

Article

The Potential and Trend of End-Of-Life Passenger Vehicles Recycling in China

Yang Li ¹, Kiyoshi Fujikawa ², Junbo Wang ³, Xin Li ³, Yiyi Ju ^{4,*}  and Chenyi Chen ¹

¹ School of Business Administration, Zhongnan University of Economics and Law, Wuhan 430073, China; liyang@zuel.edu.cn (Y.L.); crystal_chen97@icloud.com (C.C.)

² Applied Social System Institute of Asia, Nagoya University, Nagoya 4648601, Japan; fujikawa@gsid.nagoya-u.ac.jp

³ College of Management Science, Chengdu University of Technology, Chengdu 610051, China; wangjunbo2019@gmail.com (J.W.); lixin2012@cdut.cn (X.L.)

⁴ Institute for Future Initiatives, The University of Tokyo, Tokyo 1130003, Japan

* Correspondence: juyiyi@ifi.u-tokyo.ac.jp

Received: 17 January 2020; Accepted: 12 February 2020; Published: 15 February 2020



Abstract: The contradiction between limited resources and rapid development in the automobile industry has been driving society to seek the supply of recyclable resources from End-of-Life Vehicles (ELVs). It has become an urgent need for vehicle recycling policymakers to have an overall understanding of the end-of-life (EoL) vehicle population, as well as for vehicle producers to note what and how they can benefit from ELV recycling. This paper estimated the potential population of EoL passenger vehicles, all recyclable resources from them, as well as the economic values of these recyclable resources. The results show that in 2030, with a lighter-weight trend of passenger vehicles, more than 26.3 million passenger vehicles will be retired with 19.1 million tons of recyclable steel and 6.2 million tons of plastics. The theoretical economic value of all recyclable resources will reach 101.3 billion yuan (\$14.4 billion) in 2030, which is an average of approximately 2.4 thousand yuan (\$341.8) for each EoL passenger vehicle. It is time for the vehicle producers to shift to a manufacturing mode considering such large potential of ELV recycling. The scenario analysis suggests that in the context of a light-weighting trend, ELV resource recovery in the future calls for improvement in the recycling and reuse technologies of plastics and rubbers.

Keywords: End-of-Life passenger vehicles; recyclable resources; urban mining; scenario analysis

1. Introduction

The past decades witnessed the increasingly acute contradiction between limited in-ground ore deposits and the demand for resources along with rapid urbanization [1]. Such contradiction has been driving society to search for other supply sources of secondary materials, compounds, or elements from anthropogenic stocks, namely, through urban mining [2]. These anthropogenic stocks include buildings, infrastructure, products, and other forms, among which end-of-life vehicles (ELVs) are one typical example of products containing plenty of resources available to be recycled [3].

Since the market of automobiles in China became the largest in the world in 2009, its scale of both production and sales has remained the top for ten continuous years. According to the China Association of Automobile Manufacturers [4] (2019), in 2018, the production and sales of vehicles in China were 27.81 million and 28.08 million vehicles, respectively, among which the production and sales of passenger cars are 23.53 million and 23.71 million, occupying a large share (over 80%) of the industry, with the rest of commercial vehicles such as buses and trucks (less than 20%). However, the rapid development of passenger vehicle ownership also leads to the concern of a boom in end-of-life

(EoL) passenger vehicles. Li et al. [5] (2019) investigated that the problem of recycling ELVs will become increasingly serious; a large number of scrapped vehicles flow into informal channels and black markets for resale, which results in significant environmental problems and safety hazards. Calling for the solution to the poor capacity and efficiency of recycling ELVs in China, as a premise, requires a basic understanding of the potential scale of them, as well as the potential benefits. Given the unclear potential of the recyclable EoL passenger vehicle population and a relatively high average recycling cost, it has become an urgent need for both vehicle recycling policymakers to have an overall understanding of the EoL passenger vehicle population, and for vehicle producers to note whether/how they can benefit from EoL vehicle recycling. The awareness of both recycling policymakers and vehicle producers may generate more incentives to promote resource recovery within the automobile industry, and further for a more sustainable development pathway of the whole industrial network.

Regarding the literature on the estimation of ELV generation, Button et al. [6] (1993) and Kobo et al. [7] (2003) estimated such generation of ELVs by dynamic models of the in-use stocks and the lifetime spans of vehicles. Azmi and Tokai [8] (2017) demonstrated the necessity of estimating the population of ELVs in response to the changes in the vehicle ownership level. Pan and Li [9] (2016) revealed the benefits based on the technology adopted by leading enterprises, which is used in calculating the gross income and reduction of energy consumption and greenhouse gas emissions. Hedayati and Subic [10] (2011) proposed a decision-making support framework for the recovery of ELVs to provide an integrated sustainable treatment option. Frits M. Andersen et al. [11] (2007) described a model for the projection of the number of ELVs and presented a baseline projection, which adopted Weibull distribution functions to estimate the lifetime of vintages of vehicles. Hu et al. [12] (2013) further modeled the projected population of ELVs in China in 2015, 2017, and 2020, with the consideration of provincial diversities in China.

Regarding the literature on the local development of passenger vehicles in China, Qiao et al. [13] (2019) focused on the economic and environmental benefits of electric vehicle recycling in China, based on the technology adopted by leading enterprises, the gross income and reduction of energy consumption, and greenhouse gas emissions are calculated to reveal the benefits. Flavius Ioan Rovinaru et al. [14] (2019) investigated the ecological and environmental impacts of ELV dismantling/recycling activities in Romania. Besides, Idiano D'Adamo et al. [15] (2020) presented some policy implications in terms of both the economic importance of the Likert scale and the relevance of synergy between the Circular Economy (CE) and technology.

