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Comparative Life-Cycle Assessment of Liquefied Natural Gas and Diesel Tractor-Trailer in China

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Abstract: Many countries, especially China, have extensively promoted liquefied natural gas (LNG) to replace diesel in heavy-duty vehicles for to achieve sustainable transport aims, including carbon peaks and neutrality. We developed a life-cycle calculation model for environmental load differences covering vehicle and fuel cycles to comprehensively compare the LNG tractor-trailer and its diesel counterpart in China on a full suite of environmental impacts. We found that the LNG tractor-trailer consumes less aluminum but more iron and energy; emits less nitrogen oxide, sulfur oxide, nonmethane volatile organic compounds, and particulate matter but more greenhouse gases (GHG) and carbon monoxide (CO); and causes less abiotic depletion potential, acidification potential, and human toxicity potential impacts but more global warming potential (GWP) and photooxidant creation potential (POCP) impacts. Poor fuel economy was found to largely drive the higher life-cycle GHG and CO emissions and GWP and POCP impacts of the LNG tractor-trailer. Switching to the LNG tractor-trailer could reduce carbon dioxide by 52.73%, GWP impact by 44.60% and POCP impact by 49.23% if it attains parity fuel economy with its diesel counterpart. Policymakers should modify the regulations on fuel tax and vehicle access, which discourage improvement in LNG engine efficiency and adopt incentive polices to develop the technologies.

Keywords: life cycle; environmental impacts; liquefied natural gas; heavy-duty vehicle; tractor-trailer; China

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1. Introduction

As the cleanest burning fossil fuel, natural gas (NG) and liquefied NG (LNG) play a significant role in alleviating oil shortages and preventing environmental degradation [1–3]. NG vehicles are also considered an important transitional type of vehicle towards the goal of carbon peak and neutralization since NG has a lower carbon content than oil [4,5]. Additionally, LNG heavy-duty vehicle (HDV) has a longer driving range and better safety [4,6–8] and reduce long-term operation costs [9–11]. Thus, LNG HDVs are regarded as a viable alternative to conventional diesel HDVs.

The number of LNG HDVs on roads in China has reached 578 thousand in 2020, with an average annual growth rate of 49.37% from 2010 to 2020. The share of LNG HDVs in HDVs has increased from 0.15% in 2010 to 6.78% in 2020 [12,13]. Many cities in China, such as Beijing, have formulated policies that ban diesel HDVs due to their high pollutant emissions. At the same time, the promotion of LNG HDVs is encouraged by policy in some areas with abundant NG sources, such as Sichuan and Chongqing [14–16]. With the increasing use of LNG HDV as a substitute for diesel HDV in China, it is urgent to compare the environmental performance between LNG HDV and its diesel counterpart to identify how the expansion of LNG HDVs meets existing environmental challenges in China such as air pollution, resource shortage, and climate change.

As a practical method of assessing the environmental performance of a product system, life-cycle assessment (LCA) has been used by many researchers to quantitatively calculate the environmental changes brought by replacing internal combustion engine vehicles (ICEVs) with new energy vehicles, such as battery electric vehicles (BEVs) and fuel cell cars [5,17–22]. However, similar studies regarding NG vehicles, especially regarding LNG HDVs, are very few.

As shown in Table 1, previous studies regarding the environmental performance of LNG HDVs mainly focus on one or two types of environmental loads, such as greenhouse gas (GHG) or criteria air pollutants. There is a lack of comprehensive assessments considering a full suite of environmental impacts. Cooper et al. [23] first conducted a comparative LCA of LNG/diesel/other alternatives as fuels for heavy-duty good vehicles (HGVs) in the UK, taking the following environmental impacts into account: climate change, land use change, air quality, human health, and resource depletion. Furthermore, most studies have only considered the impacts in the usage stage or fuel cycle, i.e., well-to-wheel (WTW), and ignored the vehicle cycle covering vehicle production and end-of-life treatment. During the literature review, we found only three peer reviewed China-oriented environmental studies on LNG HDVs considering both the fuel cycle and vehicle cycle: Tu, Yang, Xu, and Chen [24]; Tu, Yang, Xu, and Chen [25]; and Song, Ou, Yuan, Yu, and Wang [4]. In addition, the number of comparative studies on the environmental performance of Chinese LNG/conventional HDVs is still far from adequate considering the growing popularity of LNG HDVs in China.

Targeting the product with the largest share in the Chinese HDV market, the tractor-trailer, this study aims to comprehensively compare the environmental performance of the LNG tractor-trailer and its diesel counterpart in China during the whole life cycle, covering both fuel cycle and vehicle cycle. The results can be used to identify the potential environmental impacts associated with switching from diesel HDV to LNG HDV in China and provide valuable information to decision-makers regarding the development of LNG HDV.

Compared to previous environmental studies on LNG HDVs, the novelty of this study includes (1) the development of a life-cycle model to quantify differences in ore material consumption, energy consumption, and air emission between the LNG tractor-trailer and its diesel counterpart covering both vehicle cycle and fuel cycle, and (2) the comprehensive consideration of a full suite of environmental impacts related to resource depletion, air quality, and climate change, which could provide a more holistic view of the trade-offs associated with switching from diesel to LNG tractor-trailers in China.

Table 1. Previous studies regarding the environmental performance of LNG HDVs.

Authors	Vehicle Type	Country/ Region	Research Boundary	Assessed Environmental Loads/Impacts
Arteconi, et al. [26]	HGVs powered by diesel, LNG under two procurement scenarios (the regasification terminal or producing LNG locally with small-scale plants)	EU-15 (i)	Fuel cycle	GHG emissions
Tong, Jaramillo, and Azevedo [27]	7 types of medium- and heavy-duty vehicles powered by conventional gas, diesel, and NG-based fuels	U.S.	Fuel cycle	GHG emissions
Tu, Yang, Xu, and Chen [25]	LNG and diesel mixer	China	Fuel cycle + vehicle cycle	GHG and criteria air pollutant emissions

Table 1. *Cont.*

Authors	Vehicle Type	Country/Region	Research Boundary	Assessed Environmental Loads/Impacts
Tu, Xu, Chen, and Yang [24]	LNG and diesel mixer	China	Fuel cycle + vehicle cycle	Energy consumption
Cai, et al. [28]	LNG combination short-haul truck, compressed natural gas (CNG) transit bus, CNG refuse truck and their diesel counterparts	U.S.	Fuel cycle	Freshwater consumption, GHG emissions, NO_x and PM emissions
Song, Ou, Yuan, Yu, and Wang [4]	LNG and diesel HDVs (tractor, dump, freight, and special truck)	China	Fuel cycle + vehicle cycle	Energy consumption and GHG emissions
Ozbilen, et al. [29]	Class 8 trucks powered by LNG, CNG, Euro IV diesel, Biodiesel, Fisher–Tropsch diesel	Canada	Vehicle cycle + Operation stage + road cycle	Global warming potential (GWP)
Cooper, Hawkes, and Balcombe [23]	HGVs powered by CNG, LNG (dedicated and dual fuel), diesel, biodiesel, dimethyl ether, and electric battery	U.K.	Fuel cycle	GWP, land use change, particulate matter and photochemical ozone formation potential, human toxicity potential and metals depletion, and fossil fuel depletion potential
Langshaw, et al. [30]	LNG and diesel long-haul HGVs	U.K.	Fuel cycle	GHG emissions
Yuan, Ou, Peng, and Yan [5]	CNG, LNG and diesel transit buses with 12.5–14.5 ton and heavy-duty truck with 20–25 ton	China	Fuel cycle	GHG emissions

Note: (i) Fifteen member states of Europe, including Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

2. Materials and Methods

2.1. Goal and Scope Definition

The goal of this study is to provide a comparative LCA of a representative LNG tractor-trailer and its diesel counterpart. Thus, the system boundary covers all the processes related to the main differences between the two alternatives from a life-cycle perspective. The processes in which no or negligible differences exist are excluded. It is generally regarded that there is no difference between the two alternatives during vehicle assembly, so the process of vehicle assembly is not taken into account in this study. The differences in energy consumption and environmental emissions during end-of-life treatment of the two alternative HDVs are negligible, so this study only considers recycled materials in the stage of recycling.

The main differences in environmental impacts between the two alternatives are associated with their different fuel uses and congeneric accessories, which differ in material composition. Therefore, the scope of this study includes vehicle operation (i.e., "tank-to-wheel", TTW), fuel production (i.e., "well-to-tank", WTT), accessory production (covering ore material acquisition, material preparation and accessory manufacturing), and recycling. Figure 1 shows the system boundary and processes of the system under study.

