Assessing the Energy-efficient Potential of a Closed-loop Supply Chain for Household Durable Metal Products in China

Abstract: The dramatic increase in Chinese residents' income has driven a sharp increase in the purchase of household durable metal products (HDMPs), which are classified into automobiles and other durable products, mainly appliances and electronics. To explore the energy-efficient potential of the closed-loop supply chain (CLSC) for the HDMP industry in China, we develop a comprehensive evaluation framework based on dynamic material flow analysis and life cycle assessment, which combines macro prediction of demand and scrap with micro calculation of material flow. The results show that the demand for appliances and electronics and for electric cars will reach peaks in 2028 and 2035, respectively, and annual scrap for appliances and electronics and for electric cars will reach peaks in approximately 2036 and 2040, respectively. The recycling of scrap iron, aluminium, and copper can achieve energy conservation of approximately 72%, 94%, and 82%, respectively, compared with metal primary production, while remanufacturing processes can further reduce energy consumption by approximately 68%, 57%, and 72%, respectively. If the energy consumption of metal production, recycling rate, and remanufacturing rate can reach internationally advanced levels by 2035, approximately 50.5 Mtce (million-ton coal equivalent) will be saved compared to low-speed development by 2050; among these factors, the regeneration of waste metals can achieve the most significant energy-efficient effect.

Keywords: Energy-efficient; Household durable metal products; Closed-loop supply chain; Energy intensity; Dynamic material flow analysis; Life cycle assessment

1. Introduction

The rapid innovation of technologies and increase in residents' income has revolutionized societal investments in infrastructure for networking and the rapid expansion of international commerce (Williams 2011). Simultaneously, the improvements in productivity and technological innovation have greatly promoted the iteration rate and popularity of industrial products, especially HDMPs. China's vehicle production has accounted for over 1/4 of the world's total since 2015 (Hao et al. 2017), and China has become the largest electronic product manufacturing and consumption country since 2013 (Zhang et al. 2015). A sharp increase in end-product demand will inevitably lead to higher energy consumption in the manufacturing process and primary production of raw materials in the upstream supply chain. DENBSC (2021) determined that China's total energy consumption in 2020 was 3.4 times higher than that two decades ago and increased to approximately 49.8 billion tce, of which the industrial production process accounted for approximately 67% of the total energy consumption. However, the average ownership of HDMPs for Chinese residents is still relatively low compared to that of developed countries due to the large population of over 1.4 billion. For example, Chinese residents' private passenger car ownership was approximately 158 vehicles per 1,000 people in 2020, while it was 800 vehicles per 1,000 people (including cars and light-duty trucks) in the U.S., 450-600 vehicles in European countries, and 400 vehicles in Japan (Huo and Wang 2012). In other words, the ownership of passenger cars in China and other developing countries will further increase in the future (Kosai et al. 2020), while many developed countries have reached the saturation point of ownership. The continuously increasing demand for HDMPs will further promote the rapid development of raw material production, energy supply, processing and manufacturing, and many other industries. Energy consumption and symbiotic development of energy conservation targets under the dual carbon context have become important issues to confront. Facing increasing demand, if extreme shocks or material disruptions occur in the future, resource shortages and hyperinflation may lead to long-term shortages of components, energy, capital, and labour in the supply chain of the whole industry (Ivanov and Dolgui 2022).

However, recycling and remanufacturing are effective measures to hedge against the potential shortage risk in the future (Ivanov et al. 2017), and environmental, social, and economic concerns motivate the operation of CLSC networks in many industries (Keyvanshokooh et al. 2016). The recycling and remanufacturing of waste products with relatively high metal content are efficient, energy-saving, and low-cost approaches to greatly shorten the process of mining, processing, production, transportation, and other processes of metal raw materials. At the same time, the shortening useful life expectancy of the product, driven by rapid innovation, miniaturization, and affordability, has further led HDMPs to a major increase in sales as well as the accumulation of scrap waste, especially end-of-life vehicles (ELV) and waste electrical and electronic equipment (WEEE) (Zeng et al. 2020). However, less than 30% of the scrap HDMPs are recycled by qualified enterprises through formal procedures (ATIEPR 2021; ADAC 2021). Most of them flow into the black market for disassembly through illegal recycling and are sold to rural or other low-end markets as second-hand goods, which cause serious safety hazards, resource waste, and pollutant discharge (Krug et al. 2021). The remanufacturing rate of spare parts is only less than 23% for cars and 10% for appliances and electronics (MRAC 2019), which is much less than in developed countries (45-55% and 20%) (Dong et al. 2022). In contrast, more than 70% of the parts in the US vehicle maintenance market are remanufactured products, and 94% of the scrap engines recycled by BMW can be repaired and remanufactured with advanced technologies (MRAC 2019). A low recycling rate leads to lower amounts of recycled materials, especially metals, while the primary production of metals consumes more energy and emits large amounts of pollutants. In addition, in the developing background of carbon neutrality and carbon peaks, energy conservation and pollutant abatement have become the trend for sustainable development of all manufacturing industries in the future. The Chinese government has realized that end-of-life HDMPs contain large economic and environmental benefits and issued the latest policy to strongly support the development of recycling and remanufacturing industries (SCC 2019).

Previous studies have usually adopted one or more approaches, such as (dynamic) material flow, forecasting based on macrosocioeconomic indicators, and life cycle assessment, to set up the research framework and focused on economic benefits, environmental benefits, or energy consumption for a series of metal materials, products, and processes such as recycling and remanufacturing. However, existing models and research have generally paid little attention to the quantitative energy-efficient evaluation potential of CLSCs and the organic combination of dynamic material flow analysis and life cycle assessment. Five main research gaps need to be addressed: (1) The CLSC, which takes the whole link of different processes and stages into account, has not been widely applied to the quantitative material flow framework. (2) While forecast models have been used by some researchers to estimate the ownership of vehicles or other appliances and electronics, the relatively high price of vehicles makes the increasing trend of car ownership significantly different from the trends of the ownership of other products, and few studies adopt two sets of forecasting models to calculate ownership, and there is a lack of forecasting based on the newest national long-term plan and the development trend of socioeconomic indicators. (3) Although some researchers have evaluated the energy consumption and energy-efficient potential of metals or metal products, there has been insufficient research on the evaluation of discharged pollutants and the environmental benefit potential. Due to the advantage of the CLSC framework, we have made up for this deficiency and provided the research idea for the assessment of environmental benefit potential. (4) In studies on the modelling of material flow, recycling, and remanufacturing of different metals or end-products, there are few examples of its application in the HDMP whole link industry, especially its combination with the macro forecast model according to the national long-term development plan to simultaneously evaluate the energy-efficient potential. (5) The existing studies lack detailed data for the upstream production input–output ratio, unit energy consumption at each production stage, and production and emission for copper and copper products.

This research aims to address these research gaps and proposes an integrated quantitative evaluation model for energy-efficient potential according to the newest national medium- and long-term development plans. The contributions of this research can be summarized as follows. First, the macro forecast model adopts two different prediction functions of ownership to better suit the characteristics of the vehicle and other durable products simultaneously. Second, we collected and sorted the data of the latest national plans and socioeconomic indicator development trends and integrated them into our prediction model to further enhance the credibility of the results. Third, this paper constructs a CLSC of Chinese residents' HDMPs to evaluate the energy-efficient potential, which provides a relatively integrated quantitative research framework of CLSCs. Finally, we fully grasp the idea of material flow accompanied by energy flow, not only calculating the energy consumption and energy-efficient potential but also evaluating the pollutants discharged by the whole HDMP industry. Furthermore, this paper focuses on the benefits and potential of energy efficiency and pollutant abatement through recycling and remanufacturing processes from the perspective of the life cycle assessment and carries out scenario prediction and analysis according to the national development plan to further evaluate the potential in the future.

The remainder of the paper is organized as follows. We provide a brief review of the relevant literature in Section 2. Section 3 describes the methodology. In Section 4, we present the results, which are discussed in Section 5. Section 6 provides conclusions and future research.

2. Literature review

2.1. Energy consumption of the industrial CLSC of HDMPs

Supply chains are multistructural systems composed of organizational, informational, financial, technological, process, product, and energy structures (Ivanov 2022). CLSCs are undoubtedly one of the main drivers of sustainability, which can reduce the volume of primary materials that end up in landfills (Kazemi et al. 2019). However, it is a challenge to determine the energy consumption and even more challenging to understand the impact of design and operational decisions on the energy consumption along China's industrial CLSC (Jain et al. 2013), which may affect the efficient implementation and investment of green technologies (Shen et al. 2021). Xu et al. (2014) used the logarithmic mean divisia index and production-theoretical decomposition analysis to decompose the major driver of China's industrial carbon emissions, and they found that economic output is the most effective, followed by population scale and energy structure effects. With the continuous increase in residents' disposable income, Huo and Wang (2012) predicted that China's car ownership would further increase in the future. In addition, Tian et al. (2022) and Zhang et al. (2018) forecasted that there still has growth space in domestic demand for household appliances and electronics in the future. Facing a further increase in metal demand, Jiang et al. (2020) built an industrial structure evaluation model to identify the input–output linkages of energy-consuming industries and provided suggestions for industrial structure optimization. However, the production and energy structure is relatively stable in the short term; for instance, China has been using coal as the main energy type for producing thermal power and electricity until now. Therefore, Mills and Schleich (2012) proposed that optimizing the production process and improving the energy-efficient process are more effective means of energy efficiency and emission reduction. In industrial production and HDMP manufacturing, iron, aluminium, and copper are the three most commonly used metal materials. An et al. (2018) constructed the long-term energy-efficient and emission abatement potentials of common metals from the perspectives of production capacity adjustment, structural optimization, and energy-efficient technology application.