Regarding the literature on recyclable resources from ELVs, Jody et al. [16] (2006) divided the recoveries from ELVs into two categories including: i) rare metal and nonmetal elements with independently high economic values; ii) materials such as metal, plastics, and glasses, that may be blended again with virgin materials in the manufacturing process of vehicles. Xu et al. [17] (2016) targeted 17 rare earth elements from ELVs, which are typical examples of the mentioned first category, as well as designed four scenarios in Japan to explore the potential recovery. Their results show that NiMH batteries and motors containing NdFeB magnets can be identified as target components and 2700 ($\pm$ 500) tons of rare earth elements can be recovered in 2030. This paper mainly focuses on the second category to provide an overall view of more resource forms. However, the estimation of recyclable resources from ELVs considering long-term economic factors has not been thoroughly discussed. Instead of discussing the policies directly influencing the resource recycling from ELVs, such as subsidies on legal ELV recycling, adjusting qualification standard of automobile dismantling, and the like, this paper focused on the trend of passenger vehicle retirement in response to the long-term economic factors (income growth and market demand saturation), which lays the foundation for further analysis of short-term policy changes. Li and Fujikawa [18] conducted an empirical analysis to estimate the potential of recyclable resources from EoL passenger vehicles. The estimated EoL passenger vehicles will reach 21.8 million, leading to the potential of 74.1 million tons of recyclable resources by 2020. This paper is an upgraded work of this previous work, with a focus on passenger vehicles (conventional fuel passenger vehicles and new energy passenger vehicles), the extended

data to 2030, and additional estimation of the economic values of recyclable resources from EoL passenger vehicles.

In this paper, Weibull distribution functions are adopted as the tool to reveal the distribution pattern of lifetime spans for durable goods, namely the passenger vehicles. Based on such distribution, together with the estimation of new vehicle demands in the future, the generation of EoL passenger vehicles in China from 2020 to 2030 can be estimated. We further quantified the recyclable resources from EoL passenger vehicles and their economic value in order to provide important references for the potential supply of secondary resources through urban mining, as well as to reveal the possible incentives to vehicle producers to participate in the promotion of ELV recycling. One scenario is designed considering the light-weighting technology. Such analysis reveals how the potential of recyclable resources from EoL passenger vehicles may benefit from possible changes in recycling policy or production technology in the long run.

2. Materials and Methods

The estimation of the potential population and recyclable resources of end-of-life vehicles, as well as their economic values, is modeled considering the retiring process of in-use passenger vehicles in China, as shown in Figure 1.

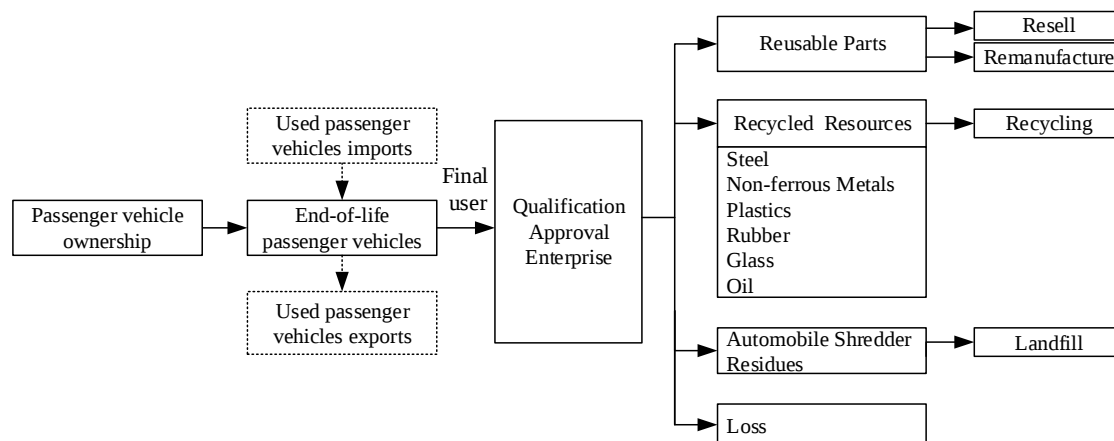


Figure 1. The official route of passenger vehicle recycling in China.

The demand for new passenger vehicles is estimated by the polynomial regression based on the historical consumption (demand) of vehicles (Section 2.1). The generation of end-of-life passenger vehicles (Section 2.2) is estimated by Weibull distribution functions. The total recyclable resources from these end-of-life passenger vehicles are estimated by different types of resources of passenger vehicles (Section 2.3).

2.1. Estimation of Passenger Vehicle Demand

The demand for new vehicles in the future determines the in-use stocks of vehicles and thus determines the generation of EoL passenger vehicles in the future. In this paper, based on the historical consumption (demand) of vehicles, polynomial regression is adopted to estimate the demand for vehicles in the future. In the t th year, the vehicle demand, $P(t)$, can be formulated in Equation (1),

$$P(t) = at^3 + bt^2 + ct + \mu \quad (1)$$

where parameters a , b , and c describe the shape of the polynomial regression curve, μ refers to the corresponding random errors. The demand for vehicles includes the consumption of domestic imported vehicles. Compared with Huo and Wang [19] (2012) and Azmi and Tokai [8] (2017), both using vehicle ownership rate and income level as a straightforward tool to reveal the trend of vehicle demand along

with time, this paper considers a polynomial regression with one single variable. Such modeling reaches the necessary accuracy, especially when the system boundary of time (in this paper, the estimation from 2020 to 2030) is within the longest lifetime span of vehicles involved.

2.2. Estimation of End-Of-Life Passenger Vehicles: Weibull Distribution

The generation of EoL passenger vehicles is estimated by Weibull distribution functions. Weibull distribution has been widely applied in the lifetime span estimation of durable goods including vehicles (Li and Fujikawa [18] 2017; Nakamoto [20] 2017), electrical and electronic appliances (Wang et al. [21] 2018; Parajuly et al. [22] 2017), substance and materials (Wang et al. [23] 2017; Wen et al. [24] 2015), etc. Compared to other distributions, such as the uniform lifetime distribution, exponential and normal lifetime distribution, and logarithmic lifetime distribution, Weibull distribution provides a relatively accurate distribution pattern of lifetime spans even with limited available data accesses. Sano [25] (2008) stated that vehicles well fall in the application scope of Weibull distribution, as the accumulated retirement rates increase along with time. In this model, the accumulated retirement rate in year t , $W(t)$, follows the Weibull distribution with a scale parameter, η , the position parameter γ , and a shape parameter, m , formulated as Equation (2),

$$W(t) = 1 - \exp[-((t - \gamma)/\eta)^m] \quad (2)$$

Therefore, the survival rate of passenger vehicles in the year t , $R(t)$, can be formulated as,

$$R(t) = 1 - W(t) = \exp[-((t - \gamma)/\eta)^m] \quad (3)$$

where γ , namely the position parameter, represents the minimum time left for passenger vehicles to get retired, $\gamma \leq t < \infty$, $m > 0$, $\eta > 0$. It is assumed that all passenger vehicles registered in year t will not retire in the same year. Therefore, the position parameter, γ , is set as zero.