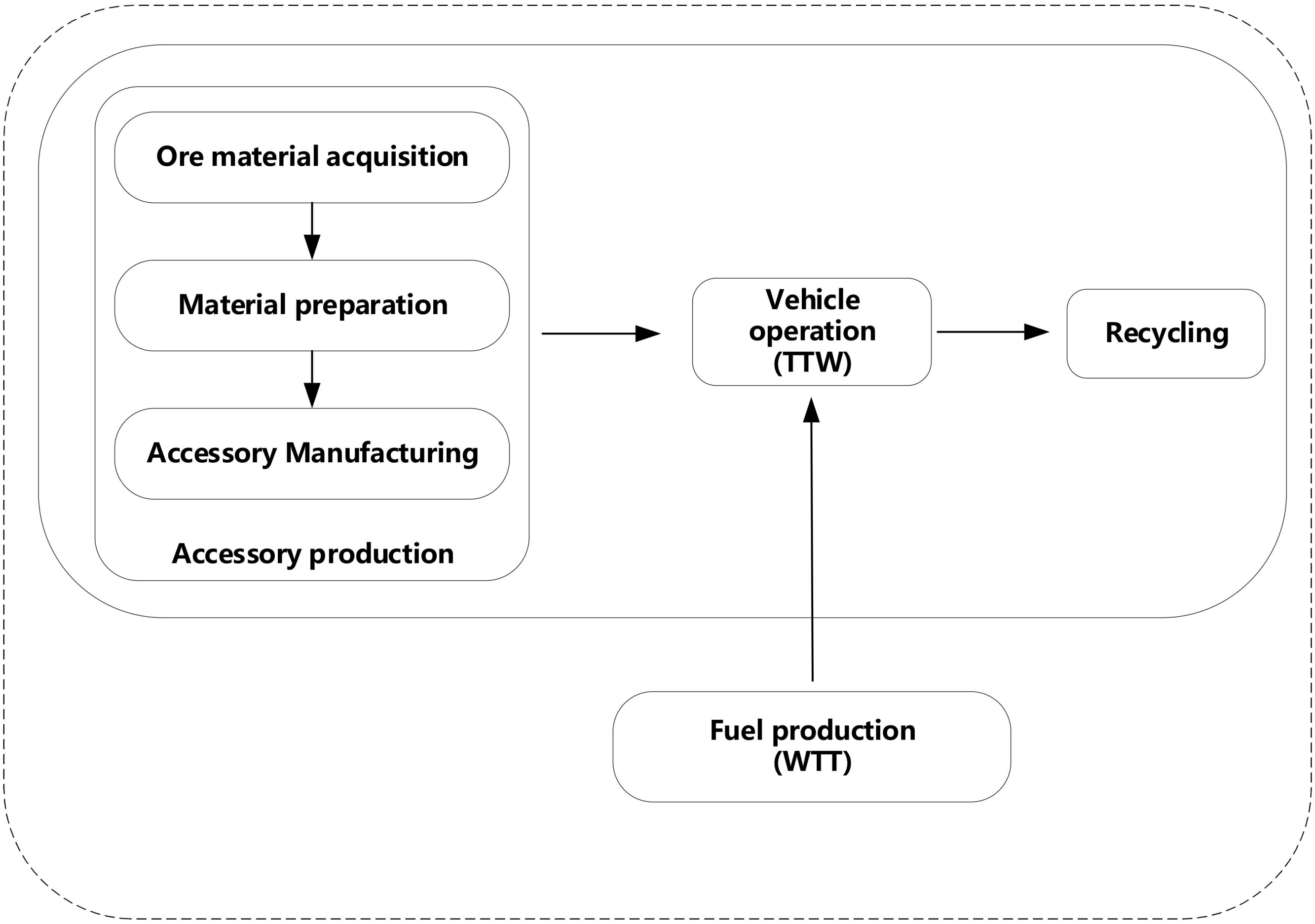

Figure 1. System boundary of this study.

In this study, we used a tractor-trailer with a tractive weight of 40 tons and a lifetime of 400,000 km under average Chinese conditions as a functional unit. To ensure the comparability of our case vehicles, we adopted the following criteria for selection of specific models: (1) the two alternatives should be the same class with similar boundary dimensions and curb weights; (2) the two alternatives should be representative models with their respective powertrain at the leading level of their class, and the power ratings of their engines should be similar; (3) excluding powertrains, the differences between other vehicle structures should be as small as possible; and (4) both types of vehicles should have similar driving experience, dynamic property, comfortability, and safety.

Following these criteria, this study selected an LNG tractor-trailer (HN4250NGX41C9M5) and its diesel counterpart (HN4250H40C4M5) manufactured in 2017 by Hualing Xingma Automobile (Group) Co. Ltd. (CAMC) in Anhui Province of China as the representative model (see Figure 2) since CAMC is one of the primary HDV manufacturers in China. The details on their specification are listed in Table A1.

2.2. Life-Cycle Inventory (LCI) Analysis

Based on the previous studies of Hunan University [24,25,31], this study developed an LCI model for quantitatively comparing the difference in environmental loads between the LNG HDV and its diesel counterpart in a life cycle considering vehicle cycle and fuel cycle, which considers not only the differences in energy consumption and air emission but also ore material consumption. We compiled the model by MATLAB software to obtain the results.

(a) (b)

Figure 2. The selected tractor-trailers for comparison: (**a**) LNG tractor-trailer (HN4250NGX41C9M5); (**b**) Diesel tractor-trailer (HN4250H40C4M5).

2.2.1. Model for Differences in Environmental Loads

1. Matrix for mass difference of accessory materials

The difference in mass of accessory materials leads to the difference in ore material consumption, energy consumption and air emission during ore material acquisition and preparation between the two alternative vehicles. Thus, we first established a matrix for the mass difference (***MD***) of accessory materials (see Equation (1)):

$$\boldsymbol{MD_a} = \left(ml_{a_{ij}}\right)_{k\times n} - \left(mc_{a_{ij}}\right)_{k\times n} \tag{1}$$

where $ml_{a_{ij}}$ (kg) and $mc_{a_{ij}}$ (kg) represent, for LNG HDV and its diesel counterpart, respectively, the mass of material j used in accessory i, k denotes the number of types of accessories that differ in material composition between the two alternatives, and n represents the number of total material types used in these accessories. If the number of material types used in accessory j of a certain HDV is less than n, the vacant elements are replaced with 0.

2. Calculation of ore material consumption difference

Assuming that all of the materials used in HDVs come from raw ore, the matrix for life-cycle difference in ore material j consumption can be established as Equation (2):

$$\boldsymbol{MD_o} = \boldsymbol{MD_a} \times (\boldsymbol{I_n} - \boldsymbol{\eta}_r) \times \boldsymbol{\eta}_p^{-1} \times \boldsymbol{\eta}_m^{-1} = \left(md_{o_{ij}}\right)_{k\times n} \tag{2}$$

where $\boldsymbol{\eta}_p$, $\boldsymbol{\eta}_m$ and $\boldsymbol{\eta}_r$ respectively represents the n order diagonal matrix for the material use ratio during ore material preparation, et. $\boldsymbol{\eta_p} = diag\left(\eta_{p_1}, \cdots, \eta_{p_j}, \cdots, \eta_{p_n}\right)$, and the material use ratio during accessory manufacture, et. $\boldsymbol{\eta_m} = diag\left(\eta_{m_1}, \cdots, \eta_{m_j}, \cdots, \eta_{m_n}\right)$, the material recovery rate during vehicle recycling, et. $\boldsymbol{\eta_r} = diag\left(\eta_{r_1}, \cdots, \eta_{r_j}, \cdots, \eta_{r_n}\right)$, η_{p_j}, η_{m_j} and η_{r_j} respectively denote the use ratio during acquisition and preparation, the use ratio during manufacturing and assembly, and the recovery ratio during vehicle recycling for material j. $md_{o_{ij}}$ (kg) represents the difference in ore material j consumption for accessory i between the two alternatives.

Accordingly, the life-cycle difference in ore material j consumption can be calculated as Equation (3).

$$md_{oj} = \sum_{i=1}^{k} md_{o_{ij}} \tag{3}$$

3. Calculation of the difference in energy consumption and air emission

The difference in energy consumption and air emission between LNG and diesel HDVs is derived from their differences in material and fuel use as well as the manufacturing process of similar accessories, which is related to the following stages: ore material acquisition, material preparation, accessory manufacture, vehicle operation (TTW), and fuel production (WTT).

