to the International Organization of Motor Vehicle Manufacturers, approximately 67 million cars were produced in 2019, while road transport is responsible for 15.9% of global CO₂ emissions [3]. Dargay et al. showed that vehicle ownership increases with income, reaching a different saturation level for each country [4].

Under such circumstances, changing the material composition of vehicles from steel to alternative materials, such as high-tensile steel, aluminum, magnesium, and carbon fiber reinforced polymer (CFRP), and diversifying such materials based on the purpose of each automobile part, i.e., “multi-materialization,” is being examined as a method of weight reduction [4–6]. Reducing the weight of vehicles would lead to improved fuel consumption, resulting in a significant reduction in vehicular CO₂ emissions [7].

However, a balance should be met between the use stage environmental impact, by the reduction of operational consumption, and effects on the production and end-of-life (EOL) stages [8]. The literature reveals that, in contrast to operational impact reduction, innovative lightweight design normally entails higher energy consumption and CO₂ emissions for production and EOL stages [9]. Therefore, there are several studies evaluating CO₂ emissions at the production, usage, and EOL stages considering the manufacturing, implementation, and recycling of alternative materials, such as high-tensile steel, aluminum, magnesium, and CFRP through the life cycle assessment (LCA) [10–14]. These studies assessed CO₂ emission reduction under multiple scenarios.

However, when exploring future scenarios of weight reduction in vehicles, the interaction between the LCA of production, usage, and EOL stages must be considered. For example, aluminum, which is an alternative material for vehicles, is manufactured via the Hall–Héroult process, which consumes a large amount of electricity [15]. However, in the future, when the source of electricity for the electrolytic refining of aluminum is changed to renewable energy, the CO₂ emissions from the manufacturing of aluminum can be reduced.

Moreover, at present, magnesium is manufactured via electrolysis [16] or the Pidgeon process [17]; however, in the future, when electrolysis employing renewable resources is introduced on a large scale, the CO₂ emission intensity associated with the manufacturing of magnesium could be reduced. Thus, reducing the intensity of CO₂ emissions associated with aluminum and magnesium improves the potential of alternative weight reducing materials to improve CO₂ emissions. In addition, if the use of aluminum and magnesium as alternative weight reducing materials is increased, material recycling from EOL scrap would also be promoted.

At present, in Japan, a portion of aluminum used in vehicles is recycled from EOL vehicle scrap, aluminum sash, and aluminum cans. However, cast and die cast products are the only aluminum parts that are recycled, and rolled products are excluded [18]. This is because the production of wrought aluminum requires a low level of impurity, and therefore, scrapped wrought products are largely downcycled into cast aluminum products. In an effort to realize the multi-materialization of vehicles, usage of rolled aluminum products is expected to increase. Furthermore, if the demand increases, closed-loop recycling from old rolled products into new rolled products may be achieved. For magnesium, more than half of the magnesium used in Japan is included as an additive to aluminum; thus, if the demand for aluminum increases, the demand for magnesium will increase as well. In Japan, recycling of automobile EOL scrap for magnesium has not begun [19]; however, it could be achieved if there is sufficient demand.

As such, if aluminum and magnesium are used as alternative materials for vehicles, the CO₂ emission intensity of production and manufacturing, implementation into vehicles, and amount of recycling are assumed to be correlated. To analyze this relationship and estimate the CO₂ reduction effect across the life cycle, it will be important to create scenarios by considering the logistics balance from material production to recycling with a dynamic substance flow analysis (SFA).

Therefore, in this study, the amount of renewable energy, as well as the various alternative materials employed in vehicles and the demand for aluminum and magnesium are predicted through several multivariate analyses to prepare future scenarios. Based on these scenarios, dynamic SFA is performed on aluminum and magnesium. The amount of material that could be recycled from the EOL scrap is estimated, while the LCA of CO₂ emissions from manufacturing, operating (driving a car), and recycling is evaluated. In this manner, the effects of CO₂ reduction through the introduction of renewable energy, weight reduction of vehicles, and recycling are compared.

Through the above assessment, this study clearly demonstrates the relationship between the conditions set for future scenarios and the effect of CO₂ reduction, which is expected to contribute to policy formulation and research and development towards the reduction of CO₂ in the transportation sector.