The total number of passenger vehicle ownership in year t , $\hat{H}(t)$, is formulated as

$$\hat{H}(t) = \sum_{k=1}^n [P(t, k) * R(t, k)] \quad (4)$$

where n represents the maximum year for passenger vehicles to get retired; k represents the vehicle age; $P(t, k)$ represents the total demand for passenger vehicles in year $(t - k)$; $R(t, k)$ represents the survival rate of passenger vehicles registered in year $(t - k)$.

To keep the estimation of passenger vehicle ownership number in year t , $\hat{H}(t)$, consistent with the observation of passenger vehicle ownership number in year t , $H(t)$, the sum of the squared deviation $(\hat{H} - H)$ should be minimized as shown in Equation (5). Therefore, the scale parameter, η , and the shape parameter, m , can be calculated by

$$\min_{m, \eta} \sqrt{\sum_{k=1}^n [\hat{H}(t) - H(t)]^2} \quad (5)$$

By adopting these two parameters, the total number of end-of-life passenger vehicles in year t , $\hat{B}$, can be formulated as

$$\hat{B}(t) = \sum_{k=1}^n [P(t, k) * W(t, k)] - \sum_{k=1}^n [P(t - 1, k) * W(t - 1, k)] \quad (6)$$

where $W(t, k)$, represents the accumulated retirement rate of passenger vehicles with a vehicle age of k years in year t . The total number of end-of-life passenger vehicles in year t is calculated by the difference of the in-use vehicles in year t and the year before year t .

2.3. Estimation of Recyclable Resources and Their Economic Values

The total recyclable resources from these EoL passenger vehicles are estimated by different types of resources and different categories of passenger vehicles. The estimation of the j th type of recyclable resources from the i th category of passenger vehicles in year t , $\hat{Q}_j(t)$, can be formulated as

$$\hat{Q}_j(t) = \sum_{i=1}^h S I_{i,j} C_i \hat{B}_i(t) \quad (7)$$

where S represents the standard of material recycling efficiency of all EoL passenger vehicles (ton total recyclable resources/ ton vehicle); $I_{i,j}$ represents the weight share of the j th type of recyclable resources in each i th type of passenger vehicle; C_i represents the total weight of recyclable resources in each i th type of passenger vehicle; there are all h types of resources.

The estimation of the economic value of the j th type of recyclable resources from EoL passenger vehicles in year t , $\hat{V}_j(t)$, can be formulated as

$$\hat{V}_j(t) = \hat{Q}_j(t) U_j \quad (8)$$

where U_j represents the average unit price of the j th type of recyclable resources from EoL passenger vehicles [18].

2.4. Data Sources and Scenario Settings

Sources of the mentioned variables and parameters are listed in Table 1.

Table 1. Data sources.

Variable/ Parameter	Details	Source
P	The demand for new passenger vehicles	China Automotive Industry Yearbook (1996–2018)
S	The standard material recycling efficiency of end-of-life passenger vehicles	Automotive product recycling technology policy (2006); Auto recycling statistics (2019)
$I_{i,j}$	The weight share of the j th type of recyclable resources in each i th type of passenger vehicle	Automotive Industry Green Development Report (2017)
C_i	The total weight of recyclable resources in each i th type of passenger vehicle	Automotive Industry Green Development Report (2017)
U_j	The unit price of the j th type of recyclable resources in the i th category of passenger vehicles in 2013	China Automotive Industry Yearbook (2014)

Regarding the counter i , passenger vehicle types discussed in this paper include conventional fuel passenger vehicles and new energy passenger vehicles (i.e., battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell electric vehicles). The market of China's new energy passenger vehicles is still in an emerging period, providing a relatively small population for future retirement. Moreover, although the batteries in new energy passenger vehicles, which are not included in the estimation of this paper, may be replaced with a relatively higher frequency, the rest of the new energy passenger vehicles hold a similar lifespan compared to the conventional fuel passenger vehicles [26]. Considering such lifespan as 15 years (the current mandatory retirement requirement in China), the share of EoL new energy passenger vehicles should be similar to the new vehicles produced from 2005 to 2015. Therefore, it is assumed in this paper that both types of passenger vehicles share the same retirement distribution; at the same time, the share of new energy ELVs in China from 2020 to 2030 remains 1%.

Regarding the counter j , recyclable resource types discussed in this paper include steel, nonferrous metal, plastic, and rubber.

Regarding the standard of material recycling efficiency in China, S , the *Automotive product recycling technology policy* [27] (2006) has been issued by the National Development and Reform Commission, the Ministry of Science and Technology, and the State Environmental Protection Administration in order to clarify the standard of ELV recycling. The recovery rate target of all materials from EoL passenger vehicles in China was set as over 95%, with a recycling rate target over 85% by 2017. A recent report from auto recycling statistics [28] (2019) shows that about 80% of a vehicle (by weight) can be recycled. In Japan, Toyota [29] (2017) reported a higher recovery efficiency close to over 99% in automobile manufacturers. In the EU, the DIRECTIVE 2000/53/EC has been issued to set the standard of material recycling efficiency in order to prevent waste from vehicles as well as to improve the reuse, recycling, and other forms of recovery of ELVs (EU 2003). The recovery rate target of all materials from ELVs in the EU was required to exceed 95%, with a recycling rate target over 85% by 2015 [30]. Since the long-term analysis in this paper extends to 2030, considering the recovery efficiency standards in developed regions and China, together with the real efficiency in leading entities in the automobile industry, the parameter S was set with the current standard of recycling efficiency at 85%. To reach a high resource recovery level as developed countries, the recovery rate target of all materials from EoL passenger vehicles in China was set as over 95%, with a recycling rate target over 85% by 2017. Since the long-term analysis in this paper extends to 2030, considering the recovery efficiency standards in developed regions and China, together with the real efficiency in leading entities in the automobile industry, the parameter S was set with the current standard of recycling efficiency at 85%.

Two scenarios discussed in this paper include a BAU scenario (Business-as-Usual scenario) and an LW scenario (Light-Weight scenario) considering the lighter-weight trend of passenger vehicles in the next 10 years. With a lighter weight, passenger vehicles will have better performance in energy consumption and achieve the largest CO₂ reduction.

Regarding the weight share of the j th type of recyclable resources in the i th type of passenger vehicles, $I_{i,j}$, the benchmark is set based on the 2017 Automotive Green Development Report [18] in the BAU scenario, shown in Figure 2.