First, matrices for the difference in energy consumption and air emission during ore material acquisition and preparation are respectively established as given in Equations (4) and (5).

$$\boldsymbol{ED}_b = \left(\boldsymbol{MD_a} \times \boldsymbol{\eta}_p^{-1} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}\right) \times \left(e_{o_{jx}}\right)_{n \times s_b} + \left(\boldsymbol{MD_a} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}\right) \times \left(e_{p_{jx}}\right)_{n \times s_b} = \left(ed_{b_{ix}}\right)_{k \times s_b} \quad (4)$$

$$\boldsymbol{PD}_b = \left(\boldsymbol{MD_a} \times \boldsymbol{\eta}_p^{-1} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}\right) \times \left(p_{o_{jy}}\right)_{n \times t} + \left(\boldsymbol{MD_a} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}\right) \times \left(p_{p_{jy}}\right)_{n \times t} = \left(pd_{b_{iy}}\right)_{k \times t} \quad (5)$$

where $\boldsymbol{MD_a} \times \boldsymbol{\eta}_p^{-1} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}$ (kg) and $\boldsymbol{MD_a} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}$ (kg) represent the matrix for mass difference of ore materials acquired for preparation and materials prepared for accessory manufacture, respectively; $e_{o_{jx}}$ (kgce/kg) and $e_{p_{jx}}$ (kgce/kg) denote the intensity of energy x for acquiring and preparing material j, respectively; $p_{o_{jy}}$ (kg/kg) and $p_{p_{jy}}$ (kg/kg) denote the intensity of air emission y for acquiring and preparing material j, respectively; $ed_{b_{ix}}$ (kgce) and $pd_{b_{iy}}$ (kg) represent the amount difference in energy x consumption and air emission y for acquiring and preparing materials to manufacture accessory i, respectively; and s_b and t denote the number of total energy types and total emission types related to ore material acquisition and material preparation, respectively. If the number of energy types for acquiring and preparing material j or emission types for acquiring and preparing material j is less than s_b or t, the vacant elements are replaced with 0. When there are no respective data on energy or emission intensity during the two stages, the integrated data for the two stages ($e_{o+p_{jx}}$ or $p_{o+p_{jy}}$) can be used for the calculation as given in Equation (6) or Equation (7).

$$\boldsymbol{ED}_b = \left(\boldsymbol{MD_a} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}\right) \times \left(e_{o+p_{jx}}\right)_{n \times s_b} = \left(ed_{b_{ix}}\right)_{k \times s_b} \quad (6)$$

$$\boldsymbol{PD}_b = \left(\boldsymbol{MD_a} \times \boldsymbol{\eta}_{\boldsymbol{m}}^{-1}\right) \times \left(p_{o+p_{jy}}\right)_{n \times t} = \left(pd_{b_{iy}}\right)_{k \times t} \quad (7)$$

where $e_{o+p_{jx}} = {\eta_{p_j}}^{-1} \times e_{o_{jx}} + e_{p_{jx}}$ and $p_{o+p_{jy}} = {\eta_{p_j}}^{-1} \times p_{o_{jy}} + p_{p_{jy}}$.

Then, the life-cycle differences in energy consumption and air emission y are calculated respectively by Equations (8) and (9).

$$\begin{aligned} ed = & \underbrace{\sum_{i=1}^{k}\sum_{x=1}^{s_b} ed_{b_{ix}}}_{\substack{Energy\ consumption\ difference\\ during\ ore\ material\ acquisition\\ and\ material\ preparation}} + \underbrace{\sum_{i=1}^{k}\sum_{x=1}^{s_m} ed_{m_{ix}}}_{\substack{Energy\ consumption\ difference\\ during\ manufacturing\ accesories}} \\ & + \underbrace{D \times (el_o - ec_o)}_{\substack{Energy\ consumption\ difference\\ during\ vehicle\ operation}} + \underbrace{D \times \sum_{x=1}^{s_u}(el_o \times el_{ux} - ec_o \times ec_{ux})}_{\substack{Energy\ consumption\ difference\\ during\ fuel\ production}} \end{aligned} \quad (8)$$

$$pd_y = \underbrace{\sum_{i=1}^{k} pd_{b_{iy}}}_{\substack{Air\ emission\ difference\\ during\ ore\ material\ acquisition\\ and\ preparation}} + \underbrace{\sum_{i=1}^{k} pd_{m_{iy}}}_{\substack{Air\ emission\ difference\\ during\ manufacturing\ accesories}} + \underbrace{D \times (pl_{oy} - pc_{oy})}_{\substack{Air\ emission\ difference\\ during\ vehicle\ operation}} + \underbrace{D \times (el_o \times pl_{uy} - ec_o \times pc_{uy})}_{\substack{Air\ emission\ difference\\ during\ fuel\ production}} \quad (9)$$

where $ed_{m_{ix}}$ (kgce) and pd_{miy} (kg) represent the amount difference in energy x consumption and air emission y for manufacturing accessory i between the two alternatives, D represents the total distance travelled during the vehicle lifetime (100 km), el_o (kgce/100 km) and ec_o (kgce/100 km) represent the amount of LNG and diesel consumption per unit distance, respectively; pl_{oy} (kg/100 km) and pc_{oy} (kg/100 km) denote the amount of air emission y for travelling a unit distance by LNG HDV and its diesel counterpart, respectively; el_{ux} (kgce/kgce) and ec_{ux} (kgce/kgce) denote the amount of energy x consumption for producing a unit of LNG and diesel, respectively; pl_{uy} (kg/kgce) and pc_{uy} (kgce/kgce) denote the amount of emission y for producing a unit of LNG and diesel, respectively; and s_m and s_u represent the number of total energy types related to accessory manufacturing and producing a unit of LNG or diesel, respectively. If the number of energy types for producing a certain accessory or producing a unit of a certain fuel is less than s_m or s_u, the vacant elements are replaced with 0.

2.2.2. Data and Assumption

According to the model established above, we first identified the accessories that differ in material composition and obtained the data on their material composition by field survey on CAMC. The details are shown in Table 2.

Table 2. The differences in accessory materials between the two alternative tractor-trailers.

Vehicle and Accessory Types	Material Types	Mass (kg) Steel	Mass (kg) Al–Mg Alloy
LNG tractor-trailer	Fuel tank (LNG cylinder)	510	0
(HN4250NGX41C9M5)	Bracket	142	0
Diesel tractor-trailer	Fuel tank (diesel tank)	0	46
(HN4250H40C4M5)	Bracket	39	0

Data source: CAMC.

Based on the identification of accessory materials, we collected other data for use in the model, including use ratios and recovery ratios, energy, and air emission intensities in different life-cycle stages.

To keep the data as consistent as possible, we acquired the data during ore material acquisition, material preparation, and diesel production from one database named SinoCenter [32] for the material and energy life-cycle inventory in China since most production occurs in China. According to the Chinese Bureau of Statistics, the production of steel in China was higher than the sales, and cast aluminum production and sales occurred in similar amounts in 2018; diesel imports only account for 0.04% of Chinese diesel consumption in 2018. In addition, the data on Al–Mg alloy were assumed to equal those of cast aluminum due to the data availability. We adopted data on the energy and air emission intensity during diesel production from GREET 2020 [33], which was developed for the US, as most LNG in China is imported from overseas and the US is one of China's importers. The data on the energy intensities during accessory manufacturing were obtained through Tu, Yang, Xu, and Chen's study [24] and the SinoCenter database. Tu, Yang, Xu, and Chen's study [24] provides the amount of direct energy consumption for manufacturing the fuel tank and bracket of a diesel HDV and its LNG counterpart in China in coal equivalent, which was converted to electricity by the conversion factor. SinoCenter provides the average amount of coal, crude oil, and NG consumption for producing 1 kW·h electricity in China. We multiplied the two together to obtain the amount of coal, crude oil, and NG consumption for manufacturing the fuel tank and bracket of a diesel HDV and its LNG counterpart. As the manufacturing processes of the metal fuel tank and bracket mainly cover stamping and welding, the direct emissions during this phase are negligible and excluded from this calculation. Regarding the air emissions during vehicle operation, NMVOC, CO, PM, and CH_4 emissions were directly collected from the enterprise, while SO_x and CO_2 emissions were obtained through external sources. CO_2 emissions during vehicle operation were calculated by the amount of fuel consumption, calorific value and CO_2 emission factor of fuel provided by the IPCC. Based on the method in the "Technical Guidelines for Compiling Air Pollutant Emission Inventory of On-Road Vehicles (Trial)" [34], issued by the Ministry of Ecology and Environment of the People's Republic of China (formerly Ministry of Environmental Protection of the People's Republic of China) in December 2014, SO_x emissions during vehicle operation were calculated by the amount of fuel consumption and sulfur contents of fuel, which can be acquired according to the regulations on oil product standards.

The details on the data sources are shown in Table 3, and the specific inventories are listed in Table A2.

Table 3. Data sources of inventory data for different life-cycle stages.