2. Background

Several studies have evaluated the impact of CO₂ emissions by LCA considering alternative materials used in lightweight vehicles. Krzysztof Danilecki et al. [10], Jarod C. Kelly et al. [7], Thiel et al. [20], and Jürgen Hirsch [21] evaluated the total life-cycle Green House Gas (GHG) emissions, or well-to-wheel CO₂ emissions, considering the vehicle weight reduction by material substitution. Alexandre Milovanoff et al. [22] (fleet-based life cycle model), Palencia et al. [2] (bottom-up dynamic accounting model), and Roja Modaresi et al. [23] (dynamic stock model) developed specific models to estimate the GHG or CO₂ emission changes due to reduced weight.

However, these studies did not consider the effect of renewable energy and SFA. To create a more realistic scenario, the correlation between renewable energy, weight reduction of vehicles, and recycling must be considered.

Currently, the manufacturing of alumina and electrolytic refining of aluminum requires a large amount of electricity and heat [24,25]. Japan outsources the electrolytic refining process of virgin aluminum ingots and alloys overseas, where the cost of electricity is cheaper [26]. Assuming that a large amount of renewable energy is supplied in a country that imports virgin aluminum ingots and alloys, reducing CO₂ emissions from electricity is plausible.

Meanwhile, aluminum demand in Japan was approximately 4.1 million ton/year in 2016, which was satisfied by importing virgin ingots and alloys derived from bauxite and alumina, along with secondary ingots and alloys [19,27]. The amount of secondary ingots and alloys reached approximately 1.3 million ton/year in 2016, owing to Japan's well-developed aluminum recycling industry, in which approximately 30% of the aluminum demand is satisfied by secondary ingots and alloys [19].

According to annual statistical reports on aluminum [27], aluminum is classified as either rolled products, die cast products, cast products, electric wires, forgings, or powders. These products are mainly used for food (body, lids, packaging, and containers), construction (sashes, doors, interior, and exterior), and transportation equipment (vehicles and aircraft). To manufacture secondary ingots and alloys of aluminum, primarily scraps of sash from construction, aluminum cans for beverages and foodstuffs, and automobile parts that are formulated as die cast and cast products are used. If these secondary ingots and alloys of aluminum could be recycled as rolled products, further CO₂ reduction would be possible [28] in addition to the CO₂ reduction from a large-scale provision of renewable energy.

In contrast, magnesium is produced through electrolysis and the Pidgeon process [17]. If electrolysis is introduced in a country that imports virgin ingots and alloys of magnesium, and the source of electricity is renewable, CO₂ emissions from manufacturing could be reduced. The total demand for magnesium in Japan was approximately 40,000 tons/year in 2016, where virgin ingots and alloys manufactured through the Pidgeon process are imported from China [19].

Similar to aluminum, magnesium is used as a rolled product, die cast product, and cast product, as well as an additive to aluminum. In fact, in 2016, approximately 24,000 tons/year of magnesium was used as an additive to aluminum [19]. This shows that the relationship between the consumption of aluminum and magnesium is significant.

In Japan, magnesium is used for producing motorcycle parts, sound equipment, laptops, mobile phones, housing of electric tools, aircraft parts, and in Medical Welfare [29]. In addition to vehicles, material recycling from EOL scraps is only performed for laptops, and not for vehicles.

Presently, Japanese-made vehicles only use magnesium in the core of the steering wheel and key lock materials, and not as a structural material. If the amount of magnesium used as structural material in vehicles increases, material recycling of EOL scrap from vehicles can be achieved. If secondary ingots and alloys of magnesium could be used as die cast products for vehicles, similar to aluminum, an additional reduction of CO₂ could be possible.

Companies worldwide, especially those in Europe, tend to employ materials with low CO₂ intensity to contribute to sustainable development goals. Considering the CO₂ intensity per unit

volume, aluminum and magnesium have the scope to be more effective in CO₂ reduction than high-tensile steel in the LCA.

Therefore, when preparing future scenarios of alternative materials for vehicles, the relationship between three factors—manufacturing, implementation, and recycling of alternative materials—must be considered. Within this relationship, the logistics of alternative materials in the future needs to undergo dynamic SFA. This allows for the accurate assessment of the CO₂ reduction effect by introducing alternative materials for vehicles.