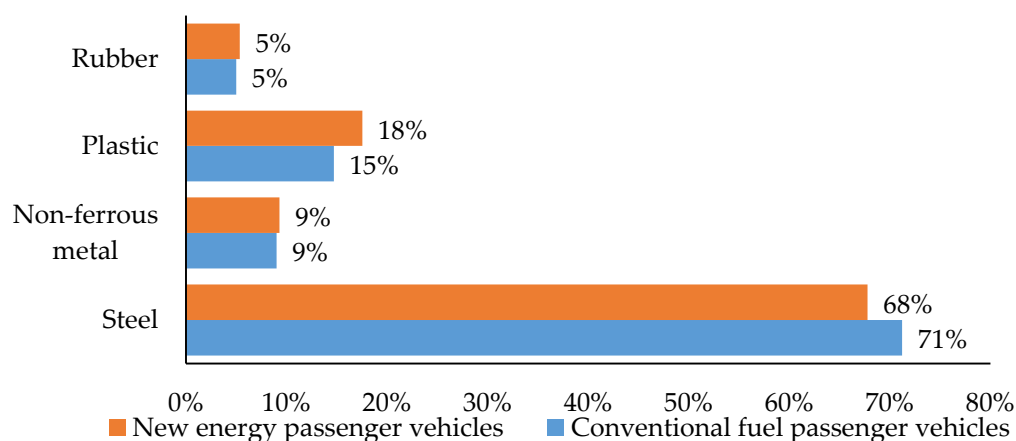


Figure 2. The weight share of all types of recyclable resources in conventional fuel passenger vehicles under the BAU scenario.

Regarding the total weight of recyclable resources in each i th type of passenger vehicle, C_i , the benchmark is set based on the 2017 Automotive Green Development Report [26] as 1.4 metric tons for both conventional fuel passenger vehicles and new energy passenger vehicles, with each new energy passenger vehicle carrying a battery of 0.4 metric ton average. Under the BAU scenario, such a benchmark is adopted. Under the LW scenario, based on the same benchmark, a lighter weight is mainly achieved by replacing iron and steel with aluminum and plastics, such as carbon fiber-reinforced

polymer (FRP) and glass FRP mentioned by Palencia et al. [22] (2004). We further assume that the weight share of steel will decrease by 1% annually from 2020, while the weight share of nonferrous metals and plastics will increase by 0.5% annually. Such assumption is based on the experience in North America [31] (76% of steel, 5% of nonferrous metals in 1975; 65% of steel, 13% of nonferrous metals in 2012), a similar assumption in the case of Japan [32] (78% of steel in 1980, further assumed 65% in 2020), as well as the consideration of high market share of made-in-Japan passenger vehicles in China.

3. Results and Discussion

3.1. Demand for New Passenger Vehicles

The demand for passenger vehicles before 2030 is formulated as

$$y_1 = -0.1767x^3 + 12.601x^2 - 65.789x + 170.25 \quad (R^2 = 0.99) \quad (9)$$

where the variable x ranges from 1 to 34, representing the years 1997 to 2030, the R -square shows that the goodness-of-fit can be acceptable.

The total demand for new passenger vehicles from 2020 to 2030 is shown in Figure 3.

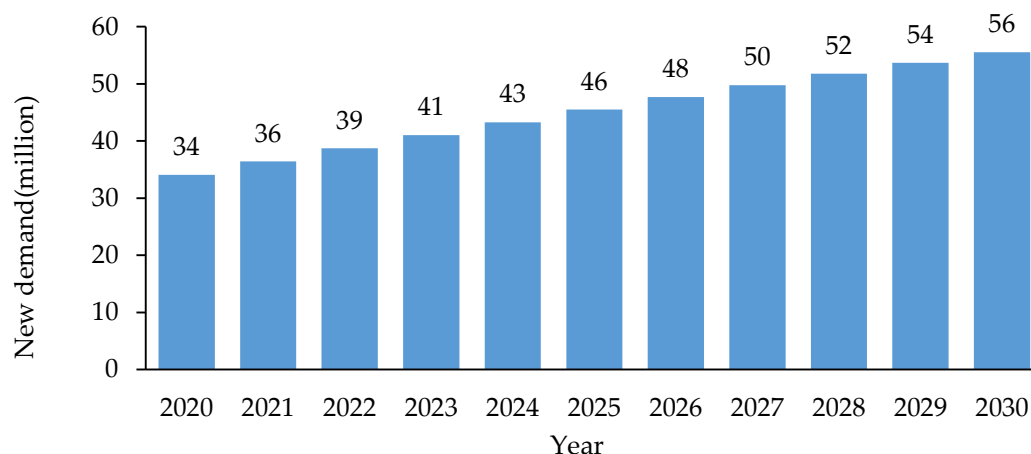


Figure 3. The demand for new passenger vehicles in China from 2020 to 2030 (in millions).

According to our estimation, a stable increase in the demand for passenger vehicles can be observed from 2020 to 2030, with a growth of 1.63 times in total. The demand for passenger vehicles will grow to 55.55 million in 2030. Considering that the rapid development of the automobile industry in China started late compared to other developed countries, room will still remain for China's passenger vehicle ownership rate to reach a saturation level. The steady growing vehicle demand may also ensure the large potential of vehicle recycling.

3.2. Generation of the End-Of-Life Passenger Vehicles

The parameters describing the shape of the survival rate of passenger vehicles (the scale parameter, η , and the shape parameter, m) in this paper are $m = 3.02$, $\eta = 14.61$. The survival rate and retirement rate of passenger vehicles in China are shown in Figure 4. The axis of vehicle ages is plotted from 0 to a maximum of 30, which is the compulsory retirement age of vehicles in China.