Life-Cycle Stage	Data Types	Data Source
Ore material acquisition and material preparation	Use ratios during ore material acquisition and material preparation for steel (i) and cast aluminum (ii)	SinoCenter [32]
	Integrated energy intensity data on coal, crude oil, and NG for acquiring and preparing steel (i) and cast aluminum (ii)	SinoCenter [32]
	Integrated emission intensity data on NMVOC, SO_x, NO_x, CO, CO_2, PM and CH_4 for acquiring and preparing steel (i) and cast aluminum (ii)	SinoCenter [32]
Accessory manufacture	Use ratios of steel and cat aluminum during accessory manufacture	WorldAutoSteel (2017) [35]
	Amount of direct energy consumption for manufacturing fuel tank and bracket in coal equivalent	Tu, Yang, Xu and Chen (2013) [24]
	Conversion factor from electricity to coal equivalent	China Energy Statistical Yearbook 2019 [36]
	Amount of coal, Crude oil, and NG consumption for producing 1 kW·h electricity	SinoCenter [32]
Recycling	Recovery ratio of steel and aluminum	WorldAutoSteel (2017) [35]
Fuel production	Amount of coal, crude oil, and NG consumption for producing a unit of LNG (iii)	GREET 2020 [33]
	Amount of NMVOC, SO_x, NO_x, CO, CO_2, PM, and CH_4 emissions for producing a unit of LNG (iii)	GREET 2020 [33]
	Amount of coal, crude oil, and NG consumption for producing a unit of diesel (iv)	SinoCenter [32]
	Amount of NMVOC, SO_x, NO_x, CO, CO_2, PM, and CH_4 emissions for producing a unit of diesel (iv)	SinoCenter [32]
Vehicle operation	Amount of LNG and diesel consumption per unit distance	CAMC
	Amount of NMVOC (v), NO_x, CO, CO_2, PM, and CH_4 emission per unit work for operating LNG tractor-trailer and its diesel counterpart	CAMC (tested by National Motor Vehicle Quality Supervision and Inspection Center through ESC and ELR experiments)
	Sulfur in diesel fuel (vi)	GB 19147—2016 [37]
	CO_2 emission factor of natural gas and diesel	IPCC 2006 [38]

Table 3. *Cont.*

Life-Cycle Stage	Data Types	Data Source
	Conversion factor from heat and electricity to coal equivalent and calorific value of diesel	China Energy Statistical Yearbook 2019 [36]
	Calorific value of LNG and diesel density	BP Statistical Review of World Energy 2020 [39]
	LNG density	https://www.unitrove.com/engineering/gas-technology/liquefied-natural-gas (15 October 2021)

Note: (i) The system boundary covers iron ore mining, iron ore dressing, sintering and ironmaking (BF), steel-making (BOF, EAF), the main process during material primary rolling, production of related auxiliary materials (metallurgical lime, metallurgical coke, ferrosilicate) and main raw materials (ore, coal, etc.) transport but excludes production equipment manufacturing and infrastructure (e.g., plant) construction. The time boundary is 2014 for material and 2017 for energy. The technical level is China's average level for the BF-BOF process and EAF process. All data are from enterprise surveys. (ii) The system boundary is from cradle to gate (products). Chinese typical aluminum production processes including mining bauxite, alumina production, cryolite molten salt electrolysis of alumina, electrolytic aluminum liquid purified (subtraction) and casting aluminum ingots, auxiliary materials (prebaked anode or self-baking carbon anode paste) production, transport of the main materials, and aluminum alloy production and forging, but excluding production equipment manufacturing and infrastructure construction. The time boundary is 2014 for material and 2017 for energy. The technical level is China's average level for mixed alumina–electrolysis. The data are from enterprise surveys, literature, and statistical yearbooks. (iii) The system boundary covers natural gas exploitation, processing, and transportation and takes into account the interaction and influence of various types of energy production but excludes production equipment manufacturing and infrastructure construction. The time boundary is 2017. The technical level is China's average level. The data are from enterprise surveys, literature, and statistical yearbooks. (iv) The system boundary covers crude oil exploitation, processing, and transportation and takes into account the interaction and influence of various types of energy production but excludes production equipment manufacturing and infrastructure construction. The time boundary is 2017. The technical level is China's average level. The data are from enterprise surveys, literature, and statistical yearbooks. (v) The test item for the LNG tractor-trailer is NMHC and HC for the diesel tractor-trailer, and NMVOC is primarily composed of HC. This study used the amounts of NMHC and HC to represent the amount of NMVOCs to remain consistent with other life-cycle stages. (vi) According to the latest Chinese national standard for automobile diesel fuels (GB 19147—2016), the sulfur limit in diesel fuel was set to 10 mg/kg to meet the China V emission standard. Due to the data availability, this study used the limit of 10 mg/kg as the value on sulfur in HDV diesel fuel.

2.3. Life-Cycle Impact Assessment (LCIA)

This study used the CML 2001 model at the midpoint level for classification and characterization. The CML 2001 model has been extensively adopted to assess the environmental impacts of resource consumption and environmental emissions in China since the indicators in this model were considered to represent Chinese environmental problems well [31,40,41].

The characterization process formula is defined by Equation (10) [42].

$$IS_i = \sum_j EF_{ij} \times AMT_{ij} \quad (10)$$

where IS_i denotes the potential of the impact category i, EF_{ij} denotes the characterization factor for substance j that contributes to the impact category i, and AMT_{ij} denotes the quantity of substance j that contributes to the impact category i.

The environmental loads identified in the LCI were sorted with regard to five relevant CML 2001 impact categories: abiotic depletion potential (ADP), global warming potential (GWP 100), acidification potential (AP), human toxicity potential (HTP), and photooxidant creation potential (POCP). These impacts indicate actual environmental problems occurring in China, such as air pollution, resource shortages, and climate change. The description, units, and main contributors of impact categories considered in this study are shown in Table 4. We used the latest characterization factors of ADP available for China calculated by Zhang, Feng, and Wang (2016) [43] and adopted other factors from Oers (2015) [44] due to data availability. The details on the characterization factors are shown in Table A3.

Table 4. The description, units, and main contributors of CML 2001 impact categories.

Impact Category	Description	Unit	Main Contributors
ADP	Resource depletion	kg antimony eq.	Diesel, NG, Iron ore, Aluminum ore
GWP 100	Climate change within a time horizon of 100 years	kg CO_2 eq.	CO_2, N_2O, CH_4
AP	Environmental deterioration: acid rain corrosion	kg SO_2 eq.	SO_x, NO_x
HTP	Health damage	kg 1,4-dichlorobenzene eq.	SO_x, NO_x, PM
POCP	Environmental deterioration: photochemical smog pollution	kg C_2H_4 eq.	SO_x, CO, NMVOC, CH_4

2.4. Sensitivity Analysis

Fuel tank (gas cylinder and oil tank) and engine are two prominent differences between LNG and diesel HDVs. Currently, the technologies of gas cylinders and oil tanks are very mature; however, there is still plenty of room for improvement of engine technology. With the continuous progress and maturity of gas engine technology, equivalence ratio combustion, blending combustion, dual fuel combustion, and high-pressure direct injection will be increasingly applied to engines in the near future. However, the above assessment was conducted based on the current level of engine technology and does not consider the development of engine technology. We selected the fuel consumption rates of LNG and diesel tractor-trailer (L/100 km) to reflect the level of engine technology for the sensitivity analysis. The higher fuel the consumption rate, the worse the fuel economy and vice versa. The development of engine technology alone can lead to a 30% reduction in fuel consumption [45]. The two factors are thus reduced by 30% to examine the influence of that factor on the five categories of environmental impacts.

3. Results and Discussion

3.1. LCI Results

3.1.1. Resource Consumption

The ore material consumption differences between the two alternatives result from the differences in material composition and mass of their fuel tanks and brackets. As shown in Figure 3a, the LNG tractor trailer consumes 227.85 kg more iron ore and 47.37 kg less aluminum ore than its diesel counterpart. This is because the LNG cylinder is made of steel, while the diesel tank is made of Al–Mg alloy.