3. Method for Scenario Creation, Substance Flow Analysis, and LCA

In this section, future scenarios that consider the relationship between manufacturing, implementation, and recycling of alternative materials of vehicles are presented. In addition, the dynamic SFA method used to address the future logistics of alternative materials and the method used to assess the effects of CO₂ reduction based on LCA are described.

This study targets aluminum and magnesium as alternative materials. Future scenarios for 2040 are presented, whereas SFA is performed for 2016 and 2040.

3.1. The Boundary of Life Cycle Assessment and the Scenario Planning Method

In this study, the effect of replacing steel in vehicles with aluminum and magnesium on reducing CO₂ through the resulting vehicular weight reduction is examined. In this effort, in terms of the CO₂ reduction effect, the manufacturing, implementation, and recycling of materials are all estimated by the LCA. In this section, the boundary of the LCA is described. The amount of CO₂ emissions is used as a parameter describing the environmental effect in this LCA study.

This study prepares several future scenarios in which renewable energy provides the electricity required to manufacture aluminum and magnesium. To that end, CO₂ emissions from the mining of bauxite, dolomite, and magnesite to manufacture ingots and alloys of aluminum and magnesium are all included in the LCA. All these processes are performed outside Japan.

The CO₂ emissions from the importation of manufactured ingots and alloys (imported ingots are turned into alloys in Japan) and subsequent processing to produce automobile parts in Japan are also included in the LCA. However, the processing of automobiles is not included in the assessment because it is unrelated to the comparison of different scenarios.

The operation of automobiles, in other words, CO₂ emissions from driving, is included in the assessment. In 2040, different operations, such as car sharing, are anticipated; however, because the present study aims to specialize in preparing a scenario related to alternative materials, scenarios related to driving methods of vehicles are not considered. Presently, only scenarios involving changes in the weight of vehicles due to the introduction of alternative materials are prepared, and their effects are analyzed with the LCA.

With regards to recycling, energy and CO₂ emissions associated with the collection of EOL scraps from vehicles are not included in the LCA, due to the insufficiency of data. However, the melting and processing of recovered EOL scraps into secondary alloys are included. As mentioned earlier, in Japan, aluminum in EOL scrap is already recycled. However, secondary aluminum alloys are all used as die cast and cast products for vehicles. The present study assumes the use of such alloys as rolled products in the future scenario. In contrast, as all the magnesium in vehicles is in the form of die cast products, there is no need to separate rolled products and die cast products in the future scenario of recycled magnesium.

Figure 1 shows items in future scenarios and boundaries of the LCA.

Figure 1. Boundaries of the life cycle assessment and items considered in future scenarios.

3.2. Future Scenarios and Life Cycle Assessment of Alternative Material Manufacturing

In this study, the CO₂ intensity of manufacturing aluminum and magnesium as alternative materials to reduce the weight of vehicles is prepared as a future scenario.

With regard to aluminum, the inventory data from the International Aluminum Institute [25] are used as the reference. To manufacture aluminum alloys, bauxite is mined, and alumina is manufactured; then, ingots are produced through electrolytic refining, melted, and then processed. The CO₂ emission associated with bauxite mining is based on IAI (International Aluminum Institute) documentation, from which the input of bauxite per 1 kg of aluminum is determined to be 5.569 kg. CO₂ emissions associated with alumina manufacturing are obtained from the input of fossil fuel and CO₂ emissions of each fossil fuel based on IAI documentation.

As for electrolytic refining, the CO₂ emissions associated with electrolytic power and transportation of alumina are obtained based on the input of fossil fuels and the CO₂ emission coefficient of each fossil fuel for the power supply configuration of the country that supplies aluminum to Japan, according to trade statistics [30]. The power supply configuration of each country is determined based on the IAI and Japan Aluminum Association documentation [26]. From this documentation, the following are obtained: (1) CO₂ emissions from the anode are assumed to be equivalent to be equivalent to the “CO₂ from non-fuel combustion use”. (2) CO₂ emissions associated with the heat of manufacturing anodes are obtained from the input of fossil fuels and the CO₂ emission coefficient of each fossil fuel. (3) The raw material input for anodes is estimated as the weighted average of 0.439 kg, assuming that the Prebake method (0.429 kg per 1 kg of aluminum) comprises 89% of the raw material and the Soderberg method (0.527 kg per 1 kg of aluminum) comprises 11% [25].