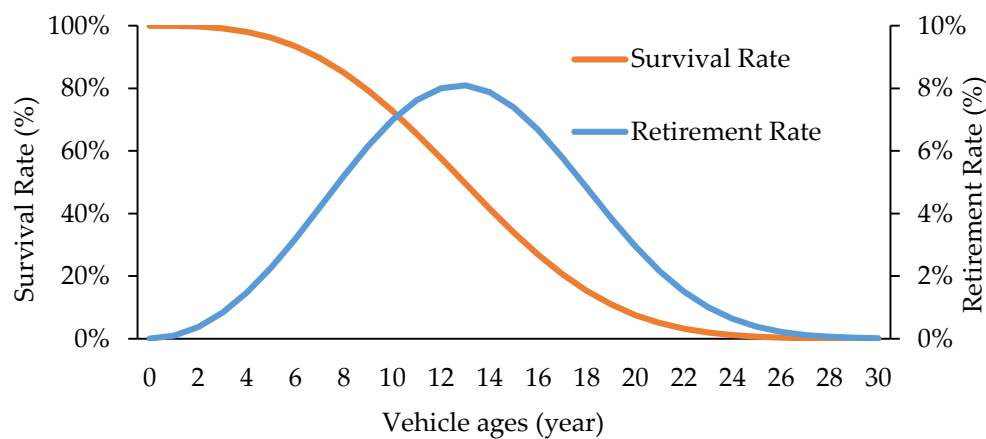


Figure 4. Simulation results of survival rate and retirement rate of passenger vehicles in China.

The results show that for the vehicles with the same vehicle age, few of them retired in the first 8 years; the retirement rate reached a higher level from year 9 to year 16 and peaked at year 13, with an annual retirement rate of 8.09% and surviving rate of 49.53%; the surviving rate reached approximately 0% at year 25. The results of the survival rate and retirement rate reflected the current situation and development pattern of China, in terms of the preference of vehicles and ongoing ELV policies. In 1986, a compulsory retirement standard was implemented in China and officially announced as the “Automobile scrapping standard” in 1997. According to the standard, the mandatory scrapping standard of passenger vehicles is 10 years (or a service distance over 100 thousand kilometers). With the rapid development of the automobile industry in China, the restriction was extended to 15 years in 2000. In the latest “standard for compulsory scrapping of motor vehicles” announced in 2013, the mandatory retiring age of small- and medium-size non-operating passenger vehicles was canceled (instead, the service distance limitation is set at 600,000 kilometers). If the passenger vehicles traveled an average of 20,000 kilometers per year, the service time can be 25–30 years.

The total number of EoL passenger vehicles ($\hat{B}$) from 2020 to 2030 estimated by this paper is shown in Figure 5.

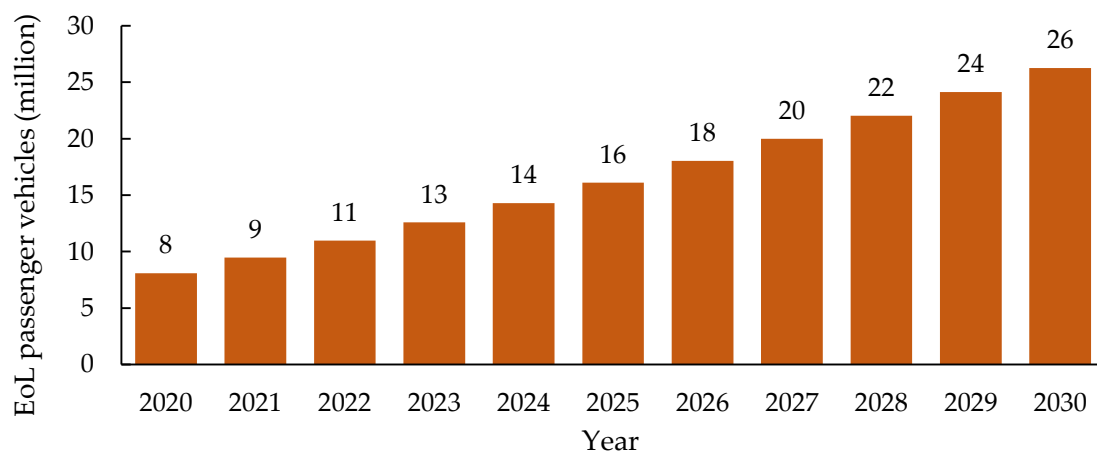


Figure 5. The generation of end-of-life passenger vehicles in China from 2020 to 2030 (million).

In 2030, the total EoL passenger vehicles will be 26.3 million, almost 3.3 times the number in 2020, with an annual growth rate from 2020 to 2030 over 13%. It indicates that a rapid increase in the population of EoL passenger vehicles can be expected in the next 10 years. It is better for vehicle producers to shift to a manufacturing mode considering the large potential of recycling EoL passenger vehicles. However, the current level of recycling is relatively low, as shown in Figure 6.

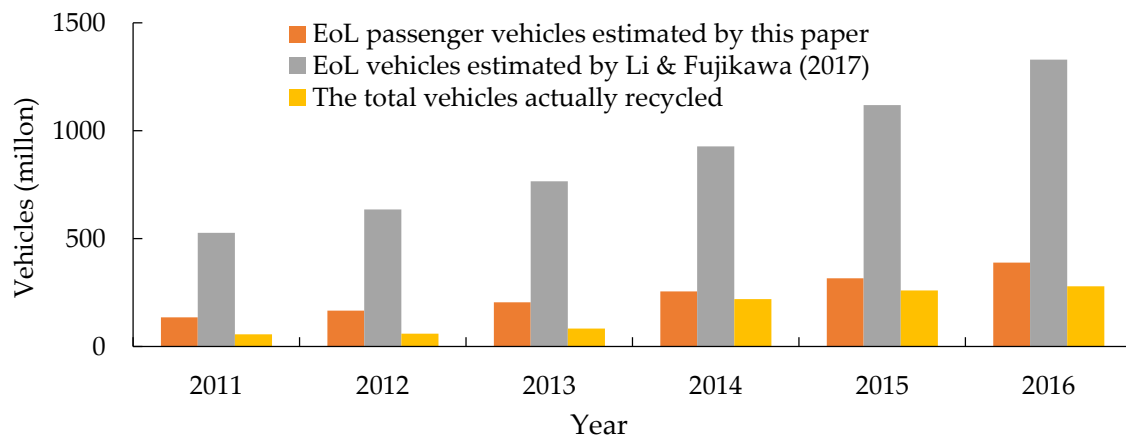


Figure 6. The comparison of estimated end-of-life (EoL) vehicles and vehicles actually recycled.