In addition to economic benefits, recycling metals can also save large amounts of energy consumption in the metal primary manufacturing process, which could bring tremendous environmental and economic benefits (Shankar et al. 2018). Liu et al. (2020) modelled a recycling flow of end-of-life vehicles and found that recycling one unit vehicle can reduce 3816 kgCO_2eq compared with the equivalent metals' primary production. Similarly, many papers have focused on metallic or nonmetallic material recycling from end-of-life products and the evaluation of the economic and environmental benefits compared with equivalent materials in primary manufacturing (Gorman et al. 2022). However, building a CLSC from the primary production to the recycling process is a complex task that requires a large amount of empirical data. Although some researchers have attempted to apply this framework, there is still a lack of comprehensive assessments for energy consumption, recycling, remanufacturing, environmental benefits, etc., from the entire CLSC perspective. Much previous research in the fields of energy efficiency and CLSC has focused on consumers' perceptions of remanufactured products in CLSC (Abbey et al. 2015), pricing competition (Shen et al. 2022), eco-efficiency of products in CLSC (Quariguasi-Frota-Neto and Bloemhof 2012), green product strategies (Shen et al. 2020), etc.

Overall, the existing research mainly constructs CLSC models from a qualitative perspective and is inadequate to model the quantitative research framework of CLSCs, especially in the evaluation of energy-efficient potential. However, although some researchers try to set up quantitative CLSC models, another typical characteristic shortcoming is that most of them only build static CLSC structures based on one certain base year and lack the combination with macro forecast models to achieve the effect of dynamic assessment of the whole industry in the future. This research has made up for these deficiencies to some extent. Specifically, we construct a quantitative CLSC framework and build a macroprediction model based on long-term development plans and socioeconomic indicators, which is different from previous studies. Furthermore, through macro forecasting and micro quantitative calculation, this study can comprehensively evaluate the energy efficiency and pollutant abatement potential of the HDMP industry in the future and identify the key influencing factors.

2.2. Dynamic material flow analysis (DMFA) and life cycle assessment (LCA)

Material flow is usually accompanied by energy flow, information flow, and capital flow. Simulating the flow of material production and evaluating the sustainable development of the industry from the perspective of the economy and environment is an effective method, and this has become a popular method in the fields of a low-carbon economy and environmental sustainability (Haberl et al. 2019). In the context of carbon neutralization, Shafique et al. (2022) used material flow analysis (MFA) to assess the future U.S. and Chinese lithium-ion battery markets and their demand for materials, and they calculated that recycled nickel alone could create an economic value of approximately $725 million in 2030, and most of the used lithium batteries can be reused for low-end products. Dynamic material flow is a method to calculate the future sales and scrap volume of products by considering the average lifetime through inventory changes, which can be obtained from some ownership forecast functions. The dynamic characteristic of dynamic material flow analysis (DMFA), which is different from MFA, is reflected in the simulation of the inflow and outflow of materials through inventory changes, while the material outflow usually uses the Weibull distribution to calculate the theoretical scrap (that is, the outflow) (Mazhar et al. 2007) and further combines the predicted inventory changes to simulate the inflow (that is, the new sales) (Kamran et al. 2021). Therefore, the future theoretical demand and scrap volume can be estimated by fitting the historical sales and scrap volume data and forecasted according to the future inventory changes obtained from the inventory prediction functions (Krausmann et al. 2017). Zhang et al. (2018) adopted DMFA to forecast the future demand for iron and steel in China and evaluated the energy-efficient potential. In general, DMFA is a macro prediction method based on inventory change, while MFA is a micro analysis method of material flow in the system. They are commonly used as a mixed prediction and quantitative research method.

Life cycle assessment (LCA) is usually used to assess the economic and environmental benefits of products or materials from “cradle to grave” (Matos and Hall 2007), which is widely used as an assessment tool for evaluating the environmental impact of product development (Wang et al. 2015). The application of LCA is mainly divided into two major areas. One is to study sustainable product design and enterprise performance evaluation from the perspective of LCA. For small and medium-sized enterprises, the advantages of simplified LCA in terms of product design, process structure, and environmental impact can greatly benefit their sustainable development (Heidrich and Tiwary 2013). The life cycle model has important implications for value creation in professional service operations management; for instance, Lawrence et al. (2016) developed a professional service life cycle model to describe the changes in professional work over time and explored the drivers for specific professional services. Another research direction of LCA is to evaluate the economic and environmental sustainability of an industry or product based on macro panel data. Zeng et al. (2020) combined DMFA and LCA to simulate the response of copper supply chain participants to China’s solid waste import ban and the influence of COVID-19 and concluded that China’s solid waste import ban increased primary refining and offset the environmental impact of scrap copper refining. Keivanpour and Ait Kadi (2017) adopted LCA to evaluate the economic and environmental benefits of end-of-life aircraft and construct an integrated framework for modelling the end-of-life phase of complex products. In general, LCA provides a valuable reference for the design of products in terms of their environmental impact.

In general, previous studies mainly adopt DMFA to forecast the demand and scrap volume of products or use LCA to evaluate the benefits of scrap recycling compared with primary production, which is inadequate to construct a comprehensive assessment model using a combination of DMFA and LCA simultaneously. However, although some researchers have built assessment models of aluminium, iron, plastic, copper, vehicles, etc., there is currently no research to evaluate the energy-efficient potential of automobiles, household appliances, and electronics. This research has made up for these deficiencies, which also broadens the quantitative research ideas. The detailed contribution and research gap are shown in the next subsection.

2.3 Research gap and contribution

Table 1 Comparison of recent representative quantitative research on supply chain management.

References	CLSC	Energy-efficient	Inventory forecast	Recycle	Remanufacture	Pollutant evaluation	Application
(Wang et al. 2022)		√					Dysprosium
(Wang et al. 2014)	√	√					Steel
(Liu et al. 2020)	√		√		√	√	Waste paper
(Tian et al. 2022)		√	√				Aluminium
(Zhang et al. 2018)		√	√				Steel
(Liu et al. 2020)	√		√	√	√		Vehicle
(Sato et al. 2019)	√	√		√			Vehicle
(Dong et al. 2022)	√	√	√	√			Copper
(Keivanpour and Ait Kadi 2017)		√		√			Aircraft
(Mayanti and Helo 2022)	√	√		√			Plastic
This paper	√	√	√	√	√	√	HDMPs

References in Table 1 are the recent relevant studies to our work, and the last row shows the characteristics of our study. In general, previous studies are inadequate to construct a comprehensive model that combines the macro forecast model with the micro material flow of the CLSC framework and the exhaustive potential evaluation of energy-efficient and environmental benefit, as well as the lack of specific research on HDMPs. This paper calculates the energy consumption and pollutant emissions through the material flow of the whole CLSC for HDMPs and evaluates the energy conservation and pollutant abatement of recycling and remanufacturing based on LCA. This study innovatively combines macroprediction with microquantitative research and provides a new approach to the quantitative empirical method of recycling and remanufacturing.

3. Methodology

In this section, we introduce specific research methods and data sources. A brief research approach diagram is shown in Figure 1.

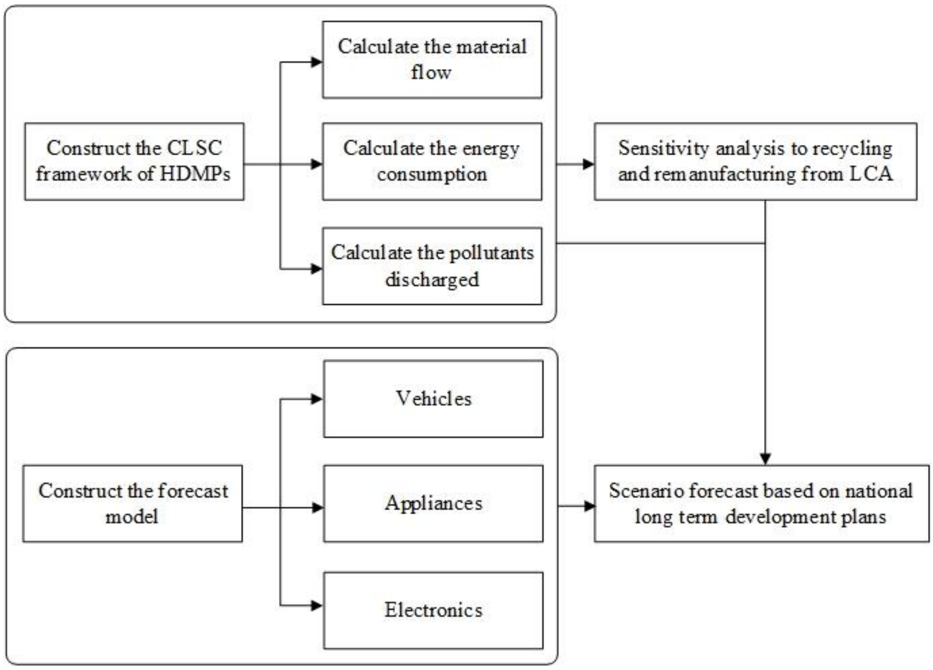

Figure 1 Caption: Diagram flow of research approach.

Figure 1 Alt Text: An overall structure of the research approach includes building the CLSC framework, building the forecast mode, sensitivity analysis, and scenario forecasting.

3.1. Modelling future sales and scrap volume of HDMPs

It is well recognized that disposable income and price are two primary driving forces for the growth of the ownership of HDMPs, such as cars, home appliances, and electronics; that is, residents with higher income are more likely to purchase them. Due to the relatively high price of cars, the difference in household income shows a stronger significant effect on car purchases than on the purchase of other durable products. As early as decades ago, De Wolff (1938) proposed that the relationship between income and population (in percentage) can be described by a log-normal distribution function, as shown in Figure 2.

