Comparative lifecycle greenhouse gas emissions and their reduction potential for typical petrochemical enterprises in China

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ABSTRACT

Petrochemical enterprises have become a major source of global greenhouse gas (GHG) emissions. Yet, due to the unavailability of basic data, there is still a lack of case studies to quantify GHG emissions and provide petrochemical enterprises with guidelines for implementing energy conservation and emission reduction strategies. Therefore, this study conducted a life cycle assessment (LCA) analysis to estimate the GHG emissions of four typical petrochemical enterprises in China, using first-hand data, to determine possible emission reduction measures. The analytical data revealed that Dushanzi Petrochemical (DSP) has the highest GHG emission intensity (1.17 tons CO_2e/ton), followed by Urumqi Petrochemical (UP) (1.08 tons CO_2e/ton), Dalian Petrochemical (DLP) (average 0.58 tons CO_2e/ton) and Karamay Petrochemical (KP) (average 0.50 tons CO_2e/ton) over the whole life cycle. At the same time, GHG emissions during fossil fuel combustion were the largest contributor to the whole life cycle, accounting for about 77.31%–94.27% of the total emissions. In the fossil-fuel combustion phase, DSP had the highest unit GHG emissions (1.20 tons CO_2e), followed by UP (0.89 tons CO_2e). In the industrial production phase, DLP had the highest unit GHG emissions (average 0.13 tons CO_2e/ton), followed by UP (0.10 tons CO_2e/ton). During the torch burning phase, torch burning under accident conditions was the main source of GHG emissions. It is worth noting that the CO_2 recovery stage has "negative value," indicating that it will bring some environmental benefits. Further scenario analysis shows that effective policies and advanced technologies can further reduce GHG emissions.

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Introduction

Global climate change has become one of the most serious threats humans are faced with in the 21st century (Zhao et al., 2019a). According to the United Nations Intergovernmental Panel on Climate Change (IPCC), most of the rising temperatures observed since the mid-20th century are likely to be caused by increased greenhouse gas (GHG) concentrations (IPCC, 2007), and fossil fuel consumption is a major source of these emissions (Alicja, 2015). Global GHG emissions growth was 2.0% in 2018 and there is as yet no sign of any of these emissions peaking (PBL, 2019). Petrochemicals and their by-

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products, however, contribute a great deal to the prosperity of industrialization-based urbanization despite their negative impact on the environment. They provide both job opportunities and integration with other industrial sectors through mid-range products (Park, 2005). The petrochemical industry has therefore become a highly sought-after field for many industrialized/industrializing countries (Wu et al., 2015), and China has been no exception. Petrochemicals still play a vital role in China's economic development (Burnham et al., 2012). In 2016, China's energy consumption accounted for more than 23% of the world's total energy consumption, and their GHG emissions accounted for nearly 30% of the world's total emissions (Zhou et al., 2014).

One of the most effective measures to reduce GHG emissions is to focus on key industrial sectors and allocate emission reduction targets to these sectors (Hao et al., 2017; Alivia et al., 2019). The petrochemical industry is one of these key industrial sectors, and in addition to emitting GHGs when its products are burned, it also consumes considerable energy, and has become one of the main sources of GHG emissions from the production aspect as well as from the consumption one (Liu et al., 2007; Tao et al., 2009). According to the statistics published by the National Development and Reform Commission, petrochemical enterprises constitute more than one-third of key high-energy-consuming enterprises (340 of 1000). In 2000, the petrochemical industry consumed 270.4 million tons of standard coal, about 28.3% of the country's industrial energy consumption. In 2017, the industry's consumption reached 795.5 million tons of standard coal, 27.0% of industrial energy consumption (NBS, 2000, 2019). As an energy-intensive industry with high GHG emissions and high energy consumption, the petrochemical industry needs more research on its GHG emissions (Yune et al., 2016).

Because of the increasing awareness of GHG emissions and pressure from various governmental bodies and environmental activists, many studies have been conducted to analyze the petrochemical industry's energy consumption and its environmental impact (Glew et al., 2012; Ravanchi et al., 2011). Fan et al. (2015) used the Log-Mean Divisia Index method to quantitatively analyze the change in GHG emissions in China's petrochemical industry and decomposed it into economic output effect, industrial structure effect, and technological effect. Zhang et al. (2019) utilized a logarithmic mean decomposition index method to explore the driving force of changes in GHG emissions in the petrochemical industry. Usapein et al. (2017) used the Measurable, Reportable, and Verifiable (MRV) guidelines for the Thailand Voluntary Emission Trading System (Thailand V-ETS), so that the factories participating in this system can effectively, consistently, reliably, and compatibly report their GHG emissions. Using first-hand data from 23 coal chemical companies, Zhang et al. (2019) reported the local GHG emission factors for coal chemical products in China and extrapolated the total GHG emissions from China's coal chemical industry. Han et al. (2017) proposed energy and GHG emission analysis and a prediction method to analyze key parameters affecting energy and GHG emissions of complex petrochemical systems. Lu et al. (2020) adopted the backpropagation neural network (BP) model to predict the future GHG emissions of the heavy chemical industry for 2017–2035. Huang et al. (2019) exploited constrained non-