If comparing the total vehicles actually recycled from 2011 to 2016 (yellow in Figure 7) with the recyclable EoL passenger vehicles estimated by this paper (orange in Figure 7), the former one, containing both EoL passenger and commercial vehicles, is still smaller than our estimation. Moreover, if comparing the total vehicles actually recycled from 2011 to 2016 (yellow in Figure 7) with the total recyclable EoL vehicles estimated by our previous study, (Li and Fujikawa [18] 2017, grey in Figure 7), the EoL passenger vehicles actually recycled have been only occupying an average of 17% of the recyclable EoL vehicles we estimated. Both comparisons lead to the conclusion that the current recycling efficiency of passenger vehicles in China should be improved. Except for the regulation and enforcement of recycling policies and standards, one of the main reasons for the low recycling efficiency lies in the high recycling costs (mainly the costs of recycling ELVs, instead of the costs of resource recovery from ELVs) due to the small scale of retired vehicles available for recycling. An expansion of the scale of EoL passenger vehicles can reduce the average recycling costs [31]. Together with the improvement of ELV dismantling technologies, vehicle producers are able to benefit more from participating in recycling promotion, and therefore obtain more incentives to perform their extended recycling responsibility. The detailed benefits, namely the recyclable resources from EoL passenger vehicles and their economic value, will be shown in Section 3.3.

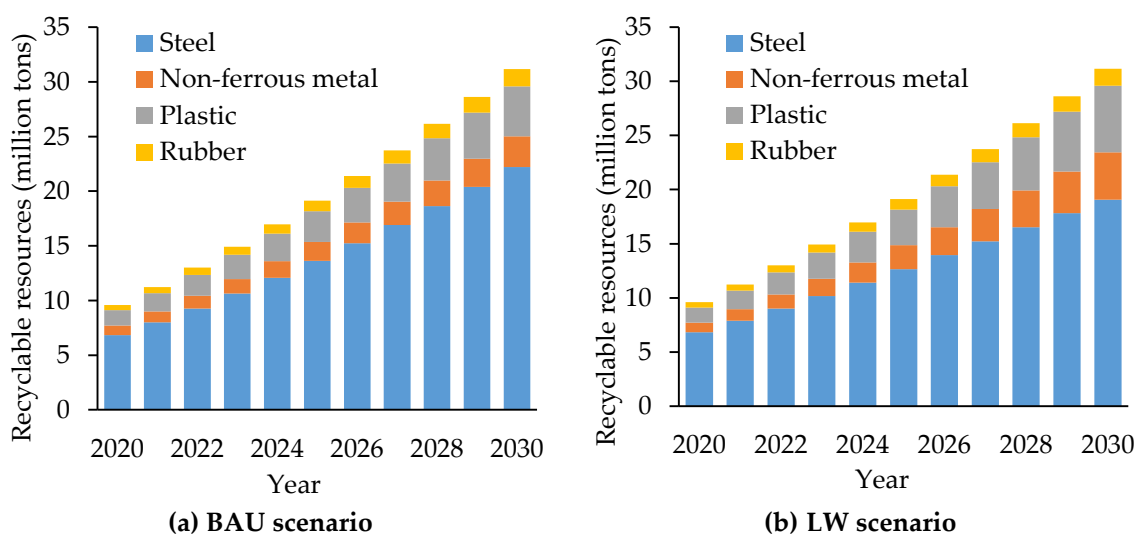


Figure 7. Recyclable resources from end-of-life passenger vehicles from 2019 to 2030 (million tons).

3.3. Recyclable Resources from End-Of-Life Passenger Vehicles and Their Economic Values

The total recyclable resources from EoL passenger vehicles ($\hat{Q}_j$) from 2020 to 2030 estimated by this paper are shown in Figure 7, assuming that all EoL passenger vehicles are legally registered as scrapped and completely recycled.

According to our results, in 2030, steel will still be the largest category of resources that can be recycled from EoL passenger vehicles, reaching 22.2 million tons under the BAU scenario. The rest will include 2.8 million tons of nonferrous metals, 4.6 million tons of plastics, and 1.6 million tons of rubber. Under the LW scenario, recyclable plastics from EoL passenger vehicles will largely increase to 6.2 million tons, 1.3 times of which are under the BAU scenario. A slight increase can also be observed in the total amount of recyclable rubber. From 2020 to 2030, along with the growth in the population of EoL passenger vehicles, the recyclable resources in each category will also increase. Moreover, since the technology of dismantling ELVs may improve in the near future and the cost of recycling resources will decrease, it can be expected that, with the same potential population of EoL passenger vehicles, the theoretical level of total recyclable resources may remain at a similar level in weight, but leading to a quite different total economic value.

The economic value for each category of recyclable resources from EoL passenger vehicles ($\hat{V}_j(t)$) in 2020, 2025, and 2030 under both the BAU and LW scenarios are shown in Table 2. Assuming that all EoL passenger vehicles are legally registered as scrapped and completely recycled, the theoretical economic value of all recyclable resources will reach 101.3 billion yuan in 2030, which is an average of approximately 2.4 thousand yuan for each EoL passenger vehicle. If all recyclable resources are used to produce new vehicles to meet the market demand in the same year, the economic value will be approximately 1.3 thousand yuan for each new vehicle under the BAU scenario (1.2 thousand yuan/new vehicle under the LW scenario), which is considerable compared to the average production cost of one passenger vehicle (46.4 thousand yuan, Deloitte 2018).

Table 2. Estimation of the economic value of total recyclable resources.

Scenario	Year	Steel	Nonferrous Metals	Plastics	Rubber	Total
BAU	2020	106.6	2.4	5.6	0.1	114.7
	2025	197.5	6.2	13.4	0.2	217.4
	2030	297.4	12.6	25.5	0.4	335.9
LW	2020	106.6	2.4	5.6	0.1	114.7
	2025	183.6	8.0	15.7	0.2	207.5
	2030	255.6	19.5	34.2	0.4	309.7

Notes: The unit of s (the economic value of recyclable resources from total end-of-life passenger vehicles) is 10^8 yuan.

Under the lightweight trend scenario, the potential of plastic and rubber recycling of ELVs can be expected to overweight the potential of metal recycling, especially steel recycling in the long run. Such a difference indicates that the improvement of the recycling technology and efficiencies should consider the changes in the population of recyclable resources. A larger economic incentive can be expected as more recyclable copper will be found in ELVs, especially new energy passenger vehicles. At the same time, better recycling and reuse technologies of plastics and rubbers are important for ELV dismantling companies, as the weight share of heavy components like steel will be shrinking.