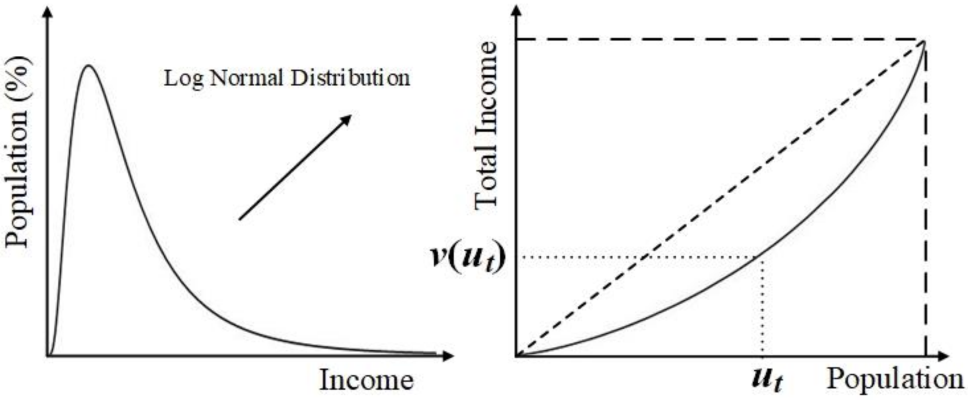

Figure 2 Caption: Income distribution function and Lorenz curve.

Figure 2 Alt Text: The relationship between income and population is presented in the form of a log normal distribution function, and the relationship between cumulative income and population is depicted by a Lorentz curve, which can be used to calculate the Gini coefficient.

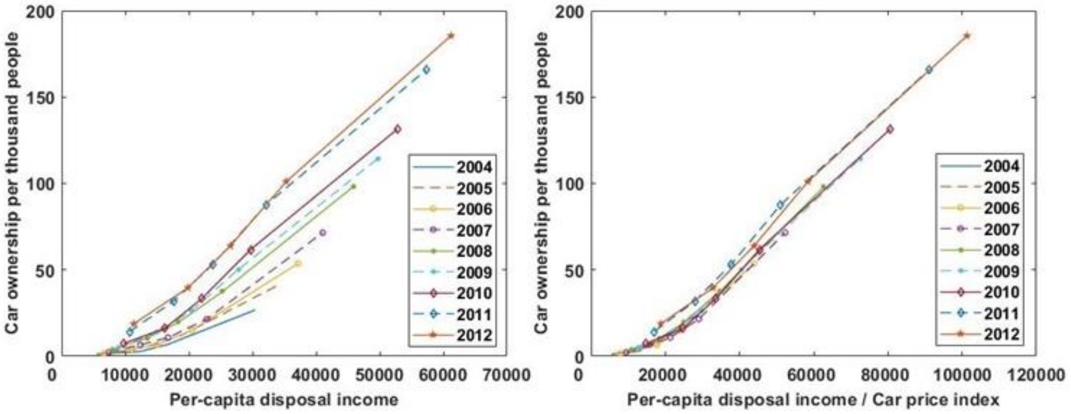

Figure 3 Caption: The linear relationship of private car ownership, income, and price index.

Figure 3 Alt Text: The data of three indicators are derived from (DUSENBSC 2021; NBSC 2022).

Furthermore, the cumulative function of the income distribution function constitutes the Lorenz curve, which can generate the Gini coefficient to estimate the inequality of different income residents. NBSC (2022) surveyed approximately 66,000 families from 2004 to 2012. Households were divided into eight groups according to different incomes in this time period and counted the ownership of durable goods, such as private cars and refrigerators, under different groups. However, the sampling survey of different income groups has been cancelled since 2013. The relationship between residents' income and car ownership is shown in Figure 3. Not surprisingly, car ownership will increase with the increase in residents' income. However, there are different degrees of vertical displacement in the curve between adjacent years, which is caused by the price index. Referring to the historical data of developed countries, car prices will decline with the development of technologies. In other words, the rise in residents' income and the decline in car prices have jointly driven the increase in total ownership. Figure 3 shows that the interval of different years is significantly decreased after taking car prices into account. Therefore, we can take per-capita disposal income over the price index (ratio of price in year t compared to the base year) as residents' purchasing ability for durable products.

The total inventory of HDMPs generally shows a trend of increasing continuously until it reaches saturation and then remains stable. The ownership of cars maintains an S-shaped growth that can be described by three growth functions (Huo et al. 2007), while the ownership of home appliances and electronics is not as significantly affected by income differences as cars, so a simplified saturation logarithmic function can generally be used to forecast future saturation level (Zhang et al. 2018), as shown in Figure 4. Therefore, we classify the ten different HDMPs into two research series, using the growth function and simplified saturation logarithmic function as ownership fitting and prediction tools for automobiles and other HDMPs, respectively.

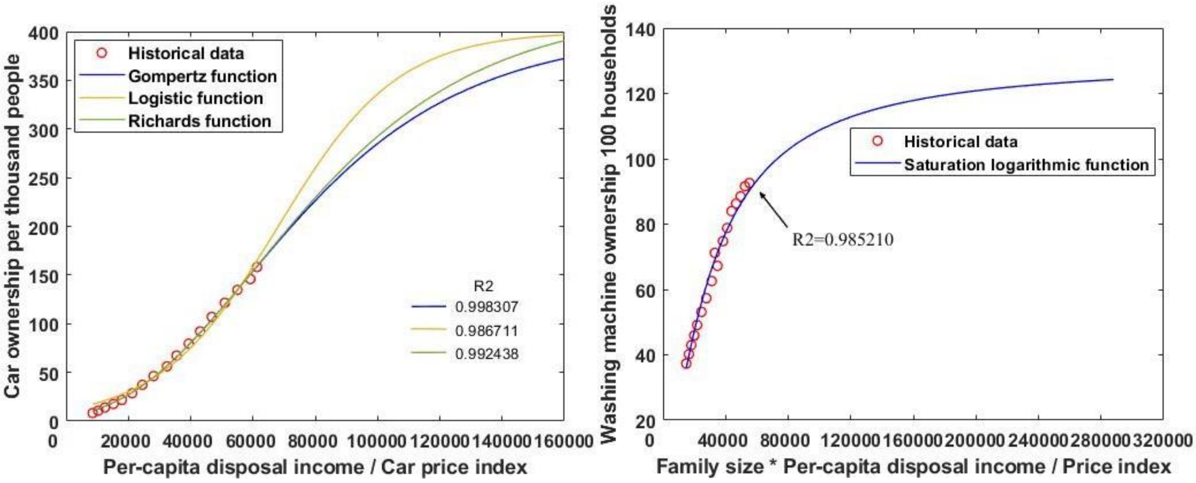

Figure 4 Caption: Fitting results of the ownership for HDMPs.

Figure 4 Alt Text: Referring to (Huo and Wang 2012; Zhang et al. 2018), the fitting results of three growth functions and saturation logarithmic function show the high goodness of fit for historical data.

The Gompertz function modified logistic function and Richards function are commonly used to describe the S-shaped curve of vehicle ownership. We adopt the Gompertz function and income distribution function to predict future car ownership because the Gompertz function has superior goodness of fit for the past real data, which is higher than the other two functions (see Figure 4). Similarly, the ownership of other durable products is also influenced by price and income differences. Due to the relatively low price and high utilization rates of home appliances and electronics, the imbalance in ownership of appliances and electronics caused by income differences is not as significant as private cars. Therefore, we adopt the simplified saturation logarithmic function (Zhang et al. 2018) to estimate the inventory of appliances and electronics, which can be calculated using Eq. (1). However, although the Gompertz function can make a fuzzy prediction of future car ownership (Meyer et al. 2012), we refer to a more accurate calculation method that combines the Gini coefficient, population and purchase behaviours (Huo and Wang 2012), shown as Eq. (2).

$$O_{i,t} = a + b * \text{In}(r_t x / \sigma_{i,t}) \tag{1}$$

$$O_{v,t} = POP_t \int_{x=0}^{\infty} [f(x)_t s(x/\sigma_{v,t}, y_t)]\, dx \tag{2}$$

where $O_{v,t}$ and $O_{i,t}$ refer to the total ownership of private cars and other durable products i in year t, x refers to the per-capita disposal income, POP_t is the total population in year t, $f(x)_t$ is the income distribution function for year t, $\sigma_{v,t}$ represents the car price index in year t, which is compared with the base year, $s(x/\sigma_{v,t}, y_t)$ is the function of car ownership versus per-capita disposal income and car price index, r_t refers to the family size in year t, and $\sigma_{i,t}$ is the price index of durable product i in year t. The detailed methods for obtaining the key functions and parameters can be found in Appendix 2.1.

People purchase new cars primarily for two main reasons: to own one or more when their income rises (new-growth purchase) or to replace old and end-of-life cars they already own (replacement purchase) (Huo and Wang 2012). The number of new-growth purchases for products can be seen as the accumulation of differential new purchases as the mean per-capita disposal income increases from $\bar{x}_{t-1}$ to $\bar{x}_t$, and the others motivated by replacement purchases can be calculated through the scrap volume of products sold before year t, as shown below.

$$S_{v,t}^{N} = POP_t \int_{\bar{x}_{t-1}}^{\bar{x}_t} \int_{x}^{\infty} [f'(x)_t s(x/\sigma_{v,t}, y_t)]\, dxdy \tag{3}$$

$$S_{v,t}^{R} = \sum_{l=1}^{l_{v,m}} S_{v,t-l}^{N} d_{v,l} \tag{4}$$

$$T_{v,t}^{out} = \sum_{l=1}^{l_{v,m}} (S_{v,t-l}^{N} + S_{v,t-l}^{R}) d_{v,l} \tag{5}$$

where $S_{v,t}^{N}$ and $S_{v,t}^{R}$ represent the sales of private cars in year t motivated by first and second purchase reasons, respectively, $T_{v,t}^{out}$ is the theoretical scrap volume of cars in year t, $d_{v,l}$ is the deterioration rate of cars for using l years, which follows a Weibull distribution, and $l_{v,m}$ is the average lifetime of cars. Weibull distribution has been widely used in research on forecasting product life, and the average lifetime can better reflect the depreciation and scrap situation. After forecasting future inventory changes in HDMPs, a dynamic material flow model can be used to predict the scrap volume of HDMPs in the future. In general, the total scrap volume and new sales of products can be calculated by using Eq. (6) and Eq. (7) (Liu et al. 2020). The detailed description for obtaining $d_{v,l}$ and $d_{i,l}$ can be found in Appendix 2.2.

$$T_{i,t}^{out} = \sum_{i=1}^{l_{i,m}} T_{i,t-l}^{in} * d_{i,l} \tag{6}$$

$$\Delta S_{i,t} = T_{i,t}^{in} - T_{i,t}^{out} \tag{7}$$

where $T_{i,t}^{out}$ refers to the outflow (that is, theoretical scrap volume) of household durable appliances and electronics i in year t, $T_{i,t}^{in}$ refers to the inflow (that is, new sales volume) of household durable appliances and electronics i in year t, and $\Delta S_{i,t}$ represents the total inventory change of product i in year t, which can be obtained by the previous forecasting model.