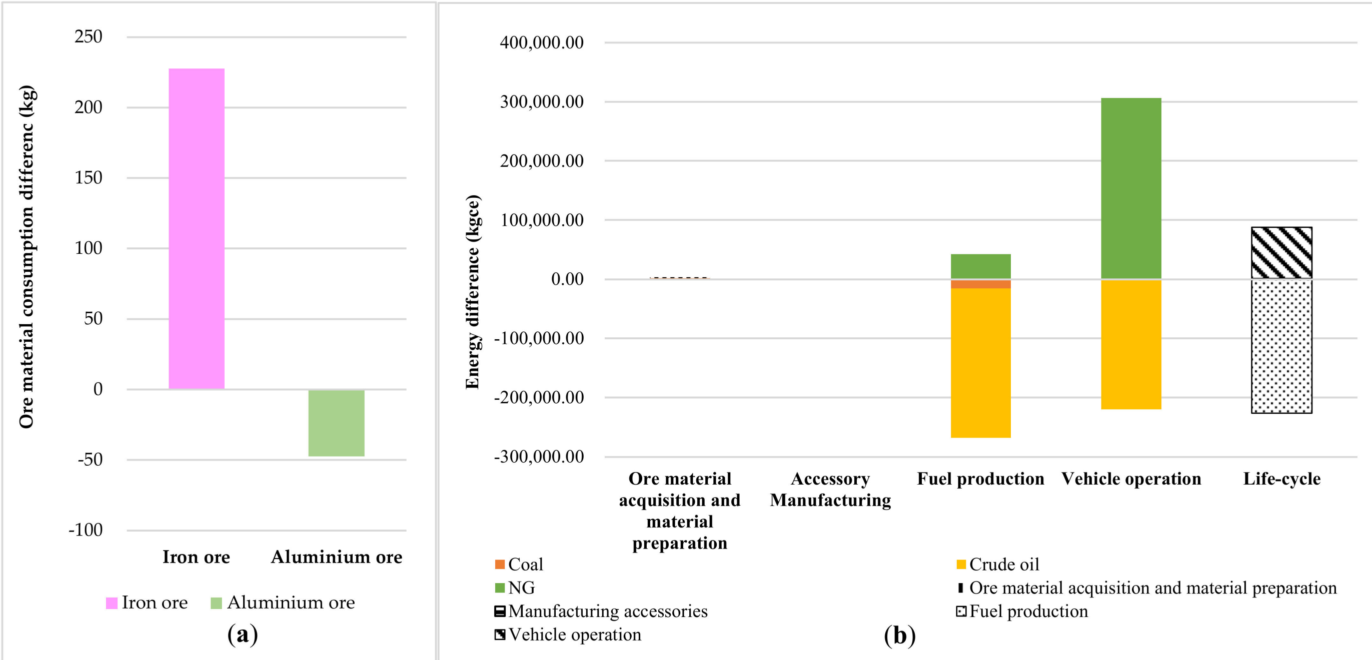

Figure 3. Resource consumption of the LNG tractor-trailer compared to the diesel tractor-trailer: (**a**) ore material; (**b**) energy.

As shown in Figure 3b and Table 5, the life-cycle energy consumption of the LNG tractor-trailer is 138,215.61 kgce lower than that of its diesel counterpart. This result is predominantly caused by the and fuel production stage (71.96%). The energy consumption for operating the LNG tractor-trailer is 86,538.02 kgce higher than that for operating its diesel counterpart, while the energy consumption for producing LNG of the LNG tractor-trailer is 226,132.93 kgce lower than that for producing the diesel of its diesel counterpart. The increase in energy consumption of the LNG tractor-trailer during operation is far less than the reduction in its energy consumption during fuel production. The lower life-cycle energy consumption of the LNG tractor-trailer is mainly due to its much lower crude oil consumption for producing LNG.

Table 5. Energy consumption of the LNG tractor-trailer compared to the diesel tractor-trailer.

Processes / Difference	Ore Material Acquisition and Material Preparation	Accessory Manufacturing	Fuel Production	Vehicle Operation	Life-Cycle
NG (kgce)	−52.33	−3.53	42,096.57	306,381.71	348,422.41
Crude oil (kgce)	−205.53	−0.34	−252,950.12	−219,843.69	−472,999.68
Coal (kgce)	1744.40	−103.37	−15,279.37	0	−13,638.34
Total energy (kgce)	1486.54	−107.24	−226,132.93	86,538.02	−138,215.61

3.1.2. Air Emission

As shown in Figure 4 and Table 6, the LNG tractor-trailer emits 1860.07 kg less NO_x, 423.95 kg less SO_x, 61.00 kg PM, and 15.10 kg less NMVOC, but 2.72 tons more CO_2, 542.93 kg more CO, and 2456.05 kg more CH_4 than its diesel counterpart during the whole life-cycle.

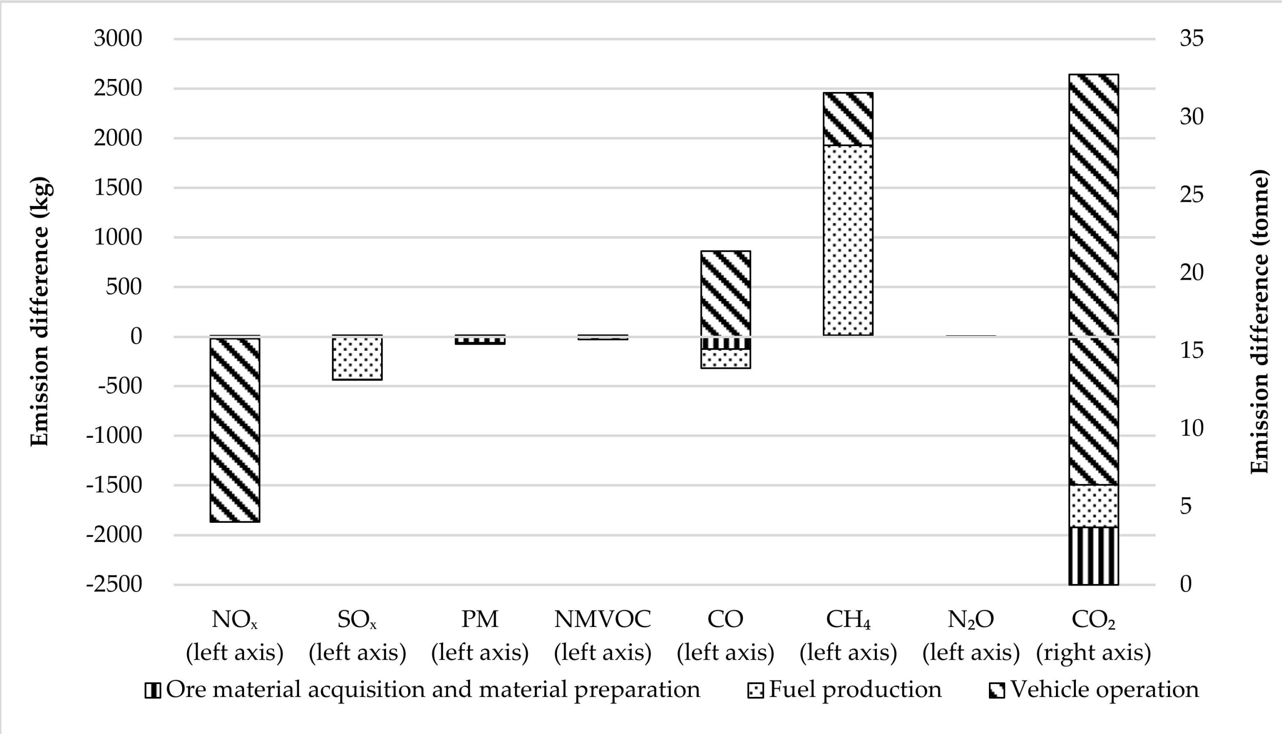

Figure 4. Air emissions of LNG compared to diesel tractor-trailer and contribution of different stages to the emission differences.

Table 6. Air emissions of LNG tractor-trailer compared to diesel tractor-trailer.

Processes / Difference	Ore Material Acquisition and Material Preparation	Fuel Production	Vehicle Operation	Life-Cycle
NO_x (kg)	8.77	−21.9	−1846.94	−1860.07
SO_x (kg)	12.55	−433.48	−3.02	−423.95
PM (kg)	−63.02	14.55	−12.53	−61
NMVOC (kg)	0.06	15.26	−30.42	−15.1
CO (kg)	−126.98	−192.33	862.25	542.93
N_2O (kg)	−0.01	0.01	0	0
CH_4 (kg)	15.17	1914.66	526.22	2456.05
CO_2 (t)	3.68	2.72	26.32	32.72

The ore material acquisition and material preparation stage, fuel production stage, and vehicle operation stage predominantly contribute to the lower life-cycle PM emissions (69.95%), SO_x emissions (96.53%), and NO_x and NMVOC emissions (98.37% and 66.51%), respectively. The PM emission during ore material acquisition and material preparation for the LNG cylinder and its bracket is 63.02 kg lower than that for the diesel tank and its bracket; the SO_x emission during fuel production for the LNG tractor-trailer is 433.48 kg lower than that for its diesel counterpart; and the NO_x and NMVOC emission during operation of the LNG tractor-trailer is, respectively, 1846.94 kg and 30.42 kg lower than that during the operation of its diesel counterpart. The lower life-cycle PM emission of the LNG tractor-trailer is primarily attributable to its lower aluminum consumption and the fact that acquiring and preparing aluminum has a 38.78 times higher PM emission intensity than acquiring and preparing steel (see Table A2), which results in its much lower PM emission during ore material acquisition and material preparation. The lower life-cycle SO_x emissions of the LNG tractor-trailer can be largely attributed to the far lower coal consumption for producing LNG (see Table A2), which leads to much lower SO_x emissions during LNG production. The lower life-cycle NO_x emissions are mainly because operating the LNG tractor-trailer has a NO_x emission intensity 81.14% lower than its diesel counterpart (see Table A2). The lower life-cycle NMVOC emissions of the LNG tractor-trailer are mainly because of its much lower NMVOC emissions during operation.