3.4. Discussion

The rapid increase shown in the result of the EoL passenger vehicle population in the next 10 years ensures the potential of all recyclable resources. It is time for vehicle producers to shift to a manufacturing mode considering such large potential of ELV recycling. One typical example of such manufacturing mode is extending the production chain of automobiles to involve the recycling of EoL passenger vehicles as the responsibility of vehicle producers.

Moreover, the current understanding of ELV resource recovery only focuses on metal materials, especially steel (the dominant component in a passenger vehicle) and rare metal materials (high unit price). Our results suggest that, in the context of a light-weighting trend, ELV resource recovery in the future calls for improvement in the recycling and reuse technologies of plastics and rubbers. If recyclable plastics are sorted with a more detailed standard and processed with the same category, the economic value of recyclable plastics may increase. This is also suggested in Zhang and Chen [33] (2014), that the plastic parts are dismantled by workers before the ELVs turn into shreds, which makes scrap automotive plastics easier and cheaper to recycle in China. Sandra Belboom et al. [34] (2016) modeled the three steps of ELV recycling routes based on the industrial data. Regarding the increasing EoL new energy vehicles, Katja Tasala Gradin et al. [35] (2013) suggested focusing on the value of materials such as rare earth elements and copper. By doing so, vehicle producers, together with dismantling plants, are able to benefit more from participating in recycling promotion, and therefore obtain more incentives to perform their extended recycling responsibilities.

Regarding the limitations of this paper, a more accurate estimation of new passenger vehicle demands can be reached if the price of passenger vehicles and income level are taken into consideration. In the policy dimension, as the updating policies and standard directly related to the ELV recycling (such as the compulsory automobile retirement, the ban of fuel vehicle sales after 2030, the qualification standard of automobile dismantling, likewise) have not been officially announced, we did not model the impact of policies on the recycling efficiency (namely, how well the EoL passenger vehicles are recycled legally and traceable). The scenarios considering such policies will be discussed in our next work. In the technology dimension, we considered the lighter-weight trend of passenger vehicles, but the impacts of the automobile dismantling technology are not included.

The recycling of end-of-life passenger vehicles does not have high involvement in imported end-of-life goods. Especially in China, both the export and import of end-of-life goods are highly regulated, with only some exceptional pilot projects (i.e., a pilot zone of recycling operation of imported end-of-life vehicles in Zhangjiagang, Jiangsu, China, in 2005) covering a small scale of imported end-of-life vehicles. Therefore, the imported end-of-life vehicles are not considered to estimate the total amount of resources from end-of-life vehicles in China. UN Contrade [36] (2018) investigated that China has been the largest import country of plastic scraps to meet the increasing demand for plastic raw materials. The China Plastics Processing Industry Association [37] (2017) revealed that the imported plastic scraps occupied approximately 28% of the total domestic plastic scrap supply, which was a large shock to the plastic supply in China. However, the ban can be regarded as a chance to improve the domestic market of plastic scrap recycling in the long run. According to the results of this paper, under the LW scenario, the total recyclable plastics from domestic EoL passenger vehicles may reach 6.2 million tons in 2030. If these plastic scraps can be recycled efficiently, the negative impact of the scrap import ban may be improved to some extent.

4. Conclusions

In this paper, the demand for new passenger vehicles in China in the next ten years was estimated. Based on the results, the total number of end-of-life passenger vehicles was estimated by adopting Weibull distributions. The recyclable resources from end-of-life passenger vehicles and their economic values were further revealed.

The results show that more than 19.1 million tons of recyclable steel and 6.2 million tons of plastics can be recycled in 2030. It is better for vehicle producers to shift to a manufacturing mode considering the large potential of recycling end-of-life passenger vehicles. An introduction of recycling policy instruments leading by vehicle producers, such as the deposits to vehicle producers for recycling the end-of-life vehicle (an implementation of extended producer responsibility), may reduce the government expenditure on promoting legal vehicle recycling and, at the same time, provide additional incentives (the theoretical value of recyclable resources can reach approximately 1.3 thousand yuan for each new vehicle being produced) to vehicle producers to reduce their production costs. Such an

instrument provides the solution to a more sustainable development pathway in the context of the rising potential of urban mining.

Author Contributions: The contributions of each author are listed as follows: conceptualization, Y.L. and Y.J.; methodology, Y.L. and K.F.; software, Y.L.; resources, C.C. and J.W.; data curation, X.L.; writing—original draft preparation, Y.L. and Y.J.; writing—review and editing, Y.L. and Y.J.; visualization, Y.L. and Y.J.; supervision, Y.L. and Y.J.; project administration, Y.L. and Y.J.; funding acquisition, Y.L. and K.F. All authors have read and agree to the published version of the manuscript.