3.2. MFA framework

Material flow analysis (MFA) identifies the input and output of materials in a fixed time and space, which can cover material flow, energy flow, etc. In this section, all stocks and flows in the MFA framework can be categorized into 5 stages and 5 flows (Wang et al. 2022), as shown in Figure 5. The 5 stages refer to the links in the production processes: (1) Stage 1: Mining and processing of ores; (2) Stage 2: Smelting and refining; (3) Stage 3: Manufacturing; (4) Stage 4: Using; (5) Stage 5: Waste management. The 5 flows represent the trend in the whole industry: (1) Import & Export flow: the import and export of commodities; (2) Feed-in flow: the inflow to each life cycle stage from its former one (based on the mass balance principle); (3) Loss flow: residue, production losses, nonrecycled wastes, etc.; (4) Recycling flow: the recycling of end-of-life products; (5) Remanufacturing flow: recycled scrap products with remanufacturing qualifications will be remanufactured. Considering the availability and consistency of HDMP ownership data for rural residents and urban residents from 2004-2020, we selected ten kinds of HDMPs in three categories as the research object of this paper. The detailed quantification of all flows can be found in Appendix Table A2.

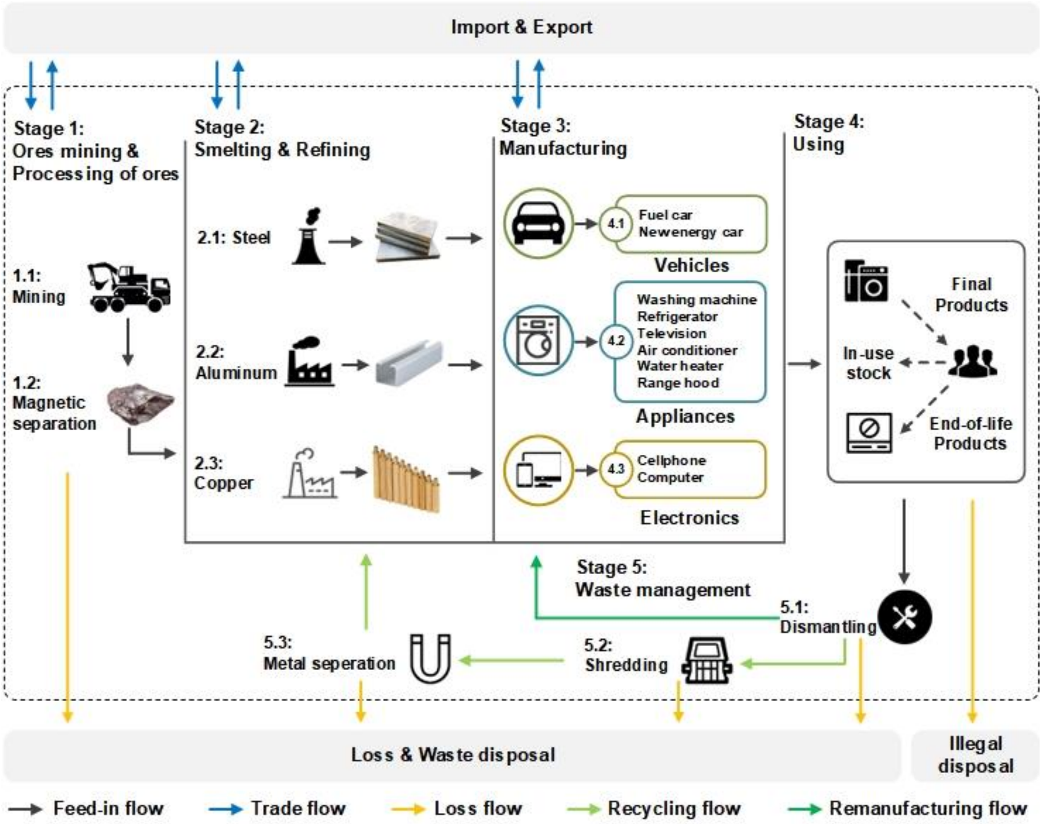

Figure 5 Caption: Material flow framework of HDMPs in China.

Figure 5 Alt Text: The MFA framework of HDMPs includes five stages and flows, which construct the CLSC structure of the HDMP industry for further calculation and analysis.

3.3. Energy consumption and intensity

To calculate the energy consumption and energy-efficient potential of the whole industrial system for the HDMP industry, an energy consumption and intensity evaluation model is established to estimate the energy consumption based on metal material flow in the whole system. This energy efficiency indicator is widely used for evaluating the energy efficiency of each process and the entire industry system (Siitonen et al. 2010), as shown below.

$$EC_t = EMP_t + EPM_t + EREC_t + ERMF_t + ERMT_t \tag{8}$$

$$EI_{j,t} = (EMP_{j,t} + EPM_{j,t} + EREC_{j,t} + ERMF_{j,t} + ERMT_{j,t})/MD_{j,t} \tag{9}$$

where EC_t represents the total energy consumption of the whole industrial system in year t; EMP_t, EPM_t, $EREC_t$, $ERMF_t$, and $ERMT_t$ represent the energy consumption of metal production, end-product manufacturing, the recycling stage, spare parts remanufacturing, and scrap metal remelting, respectively. $EI_{j,t}$ refers to the energy intensity for producing metal j in year t; $MD_{j,t}$ represents the total demand for metal j in year t.

3.4. Life cycle assessment

As an analysis tool, LCA is widely used to quantify the various resource consumption, emissions, energy use, and discharged pollutants derived from the processing of raw materials to the final product (Wang et al. 2018). Compared to other assessment tools or methods for environmental or energy accounting, the unique advantage of LCA lies in containing the entire life cycle of the product from raw material production to scrap disposal, rather than the only individual manufacturing process for the end-products (Deutz and Bardow 2021).

In this research, the life cycle of HDMPs and three main metal material components were assessed, and the energy consumption and pollutant emissions in the corresponding life cycle closed-loop supply chain were analysed based on the research framework of LCA. We also evaluate the benefits of energy efficiency and pollutant abatement for recycling and remanufacturing compared with the same amount of metal materials in primary production stages. Moreover, we set up four scenarios according to national long-term development plans to estimate the total energy-efficient and environmental potential when the recycling rate, remanufacturing rate, and average energy consumption of every stage reach the international advanced level.

3.5. Data collection and basic assumptions

The historical durable product ownership data were collected from NBSC (2022). Socioeconomic indicators such as per capita disposable income, population, urbanization rate, and households that need to be used in macro forecasts are derived from previous research and official data (see Appendix Tables A3 and A4). The weights and metal material ratios of the ten products selected for this paper are obtained from previous research (see Appendix Table A5). The material flows are collected in previous studies (see Appendix Table A2), and the energy consumption and pollutant emissions for each process are derived from MEEC (2021) and MIITC (2014) (see Appendix Table A6). To improve reliability and credibility, we adopt two-level principles to collect and process the original data. First, we mainly rely on the data released by the national official institutions. Second, if the official data are lacking, we will collect and sort out the required data from relevant authoritative literature. Hence, the data collated in this paper have relatively strong reliability.

The basic assumptions required by the model are listed below.

· Changes in energy structures and advances in production technologies may affect energy consumption and the input–output ratio for production. However, the change processes are relatively slow and uncertain, so we assume that the energy structures and input–output flow of materials in manufacturing processes remain unchanged.

· The production loss of end products is affected by different enterprises' technological levels and product types, so it is difficult to evaluate the loss in the production process of the end products, and the main loss is concentrated in the mining and smelting process of the metals. Referring to Liu et al. (2020), we assume that there is no loss of metals in the end-product manufacturing process.

· The different energy types, such as electricity and diesel, are converted to standard coal equivalents according to SAMRC (2021).

· This paper only studies the future domestic sales demand and scrap volume of HDMPs.

· Various processes, accidents, and technological breakthroughs may cause more material and energy loss or savings, and it is almost impossible to take all factors into account. We assume that consumer demand preferences, market environment, and other external factors that may influence the results remain stable.

· For the sake of uniformity, this paper uses 2020 as the base year because 2020 is the latest year for some yearbooks and officially released data within the model time of this study.