If the electricity used for the electrolytic refining of aluminum is converted to renewable energy, the CO₂ intensity of manufacturing can be greatly reduced. Japan presently imports aluminum that is electrolytically refined in South Africa, India, Indonesia, Tajikistan, Bahrain, UAE, Canada, Argentina, Brazil, Russia, Australia, and New Zealand [30]. This study assumes two future scenarios for the introduction of renewable energy in these countries. Below, some methods for estimating the introduction of renewable energy in future scenarios are described.

3.2.1. Business as Usual Scenario

The business as usual (BAU) scenario in this study refers to the lack of change in renewable energy introduction, weight reduction of vehicles, and recycling. This scenario was prepared to evaluate the effect of CO₂ reduction by providing a baseline for comparing the CO₂ emissions of other scenarios.

3.2.2. Current Trend Scenario

The current trend scenario in this study refers to how renewable energy introduction, weight reduction of vehicles, and recycling will change considering the current trend. For aluminum, this scenario predicts the implementation of renewable energy in aluminum export countries until 2040 by multiple regression analysis using real GDP/capita [31] and population [32] as explanatory variables. For magnesium, this scenario predicts that the electricity supply in the Pidgeon process [33] is fully dependent on renewable energy in China, which is the main export country for Japan. The CO₂ intensity of transport is estimated assuming that magnesium alloys and ingots are transported between China and Japan (approximately 2500 km) using a tanker by 0.00412 kg-CO₂/ton-km of CO₂ emissions [34].

3.2.3. Sustainable Scenario

The World Energy Outlook 2019 (WEO-2019) [35] forecasts the implementation of renewable energy until 2040 for various scenarios. For aluminum, the ‘sustainable scenario’ in this study refers to the WEO-2019 ‘Sustainable development scenario’ to determine the implementation of renewable energy in countries that export aluminum alloys and ingots. WEO-2019 includes some countries that have not published their data; thus, for these countries, the renewable energy introduced in the surrounding countries is used. In terms of the electric power configuration, only the introduction of renewable energy is referred to, whereas the proportions of other fossil fuels are not considered. This is because countries that perform electrolytic refining of aluminum do not use multiple fossil fuels as power sources [26]. For magnesium, this scenario determines the implementation of renewable energy considering that magnesium alloys and ingots are manufactured by electrolysis (AM method) [16], which can manufacture magnesium with lower CO₂ emissions than the Pidgeon process. Since detailed data on CO₂ emissions from the AM method are unobtainable, the CO₂ intensity of manufacturing magnesium is determined by considering that all electricity in this method is provided by renewable energy [36].

As such, predictions of renewable energy introduction in countries that export virgin aluminum ingots and alloys are presented in Table 1, classifying the scenarios into the BAU scenario, sustainable scenario, and current trend scenario categories.

Based on the results of Table 1, the CO₂ intensities of manufacturing aluminum and magnesium are summarized in Table 2.

3.3. Future Scenarios and Life Cycle Assessment for Weight Reduction in Vehicles

This study prepares future scenarios for the implementation of alternative materials to reduce the weight of vehicles and thus CO₂ emissions from driving.

3.3.1. Production Volume of Vehicles in Japan

The production and waste of vehicles in Japan until 2040 is not distinguished as a future scenario. All scenarios use the same prediction method.

The production of vehicles is first determined by predicting the number of vehicles that will be owned in the future up until 2040.

Table 1. Electricity composition (%) in aluminum exporting countries.

Country	BAU Scenario					Current Trend Scenario					Sustainable Development Scenario				
	Renewables	Coal	Oil	Gas	Nuclear	Renewables	Coal	Oil	Gas	Nuclear	Renewables	Coal	Oil	Gas	Nuclear
Australia	9	91				18.1	81.9				62.6	37.4			
Russia	74.7	24.6			0.7	74.7	24.6			0.7	74.7	24.6			0.7
Saudi Arabia		56.3		43.7		0.1	56.2		43.7		52.9	26.5		20.6	
Brazil	100					100					100				
New Zealand	100					100					100				
UAE				100		4.1			95.9		52.9			47.1	
South Africa		100				3.2	96.8				67.7	32.3			
Argentina	59			41		59			41		85.8			14.2	
Canada	100					100					100				
Malaysia	19	30	1	49	1	94.7	2		3.3		70.8	3.9	0.4	24.2	0.8
Indonesia	100					100					100				
Others	30	69		1		67.4	6.3	0.5	14.4	11.4	67.4	6.3	0.5	14.4	11.4

