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Environmental Benefits of Engine Remanufacture in China's Circular Economy Development

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Supporting Information

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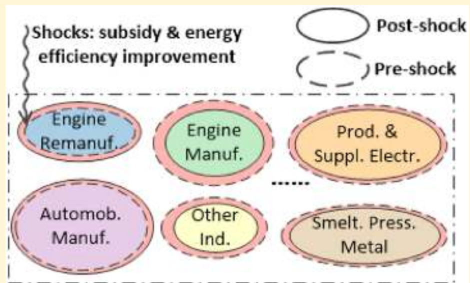
ABSTRACT: China has recently implemented broad strategies aimed at achieving a circular economy by providing subsidies for the remanufacture industry and setting a target of 15% increase in energy efficiency in industrial production across sectors, among other strategies. Here, we examine the environmental implications of these policies in the context of engine remanufacture, using an environmental computable general equilibrium (CGE) model. Results indicate that both the subsidy policy and energy efficiency improvement target can contribute to economic growth and emission reductions, but the subsidy policy is estimated to have far greater impacts. The implementation of both can reinforce each other, generating higher economic and environmental benefits than the sum of each occurrence alone. Another major finding from our model is that an additional remanufactured engine only displaces 0.42 (90% confidence interval from 0.32 to 0.47) of a new engine (comprised of new parts), mainly because the lower prices of remanufactured engines lead to greater consumption. This ratio is much lower than the 1:1 perfect displacement commonly assumed in life cycle assessment (LCA) studies. Overall, our study suggests that the subsidizing of engine remanufacture in China can help promote the industry, improve overall economic welfare, and contribute to environmental targets. Our study also contributes to the estimation of more realistic product displacement ratios in LCA.



1. INTRODUCTION

Over the past three decades, China has experienced rapid and sustained growth in car ownership, from 0.82 million in 1990 to ~200 million in 2017.[1] China is now the world's largest automobile market. Even though cars have greatly improved and enriched the quality of life for Chinese people, they also pose significant challenges to the environment, a major one being end-of-life management. Along with the growth in car ownership, China has accumulated a large inventory of scrapped cars, which continues to increase and is projected to reach 14 million by 2020.[2]

The proper recycling of automobile materials has important implications for solid waste management, greenhouse gas emissions, energy use, and conservation of primary materials in China.[3] Remanufacture has been proposed as an important solution to these challenges as part of China's comprehensive plans to develop a circular economy.[4] The remanufacture of vehicle parts leads to a reduction in the amount of solid waste and may yield environmental benefits when restored parts displace those made from new materials.[5] The Chinese government has issued numerous regulations, legislations, and development plans to advance the remanufacture industry. For instance, the Ministry of Industry and Information Technology (MIIT) organized the first and second groups of remanufacture pilots in 2009 and 2016, respectively. In 2013, MIIT promulgated the "internal combustion engine remanufacture propulsion plan" to improve the remanufacture standard system, accelerate remanufacture innovations, and facilitate the development of reverse logistics technologies. A widely known incentive policy in China is the exchange of used parts for remanufactured equivalents jointly issued by five national administrative departments. Under this policy, buyers will receive a subsidy for returning used parts and purchasing remanufactured counterparts. This subsidy policy involves mainly engines, which, in comparison with other parts, possess a much higher added-value.[6]

However, the extent to which the subsidy might promote engine remanufacture and lead to environmental benefits remains unclear. Previous studies have largely relied on life cycle assessment (LCA) models, such as process and input-output LCA, to determine the environmental benefits of remanufactured engines by comparing them with new engines (i.e., newly manufactured and comprised of new parts).[7−9] These LCA models, however, suffer from two major limitations. First, they operate at the product level, which is useful for policies with a specific output target (e.g., mandating certain number of remanufactured engines to be produced and

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used) but falls short for market-based policies such as a subsidy. The impact of a subsidy on remanufactured engine output is unknown and needs to be estimated, depending on an array of economic factors from the scale of the subsidy to the prices of remanufactured and new engines.