4. Results analysis

4.1. Material flow, energy consumption, and pollutant emissions in 2020

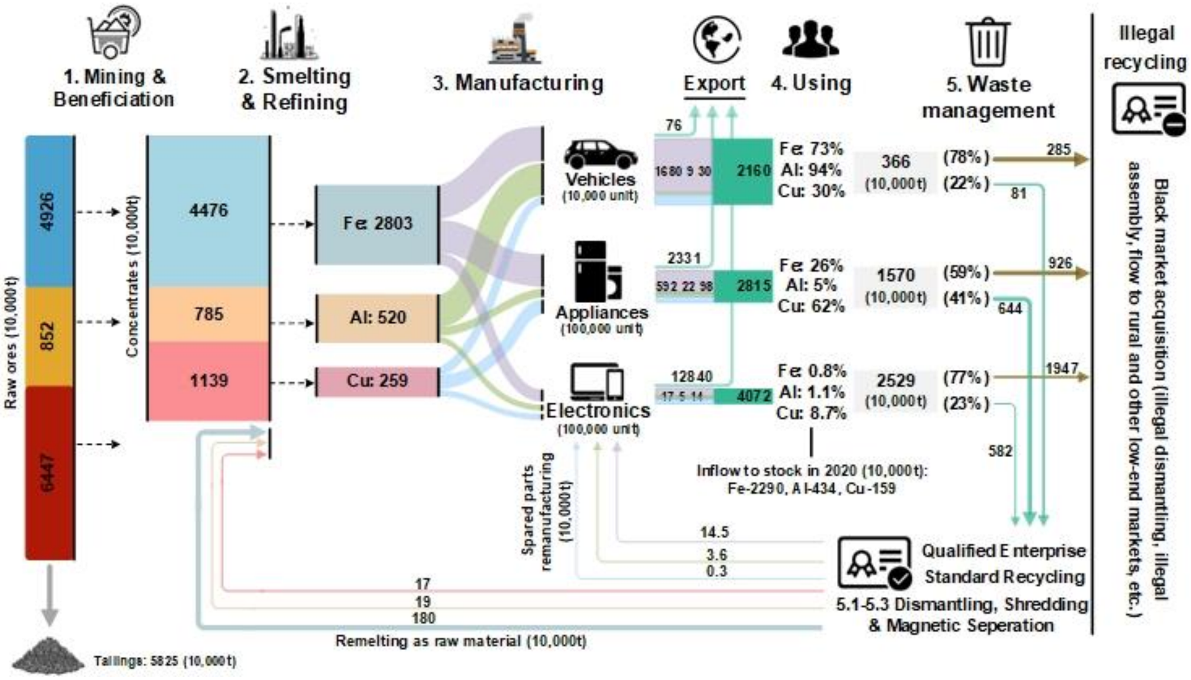

Figure 6 Caption: The material flow of HDMPs in 2020.

Figure 6 Alt Text: The calculation results of material flows of three metals for five stages, while the scrapped HDMPs flowing into illegal enterprises are not included in the CLSC framework.

The material flows of the HDMP industry in 2020 are shown in Figure 6. The extraction rate of copper (Cu) concentrates is significantly lower than that of iron (Fe) and aluminium (Al) concentrates due to the generally low grade of Cu ores in nature. As a result, a large number of tailings are left behind during the Cu concentrate beneficiation stage and need to be decontaminated. Although the sales volume of cellphones and computers is the highest, the metal demand for electronics is relatively low compared with that of the other two categories due to the low weight and content of metals for each electronic device. Among the three types of HDMPs, the export volume of electronics is greater than domestic sales, the export volume of appliances is slightly lower than domestic sales, and the export volume of vehicles is the lowest. Export volume can reflect the development level of the manufacturing industry to a certain extent, and China's automotive industry manufacturing may still have a technology gap with developed countries.

The recycling rates of the three categories are approximately 22%, 41%, and 23%, respectively, which are much lower than those of 65-85% (ELV) and 75% (WEEE) in developed countries (Dong et al. 2022). Most of them flowed into the black market and unqualified enterprises for illegal dismantling and assembling. Then, they will be sold as second-hand goods to low-end markets such as rural or remote areas, which makes them very difficult to recycle. After entering a qualified recycling channel, the scrap products are dismantled into various components, of which approximately 23% for ELV and 10% for WEEE can be remanufactured. Due to the lack of detailed data on spare parts remanufacturing, we use universal remanufactured parts to calculate the material flow and energy consumption. In general, the remanufacturing process can save 60% of energy and 70% of metal material in China (Liu et al. 2020; Xu 2010). The rest of the spare parts that are not capable of being remanufactured will be shredded, and the metal materials will be separated by magnetic separation and sold to metal smelting enterprises for remelting. Overall, the metals remelted and remanufactured accounted for less than 6% of the total demand in 2020. The recycling rate and utilization rate of scrap metals are relatively low.

In 2020, China’s HDMP industry consumed approximately 27.3 million tce, which accounted for 0.548% of the total energy consumption. Most of the energy consumption was concentrated in the production of metals, and the manufacturing of end-products accounted for approximately 13.4%, as shown in Table 2. Due to the low energy consumption of recycled metals and the low recovery rate, the recycling industry only accounted for approximately 1.2% of the total. The energy consumptions for the original metal production of Fe, Al, and copper are approximately 552 kgce/t, 2367 kgce/t, and 880 kgce/t, respectively, and the unit energy consumption of Al is the highest. The core process of Al production is electrolysis, which consumes a large amount of energy. The copper refining process also requires electrolysis, but the energy consumption is much lower than that of Al. In addition, the average energy consumption of the three metals decreased to approximately 523 kgce/t, 2276 kgce/t, and 765 kgce/t after integrating the recycled metals into the whole system from the perspective of the CLSC and LCA. Therefore, recycled metals can save much energy compared to the original production process.

The results show that pollutant emissions from metal primary production processes are much higher than those from end-product manufacturing and recycling processes (see Table 2). Due to the low recycling and remanufacturing rate, the energy consumption of the waste management stage is relatively low. The average unit energy consumption of the recycling and remanufacturing processes is approximately 132 kgce and 70.7 kgce, respectively, which are far less than the energy consumption of the metal primary production stage. Therefore, further improving the recycling and remanufacturing rate is the most efficient approach and the priority of China’s long-term development plan for energy conservation and pollutant abatement. The main pollutants discharged in Fe production are industrial wastewater, petroleum, volatile phenol, cyanide, fume dust, industrial dust, and nitrogen oxides. Since the core process of primary Al production is the electrolysis process, more chemical oxygen demand, industrial waste gas, and sulfur dioxide will be discharged. However, Cu ores are generally low in copper grade and are usually doped with a variety of heavy metal pollutants. Therefore, the typical pollutant in the primary production process of Cu is heavy metals. In Section 4.3, we estimate the abatement in pollutant emissions from recycled metals compared to primary production.

Table 2 Energy consumption and pollutants discharged of HDMPs in 2020

Stage		EC	UEC	IWW	COD	AN	PP	VP	CN	HMPs	IWG	FD	ID	SO_2	NOx	FL	LD
Unit		(10^4 t)	(kg)	(10^4 t)	(10 t)	(t)	(10 t)	(t)	(t)	(t)	(10^9 m^3)	(10 t)	(10 t)	(10 t)	(10 t)	(kg)	(kg)
Products production	Vehicles	285.8	132.3	7258	900		30.8				86.93						
	Appliances	75.5	2.68	1466	182	85.7	5.56										46.1
	Electronics	3.3	0.81								2.08						50.5
	Total	364.6		8724	1082	85.7	36.4				89.01						96.5
Recycling	Dismantling, etc.	2.9	12.4	172							0.056						
	Remanufacturing	1.3	70.7	827	25.3		2.97				3.04	12.2	53.3	43.7			
	Remelting	28.3	132	44	1.3		0.16				0.17	0.75	0.02	1.9			
	Total	32.5		1043	26.6		3.13				3.21	12.9	53.3	45.6			
Metals production	Fe	1171.6	552	74280	1997		163	280	88		223.7	1591	2305	767	1913		
	Al	1043.2	2367	19717	3859		3.16	1.9		2.24	543.8	178	1005	2682		153	
	Cu	119.0	880	11346	718					17.5	7.4	3.4		264.5			
	Total	2333.8		105343	6573		166	282	88	19.8	774.9	1772	3310	3713	1913	153	
Total		2730.8		115110	7682	85.7	206	282	88	19.8	867.12	1785	3364	3758	1913	153	50.5

Table 2 Alt Text. Notations: EC (energy consumption), UEC (Unit energy consumption; kg/unit for products production, kg/t for recycling, kg/t for metals production), IWW (industrial waste water), COD (chemical oxygen demand), AN (ammonia nitrogen), PP (petroleum pollutants), VP (volatile phenol), CN (cyanide), HMPs (heavy metal pollutants), IWG (industrial waste gas), FD (fume dust), ID (industrial dust), SO (sulfur dioxide), NO (nitrogen oxides), FL (fluoride), LD (lead dust).

4.2. Forecasting future demand and scrap volume

Based on the dynamic material flow and forecasting model, the future demand for ten typical HDMPs in China's domestic market is shown in Figure 7 (real data until 2020). After experiencing the outbreak of COVID-19 in 2020, the increase in income and decrease in the price index will further drive the sales of HDMPs to gradually increase. According to the United Nations, the Chinese population showed negative growth during the first two quarters in 2022 (United Nations 2022). However, the increase in disposable income and continuous decrease in average household size and price index mean that more distinct households will form and per capita purchasing power will increase in the future. These factors will further improve the sales of HDMPs until they reach a peak in approximately 2028. Subsequently, the negative effect of decreased demand will be further significantly caused by depopulation, and then the ownership of HDMPs will reach saturation. Residents' purchase behaviour will change from newly added purchases to waste replacement purchases. Domestic demand will decrease and eventually remain stable in a certain range. Moreover, the sales of electric vehicles will occupy a major market share by 2035 (SCC 2020). The market demand for fuel vehicles will continue to decline, while electric vehicles will rise from 2009 to 2035 and then fall gradually. The volumes of WEEE and ELV will reach their peaks in approximately 2036 and 2040, respectively.