This is predicted using a logistic regression model with real GDP per capita [32,37] up to 2040, which is used as explanatory variable (X). The number of vehicles owned per capita (S) is estimated as follows using the maximum number of owned vehicles (S_{max}).

$$S = \frac{S_{max}Ae^{BX}}{1 + Ae^{BX}} \quad (1)$$

S_{max} refers to the population by majority age group [38] who have a driver's license and actively drive (80 and under) in 2050 according to the population statistics of the National Institute of Population and Social Security Research.

New vehicle sales (SV) in unit/year in year (t), (SV_t), is estimated using Equation (2) from 1993 to 2040, assuming the population is (PO_t), the number of owned vehicles per capita is (S_t), and waste from vehicles, obtained from the Weibull distribution, is (W_t). The equation for the Weibull distribution is shown in Equation (3) using the shape parameter (m) as 3.6 [39]. The scale parameter (n) is examined using real (S_t) data from 1993 to 2019, obtained from the Automobile inspection and Registration Information Association in Japan [40], and the average lifetime of vehicles, which is applicable to Equations (2) and (3), is estimated to be 14.4 ($n = 15.9$) years.

$$SV_t = PO_t S_t - PO_{t-1} S_{t-1} + \sum_{1993}^t W_t \quad (2)$$

$$W_t = \frac{m}{n} \left(\frac{t}{n} \right)^{m-1} \exp \left\{ - \left(\frac{t}{n} \right)^m \right\} \quad (3)$$

The production of vehicles is estimated by adding the number of vehicles exported from Japan and domestic sales obtained by (SV_i). The number of exports is predicted by determining the number of Japanese vehicles exported from Japan to 17 major countries [41] from population and real GDP per capita [37] data of each country using a multiple regression model. The number of imported vehicles is not included in this study because this number represents less than 7% of the total consumption of Japan in 2018.

Table 2. CO₂ intensity of manufacturing aluminum and magnesium.

	BAU Scenario	Current Trend Scenario	Sustainable Development Scenario
Aluminum Hall-Héroult process	Bauxite mining	0.03	0.02
	Alumina production	1.18	1.13
	Electrolysis	8.27	5.12
	Ingot Casting	0.01	0.01
	Transportation	0.07	0.07
	Total CO ₂ (kg-CO ₂ /kg-Al)	9.56	6.35
Magnesium Pidgeon process	Dolomite mining	0.41	0.41
	Calcination	9	9
	FeSi production	9.5	9.5
	Reduction	3.61	3.61
	Refining	0.42	0.42
	Electricity	2.56	—
	Transportation	0.01	0.01
	Total CO ₂ (kg-CO ₂ /kg-Mg)	25.51	22.95
Magnesium AM process	Firing		3.73
	Neutralization		0.02
	Evaporation		2.96
	& Dehydration		
	Electrolysis		1.78
	Transportation	0.01	0.01
	Total CO ₂ (kg-CO ₂ /kg-Mg)		8.5

3.3.2. Introduction of Alternative Materials

Aluminum is presently used for the wheels of vehicles as a rolled product and for engine cylinder blocks as die cast and cast products. The weight of aluminum per vehicle was 171 kg-Al/unit in 2016, determined by dividing the aluminum demand [27] for vehicles in 2016 by production volume. The average weight of vehicles in 2016 is assumed to be approximately 1640 kg per vehicle based on Version 5.0 of the Automotive Materials Greenhouse Gas Comparison Model developed by the University of California at Santa Barbara (UCSB) [42].

As discussed earlier, magnesium is used for the core of the steering wheel and key lock mechanism in vehicles in Japan [29]. The weight of magnesium per vehicle in 2016 was 0.47 kg-Mg/unit obtained by dividing the magnesium demand for vehicles (data obtained by interviews of several experts) by production volume. Past studies have revealed that 20–34% of vehicle weight is comprised of the main body and frame, which can be substituted by aluminum and magnesium.

If the CO₂ intensity of aluminum and magnesium is reduced, as summarized in Table 2, increased introduction into vehicles might be anticipated. However, past studies have not formulated the relationship between CO₂ emission intensity and introduction into vehicles.