linear programming to optimize the deployment technology and process of the coal chemical industry for GHG emission reduction. Lee et al. (2013) identified three technical strategies for the petrochemical industry using cluster analysis, to lessen GHG emissions: "wait-and-see," "in-process-focused" and "all-round" strategies. Although many researchers have made great efforts to estimate and reduce GHG emissions in the petrochemical industry, there is currently no systematic analysis from a life cycle perspective. Therefore, this study aims to take four typical petrochemical enterprises in China as an example to explore potential GHG emissions and reductions in the petrochemical industry.

Taking typical petrochemical enterprises in China as the case study, this analysis aims to: (1) apply the Life Cycle Assessment (LCA) method to estimate the GHG emissions of four typical petrochemical enterprises; (2) analyze the GHG emission differences of petrochemical enterprises with different crude oil processing capacities; (3) understand GHG emissions in different processes of the petrochemical industry; and (4) identify the major contributors and find effective measures to reduce GHG emissions. We believe that this perception of the current petrochemical enterprises will lay a good foundation for reducing GHG emissions in China.

1. Materials and methods

1.1. Typical petrochemical enterprises

In this study, we selected four typical petrochemical enterprises in China from Xinjiang Province to Liaoning Province. Among these enterprises, Dalian Petrochemical (DLP) and Karamay Petrochemical (KP) are fuel-lubricant refineries, and Dushanzi Petrochemical (DSP), and Urumqi Petrochemical (UP) are fuel-chemical refineries. Basic information about the sample enterprises is displayed in Table 1.

1.2. Goals and scope

This study aims to apply the LCA method to evaluate GHG emissions from four typical petrochemical enterprises in China and discover potential opportunities for GHG emissions reduction. We first investigate the life cycle GHG emissions of the petrochemical enterprises, and identify the primary sources and key steps of GHG emissions generation. Four scenarios are set, to determine effective measures for potential GHG emissions mitigation. To eliminate the influence of different time periods and enterprise scales, this study adopts crude oil processing of one ton as the functional unit.

The scope of this study considers the petrochemical processes of four major petrochemical enterprises (DLP, DSP, KP, UP) in China. As is well known, a relatively full life cycle of the petrochemical production process consists of the extraction of crude oil, the operation of the petrochemical enterprise, and the export of petrochemical products. Considering the purpose of the study and the availability of data, this study mainly focuses on GHG emissions in the operation stage of the petrochemical enterprise. At the same time, indirect emissions of imported crude oil and raw materials are also considered. As

Table 1 – Basic information of sample enterprises.