Second, these LCA models generally assume that one remanufactured engine would displace one new engine, a perfect 1:1 displacement ratio that is typically assumed in comparative LCA studies.[10] This assumption, however, ignores that even though two products can provide the same function, they may differ in many other attributes that can affect consumers' choice. In this case, remanufactured and new engines differ in price and public perceptions of value. Even if they have identical physical properties, the subsidy policy could lower average engine prices, potentially leading to greater consumption of all engines, compared to (or in comparison to) if no such subsidies were implemented. This rebound effect[11−13] can offset some of the environmental benefits, if any, of remanufactured engines. Product displacement is a complicated question affected by a wide range of factors beyond functionality, and the perfect 1:1 displacement ratio generally assumed in LCA is likely unrealistic.[10] This issue has been increasingly recognized in LCA literature, with a growing body of studies that estimate more realistic displacement ratios for, e.g., biofuel vs gasoline,[11] whole vs low-fat milk,[14] and fossil-fuel vs nonfossil-fuel electricity.[15] In summary, the assessment of the subsidy policy for engine remanufacture entails a model that takes into account many of these economic aspects, particularly the effects of price changes on supply and demand, thus capturing the market reaction to the policy.

Here, we describe an environmental computable general equilibrium (CGE) model of China built to study the environmental implications of subsidizing engine remanufacture. CGE models are a major tool in economics to determine system-wide impacts of external changes such as policy interventions and technology innovation.[16] They can also be used to estimate the environmental impacts of these external changes when coupled with data on industry resource use and emissions.[11,17] Grounded in microeconomic principles, CGE models capture interactions between product and factor markets and between private and public sectors and thus can account for, e.g., the rebound effect resulting from energy efficiency improvement and price reduction.[18] CGE models have been increasingly incorporated into the LCA framework with the aim of determining the environmental impacts of policy making (e.g., a mandate, a tariff, or a taxation).[19] It should be noted that our CGE modeling focuses on the preconsumer stages of both remanufactured and new engines. For the use stage, we assume that the two types of engines do not differ, as in previous studies,[7,20] because remanufactured engines can achieve the same efficiency as new engines.[20,21]

Besides the subsidy policy, we also apply the CGE model to evaluate the environmental implications of energy efficiency improvement in the production of remanufactured engines via system optimization and technological advancement. As part of the 13th five-year plan, the Chinese government set a target of 15% improvement in energy intensity in industrial production by 2020 and proposed specific legislative regulations for energy conservation.[22] We examine and compare the environmental benefits of the subsidy policy and the efficiency improvement regulation in this article. Although our study focuses on engine remanufacture, it sheds light on China's promotion of the remanufacture industry at large as part of its broad efforts to achieve a circular economy. Our study also contributes to LCA methodology development as the framework moves beyond the conventional linear, supply chain based models, such as process and Input-Output LCA, and towards the incorporation of a broad range of different models to better estimate the environmental consequences of decision making.[19]

2. METHODS AND DATA

2.1. Brief Overview of General Computable Equilibrium (CGE). CGE is a systems model that evaluates the economy-wide effects of external changes such as policy interventions, technological advances, and environmental change.[23] The term *general* indicates that the model simultaneously takes into consideration all relevant economic activities including production, consumption, tax, and trade. The term *equilibrium* indicates that supply and demand in both commodity and labor markets are in balance at a set of prices, and an exogenous shock, such as taxation/subsidy, creates changes to the markets and leads to a new state of supply demand equilibrium at a different price. The differences between the postshock and the initial equilibrium are thus seen as the impact of the shock.

Specifically, a typical CGE model is composed of three building blocks: consumers maximizing utility, producers maximizing profits, and a state of general equilibrium. General equilibrium implies that (1) commodities are produced to the level demanded by consumers (market clearance), (2) total factor costs (inputs, labor, and capital) equal total revenue (zero profit), and (3) household expenditure equals income minus savings (income balance). The meeting of all these conditions in CGE enables us to solve simultaneously for allocation and prices of goods and factors that form a general equilibrium. The building of a CGE model generally involves a number of steps.[24] The first step is to design a basic framework tailored to a given research question and data availability. The second step is to define model structure or production and preference functions, which reflect the behaviors of producers and consumers. Commonly used functions include Leontief, Cobb-Douglas, Constant Elasticity of Substitution (CES), or a mix of them. The third step is to calibrate the model against a benchmark equilibrium recorded in a social accounting matrix (SAM) to estimate share and elasticity parameters. On the basis of the functions defined and questions answered, additional data may be needed to estimate certain elasticity parameters. The final step is to validate the model via replication, testing, and sensitivity analyses to identify errors. An environmental CGE model couples a CGE model with an environmental satellite table with data on sectoral resource use and emissions, often assuming that they are proportional to the gross output.[25]

2.2. CGE Model of China. In this section, we describe (1) the Chinese Social Accounting Matrix (SAM) used for construction and calibration of our CGE model, (2) its nested six-layer structure, (3) estimation of the elasticity of substitution between remanufactured and new engines, and (4) compilation of sectoral emissions. The details of our model are provided in the Supporting Information (SI): The PDF file provides the mathematical equations used to build our CGE model, details on scenarios definition and sensitivity analysis, and supporting tables and figures; the Excel file includes the Chinese SAM, sectoral emission factors, and elasticity

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parameters; the TXT file includes the code we used to run our model on the GAMS platform.