Therefore, in this study, based on the hypothesis that reduction of CO₂ intensity for aluminum and magnesium is proportionally related to the increase in weight volume of the vehicle, the sustainable scenario assumes an increase in aluminum and magnesium per vehicle of 86.9 kg-Al/unit and

0.94 kg-Mg/unit, respectively. The increase in aluminum in the current trend scenario was set to 14.4 kg-Al/unit, whereas it was 0.05 kg-Mg/unit for magnesium.

The relationship between the inclusion of aluminum and magnesium in vehicles and the weight of vehicles is obtained from the UCSB model [42]. Thus, the relationship between the weight of vehicles ($W_{vehicle}$) kg/unit is obtained by Equation (4) for aluminum, and Equation (5) for magnesium assuming the weight of aluminum in vehicles is (W_{Al}) kg/unit, and the weight of magnesium in vehicles is (W_{Mg}) kg/unit. In this study, aluminum and magnesium are assumed to replace steel, which is used in the main body and frame of the vehicle.

$$W_{vehicle} = 1640 - 0.49W_{Al} \quad (4)$$

$$W_{vehicle} = 1640 - 1.0W_{Mg} \quad (5)$$

The relationship between the weight of vehicles ($W_{vehicle}$) kg/unit and fuel consumption (FC) km/L-gasoline is also obtained from the JC08 data in the UCSB model [43], and it is obtained using Equation (6) (for example, fuel consumption of a 1640 kg vehicle is 16.64 km/L gasoline). The mileage of vehicles in Japan is assumed to be approximately 12,519 km/year [44], and the CO₂ emission of driving is obtained by multiplying fuel consumption, mileage, and the CO₂ intensity of gasoline. The weight of vehicles that will be sold in each year decreases considering Equations (4) and (5). Therefore, the ratio of the weight of vehicle to the number of vehicles owned each year is considered in Equation (6).

$$FC = -0.0081W_{vehicle} + 29.925 \quad (6)$$

3.4. Dynamic Substance Flow Analysis and Life Cycle Assessment of Alternative Materials for Vehicles

Presently, waste and secondary alloys in 2040 are estimated by the dynamic SFA of aluminum and magnesium. The dynamic SFA in this study is performed by considering total production, import/export, and sales of aluminum and magnesium, ratio of each usage, and ratio of each alloy for each usage. The ratio of rolled products, die cast products, cast products, and forgings of aluminum and magnesium are obtained from several databases [29,45] and interviews with experts. The amount of waste and secondary alloys is estimated using the Weibull distribution.

First, using Equation (3) and the same method as used to obtain vehicle waste (W_t), waste from rolled products, die cast products, cast products, and forgings of aluminum and magnesium from 1993 to 2040 is estimated.

In Japan, 90% of die cast products and 60% of cast products of aluminum in vehicles are fulfilled by secondary alloys [45]. Moreover, aluminum for construction and food (aluminum cans) uses rolled products, which are also used in secondary die cast alloys of vehicles [19]. Secondary alloys of magnesium are not currently used in vehicles.

As described in Section 3.3, as more aluminum and magnesium are introduced into vehicles, material recycling from these EOL scraps should be promoted.

Therefore, in the sustainable scenario, in maintaining the use of secondary aluminum alloys in die casting and casting, closed-loop recycling of rolled products (in vehicle, construction, and food) to rolled products (in vehicles) is achieved in 2040. In the current trend scenario, this type of closed-loop recycling is not achieved; however, the use of secondary alloys in casting increases from 60% to 90%. In either scenario, if there is insufficient waste, the EOL scrap would be imported from overseas. Magnesium is assumed to be achieved in both scenarios in die cast products, which is the main alloy for vehicles, and the recovery of EOL scrap from vehicles is set to 99% [46].

The consumption, as well as waste aluminum of construction and food, is estimated using a regression model.