| Sample	Crude oil processing capacity (million tons/year)	Type	Raw material	Product
Dalian Petrochemical (DLP)	20.5	Fuel oil-Lubricant oil	Russian sour crude oil, low-sulfur mixed crude oil or Daqing crude oil	Fuel oil, lubricant base oil, paraffin, benzene, polypropylene, etc.
Dushanzi Petrochemical (DSP)	10	Fuel oil - Chemical	Kazakhstan high-sulfur crude oil	Fuel oil, polyolefin, rubber, aromatic hydrocarbons, etc.
Urumqi Petrochemical (UP)	8.5	Fuel oil - Chemical	Xinjiang crude oil	Fuel oil, chemical feedstock oil, delayed petroleum coke, industrial sulfur, etc.
Karamay Petrochemical (KP)	6	Fuel oil-Lubricant oil	Northern Xinjiang crude oil	Fuel oil, lubricating oil, asphalt, etc.
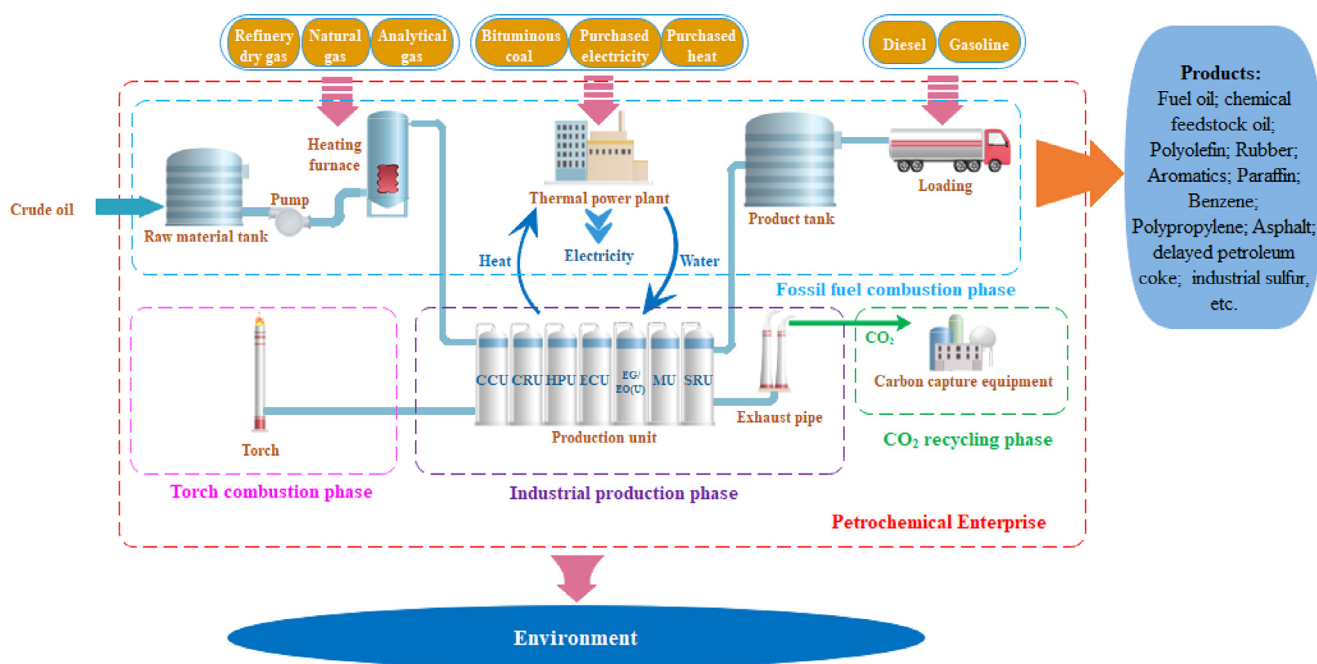
Fig. 1 – System boundary of petrochemical plants.

shown in Fig. 1, the operation phase of petrochemical enterprises includes fossil fuel combustion, industrial production, torch combustion and CO_2 recovery. Due to lack of a local LCA database, the emissions of crude oil extraction will refer to the Ecoinvent 3.3 database (Ecoinvent, 2019).

Although the geographical scope of this study is limited to four typical petrochemical enterprises, the electricity and heat imported from other regions will be included in this study. For the research period, we will consider the time ranges from DLP (2016–2017), DSP (2017), KP (2016–2018), and UP (2018).

1.3.   LCA methods

In this study, the LCA method was mainly used to estimate the GHG emissions (GWP100) of petrochemical enterprises expressed in combination with the emission factors of "GHG

Emission Accounting Methods and Reporting Guidelines for Petrochemical Enterprises in China (Trial)". The appropriate quantitative method is chosen for all recognizable emission sources in this study (Zhao et al., 2019b). The industry GHG emissions can then be reckoned by accumulating emissions from each source (Donald et al., 2015; Pandey et al., 2011). The nomenclature of calculation parameters is shown in Table 2.

Considering the availability of data, this research focuses on fuel consumption and raw material consumption in industrial production processes, while ignoring some exhaust gas treatment materials and carbon capture materials. Thus, the total GHG emissions (Q_t) of the petrochemical enterprise are then calculated, as shown in Eq. (1).

$$Q_t = E_f + E_i + E_t + R_C \qquad (1)$$

Table 2 – Nomenclature of calculation parameters.