2.2.1. Chinese Social Accounting Matrix (SAM). A SAM is an extended input-output (IO) table describing the transactions and transfers between different agents within an economy and with the rest of the world over a specific accounting period, typically a year.[26] The Chinese SAM was derived from the latest Chinese IO tables (for the year 2012) from the National Bureau of Statistics,[27] supplemented with additional information collected from the literature on factors, consumers, investments, savings, and the rest of world. Given the goal of our study, we singled out *New Engine Manufacture* and *Engine Remanufacture* as two individual sectors while keeping the rest relatively aggregated for ease of computation. Because the original Chinese IO tables do not have detailed data on engine manufacture or remanufacture, they were disaggregated from *Automobile Manufacture* industry based on prior work.[28,29] Physical flows and parameters for disaggregation were derived from National Bureau of Statistics and onsite investigation at SINOTRUK, Jinan Fuqiang Power Corp. Ltd., a large engine remanufacturer in China (Table 1). In total, our SAM is comprised of 31 sectors and 31 corresponding commodities, a level of aggregation that is common in CGE models.[30−32] See SI 2 for details.

Table 1. Summary of Data for Disaggregation of New Engine Manufacture and Engine Remanufacture

Data	Sources
Bill of Material (BOM) of the diesel truck, newly manufactured and remanufactured engine and their prices	SINOTRUK, Fuqiang Power Corp. Ltd.
Quantity of vehicles produced in 2012	National Bureau of Statistics of China[1]
Quantity of vehicles recycled in 2012	Remanufacture Committee of China Association of Automobile Manufacture
Differences in materials and energy use by the two types of engines	Xu et al.[33]

2.2.2. Nested Six-Layer Structure. Following Hosoe et al.,[34] we applied a nested six-layer structure in our Chinese CGE model (Figure 1). The widely used constant elasticity of transformation (CET) function was applied to describe substitution between domestic commodities and imports consumed by households, between capital-energy bundle and labor, between capital and energy, between electricity and fossil fuels, and further between fossil fuels. The CES function was also applied to describe the substitution between new and remanufactured engines, a parameter that is critical to understanding the impact of engine remanufacture. For all other intermediate inputs, we used the Leontief function, which assumes fixed relationships between inputs and outputs with no substitution.[35]

2.2.3. Elasticity of Substitution between New and Remanufactured Engines. In our nested model (Figure 1), the elasticity of substitution needs to be estimated where CES functions were applied. We focused on estimating the elasticity of substitution between remanufactured and new engines as it is one of the most important parameters determining the potential environmental benefits of remanufactured engines. The higher the elasticity, the higher the substitution, and as a result, more emissions associated with new engines can be avoided. Other elasticity parameters are from previous econometric research.[36] The commonly used approaches for a two-level CES include Kmenta Approximation,[37] the single equation estimates proposed by Moroney[38] and Arrow et al.,[39] and systems estimation using simultaneous equations.[40] Here, we used a simple econometric model to estimate the elasticity, as shown in eq 1, which describes the willingness of buyers (including automobile manufacturers and households) to replace new engines with remanufactured ones.

$$\sigma_{rn} = \frac{\partial \ln(Q_r/Q_n)}{\partial \ln(P_n/P_r)} \tag{1}$$

where Q_r and Q_n and P_r and P_n are the production quantities and prices of remanufactured and new engines, respectively.