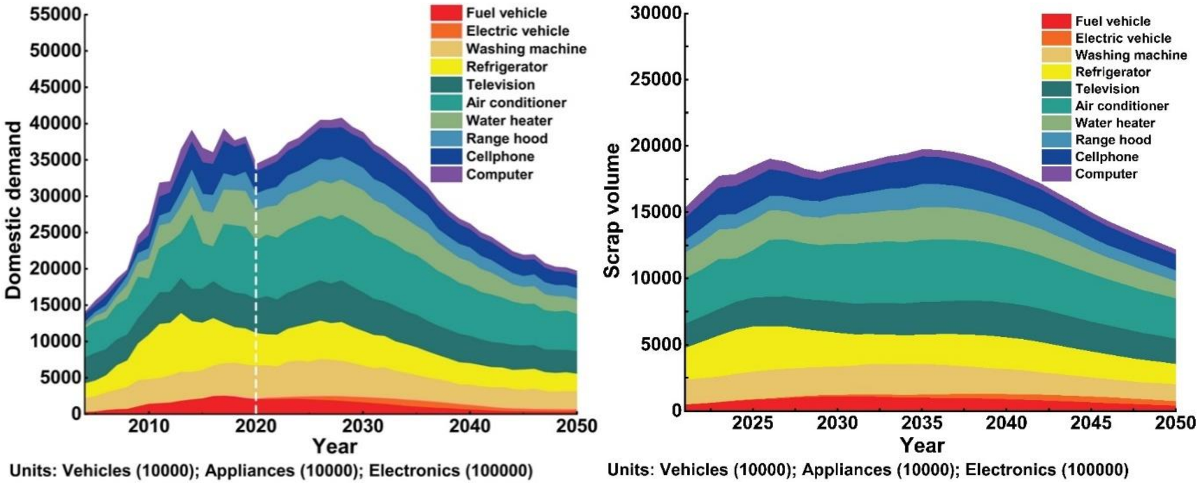

Figure 7 Caption: Forecasting results of demand and scrap volume for HDMPs.

Figure 7 Alt Text: The white line represents the base year of the research, with actual data for years before 2020 and predicted results after 2020.

4.3. Energy and environmental benefits from the LCA perspective

This section calculates the energy consumption and pollutant emissions of the primary production, recycling, and remanufacturing of three metals. Primary production represents the forwards flow process from ore mining to metal smelting. Recycling and remanufacturing represent the two processes of low-efficiency regeneration and high-efficiency regeneration of end-of-life products. Remelting Fe, Al, and Cu through scrap metals can save approximately 72%, 94%, and 82% of energy consumption compared to primary production, while remanufacturing can save only 32%, 43%, and 28% of energy consumption. The energy consumption of Fe, Al, and Cu in the primary production process accounts for 123%, 112%, and 197% of the international advanced level, respectively. Cu primary production has the most significant energy-efficient potential. Overall, the energy efficiency and environmental benefits of metal recycling and remanufacturing are significantly better than those of primary production. Whether end-of-life HDMPs can be efficiently recycled determines the total amount of metals remelting and components remanufactured. See Appendix Table A7 for detailed calculation results. To further demonstrate the energy-saving and pollutant abatement benefits brought by recycling and remanufacturing, we carried out a relevant sensitivity analysis, as shown in Table 3. Recycling one unit of end-of-life vehicle, scrap appliance, and scrap electronics can save approximately 618.5 kgce, 11.3 kgce, and 1.1 kgce compared to the metals' primary production process; in addition, each 1% increase in the remanufacturing ratio for end-of-life HDMPs can also save approximately 1.233 kgce, 0.038 kgce, and 0.003 kgce, respectively. At the same time, recycling and remanufacturing can significantly reduce pollutant emissions. For example, each unit of end-of-life vehicle recycled can reduce 28.4 tons of industrial wastewater, 23165 m^3 of industrial waste gas, 1.26 kg of chemical oxygen demand, 1.11 kg of sulfur dioxide, etc., which generates significant environmental benefits.

Table 3 Sensitivity analysis of the recycling and remanufacturing process

Saving Items	Unit	Recycle one unit of each product			Unit	Remanufacturing rate increased by 1%		
		Vehicles	Appliances	Electronics		Vehicles	Appliances	Electronics
EC	kgce	618.5	11.3	1.09	kg	1.233	0.038	0.003
IWW	t	28.4	0.774	0.07	kg	76.77	2.142	0.19
COD	kg	1.26	0.034	0.004	g	0.561	0.053	0.011
PBP	g	42	0.97	0.04	mg	82	2.91	0.167
VP	g	9.9	0.23	0.009	mg	13.07	0.31	0.013
CN	g	3.1	0.07	0.003	mg	4.066	0.097	0.004
HMP	g	0.716	0.039	0.007	mg	2.1	0.12	0.022
IWG	m^3	23165	308	31.4	m^3	46.44	0.77	0.08
FD	g	546	12.2	0.4	g	1.283	0.027	0.002
ID	g	874	15.5	0.96	g	3.317	0.071	0.003
SO_2	g	1106	13.9	1.58	g	2.673	0.074	0.012
NO_x	g	666	15.6	0.62	g	0.88	0.021	0.001
FL	g	47	0.41	0.07	mg	80.22	0.72	0.123

4.4. Scenario prediction

There are two time nodes of China's future medium-term and long-term development plans. First, China will basically realize socialist modernization, build a modern economic system and form a green production and lifestyle, and the per capita GDP will reach that of moderately developed countries by 2035. Second, China will fully realize socialist modernization and become a developed country by 2050. Under the guidance of national development plans, we construct four scenarios to simulate energy consumption in the future: 1) Business as usual (BAU): The energy consumption level (ECL) of metal primary production, recycling and remanufacturing rate (RRR) of end-of-life HDMPs will reach the level of developed countries by 2050; 2) strengthen energy efficiency (SES): ECL→2035, RRR→2050; 3) strengthen recycling & remanufacturing (SRR): ECL→2050, RRR→2035; and 4) strengthen all policies (SAP): ECL→2035, RRR→2035. International advanced energy consumption for metal production in developed countries, the recycling rate, and the remanufacturing rate of end-of-life products are shown in Appendix Tables A2 and A6.

It can be seen from Figure 8 that the overall energy consumption of the HDMP industry will reach a peak in 2025. The total energy consumption in 2020-2050 under the four scenarios is approximately 585.2 Mtce, 568.7 Mtce, 548.9 Mtce, and 534.7 Mtce, respectively. If the energy consumption of metal production, the recycling rate of end-of-life products, and the remanufacturing rate of spare parts can reach the level of developed countries by 2035, the whole industry will save approximately 50.5 Mtce of energy consumption compared to the BAU scenario (see Table 4).

Table 4 Energy consumption and energy efficiency under four scenarios

Type		BAU	SES	SRR	SAP
Total energy consumption	Mtce	585.16	568.69	548.85	534.70
Total energy savings	Mtce	-	16.47	36.31	50.46

The energy intensity of Fe, Al, and Cu in the production process will decrease from 15.3 GJ/t, 66.9 GJ/t, and 23.0 GJ/t to 7.4 GJ/t, 23.6 GJ/t, and 15.0 GJ/t. Therefore, China's recycled metals have significant energy-efficient and pollutant abatement potential. Further improvements in the recycling rate and energy-efficient technologies in the metal production process are the key areas for development and progress in the future.

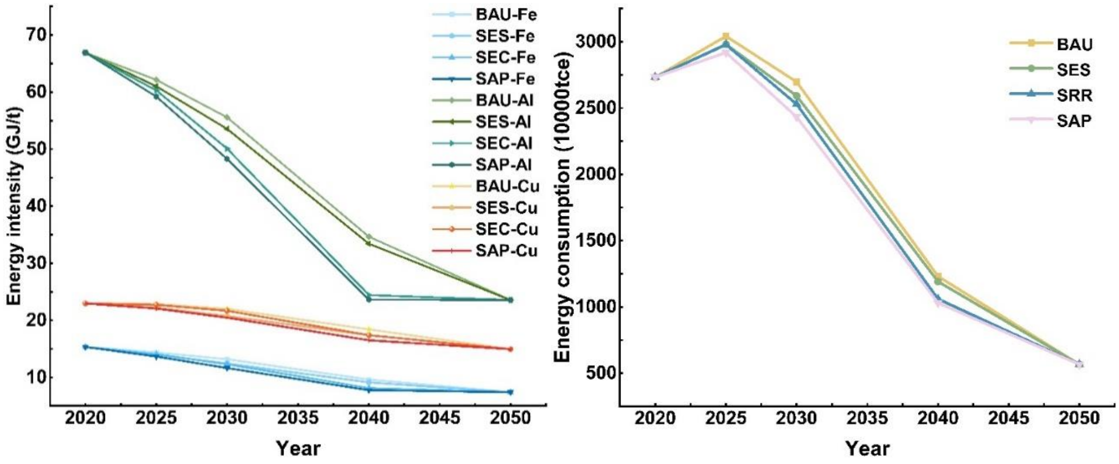

Figure 8 Caption: Energy intensity of metals and energy consumption under four scenarios.

Figure 8 Alt Text: The energy intensity of Al, Cu, and Fe shows a decreasing order, among which the production processes of Al have the highest energy-efficient potential.