Nomenclature	Parameters	Nomenclature	Parameters
Q_t	Total GHG emissions per ton (tons CO_2e)	E_f	GHG emissions per ton in the fossil fuel combustion phase (tons CO_2e)
E_i	GHG emissions per ton in the industrial production phase (tons CO_2e)	E_t	GHG emissions per ton in the torch burning phase (tons CO_2e).
R_C	GHG emissions from CO_2 recycling (tons CO_2e)	i	type of fossil fuel
j	The serial number of the facility or accidents	$AD_{i,j}$	Consumption of fossil fuel (tons or ten thousand Nm^3)
$CC_{i,j}$	The carbon content of fossil fuel (tons carbon/ton or tons carbon/ten thousand Nm^3)	OF	Carbon oxidation rate (%)
AD_f	Consumption of fossil fuel in the thermal power plant (TPP) (GJ)	EF_f	The GHG emission factor of fossil fuel (tons CO_2e/GJ or tons CO_2/MWh)
E_p	GHG emissions from the net purchased electricity and heat (tons CO_2e).	NCV	The low calorific value of fossil fuel (GJ/tons or GJ/ten thousand Nm^3)
FC_e	Net consumption of the eth fossil fuel from TPP (tons or ten thousand Nm^3).	CC_e	Carbon content per unit calorific value (tons C/GJ)
AD_e	Net purchased electricity consumption (MWh)	AD_h	Net purchased heat consumption (GJ)
EF_e	The GHG emission factor of electricity (tons CO_2e/MWh)	EF_h	The GHG emission factor of heat (tons CO_2e/GJ)
E_c	GHG emissions per ton from catalytic cracking unit (CCU) (tons CO_2e)	E_r	GHG emissions per ton from catalytic reforming unit (CRU) (tons CO_2e)
E_h	GHG emissions per ton from hydrogen production unit (HPU) (tons CO_2e)	E_e	GHG emissions per ton of ethylene cracking unit (ECU) (tons CO_2e)
E_g	GHG emissions per ton from ethylene glycol/ethylene oxide unit (EG/EO(U)) (tons CO_2e)	E_m	GHG emissions per ton from methanol unit (MU) (tons CO_2e)
R_s	GHG emissions per ton from sulfur recovery unit (SRU) (tons CO_2e)	MC_j	The amount of charring in CCU (tons)
CF_j	Average carbon content of the catalyst coking in CCU (ton carbon/ton coke)	MR_j	The amount of catalyst to be regenerated in CRU (tons)
CF_{bj}	The carbon content on the catalyst before the regeneration of the jth set of the CRU (%)	CF_{aj}	The carbon content on the catalyst after the regeneration of the jth set of the CRU (%)
AD_r	The input of production raw material r (tons or ten thousand Nm^3)	CC_r	The average carbon content of raw material r (tons C/tons or tons C/ten thousand Nm^3)
Q_{sg}	The output of synthesis gas produced by the HPU (ten thousand Nm^3)	CC_{sg}	The carbon content of the syngas produced by the HPU (%)
Q_w	The amount of various carbon-containing wastes produced by the device (tons)	CC_w	The carbon content of carbon-containing waste w (tons C/tons)
$Q_{wg,j}$	The average flow rate of the burnt tail gas of the furnace tube of the jth ECU (Nm^3/hr)	T_j	The annual cumulative scorching time of the jth ECU (hr/year)
$Con_{CO2,j}$	The volume concentration of CO_2 in the burning tail gas of the furnace tube of the jth set of ECU (%)	$Con_{CO,j}$	The volume concentration of CO in the burning tail gas of the furnace tube of the jth set of ECU (%)
RE_j	The amount of ethylene raw material used in the jth EGU (tons)	REC_j	The carbon content of ethylene raw material of the jth EGU (tons C/tons)
EO_j	The output of ethylene oxide product of the jth EGU (tons)	EOC_j	The carbon content of ethylene oxide in the j th EGU (tons C/ tons)
r	The serial number of the carbon-containing raw material of the MU	p	The serial number of the carbon-containing product of the MU
w	The serial number of carbon-containing waste in the MU	Y_p	The output of product p (tons or ten thousand Nm^3)
Q_{ag}	The amount of acid gas recovered (ten thousand Nm^3)	P	The purity of the CO_2 (%)
E_n	GHG emissions per ton from torch gas combustion under normal operating conditions (tons CO_2e)	E_a	GHG emissions per ton from torch gas combustion caused by accidents (tons CO_2e)
Q_n	The torch gas flow rate of the torch system under normal operating conditions (ten thousand Nm^3)	CC_n	The total carbon content of carbon compounds other than CO_2 in the torch gas (tons C/ten thousand Nm^3)
V_{CO_2}	Volume concentration of CO_2 in the torch gas (%)	n	Various gas components of flare gas, excluding CO_2
V_n	Volume concentration of the nth carbon-containing compound in the torch gas except CO_2 (%)	CN_n	The number of carbon atoms in the chemical formula of the nth carbon compound in the torch gas
GF_{aj}	Average torch flow velocity in the jth accident state (ten thousand Nm^3/hr)	T_{aj}	Duration of the jth accident (hr)
CN_{nj}	The average number of carbon atoms in the mole component of torch gas in the jth accident	Q_o	The volume of CO_2 gas recovered and supplied externally (ten thousand Nm^3)
Q_i	The volume of CO_2 gas recovered and used as a raw material for production (ten thousand Nm^3)	P_O	The purity of the CO_2 external supply gas (%)
P_i	The purity of CO_2 feed gas (%)	CC_p	The carbon content of product p (tons C/ tons)