The result from eq 1 represents a point estimate at a given time; however, elasticity can change over time as a result of changes in the quantities and prices. We calculated multiple elasticities using eq 1 based on a time series of 11 years (44-quarter) of data collected from the investigated remanufacturer (SINOTRUK Inc.). These data account for ∼18% of all the remanufactured engines in China. Given the importance of this elasticity, we also calculated its confidence interval to reflect the uncertainty (with the mean set as the default in model runs). We adopted a common interval estimation method[41] in which normally distributed sample points and unknown standard deviation were assumed. In this case, the confidence interval for the mean is defined as follows

$$\bar{X} \pm \frac{S}{\sqrt{n}} t_{conf} \tag{2}$$

where $\bar{X}$ is sample mean, n is the sample size, and S is the sample standard deviation; t_{conf} denotes the number from t distribution with n-1 degrees of freedom, which satisfies the confidence specifications. This interval estimation was directly performed on the MATLAB platform with samples obtained from the point elasticities (eq 1). In total, there are 217 elasticity parameters for the CET and CES functions (Figure 1) involved in the 31 sectors of our CGE model. For details on all these elasticity parameters, see SI 2.

2.2.4. Sectoral Environmental Emissions. We coupled the Chinese SAM with an environmental satellite table that records total emissions by each sector covered in the SAM for the year (2012). We focused on several major pollutants:[42] CO_2, SO_2, NO_x, dust, ammonia nitrogen (NH_3-N), and Chemical Oxygen Demand (COD). Data on these environmental emissions were collected from Chinese environmental statistics yearbook,[43] China Emission Accounts & Data sets,[44] and a study by Liang et al.[45] Note that these data are at different degrees of sectoral aggregation but are generally more detailed than the 31-sector classification in our SAM, allowing for aggregation and mapping. For the CGE computation, emission intensities for each sector were first calculated by dividing the total emissions of a sector by its gross output. This method assumes a linear relationship between economic output and environmental emissions, meaning that, for example, an increase in the output of an sector by 10% would lead to an increase in emissions by 10%. When a policy causes "disruption" throughout the economy and each sector responds by modifying its production strategy, price, and output, there are corresponding changes in their total emissions. A sum of such changes across all sectors is then the total environmental impact of the policy. This can also be interpreted as the life cycle environmental

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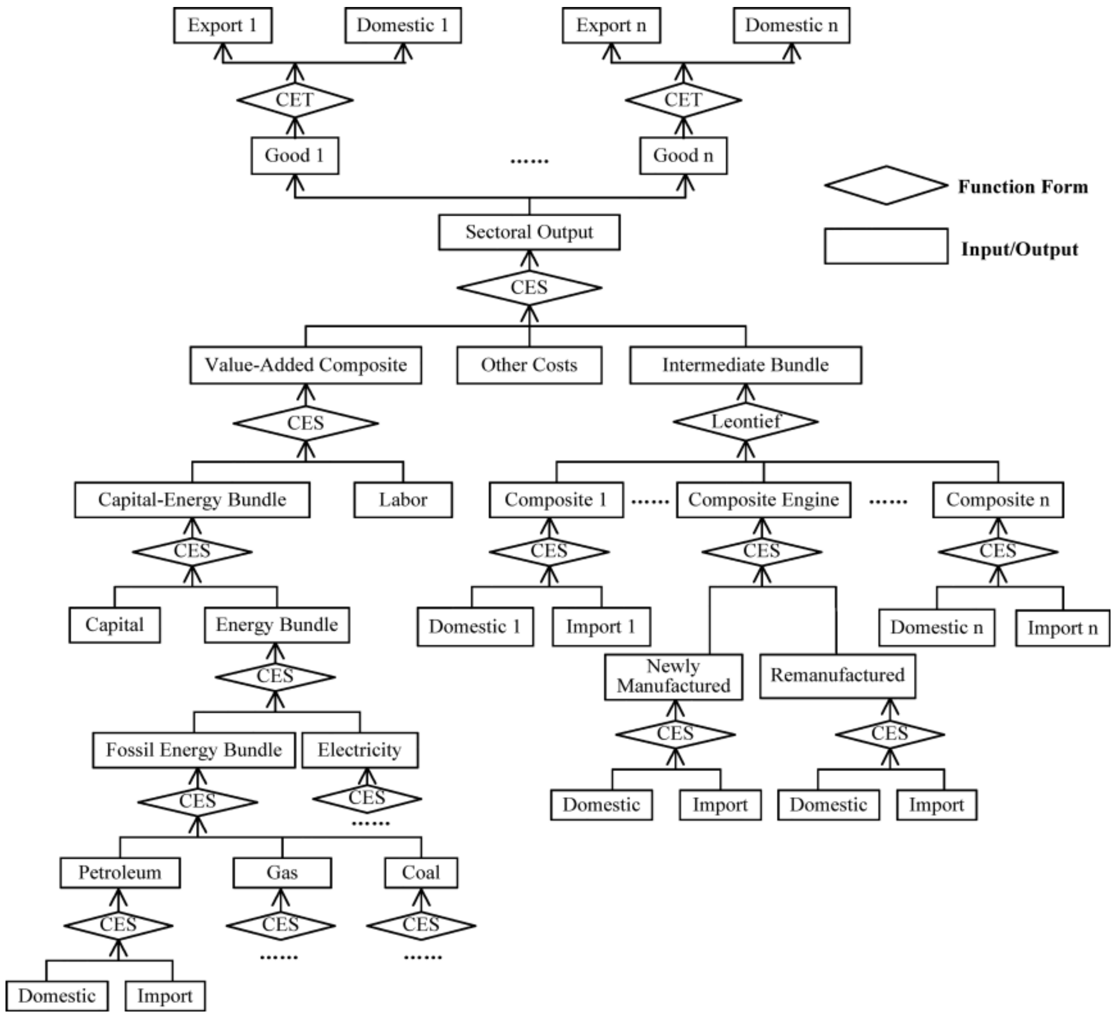