5. Discussion

In previous studies, Tian et al. (2022) and Zhang et al. (2018) forecasted the future ownership of cars, home appliances, and electronics through two socioeconomic indicators: the growth of GDP per capita and the change in the future population. Based on forecast results, they evaluated the comprehensive assessment of energy conservation and carbon mitigation in the future Fe and Al supply chain. Our research extends their model and selects four socioeconomic indicators as the independent variables to predict future inventory: per capita disposable income, which can better represent residents' purchasing power than GDP per capita; average household population, which can further metaphorize the household demand for HDMPs; total population; and product price, which would directly influence sales demand. Therefore, our calculation results are more authentic and reliable. Huo and Wang (2012) forecasted that car ownership will increase to 480 per thousand people in 2050. We further extend the historical data and make a prediction on their basis and show that private car ownership in China will reach approximately 446 per thousand people. Moreover, Liu et al. (2020) adopted a simplified growth function and dynamic material flow analysis to forecast the future amount of end-of-life vehicles that will reach a peak in approximately 2038, while our result shows a similar trend that will reach a peak in 2038-2039. However, we use a comprehensive prediction model that includes the Gini coefficient and two types of purchase decisions, so although the trend is similar, our concrete calculation results of scrap volume are more reliable. The domestic sales of HDMPs will reach a peak in approximately 2028, and the scrap volume will reach a peak in approximately 2036, which is a similar trend to the research of Zeng et al. (2020). Electric vehicles will become the main type sold in the domestic market by 2035, which refers to the medium- and long-term development plan (SCC 2020). The detailed forecasting results of the ownership of HDMPs can be found in Appendix Table A4.

In the long term, if China's metal production energy consumption continues, the recycling and remanufacturing rate can reach an internationally advanced level by 2035. Mtce compared to low-speed development by 2050, which is equivalent to almost two years of energy consumption for China's HDMP industry in 2020, and the energy intensity of Fe, Al, and Cu will decrease from 15.3 GJ/t, 66.9 GJ/t, and 23.0 GJ/t to 7.4 GJ/t, 23.6 GJ/t, and 15.0 GJ/t, respectively.

Table 5 Energy intensity of metal production compared with previous studies

Metals	2010	2015	2020	2030	2040	2050	Sources
Fe (GJ/t)		19.9	18.61	15.94	14.13	12.22	(Ma et al. 2016)
		13.78	13.17	12.2		9.64	(Wang et al. 2014)
		16.99	15.94	14.47	12.84	11.28	(Zhang et al. 2018)
			15.34	13.19	9.62	7.41	This study (BAU)
Al (GJ/t)	78.9	74.2					(Springer 2018)
		63.0					(Elshkaki 2019)
			40.16	34.95	30.0	27.15	(Tian et al. 2022)
			66.92	55.57	34.65	23.57	This study (BAU)
Copper (GJ/t)	42.02						(Zeng et al. 2012)
	34.9						(Yanjia and Chandler 2010)
			22.97	22.01	18.40	14.95	This study (BAU)

Table 5 shows the energy intensity of metal production in other relevant studies. Previous studies have also calculated the energy consumption of the production of three metals, but most of them only focus on the primary production stage and lack comprehensive closed-loop evaluation considering the recycling stage. Thus, our research takes scrap metal regeneration into account, so if the recycling and remanufacturing rates reach the international advanced level in the future, the energy consumption of Fe production will decrease to 7.41 GJ/t. The energy intensity of Fe is calculated to be lower than in other literature because the private car has the highest unit weight and the highest Fe content of the ten HDMPs selected in this paper. Moreover, Tian et al. (2022) considered energy-efficient technologies when calculating the energy consumption of Al production, so their results are generally lower than ours. However, the promotion of energy-saving technologies brings much lower energy-saving efficiency than scrap metal recycling. Due to the lack of research on the calculation of energy intensity for copper production, the results of Springer (2018), Elshkaki (2019), Zeng et al. (2012), and Yanjia and Chandler (2010) are based on data from 2015 and previous years, so their forecast results can be used for reference only. The data we collected about the energy consumption and input–output ratio of the copper industry can be used as a reference for subsequent studies and can be used directly by existing studies.

6. Conclusions and managerial implications

6.1 Production restructuring and energy-efficient technology investment

The growth of per capita disposable income and small-scale households will make the development of HDMPs in China's domestic market be expected to have a dividend period of 6-10 years. However, with the saturation of ownership and the receding of the demographic dividend period, the purchase behaviour of residents will gradually transform from the first new purchase to the alternative purchase. Domestic demand for HDMPs will show a trend of rising first and then falling in the future. The end product manufacturers need to anticipate the export market share and domestic sales strategy and continuously adjust the production capacity for overall planning in advance. In addition, automobile manufacturers need to keep up with national development plans and increase investment and publicity in electric vehicle technology research and development, which can further increase market share.

Surprisingly, more than 85% of the total energy consumption is concentrated in upstream mining, washing, production, and processing of metal raw materials, while the manufacturing of end products accounts for only approximately 13.4% of the total. However, coal-based thermal power is dominant in generating heat and electricity in China. Therefore, the carbon emissions generated by the same amount of energy consumption may be higher than in other developed countries that rely on natural gas, nuclear energy, and clean energy as their main power generation resources. The trend of vehicle lightweighting may further drive domestic Al demand in the future. Surprisingly, the energy intensity of primary copper production is approximately twice the international advanced level. It is urgent to invest in more energy-efficient technologies for primary copper production. The energy intensity of primary Al production is the highest, while that of primary Fe production is the lowest, and they are both not far behind the international advanced level. Overall, there is no large space for energy efficiency in the primary production process of metals except for copper.

6.2 Increasing recycling and remanufacturing rates of scrap HDMPs

Incorporating the recycling process into the entire industry and calculating from the perspective of LCA, it was found that recycling one unit of end-of-life vehicle, scrap appliance, and scrap electronic can save approximately 618.5 kgce, 11.3 kgce, and 1.1 kgce compared to metals' primary production process, particularly in the abatement of a series of pollutants. The comprehensive unit energy intensity of Fe, Al, and copper can be further significantly decreased by more waste metal regeneration. However, the recycling rates for ELV and WEEE were only 29.9% and 22.4% in 2020, far below the level of developed countries. Meanwhile, the scrap peak of HDMPs will come after 14-17 years, so China's recycling industry has large potential to further improve recycling technologies and standardize the recycling process. It is necessary to increase the penalties for illegal recycling, standardize the recycling process, increase investment in technologies, and further improve the extended producer responsibility system and other policies as soon as possible if more scrap metal resources are wasted.

6.3 Constructing broader evaluation methods for energy-efficient supply chains

By constructing industrial closed-loop supply chains of HDMPs, this research quantifies the energy consumption in the life cycle of HDMPs. Obviously, material flow brings energy flow, capital flow, and information flow, which can be adopted as an effective method to evaluate the energy efficiency and energy resilience of the supply chain, while the core of the material flow evaluation framework is the input–output ratio of materials and the energy consumption per unit output. Although it is a large project that requires accurate data and has uncertain heterogeneity among different manufacturers, our paper shows that this project is valuable because it can help stakeholders precisely identify the energy efficiency and the improvement space of every link in the whole CLSC. This research combines microcalculation with macroforecast results to estimate the future energy conservation potential, which provides a new idea for empirical research on the CLSC in theory and offers valuable insights for policy-makers on how to implement energy-efficient measures effectively in reality.

Due to the lack of manufacturing data, we do not consider the loss in the manufacturing process of HDMPs. One future avenue is to collect manufacturing data to further enrich the material flow in the manufacturing stage. Furthermore, this research assumes that the energy structure is consistent, but the energy structure will change year by year. Thus, another future avenue is to evaluate the carbon emissions of HDMPs based on changes in energy structure. In addition, the construction of a forecasting model and material flow framework considering green product transformation is also an interesting direction.

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Data availability statement: All data are available upon request.

References:

Abbey, J.D., Meloy, M.G., Guide Jr, V.D.R., and Atalay, S. 2015. "Remanufactured Products in Closed-Loop Supply Chains for Consumer Goods." *Production and operations management* 24 (3): 488-503.

Alliance of Technology Innovation in Extending Producer Responsibility (ATIEPR). 2021. "White paper on WEEE recycling industry in China." https://www.weee-epr.com.

An, R., Yu, B., Li, R., and Wei, Y. 2018. "Potential of energy savings and CO2 emission reduction in China's iron and steel industry." *Applied Energy* 226: 862-880.

Automobile Dealers Association of China (ADAC). 2021. "China's auto market almanac." China Commercial Press, Beijing.

De Wolff, P. 1938. "The demand for passenger cars in the United States." *Econometrica* 6 (2): 113-129.

Department of Energy of National Bureau of Statistics of China (DENBSC). 2021. "China energy statistical yearbook." China Statistics Press, Beijing.

Department of Urban Society and Economic of National Bureau of Statistics of China (DUSENBSC). 2021. "China price statistical yearbook." China Statistics Press, Beijing.

Deutz, S., and Bardow, A. 2021. "Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption." *Nature Energy* 6 (2): 203-213.

Dong, D., Tukker, A., Steubing, B., van Oers, L., Rechberger, H., Alonso Aguilar-Hernandez, G., Li, H., and Van der Voet, E. 2022. "Assessing China's potential for reducing primary copper demand and associated environmental impacts in the context of energy transition and "Zero waste" policies." *Waste management* 144: 454-467.

Elshkaki, A. 2019. "Material-energy-water-carbon nexus in China's electricity generation system up to 2050." *Energy* 189: 116355.

Gorman, M.R., Dzombak, D.A., and Frischmann, C. 2022. "Potential global GHG emissions reduction from increased adoption of metals recycling." *Resources, conservation and recycling* 184: 106424.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., and Fischer-Kowalski, M. 2019. "Contributions of sociometabolic research to sustainability science." *Nature Sustainability* 2 (3): 173-184.

Hao, H., Qiao, Q., Liu, Z., and Zhao, F. 2017. "Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case." *Resources, conservation and recycling* 122: 114-125.

Heidrich, O., and Tiwary, A. 2013. "Environmental appraisal of green production systems: Challenges faced by small companies using life cycle assessment." *International journal of production research* 51 (19): 5884-5896.

Huo, H., Wang, M., Johnson, L., and He, D. 2007. "Projection of Chinese motor vehicle growth, oil demand, and CO2 emissions through 2050." *Transportation Research Record* 2038 (1): 67-77.

Huo, H., and Wang, M. 2012. "Modeling future vehicle sales and stock in China." *Energy Policy* 43: 17-29.