The consumption of aluminum for construction (AS_t) is estimated using Equation (7), assuming that the aluminum consumption per building floor space is (AF) g/m², the population of each age in year (t) is ($PO_{g,t}$), and the new building floor space per capita in each age is (FS_g) m²/capita. The relationship

between age and (FS_g) is obtained by simple regression analysis using average age [38] and total building floor space in each year [47], based on the hypothesis that FS_g decreases when people get older.

$$AS_t = AF \times \sum_{g=0}^{100} PO_{g,t} \times FS_g \quad (7)$$

The consumption of aluminum for food is estimated using a multiple regression model using population [32] and real GDP [37] as explanatory variables. The consumption of aluminum can be obtained from the Japan aluminum recycling association [48].

4. Results of Dynamic Substance Flow Analysis and Life Cycle Analysis

In this section, the results of future scenarios, dynamic SFA, and CO₂ reduction consider the relationship between manufacturing, implementation, and recycling of alternative materials of vehicles. These results are based on the methods described in Section 3, and the LCA.

4.1. Future Scenario for 2040 and Substance Flow Analysis of Aluminum and Magnesium

Based on the method described in Section 3, the CO₂ intensity, weight, production, waste, and rate of secondary alloy in each scenario are listed in Table 3. The results of SFA for aluminum and magnesium in 2016 and 2040 are shown in Figure 2. The SFA for 2040 is the data for the sustainable development scenario.

The production of aluminum and magnesium are predicted to be 1872 kt/year and 5 kt/year in the current trend scenario, and 2602 kt/year and 14 kt/year in the sustainable development scenario. The aluminum and magnesium waste are predicted to be 938 kt/year and 3 kt/year in the current trend scenario, and 1084 kt/year and 4 kt/year in the sustainable development scenario.

As a result, it is predicted that 65% of rolled aluminum can be obtained from a secondary alloy by closed-loop recycling from rolled products in a sustainable development scenario. However, 510 kt/year of EOL scrap aluminum must be imported from overseas to achieve 90% of the secondary alloy rate in cast and die cast. This is due to the decrease of rolled alloy available from construction and food, which is caused by population decrease. For magnesium, it is predicted that 31% of die cast raw materials can be obtained from secondary alloys by recycling EOL scrap.

These results reveal that a balance in the increment of aluminum and magnesium among different usages is necessary. For example, an increase in only rolled aluminum for vehicles will cause a shortage of EOL scrap to achieve a high secondary alloy rate in cast and die cast alloys. To resolve this shortage, the increment in other aluminum usage, such as construction, food, machine, and electric equipment, must be achieved. Another example is the use of magnesium additives for aluminum. The magnesium additives will increase from 9 kt/year to 15 kt/year in the 2040 sustainable development scenario. Therefore, the demand for magnesium must be increased, as well as its recycling, to increase the rolled aluminum for vehicles.

Table 3. CO₂ intensity, weight, production, waste, and rate of secondary alloy in each scenario.

BAU			Current Trend	Sustainable Development
CO ₂ intensity				
Aluminum	kg-CO ₂ /kg-Al	9.56	8.82	6.35
Magnesium	kg-CO ₂ /kg-Mg	25.51	22.95	8.5
Weight				
Aluminum per vehicle (W_{Al})	kg-Al/vehicle	171.3	185.7	258.2
Magnesium per vehicle (W_{Mg})	Kg-Mg/vehicle	0.47	0.51	1.41

Table 3. Cont.

	BAU		Current Trend	Sustainable Development
Total vehicle ($W_{vehicle}$)	Kg/vehicle	1640	1632.88	1596.31
Production for vehicle per year				
Aluminum	kt/year	1726.48	1871.64	2602.48
Magnesium	kt/year	4.75	5.15	14.22
Waste from vehicle per year				
Aluminum	kt/year	910.15	938.89	1083.59
Magnesium	kt/year	2.51	2.59	4.39
Rate of secondary alloy for vehicle				
Rolled Aluminum	-	0	0	0.65
Die cast Aluminum	-	0.9	0.9	0.9
Cast Aluminum	-	0.6	0.9	0.9
Die cast Magnesium	-	0	0	0.31

Figure 2. Substance flow analysis for aluminum and magnesium in 2016 and 2040.

Based on the SFA of 2040, CO₂ emissions from aluminum and magnesium production for vehicles in the BAU, current trend, and sustainable development scenarios are estimated. The results are shown in Figure 3.

Figure 3. CO₂ emission from aluminum and magnesium production.