Figure 1. Nested structure of our Chinese CGE model.

Table 2. Changes in Key Economic Variables under the Three Scenarios in Comparison to Baseline Equilibrium (in Units of 100 Million Yuan except Otherwise Specified)[a]

Variables	Baseline	Scenario I	Scenario II	Scenario III
Real GDP	536800.17	0.00015%	0.00000%	0.00016%
Price of remanufactured engine (unit price)	1.00	−5.37%	−0.18%	−5.54%
Price of new engine (unit price)	1.00	−0.01%	0.00%	−0.01%
Output of remanufactured engine	80.63	25.58%	0.70%	26.58%
Output of new engine	9508.55	−0.15%	0.00%	−0.16%

[a]Scenario I: subsidy for engine remanufacture. Scenario II: energy efficiency improvement in engine remanufacture. Scenario III: a combination of scenarios I and II.

impact.[35] SI 2 provides detailed information on each sector's emission intensities and total emissions.

2.3. Scenario Development. We developed three scenarios in relation to the questions addressed in this study. Scenario I considers a subsidy for remanufactured engines. The remanufacture industry in China faces many barriers, and to help its development, the Chinese government has provided financial incentives in forms of subsidies for the production of remanufactured products.[46] The National Development and Reform Commission initiated the subsidy for remanufactured engines: the government offers ¥2000 (Chinese currency, ∼$300) for each remanufactured engine purchased.[47] The subsidy is effectively a form of tax reduction[23] and was configured as such in our CGE model. Scenario II assumes that the energy efficiency of the engine remanufacture sector increases by 15%. This scenario reflects the broad efforts in China to improve energy efficiency in industrial production. In the 13th five-year plan, the Chinese government targeted a reduction of energy consumption by 15% per GDP.[22] Scenario III is a combination of scenarios I and II, examining the joint impacts of both the subsidy and the energy efficiency improvement.

2.4. Sensitivity Analysis. Sensitivity analysis was conducted to test the robustness of our model, by varying input parameters, and demonstrate the variability of model results. We focused on three key parameters: elasticity of substitution between remanufactured and new engines, energy efficiency, and the amount of subsidy. These parameters were varied over

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a reasonable range centered around the baseline values. Hosoe et al.[34] proposed two criteria for robustness testing: (1) whether the sign of output changes remains the same in all cases and (2) similarly, whether the order of the output changes remains the same in all cases. Accordingly, we quantified the changes in sectoral output in response to changes in the key parameters and compared them against the baseline scenario.

3. RESULTS

3.1. Macroeconomic Impacts. Overall, the subsidy for remanufactured engines is estimated to have a positive impact on the economy. An important measure is real GDP, which covers gross investment, total consumption, and net exports (see eq (44) in SI 1). Under the subsidy, real GDP increases slightly, due in large part to the increased consumption of vehicles in the market (Table 2). The small increase in real GDP is expected, because engine remanufacture contributes a small share to national GPD. In addition, the subsidy reduces the price of both remanufactured and new engines, but the impact on the former (−5.37%) is much larger than that on the latter (−0.01%).