Ivanov, D. 2022. "Blackout and supply chains: Cross-structural ripple effect, performance, resilience and viability impact analysis," *Annals of operations research*. https://10.1007/s10479-022-04754-9.

Ivanov, D., Pavlov, A., Pavlov, D., and Sokolov, B. 2017. "Minimization of disruption-related return flows in the supply chain." *International journal of production economics* 183: 503-513.

Ivanov, D., and Dolgui, A. 2022. "The shortage economy and its implications for supply chain and operations management." *International journal of production research*. 60 (24): 7141-7154.

Jain, S., Lindskog, E., Andersson, J., and Johansson, B. 2013. "A hierarchical approach for evaluating energy trade-offs in supply chains." *International journal of production economics* 146 (2): 411-422.

Jiang, M., An, H., Gao, X., Liu, D., Jia, N., and Xi, X. 2020. "Consumption-based multi-objective optimization model for minimizing energy consumption: A case study of China." *Energy* 208: 118384.

Kamran, M., Raugei, M., and Hutchinson, A. 2021. "A dynamic material flow analysis of lithium-ion battery metals for electric vehicles and grid storage in the UK: Assessing the impact of shared mobility and end-of-life strategies." *Resource, Conservation and Recycling* 167: 105412.

Kazemi, N., Modak, N.M., and Govindan, K. 2019. "A review of reverse logistics and closed loop supply chain management studies published in IJPR: a bibliometric and content analysis." *International Journal of Production Research* 57 (15-16): 4937-4960.

Keivanpour, S., and Ait Kadi, D. 2017. "Modelling end of life phase of the complex products: the case of end of life aircraft." *International journal of production research* 55 (12): 3577-3595.

Keyvanshokooh, E., Ryan, S.M., and Kabir, E. 2016. "Hybrid robust and stochastic optimization for closed-loop supply chain network design using accelerated Benders decomposition." *European Journal of Operational Research* 249 (1): 76-92.

Kosai, S., Kishita, Y., and Yamasue, E. 2020. "Estimation of the metal flow of WEEE in Vietnam considering lifespan transition." *Resources, Conservation and Recycling* 154: 104621.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., and Haberl, H. 2017. "Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use." *Proceedings of the National Academy of Sciences of the United States of America* 114 (8): 1880-1885.

Krug, Z., Guillaume, R., and Battaïa, O. 2021. "Exploring the opportunities in establishing a closed-loop supply chain under uncertainty." *International journal of production research* 59 (5): 1606-1625.

Lawrence, B., Zhang, J.J., and Heineke, J. 2016. "A life-cycle perspective of professionalism in services." *Journal of operations management* 42-43 (1): 25-38.

Liu, M., Chen, X., Zhang, M., Lv, X., Wang, H., Chen, Z., Huang, X., Zhang, X., and Zhang, S. 2020. "End-of-life passenger vehicles recycling decision system in China based on dynamic material flow analysis and life cycle assessment." *Waste Management* 117: 81-92.

Liu, M., Tan, S., Zhang, M., He, G., Chen, Z., Fu, Z., and Luan, C. 2020. "Waste paper recycling decision system based on material flow analysis and life cycle assessment: A case study of waste paper recycling from China." *Journal of Environmental Management* 255: 109859.

Ma, D., Chen, W., Yin, X., and Wang, L. 2016. "Quantifying the co-benefits of decarbonisation in China's steel sector: An integrated assessment approach." *Applied energy* 162: 1225-1237.

Material Regeneration Association of China (MRAC). 2019. "China remanufacturing industry development report." China Machine Press, Beijing.

Matos, S., and Hall, J. 2007. "Integrating sustainable development in the supply chain: The case of life cycle assessment in oil and gas and agricultural biotechnology." *Journal of Operations Management* 25 (6): 1083-1102.

Mayanti, B., and Helo, P. 2022. "Closed-loop supply chain potential of agricultural plastic waste: Economic and environmental assessment of bale wrap waste recycling in Finland." *International journal of production economics* 244: 108347.

Mazhar, M.I., Kara, S., and Kaebernick, H. 2007. "Remaining life estimation of used components in consumer products: Life cycle data analysis by Weibull and artificial neural networks." *Journal of Operations Management* 25 (6): 1184-1193.

Meyer, I., Kaniovski, S., and Scheffran, J. 2012. "Scenarios for regional passenger car fleets and their CO2 emissions." *Energy policy* 41 (1): 66-74.

Mills, B., and Schleich, J. 2012. "Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of European countries." *Energy Policy* 49: 616-628.

Ministry of Ecology and Environment of China (MEEC). 2021. "Manual on methods and factors for accounting for production and discharge from statistical source surveys." https://www. mee.gov.cn.

Ministry of Industry and Information Technology of China (MIITC). 2014. "National guide to industrial energy efficiency." https://www. miit.gov.cn.

National Bureau of Statistics of China (NBSC). 2022. "China statistical yearbook." China Statistics Press, Beijing.

Quariguasi-Frota-Neto, J., and Bloemhof, J. 2012. "An Analysis of the Eco-Efficiency of Remanufactured Personal Computers and Mobile Phones." *Production and operations management* 21 (1): 101-114.

Sato, F.E.K., Furubayashi, T., and Nakata, T. 2019. "Application of energy and CO2 reduction assessments for end-of-life vehicles recycling in Japan." *Applied Energy* 237: 779-794.

Shafique, M., Rafiq, M., Azam, A., and Luo, X. 2022. "Material flow analysis for end-of-life lithium-ion batteries from battery electric vehicles in the USA and China." *Resources, conservation and recycling* 178: 106061.

Shankar, R., Bhattacharyya, S., and Choudhary, A. 2018. "A decision model for a strategic closed-loop supply chain to reclaim End-of-Life Vehicles." *International journal of production economics* 195: 273-286.

Shen, B., Cao, Y., and Xu, X. 2020. "Product line design and quality differentiation for green and non-green products in a supply chain." *International journal of production research* 58 (1): 148-164.

Shen, B., Xin, Y., Choi, T., and Zhang, K. 2022. "Integration strategies of luxury rental operations: is it wise to operate with the manufacturer or co-operate with the competitor?" *International journal of production research*. https://doi.org/10.1080/00207543.2022.2051091.

Shen, B., Zhu, C., Li, Q., and Wang, X. 2021. "Green technology adoption in textiles and apparel supply chains with environmental taxes." *International journal of production research* 59 (14): 4157-4174.

Siitonen, S., Tuomaala, M., Suominen, M., and Ahtila, P. 2010. "Implications of process energy efficiency improvements for primary energy consumption and CO2 emissions at the national level." *Applied Energy* 87: 2928-2937.

Springer, C. 2018. "Assessing energy intensity and retrofit opportunities for the aluminum industry: Lessons from Vietnam." *Resources, conservation and recycling* 131: 235-246.

State Administration for Market Regulation of China (SAMRC). 2021. "General rules for calculation of the comprehensive energy consumption." https://www.std.samr.gov.cn.

State Council of China (SCC). 2019. "Measures for the Administration of Recycling of Scrap Motor Vehicles." https://www.gov.cn.

State Council of China (SCC). 2020. "New energy vehicle industry development plan (2021-2035)." https://www.gov.cn.

Tian, S., Di, Y., Dai, M., Chen, W., and Zhang, Q. 2022. "Comprehensive assessment of energy conservation and CO2 emission reduction in future aluminum supply chain." *Applied Energy* 305: 117796.

United Nations. 2022. "World population prospects 2022." https:// www.un.org.

Wang, J., Wang, R., Zhu, Y., and Li, J. 2018. "Life cycle assessment and environmental cost accounting of coal-fired power generation in China." *Energy Policy* 115: 374-384.

Wang, P., Jiang, Z., Geng, X., Hao, S., and Zhang, X. 2014. "Quantification of Chinese steel cycle flow: Historical status and future options." *Resources, Conservation and Recycling* 87: 191-199.

Wang, Q., Chen, W., Wang, P., and Dai, T. 2022. "Illustrating the supply chain of dysprosium in China through material flow analysis." *Resources, Conservation and Recycling* 184: 106417.

Wang, X., Chan, H.K., and Li, D. 2015. "A case study of an integrated fuzzy methodology for green product development." *European journal of operational research* 241 (1): 212-223.

Williams, E. 2011. "Environmental effects of information and communications technologies." *Nature* 479 (7373): 354-358.

Xu, B. 2010. "Remanufacture engineering and its development in China." *China Surface Engineering* 23 (2): 1-6.

Xu, S., He, Z., and Long, R. 2014. "Factors that influence carbon emissions due to energy consumption in China: Decomposition analysis using LMDI." *Applied energy* 127: 182-193.

Yanjia, W., and Chandler, W. 2010. "The Chinese nonferrous metals industry--energy use and CO2 emissions." *Energy policy* 38 (11): 6475-6484.

Zeng, G., Yang, J., Song, X., and Lv, B. 2012. "Energy consumption and carbon emissions scenario analysis of pyrometallurgical copper based on LCA." *China Population, Resources and Environment* 22 (4): 46-50.

Zeng, X., Ali, S.H., Tian, J., and Li, J. 2020. "Mapping anthropogenic mineral generation in China and its implications for a circular economy." *Nature Communications* 11 (1): 1544.

Zhang, Q., Xu, J., Wang, Y., Hasanbeigi, A., Zhang, W., Lu, H., and Arens, M. 2018. "Comprehensive assessment of energy conservation and CO2 emissions mitigation in China's iron and steel industry based on dynamic material flows." *Applied Energy* 209: 251-265.

Zhang, S., Ding, Y., Liu, B., Pan, D.A., Chang, C., and Volinsky, A.A. 2015. "Challenges in legislation, recycling system and technical system of waste electrical and electronic equipment in China." *Waste management* 45: 361-373.