The fuel production stage and vehicle operation stage contribute most to the higher life-cycle CH_4 emission (77.96%) and CO and CO_2 emissions (72.98% and 80.43%), respectively. The CH_4 emission during fuel production for the LNG tractor-trailer is 1914.66 kg higher than that for its diesel counterpart, while CO and CO_2 emissions during operation of the LNG tractor-trailer are 862.25 kg and 26.32 t higher than that during the operation of its diesel counterpart, respectively. The higher life-cycle CH_4 emissions can be mainly attributed to the fact that producing LNG has a higher CH_4 emission intensity than producing diesel as well as the higher fuel consumption rate of the LNG tractor-trailer, which leads to higher CH_4 emissions during fuel production (see Table A2). The higher life-cycle CO emission is caused by the incomplete combustion of LNG and the higher fuel consumption rate of the LNG tractor-trailer, which brings about more CO emission during the operation of the LNG tractor-trailer. The higher life-cycle CO_2 emissions are primarily driven by the higher fuel consumption rate of the LNG tractor-trailer, which generates more CO_2 emissions during the operation of the LNG tractor-trailer, although the CO_2 emission factor for LNG combustion is only 75.71% of that for diesel combustion (Table A2).

3.2. LCIA Results

As shown in Figure 5 and Table 7, the LNG tractor-trailer has 337.92 kg antimony eq., 1438.78 kg SO_2 eq., and 2689.09 kg 1,4-dichlorobenzene eq. lower ADP, AP, and HTP impacts, respectively, but 101.49 t CO_2 eq. and 6.78 kg C_2H_4 eq. higher GWP and POCP impacts, respectively, than those of the diesel tractor-trailer during the whole life cycle.

Table 7. Environmental impacts of LNG tractor-trailer compared to diesel tractor-trailer.

Difference	Process	Ore material Acquisition and Material Preparation	Accessory Manufacturing	Fuel Production	Vehicle Operation	Recycling	Life-Cycle
ADP (kg antimony eq.)	Coal	0.00	0.00	−0.01	0.00	—	−0.01
	NG	0.00	0.00	0.04	0.30	—	0.34
	Crude oil	−0.15	0.00	−180.89	−157.22	—	−338.26
	Iron ore	0.36	—	—	—	−0.33	0.03
	Aluminum ore	−0.09	—	—	—	0.07	−0.02
	Sum	0.12	—	−180.86	−156.92	−0.26	−337.92
AP (kg SO_2 eq.)	SO_x	15.06	—	−520.17	−3.63	—	−508.74
	NO_x	4.39	—	−10.95	−923.47	—	−930.03
	Sum	19.44	—	−531.12	−927.10	—	−1438.78
GWP (t CO_2 eq.)	CO_2	3.68	—	2.72	26.32	—	32.72
	N_2O	0.00		0.00	0.00	—	0.00
	CH_4	0.42	—	53.61	14.73	—	68.76
	Sum	4.11	—	56.33	41.05	—	101.49
POCP (kg C_2H_4 eq.)	CO	−3.43	—	−5.19	23.28	—	14.66
	NMVOC	0.01	—	2.29	−4.56	—	−2.26
	CH_4	0.09	—	11.49	3.16	—	14.74
	SO_x	0.60	—	−20.81	−0.15	—	−20.36
	Sum	−2.73	—	−12.22	21.73	—	6.78
HTP (kg 1,4-dichlorobenzene eq.)	SO_x	12.05	—	−416.14	−2.90	—	−406.99
	NO_x	10.53	—	−26.28	−2216.32	—	−2232.07
	PM	−51.68	—	11.93	−10.27	—	−50.02
	Sum	−29.11	—	−430.49	−2229.50	—	−2689.09

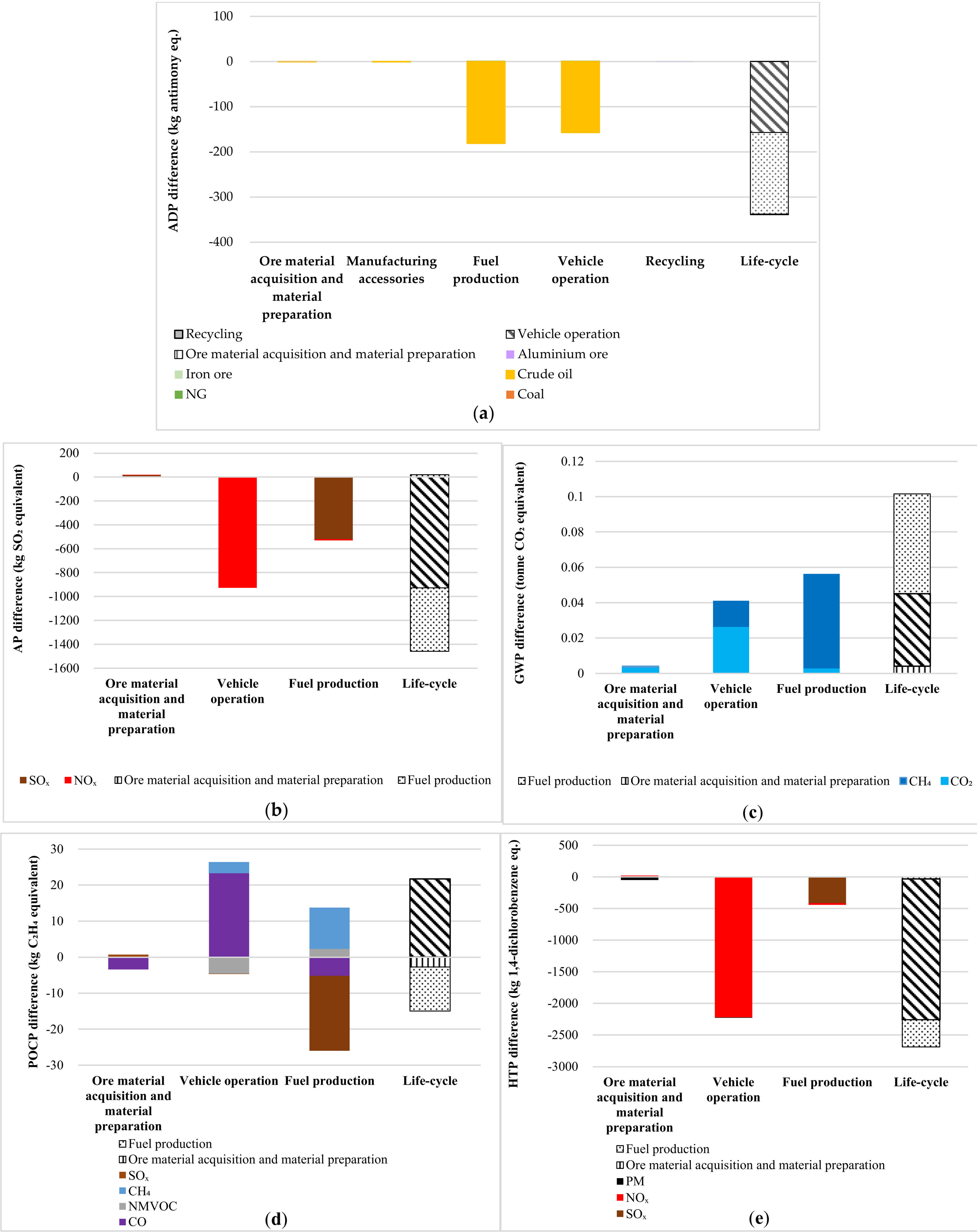

Figure 5. Environmental impacts of LNG tractor-trailer compared to diesel tractor-trailer: (**a**) abiotic depletion potential (ADP); (**b**) acidification potential (AP); (**c**) global warming potential (GWP); (**d**) photooxidant creation potential (POCP); (**e**) human toxicity potential (HTP).

Fuel production and vehicle operation were found to be the main stages contributing to the life-cycle ADP difference (accounting for 53.48% and 46.40% of the whole life cycle, respectively) and GWP difference (accounting for 55.51% and 40.45% of the whole life cycle, respectively). The lower ADP of the LNG tractor-trailer is mainly because of the much lower ADP factor of NG than crude oil and much lower oil consumption for producing LNG and operating the LNG tractor-trailer. The higher GWP impact of the LNG tractor-trailer is mainly caused by its higher CH_4 emissions during fuel production and higher CO_2 emissions during operation.