The subsidy is estimated to have differential effects across sectors (Figure 2). Unsurprisingly, it stimulates the development of *Engine Remanufacture*, resulting in an increase of ∼2.06 billion Yuan (BY) (or 25.58%) in gross output. Due to the substitution effect, *New Engine Manufacture* experiences a slight decline in output (by 1.45 BY or 0.15%). This is mainly because *Engine Remanufacture* is an emerging industry in China, producing a much smaller output than *New Engine Manufacture* (Table 2). Nevertheless, the output reduction of *New Engine Manufacture* is the most significant (Figure 2), and it contributes to the output reduction of other sectors, especially those along the supply chain such as *Smelting and Pressing of Metals*. In the end, total engine consumption grows by ∼0.62 BY, contributing to an increase in the output of *Automobile Manufacture*. Among others, *Other Industries* decreases in gross output by a relatively large amount of 0.39 BY. The reason this sector stands out as being significantly affected is likely due to its being an aggregate of 16 sectors (Figure 2; Table S5 in SI 1).

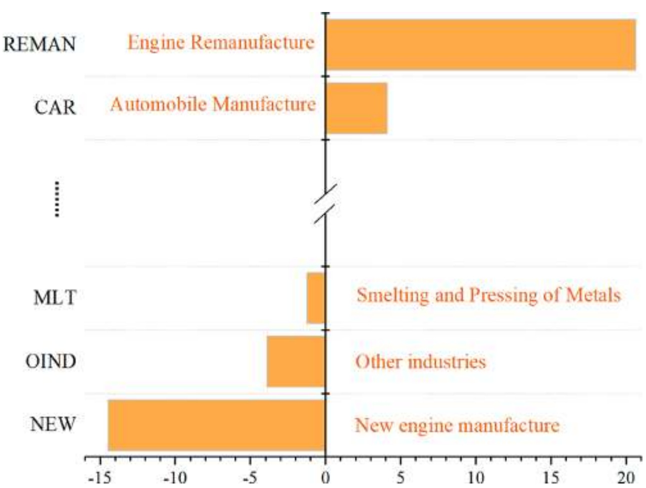

Figure 2. Changes in sectoral outputs under the subsidy scenario (unit: 100 million Yuan; for results on all sectors, see Figure S1 in SI).

In comparison with the subsidy, energy efficiency improvement in the engine remanufacture sector by 15% (scenario II) is estimated to have a much smaller impact on the key economic parameters (Table 2). Real GDP increases only slightly in this scenario, less than 3% of that under the subsidy scenario; the price of a remanufactured engine decreases by <0.2% and that of a new engine decreases by ∼0.0002%, and the output of *Engine Remanufacture* increases by ∼0.7% and that of *New Engine Manufacture* decreases by ∼0.004% given the substitution effect. Along with the remanufactured engine, the output of automobiles increases by 0.011 BY due to the lower average prices of engines. Total electricity consumption is reduced, largely because of energy efficiency enhancement in *Engine Remanufacture* (Figure 3).

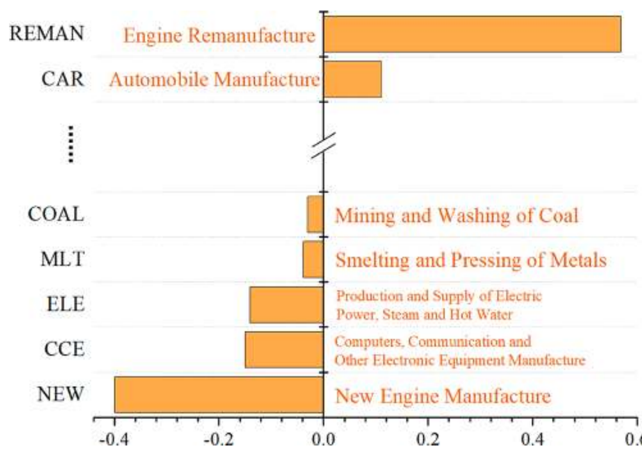

Figure 3. Changes in sectoral outputs under the energy efficiency improvement scenario (unit: 100 million Yuan; for results on all sectors, see Figure S2 in SI).

The simultaneous occurrence of subsidy and energy efficiency improvement (scenario III) is estimated to have larger economic impacts than the combined impacts of each occurrence alone (Table 2). For example, the increase in remanufactured engine output in this scenario is greater than the sum of corresponding increases in scenario I and II. These results demonstrate that policy and the efficiency improvement can reinforce each other, although the overall impact is still dominated by the subsidy for remanufacture.