Funding: This research received funding from the National Natural Science Foundation of China (No. 71804195) and the Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (No. 16KT0088). We also appreciated the financial support from the Sakura Science Plan (No. S2019F0603472) of the Japan Science and Technology Agency to organize a joint seminar where the idea of this paper was generated and discussed.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhao, Z. Superlarge ore deposits and development of China's mineral resources. *Chin. Sci. Bull.* **1999**, *44*, 94–98. [CrossRef]
2. Baccini, P.; Brunner, P.H. *Metabolism of the Anthroposphere: Analysis, Evaluation, Design*, 2nd ed.; The MIT Press: Cambridge, MA, USA; London, UK, 2012.
3. Bellmann, K.; Khare, A. Economic issues in recycling end-of-life vehicles. *Technovation* **2000**, *20*, 677–690. [CrossRef]
4. China Association of Automobile Manufacturers, 2019. Bulletins of the Production and Sales of Automobiles in China. Available online: <https://www.yicai.com/news/100098564.html> (accessed on 14 January 2019).
5. Li, Y.; Miao, L.; Chen, Y.; Hu, Y. Exploration of sustainable urban transportation development in China through the forecast of private vehicle ownership. *Sustainability* **2019**, *11*, 4259. [CrossRef]
6. Button, K.; Ngoe, N.; Hine, J. Modeling Vehicle Ownership and Use in Low Income Countries. *J. Transp. Econ. Policy* **1993**, *27*, 51–67.
7. Kobos, P.; Erickson, J.; Drennen, T. Scenario Analysis of Chinese Passenger Vehicle Growth. *Contemp. Econ. Policy* **2003**, *21*, 200–217. [CrossRef]
8. Azmi, M.; Tokai, A. Electric vehicle and end-of-life vehicle estimation in Malaysia 2040. *Environ. Syst. Decis.* **2017**, *37*, 451–464. [CrossRef]
9. Pan, Y.; Li, H. Sustainability evaluation of end-of-life vehicle recycling based on emergy analysis: A case study of an end-of-life vehicle recycling enterprise in China. *J. Clean. Prod.* **2016**, *131*, 219–227. [CrossRef]
10. Hedayati, M.; Subic, A. A framework for extended end-of-life vehicle (ELV) recovery rate based on a sustainable treatment option. *Int. J. Sustain. Des.* **2011**, *1*, 381–401. [CrossRef]
11. Frits, A.; Helge, L.; Mette, S. A European model for the number of End-of-Life Vehicles. *International Journal of Automotive Technology and Management*. *Int. J. Automot. Tech. Manag.* **2007**, *7*. [CrossRef]
12. Hu, S.; Kurasaka, H. Projection of End-of-Life Vehicle (ELV) Population at Provincial Level of China and Analysis on the Gap between the Future Requirements and the Current Situation of ELV Treatment in China. *J. Mater. Cycles. Waste. Manag.* **2013**, *15*, 154. [CrossRef]
13. Qiao, Q.; Zhao, F.; Liu, Z.; Hao, H. Electric vehicle recycling in China: Economic and environmental benefits. *Resour. Conserv. Recycl.* **2019**, *140*, 45–53. [CrossRef]
14. Rovinaru, F.I.; Rovinaru, M.D.; Rus, A.V. The Economic and Ecological Impacts of Dismantling End-of-Life Vehicles in Romania. *Sustainability* **2019**, *11*, 6446. [CrossRef]
15. D'Adamo, I.; Gastaldi, M.; Rosa, P. Recycling of end-of-life vehicles: Assessing trends and performances in Europe. *Technol. Forecast. Soc. Chang.* **2020**, *152*, 119887.
16. Jody, B.J.; Daniels, E.J.; Duranceau, C.M.; Pomykala, J.A., Jr.; Spangenberg, S.S. *End-of-Life Vehicle Recycling: State of the Art of Resource Recovery from Shredder Residue*. (No. ANL/ESD/10-8); Argonne National Lab. (ANL): Argonne, IL, USA, 2011.
17. Li, W.; Bai, H.; Yin, J.; Xu, H. Life cycle assessment of end-of-life vehicle recycling processes in China—Take Corolla taxis for example. *J. Clean. Prod.* **2016**, *117*, 176–187. [CrossRef]
18. Li, Y.; Fujikawa, K. Potential of the Renewable Resources of End-of-Life Vehicles in China. *Environ. Sci.* **2017**, *30*, 184–189. [CrossRef] [PubMed]

19. Huo, H.; Wang, M. Modeling future vehicle sales and stock in China. *Energy Policy* **2012**, *43*, 17–29. [CrossRef]
20. Nakamoto, Y. CO₂ reduction potentials through the market expansion and lifetime extension of used cars. *J. Econ. Struct.* **2007**, *6*. [CrossRef]
21. Wang, M.; You, X.; Li, X.; Liu, G. Watch more, waste more? A stock-driven dynamic material flow analysis of metals and plastics in TV sets in China. *J. Clean. Prod.* **2018**, *187*, 730–739. [CrossRef]
22. Parajuly, K.; Habib, K.; Liu, G. Waste electrical and electronic equipment (WEEE) in Denmark: Flows, quantities and management. *Resour. Conserv. Recycl.* **2017**, *123*, 85–92. [CrossRef]
23. Wang, M.; Chen, W.; Zhou, Y.; Li, X. Assessment of potential copper scrap in China and policy recommendation. *Resour. Policy* **2017**, *52*, 235–244. [CrossRef]
24. Wen, Z.; Zhang, C.; Ji, X.; Xue, Y. Urban Mining's Potential to Relieve China's Coming Resource Crisis. *J. Ind. Ecol.* **2015**, *19*, 1091–1102. [CrossRef]
25. Sano, M. *A Convenient Estimation Methodology for Survival Rate of Automobiles*; ITEC Working Paper; The Institute for Technology, Enterprise and Competitiveness, Doshisha University: Kyoto, Japan, 2008. (In Japanese)
26. *Automotive Industry Green Development Report*; China Automotive Technology & Research Center, China Industry and Information Technology Publishing & Media Group, Posts & Telecom Press: Beijing, China, 2017; ISBN 978-7-115-47175-8.
27. World Motor Vehicle Statistics. 2016. Available online: http://www.fourin.cn/img/report/STATISTICS_NENKAN_2016/STATISTICS_NENKAN_2016.pdf (accessed on 14 June 2017).
28. Auto Recycling Facts and Figures. 2019. Available online: <https://www.thebalancesmb.com/auto-recycling-facts-and-figures-2877933> (accessed on 7 August 2019).
29. Toyota. Vehicle Recycling. 2017. Available online: https://global.toyota/pages/global_toyota/sustainability/report/kururisa_jp.pdf (accessed on 1 April 2017). (In Japanese).
30. EU. Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000, on end-of-life-vehicles. Council of the European Union. *Off. J. Eur. Union* **2003**, *L269*, 34–42.
31. Forecast of China's Automobile Lightweight Market Scale and Industry Development Trend in 2017. 2016. Available online: <https://m.chyxx.com/view/459606.html> (accessed on 22 October 2016).
32. Shimbun, N.J. *Automobile Yearbook Hand Book*; Nikkei Shimbun: Kyoto, Japan, 2003. (In Japanese)
33. Zhang, H.; Chen, M. Current recycling regulations and technologies for the typical plastic components of end-of-life passenger vehicles: A meaningful lesson for China. *J. Mater. Cycles Waste Manag.* **2014**, *16*, 187–200. [CrossRef]
34. Belboom, S.; Lewis, G.; Bareel, P.F.; Léonard, A. Life cycle assessment of hybrid vehicles recycling: Comparison of three business lines of dismantling. *Waste Manag.* **2016**, *50*, 184–193. [CrossRef]
35. Gradin, K.T.; Luttrupp, C.; Björklund, A. Investigating improved vehicle dismantling and fragmentation technology. *J. Clean. Prod.* **2013**, *54*, 23–29. [CrossRef]
36. UN Contrade Database. 2018. Available online: <https://comtrade.un.org> (accessed on 1 April 2019).
37. China Plastics Processing Industry Association. *China Plastics Industry Yearbook*; China Light Industry Press: Beijing, China, 2017.