Vehicle operation was found to be the most critical stage contributing to the difference in life-cycle AP, HTP and POCP impact, accounting for 62.74%, 82.91%, and 59.24%, respectively. The lower AP and HTP impact of the LNG tractor-trailer is mainly because of its lower NO_x emissions during vehicle operation, while the higher POCP impact is mainly attributed to its higher CO emissions during operation.

3.3. Sensitivity Analysis Results

Figure 6 shows how the reduction in fuel (LNG or diesel) consumption rate affects the differences in the five categories of impacts.

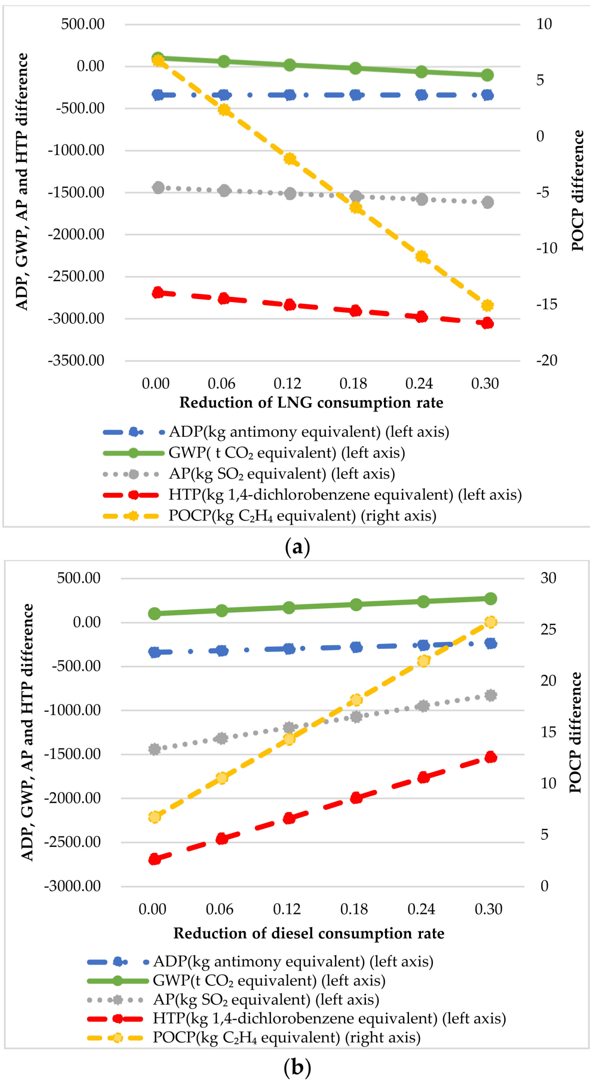

Figure 6. The impact of the fuel consumption rate on the differences in five categories of environmental impacts: (**a**) reduction of LNG consumption rate; (**b**) reduction of diesel consumption rate.

The reduction of 30% in the LNG consumption rate leads to 199.37% and 322.06% decreases in the GWP and POCP differences and 0.23%, 12.21%, and 13.45% increases in the ADP, AP and HTP differences, respectively. The results indicate that the POCP and GWP differences are significantly sensitive to the LNG consumption rate. Conversely, the AP difference and HTP differences are not very sensitive to the LNG consumption rate, and the ADP difference is insensitive to it. This implies that the improvement of LNG engine efficiency would greatly change the comparison results related to photochemical smog pollution and climate change. However, it does not significantly influence acid rain corrosion and human damage and has almost no influence on resource depletion.

Conversely, the reduction of 30% in the diesel consumption rate raises the GWP and POCP differences by 170.58% and 280.00% and decreases the ADP, AP, and HTP differences by 30.22%, 42.61%, and 43.12%, respectively. The results suggest that the POCP and GWP differences are more significantly sensitive to the diesel consumption rate, followed by the HTP difference and AP difference, while the ADP difference is least sensitive to the diesel consumption rate. This implies that the improvement of diesel engine efficiency would more significantly change the comparison results related to photochemical smog pollution and climate change, followed by health damage and acid rain corrosion, but would not have much influence on resource depletion.

Moreover, the sensitivity of the GWP and POCP differences to the LNG consumption rate is more distinguished than that to the diesel consumption rate, but the sensitivity of ADP, AP, and HTP differences to the LNG consumption rate is less distinguished than that to the diesel consumption rate. This suggests that under the same technology development trend of LNG engines and diesel engines, substituting diesel tractor-trailer with LNG tractor-trailer may have greater potential in mitigating photochemical smog pollution and global warming but less potential in saving resources and preventing acid rain corrosion and health damage.

4. Conclusions

With the aim of comparing the environmental performance of LNG tractor-trailer and its diesel counterpart in China comprehensively over the whole life-cycle, we developed a bottom-up calculation model for environmental loads differences between the two alternatives, which covers the ore resource acquisition, material preparation, accessory manufacturing, and vehicle operation and recycling stages. Based on this model, we performed a comprehensive comparative analysis of an LNG tractor-trailer and its diesel counterpart in terms of material consumption, energy consumption, and air emissions by a life-cycle inventory database specific to China. Furthermore, we evaluated the difference between the two alternatives in five categories of environmental impacts using CML 2001 model and investigated the influences of engine technology levels on the these impacts in the sensitivity analysis.

The LCI results of this study imply that replacing the diesel tractor-trailer with the LNG tractor-trailer would reduce aluminum ore consumption, energy consumption, and SO_x, NO_x, PM, and NMVOC emissions but increase iron ore consumption and CO_2, CO, and CH_4 emissions from a life-cycle perspective. These results partly contradict the perception that LNG vehicles "reduce emissions". Moreover, almost no SO_x and PM emissions during LNG combustion is a commonly stated benefit of LNG vehicles over diesel due to the hydrodealkylation, dehydration, and deacidification of LNG. Interestingly, the results of our case study show that instead of the vehicle operation stage, the fuel production stage and ore material acquisition and material preparation stage make a significant contribution to the lower life-cycle SO_x and PM emissions of the LNG tractor-trailer, respectively. It is therefore important to compare the environmental loads of LNG tractor-trailers and their diesel counterparts throughout the whole life-cycle stages, not only the operation stage.

Government statistics show that heavy-duty diesel trucks in China emitted 4,299,000 tons of NO_x and 360,000 tons of PM during operation in 2019, accounting for 69.07% and 52.2% of the total NO_x and PM emissions of in-use vehicles and 34.84% and 0.33% of the national emissions of NO_x and PM in exhaust gas, respectively (Ministry of Ecology and Environment of China, 2020a, 2020b). The LCI results of our study suggest that from a life-cycle perspective, switching diesel HDV to LNG HDV would help meet the national NO_x and PM reduction target.

Although our case study shows that poor fuel economy is the main cause of the higher life-cycle CO_2 emissions of the LNG tractor-trailer, it would have comparable life-cycle CO_2 emissions with diesel if its fuel consumption rate could be reduced by 5.42% (5.42 L/100 km) in the case of the unchanged fuel economy of its diesel counterpart. A transition to the LNG tractor-trailer could generate a reduction of up to 52.73% if the LNG tractor-trailer attains a parity fuel consumption rate with diesel.

The LCIA results indicate that replacing the diesel tractor-trailer with LNG would alleviate resource depletion, acid rain pollution, and health damage but accelerate climate change and photochemical smog pollution from a life-cycle perspective. Interestingly, the LNG tractor-trailer is superior to diesel in terms of resource depletion despite its higher energy consumption (in coal equivalent) during operation. This is mainly because crude oil is much scarcer than natural gas in China, which is reflected in the ADP factor of crude oil and natural gas. This implies that replacing the diesel tractor-trailer with LNG would be greatly favorable for China's energy security even though the fuel economy of the LNG tractor-trailer were much worse than that of its diesel counterpart.

The LCIA results also show that fuel production and vehicle operation are the most critical stages that contribute to the differences in life-cycle environmental impacts between the two alternatives. In other words, the accessory difference between the LNG tractor-trailer and its diesel counterpart has little influence on the LCIA results, while the difference in their fuel consumption predominantly contributes to the LCIA results. The high fuel-consumption rate of the LNG tractor-trailer results in more CO_2 and CO emissions during its operation, which are the main contributors to its higher GWP and POCP impact, respectively. Furthermore, the sensitivity analysis results indicate that if manufacturers can improve the relative efficiency of LNG engines, the LNG tractor-trailer would have better performance when impacted by global warming and photochemical smog pollution. The results of our study imply that the LNG tractor-trailer would have comparable life-cycle GWP and POCP impacts if its fuel consumption rate could be reduced by approximately 15.04% (15.04 L/100 km) and 9.31% (9.31 L/100 km), respectively, in the case of an unchanged fuel economy of its diesel counterpart. A reduction in GWP and POCP impact of up to 44.60% and 49.23%, respectively, is viable if the LNG tractor-trailer attains a parity fuel consumption rate with diesel.