The CO₂ emissions from aluminum and magnesium production for vehicles in the current trend scenario are predicted to be 281 kt/year less than the BAU scenario, while the sustainable development scenario is predicted to be 2034 kt/year less. Based on the scenarios described in Table 3, the scenario that considers the current trend of renewable energy implementation, vehicular weight reduction, and recycling is estimated to have less CO₂ reduction potential compared to the sustainable development scenario. This result reveals that closed loop recycling from rolled to rolled products has a large influence on CO₂ emissions from aluminum and magnesium production for vehicles.

4.2. Comparison of CO₂ Reduction Between the Three Scenarios

Based on the results described in Section 4.1, a comparison of the CO₂ reduction for the current trend and the sustainable development scenario is shown in Figure 4. The amount of CO₂ reduction is estimated from the difference between the CO₂ emissions of the BAU scenario and the current trend, or the sustainable development scenario.

Figure 4. Comparison of CO₂ reduction between the current trend and sustainable trend scenarios.

The overall CO₂ reduction in the current trend scenario is predicted to be 593 kt/year in 2040, while its reduction in the sustainable development scenario is 3920 kt/year. Moreover, the amount of CO₂ reduction in aluminum and magnesium production, which is based on renewable energy implementation and recycling, is predicted to be almost the same based on vehicular weight reduction. These results reveal that renewable energy implementation, vehicular weight reduction, and recycling have synergies toward CO₂ reduction; further, this study successfully shows that combining SFA and LCA is efficient to validate this finding quantitatively in future scenarios.

5. Discussion

Based on the hypothesis that CO₂ emission intensity of production and manufacturing of alternative materials for vehicles will correlate with its implementation into vehicles and recycling, the overall CO₂ reduction amount was estimated for manufacturing, operating (driving a car), and recycling. The results reveal that CO₂ reduction amount will be from 593 kt/year to 3920 kt/year in 2040 by renewable energy implementation, vehicular weight reduction, and recycling.

However, there are several important uncertainties which influences the result of this study. The implementation of renewable energy, as well as CO₂ emission intensity of aluminum and magnesium, was hypothesized to relate with weight volume in vehicles proportionally. Moreover, enhancement of aluminum and magnesium recycling was hypothesized to relate with its demand increase. Realistically, the weight of alternative materials for vehicles, as well as potential for these materials to recycle, relates with many other social and economic factors, which cannot be quantitatively estimated within the scope of LCA and SFA. Therefore, the typical scenario-making method is necessary to create a more realistic future scenario. There are also large uncertainties in the numbers and amounts used in this study, such as average weight of vehicles, weight of alternative materials, mileage of vehicles, and number of vehicles owned each year. These uncertainties are the limitation of this study, and sensitive analysis with some other methods must be applied to solve these uncertainties for future work.

Moreover, there are several factors which must be considered in future vehicle scenarios, such as car-sharing, vehicle electrification, fuel proportion, and rebound effects that refer to behavioral or other systemic responses after the implementation of new technologies or other measures to reduce energy consumption. This rebound effect may influence the mineral resource development, economic growth, and other social development. This is one of the reasons which suppress the realization of sustainable mobility. These factors may also be considered in mentioned scenario-making method.

6. Conclusions

In this study, the amount of renewable energy as well as the various alternative materials employed in vehicles and the demand for aluminum and magnesium were predicted through several multivariate analyses to prepare future scenarios. Based on these estimations, dynamic SFA is performed on aluminum and magnesium to estimate the amount of materials that could be recycled from these EOL scraps, while the CO₂ emissions from manufacturing, operating, and recycling are evaluated by LCA. The results of this study reveal that combining SFA and LCA is efficient to quantitatively estimate the synergies of renewable energy implementation, vehicular weight reduction, and recycling toward CO₂ reduction. The salient feature of this study is the method which combined SFA, LCA, and several multivariate analyses to examine the correlation between three CO₂ reducing factors such as implementation of renewable energy, vehicle weight reduction, and material recycling of alternative materials.

However, the method to estimate the correlation between CO₂ intensity of aluminum and magnesium, these demands, and the feasibility of recycling is insufficient in order to create more realistic future scenarios. These uncertainties and challenges are also examined, and must be further studied in the future work.

This study has clarified the relationship between the conditions set for future scenarios and the effect of CO₂ reduction, which is expected to contribute to policy formulation and research and development toward the reduction of CO₂ in the transportation sector.

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