3.2. Environmental Impacts. Overall, the subsidy for *Engine Remanufacture* is estimated to result in lower environmental emissions as compared to that with the baseline scenario (Table 3). As a result of the subsidy, some sectors, particularly *Engine Remanufacture* and *Automobile Manufacture*, increase production and output (Figure 2), hence we have more emissions. But the majority of the sectors, particularly *New Engine Manufacture*, reduce production and output, hence

Table 3. Emissions Changes under Different Scenarios (Unit: Metric Ton)

Emissions	Scenario I	Scenario II	Scenario III
CO_2	−83,426.63	−11,947.36	−98,798.26
SO_2	−175.91	−25.00	−208.07
NO_X	−152.96	−30.04	−191.42
Dust	−90.72	−7.78	−100.88
COD	−26.77	−0.81	−27.94
NH_3-N	−1.73	−0.06	−1.82

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we have lower emissions. In total, the latter outweighs the former and the subsidy is estimated to have a net environmental benefit for the pollutants studied here. Total CO_2 emissions, for example, are reduced by 83427 tons because of the subsidy.

Energy efficiency improvement in *Engine Remanufacture* (scenario II) through, for example, energy conservation or system optimization and innovation is also estimated to result in lower environmental emissions. And it appears to be effective in overall emission reduction. The environmental impacts of energy efficiency improvement are much more substantial than its economic impacts. For example, the increase in real GDP in this scenario is ∼2% of that in the subsidy scenario, but CO_2 reductions are ∼14% (11947 vs 83427 tons; Table 3). The same goes for NO_x and SO_2 emissions (Table 3). Energy efficiency improvement in *Engine Remanufacture* reduces energy demand in the market, particularly electricity generation (Figure 3), and because electricity generation in China relies heavily on hard coal, which is emission intensive,[48] the reduced electricity generation results in substantial emission savings. These impacts are partly reflected in electricity generation and coal production being the third and fifth most negatively impacted sectors in scenario II (Figure 3).

Similar to the economic impact, the subsidy policy and energy efficiency improvement are estimated to result in greater environmental benefits than the combination of each scenario occurrence alone (Table 3). Additional reductions of 3424 tons of CO_2, 7.2 tons of SO_2, and 8.4 tons of NO_x, for example, are observed in this joint scenario beyond the totals from scenarios I and II.

3.3. Displacement Ratio. Across scenarios, an increased output of remanufactured engines corresponds to a reduction in new engine output that is ∼70% the size (e.g., 20.63 vs −14.47 100 million Yuan in scenario I). This means, considering that remanufactured engines are ∼40% cheaper than new engines,[33] an additional remanufactured engine in the market displaces 0.42 of a new engine, as shown in Table 4.

Table 4. Output Changes and Displacement Ratio under Different Scenarios (Unit: 100 Million Yuan)

Emissions	Scenario I	Scenario II	Scenario III
Output change of new engine	−14.47	−0.40	−15.00
Output change of remanufactured engine	20.63	0.57	21.43
Displacement ratio (remanufactured: new)	1:0.421	1:0.422	1:0.420

This displacement ratio is based on the mean elasticity of substitution between the two products (5.94) calculated in eq 1. The ratio, however, varies between 3.22 and 8.66 (90% confidence level). When we account for this variation, we obtain a range estimate of [0.32, 0.47] for the displacement ratio. In other words, it takes roughly 2 to 3 remanufactured engines to displace 1 new engine in our policy and technology scenarios.

3.4. Sensitivity Analysis. We examined the sensitivity of the results to three key parameters: substitution elasticity (σ = 5.94), subsidy (2000 Yuan), and energy efficiency improvement (15%) (Table 5). We found that increasing or decreasing these parameters by 10% has opposite effects on the economy and emissions. In comparison with the subsidy and energy efficiency improvement, the substitution elasticity has much greater impacts on the economic indicators, suggesting its critical importance in estimating the consequences of remanufactured engine expansion. Subsidy and energy efficiency improvement both lead to CO_2 reductions from the baseline scenario, but the latter appears to exert a significantly higher influence because of the reduction in electricity consumption as discussed above. Overall, we found that the sensitivity analysis results satisfy the two criteria stated above, which demonstrates the robustness of the system (see also Table S7 in SI 1).