However, there are currently no policies in China that encourage improvements in LNG engine efficiency. Instead, the innovation of LNG engine technology may be held back by the existing Refined Oil Excise Tax. It applies to diesel at a tax rate of CNY 1.2 per liter but excludes LNG [46]. This tax differential is considered to allow lower-efficiency LNG engines to be competitive with diesel because it one-sidedly subsidizes the cost of an LNG vehicle relative to diesel. In addition, the fuel consumption rate of diesel HDVs is required to be published, but this is not mandatory for LNG HDVs in China. Not Requiring this for LNG HDVs would also limit further development of LNG HDV engines by manufacturers. Therefore, policymakers should modify the existing fuel tax policy to better reflect the external costs associated with the current technology of LNG engines. It is also suggested to adopt policies that incentivize manufacturers to improve LNG engine efficiency, such as stricter fuel economy standards on LNG HDVs and subsidies for the advanced technology of LNG engines.

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

Appendix A

Table A1. Main technical and performance parameters of the CAMC tractor-trailer functional unit used in this study.

Vehicle	Diesel Tractor-Trailer	LNG Tractor-Trailer
Boundary dimensions Length × width × height (mm × mm × mm)	7085 × 2550 × 3800	7490 × 2550 × 3800
Tractive weight (t)	40	40
Wheelbase (mm)	3400 + 1350	3800 + 1350
Curb weight (kg)	8700	9680
Volume of feed system (L)	800	1000
Rated power (kW)	327	316
Fuel consumption rate (L/100 km)	44.8	100

Table A2. Specific inventory data for different life-cycle stages.

Life-Cycle Stage	Data Types	Value	
Ore material acquisition and material preparation	Use ratios of materials during ore material acquisition and material preparation (%) (i)	Steel	32.77
		Cast aluminum	22.67
	Integrated energy intensity data for acquiring and preparing steel (kg/kg for raw coal and crude oil, kg/m^3 for natural gas)	Raw coal	1.1548
		Crude oil	0.0094
		Natural gas	0.0046
	Integrated emission intensity data for acquiring and preparing steel (g/kg)	NMVOC	0.0418
		SO_x	9.5569
		NO_x	4.4640
		CO	0.3230
		PM	9.4156
		CH_4	5.3481
		N_2O	0.0062
		CO_2	2133.7190
	Integrated energy intensity data for acquiring and preparing cast aluminum (kg/kg for raw coal and crude oil, kg/m^3 for natural gas)	Raw coal	5.8566
		Crude oil	0.6927
		Natural gas	0.2315

Table A2. *Cont.*

Life-Cycle Stage	Data Types	Value	
	Integrated emission intensity data for acquiring and preparing cast aluminum (g/kg)	NMVOC	25.2767
		SO_x	78.6827
		NO_x	25.2767
		CO	504.9787
		PM	374.7286
		CH_4	11.8997
		N_2O	0.1420
		CO_2	14,098.6340
	Conversion factors from physical unit to coal equivalent (kgce/kg for raw coal and crude oil, kgce/m^3 for natural gas)	Raw coal	0.7143
		Crude oil	1.4286
		Natural gas	1.215 (ii)
Accessory manufacturing	Use ratios of materials during accessory manufacture (%)	Steel	55
		Cast aluminum	80
	Amount of energy consumption for manufacturing fuel tank and bracket (kgce)	LNG tractor-trailer	149
		Diesel tractor-trailer	210
Recycling	Recovery ratio of materials (%)	Steel	93.3
		Cast aluminum	81.3
Fuel production	Amount of energy consumption for producing a unit of LNG (kg/kg for raw coal and crude oil, kg/m for natural gas)	Raw coal	2.4707
		Crude oil	10.3424
		Natural gas	179.3640
	Amount of energy consumption for producing a unit of LNG (Btu/mmBtu)	Raw coal	2470.6820
		Crude oil	10,342.4188
		Natural gas	179,363.9926
	Amount of air emission for producing a unit of LNG (g/kgce) (ii)	NMVOC	0.2157
		SO_x	0.3618
		NO_x	0.8039
		CO	0.5575
		PM	0.0530
		CH_4	6.5327
		N_2O	0.0048
		CO_2	325.5496
	Amount of energy consumption for producing a unit of diesel (kg/kg for raw coal and crude oil, kg/m^3 for natural gas)	Raw coal	0.1488
		Crude oil	1.1882
		Natural gas	0.0701
	Amount of air emission for producing a unit of diesel (g/kgce)	NMVOC	0.2312
		SO_x	2.4746
		NO_x	1.2199
		CO	1.6518
		PM	0.0077
		CH_4	0.3949
		N_2O	0.0066
		CO_2	441.3109
Vehicle operation	Fuel consumption rate (L/100 km)	LNG tractor-trailer	100
		Diesel tractor-trailer	44.8
	Amount of NMVOC, NO_x, CO, PM, and CH_4 emission per unit work for LNG engine operation (g/(kW · h))	NMVOC	0
		NO_x	0.2640
		CO	0.5610
		PM	0.0000
		CH_4	0.2110

Table A2. *Cont.*

Life-Cycle Stage	Data Types	Value	
	Amount of NMVOC, NO_x, CO, PM, and CH_4 emission per unit work for diesel engine operation (g/(kW · h))	NMVOC	0.0170
		NO_x	1.4000
		CO	0.3000
		PM	0.0070
		CH_4	0
	Sulfur in fuel (mg/kg)	LNG	0.0000
		Diesel	10
	CO_2 emission factor of fuel (g/MJ)	LNG	56.10
		Diesel	74.10
	Conversion factor from physical unit to coal equivalent (kgce/MJ for heat, kgce/kW · h for electricity)	Heat	0.03412
		Electricity	0.1229
	Calorific value (MJ/kg)	LNG	49.3381 (iii)
		Diesel	42.652
	Density (kg/L)	LNG	0.455 (iv)
		Diesel	0.843

Note: (i) SinoCenter provides the weight of output material and input ore, so the use ratios of materials during ore material acquisition and material preparation were calculated as the ratio of output material to input ore. (ii) According to the China Energy Statistical Yearbook 2019, the conversion factor of the physical unit of natural gas to coal equivalent is 1.100~1.3300 kgce/m^3, and this study used a median value between 1.100 and 1.3300 for calculation. (iii) The value was calculated as "*Conversion factor from* 1 *million tonnes LNG to million tonnes oil equivalent* (*i.e.*, 1.169) ÷ *Conversion factor from 1 trillion British thermal units to million tonnes oil equivalent* (*i.e.*, 0.025) × *Conversion factor from* 1 *British thermal unit to kilo joules* (*i.e.*, 1.055)", which was obtained from the "Approximate conversion factors" part of the BP Statistical Review of World Energy 2020. (iv) According to https://www.unitrove.com/engineering/gas-technology/liquefied-natural-gas (15 October 2021), LNG has a density of approximately 0.43 kg/L to 0.48 kg/L, and the median value of 0.455 kg/L was taken as the LNG density in this study.

Table A3. Characterization factors of ADP, GWP 100, AP, HTP, and POCP.

Impact Category	Contributor	Characterization Coefficient	Unit
ADP	Crude oil	2.44×10^{-5}	kg antimony eq./MJ
	Natural gas	3.34×10^{-8}	kg antimony eq./MJ
	Coal	2.78×10^{-8}	kg antimony eq./MJ
	Iron	1.05×10^{-4}	kg antimony eq./kg
	Aluminum	3.46×10^{-4}	kg antimony eq./kg
GWP 100	CO_2	1.00×10	kg CO_2 eq./kg
	N_2O	2.65×10^{2}	kg CO_2 eq./kg
	CH_4	2.80×10^{1}	kg CO_2 eq./kg
AP	SO_x	1.20×10	kg SO_2 eq./kg
	NO_x	5.00×10^{-1}	kg SO_2 eq./kg
HTP	SO_x	9.6×10^{-2}	kg 1,4-dichlorobenzene eq./kg
	NO_x	1.20×10	kg 1,4-dichlorobenzene eq./kg
	PM	8.20×10^{-1}	kg 1,4-dichlorobenzene eq./kg
POCP	SO_x	4.80×10^{-2}	kg C_2H_4 eq./kg
	CO	2.70×10^{-2}	kg C_2H_4 eq./kg
	NMVOC	1.50×10^{-1}	kg C_2H_4 eq./kg

Note: Due to data availability, the characterization factors for SO_x and PM were represented by those for SO_2 and PM10.

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