4. DISCUSSION AND IMPLICATIONS

Our results show that the subsidy policy (2000 Yuan per engine) and the energy efficiency improvement (by 15%) for the *Engine Remanufacture* sector can bring both economic and environmental benefits. The subsidy policy is estimated to have much larger economic impacts across sectors and to reduce more emissions in comparison to energy efficiency improvement. In particular, the subsidy policy leads to a significant increase (25.58%) in remanufactured engine output. The development of remanufacture industries in China encounters numerous technological and market-related barriers, and our results imply that policy interventions, such as a subsidy, can be instrumental in overcoming some of these barriers.[49] Despite its small economic impact, energy efficiency improvement in *Engine Remanufacture* appears to be effective in reducing emissions. Moreover, the simultaneous occurrences of the subsidy policy and efficiency improvement are estimated to reinforce each other, resulting in greater economic and environmental benefits than the sum of each occurrence alone. These results suggest that the subsidy policy implemented by the Chinese government, together with its broad efforts to improve energy efficiency across sectors, is conducive to promoting engine remanufacture development, improving the overall welfare, and achieving environmental targets. Overall, our study suggests that these policies are likely to contribute to China's comprehensive strategies toward achieving a circular economy.[50,51]

Our simulation results are consistent with those of previous computable general equilibrium (CGE) analyses. For example,

Table 5. Results on Sensitivity Analysis of Key Economic and Environmental Indicators to Changes in Subsidy, Energy Improvement Efficiency, and Elasticity of Substitution (Values Are Percentage Change from the Baseline)

	Subsidy		Energy efficiency improvement		Elasticity of substitution	
	−10%	+10%	−10%	+10%	−10%	+10%
Real GDP	−0.00002%	0.00002%	0.00%	0.00%	0.0022%	−0.0012%
Output of new engine	0.02%	−0.02%	0.00%	0.00%	−0.33%	0.20%
Output of remanufactured engine	−2.44%	2.55%	−0.52%	0.45%	29.00%	−18.33%
Change in CO_2 emissions (ΔCO_2)	−11.95%	12.47%	−74.65%	63.79%		

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Zhou and colleagues also found that the improvement of energy efficiency in China is an effective means to air emission reduction and water conservation, in addition to macroeconomic benefits.[31] The subsidy policy for remanufactured engines was treated as a negative tax in our model and estimated to have a positive effect on the overall economy, due in large part to the increasing consumption of remanufactured engines and automobiles. This result is consistent with those of some prior CGE models, which yielded negative economic impacts of higher coal taxation in China[32] and of petroleum subsidy removal in Malaysia.[30] Further, we found that when the subsidy policy was implemented along with energy efficiency improvement, they reinforced each other and resulted in greater impacts and benefits. Pui and Othman also found that the simultaneous introduction of energy efficiency improvement and fuel subsidy in Malaysia would enhance the policies and lead to energy savings and economic growth in the long term.[52]

Another major finding of our study is that one remanufactured engine displaces only 0.42 (most likely in the range of [0.32, 0.47]) of a new engine. In other words, it takes 2 to 3 remanufactured engines to displace a new engine. This is substantially lower than the 1:1 displacement ratio assumed in previous life cycle assessment (LCA) studies of remanufactured engines. The <1 displacement ratio (0.42) in our case is due in large part to the rebound effect; for example, the subsidy policy increases the consumption of remanufactured engines. Our result is in broad agreement with previous studies, which generally found <1 displacement ratios across a range of commodities including renewable fuel,[53] recycled cloth,[54] and metals.[55]

Finally, given the limitations of CGE models, our results should be interpreted with caution. Although CGE models incorporate a broader set of market mechanisms like price effects and input substitutions as opposed to process- and IO-based LCA models, they assume optimized behavior, which is an idealized representation of economic agents.[56,57] In addition, the results of a CGE model are highly dependent on the production functions assumed and associated elasticity parameters, some of which may be derived from limited data sets or based on expert judgements.[58] Consequently, our results should not be considered as providing definitive conclusions on the environmental benefits of remanufactured engines in China. Instead, they should be considered—as with any first study—to be preliminary, and they need confirmation by future studies, e.g., with improved parameter estimates or the application of other modeling frameworks. Our confidence will increase when more studies arrive at similar results.[35] In particular, as the environmental benefits of remanufactured engines depend crucially on the extent to which they can displace new engines, we suggest that these be further studied, e.g., using other methods like partial equilibrium analysis and econometrics. Future studies may also expand on our work by including vehicle operation stage. The subsidizing of engine remanufacture may accelerate the retirement of inefficient engines that power some old vehicles on the road and thus help to improve air quality.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b02973.

Mathematic equations used to build our CGE model, details on scenarios definition and sensitivity analysis, and supporting tables and figures (PDF)

Chinese SAM, sectoral emission factors, and elasticity parameters (XLSX)

Code we used to run our model on the GAMS platform (TXT)

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