1.3.1. Fossil fuel combustion phase

In this study, the GHG emissions from the fossil fuel combustion mainly refer to fuel oil, dry gas of refineries, gasoline, diesel, etc. used in the production unit (PU), thermal power plant (TPP) and mobile sources (MS), and net purchased electricity and heat. Total GHG emissions of fossil fuel combustion are expressed in Eq. (2).

$$E_f = \sum_j \sum_i \left(AD_{i,j} \times CC_{i,j} \times OF_{i,j} \times 44/12 \right) + \sum_{i=1}^{n} AD_f \times EF_f + E_p \tag{2}$$

The carbon content of fossil fuels can be expressed in Eq. (3).

$$CC_i = NCV_i \times EF_i \tag{3}$$

The activity level of the eth fossil fuel can be expressed in Eq. (4).

$$AD_e = NCV_e \times FC_e \tag{4}$$

The carbon dioxide emission factor of fossil fuel can be expressed in Eq. (5).

$$EF_e = CC_e \times OF_e \times 44/12 \tag{5}$$

The GHG emissions implied by the net purchased electricity and heat can be expressed in Eq. (6).

$$E_p = AD_e \times EF_e + AD_h \times EF_h \tag{6}$$

1.3.2. Industrial production phase

In this study, the industrial production process includes catalytic cracking, catalyst scorching, catalytic reforming catalyst regeneration, hydrogen production process, sulfur recovery, etc. The GHG emissions of industrial production processes should be equal to the sum of the GHG emissions of each production facility. The GHG emissions of the industrial processes are expressed in Eq. (7).

$$E_i = E_c + E_r + E_h + E_e + E_g + E_m + R_s \tag{7}$$

(1) Catalytic cracking unit (CCU)

The catalytic cracking processes generate coke as a by-product which reduces its catalytic properties because it collects on the active surface. Therefore, it is necessary to improve the catalyst activity by burning the coke (Ferella et al., 2016). The GHG emissions in the continuous scorching process of the catalytic cracking unit are expressed in Eq. (8).

$$E_c = \sum_{j=1}^{N} \left(MC_j \times CF_j \times OF \times 44/12 \right) \tag{8}$$

(2) Catalytic reforming unit (CRU)

Catalytic reforming is a chemical process used to transform low-octane numbers produced during petroleum refining into high-octane numbers of liquid products (Portha et al., 2010).

The GHG emissions during intermittent charring of the catalytic reforming unit are expressed in Eq. (9).

$$E_r = \sum_{j=1}^{N} (MR_j \times (1 - CF_{bj}) \times (CF_{bj}/(1 - CF_{bj})$$
$$- CF_{aj}/(1 - CF_{aj}) \times OF_j \times 44/12) \tag{9}$$

(3) Hydrogen production unit (HPU)

The GHG emissions of the hydrogen production unit are calculated by the carbon mass balance method, and the CO_2 used as the production raw material should also be included in the raw material input. The GHG emissions of the hydrogen plant can be expressed in Eq. (10).

$$E_h = \sum_{j=1}^{N} (AD_r \times CC_r - (Q_{sg} \times CC_{sg} + Q_w \times CC_w)) \times 44/12 \tag{10}$$

(4) Ethylene cracking unit (ECU)

Industrial ethylene is the pillar of the petrochemical industry, and its yield reflects the development level of the petrochemical industry in a country (Yuan et al., 2019). Its GHG emissions also account for the important all-around index for measuring the technical performance of units (Geng et al., 2017). The GHG emissions of the ethylene cracking unit comes from the coking emissions after coking, onto the inner wall of the furnace tube. The emissions can be determined according to the gas flow at the exhaust port of the furnace tube and the concentration of CO_2 and CO in the process of coking. The GHG emissions of the ethylene cracking unit can be expressed in Eq. (11).

$$E_e = \sum_{j=1}^{N} \left(Q_{wg,j} \times T_j \times \left(Con_{CO2,j} + Con_{CO,j} \right) \times 19.7 \times 10^{-4} \right) \tag{11}$$

(5) Ethylene glycol/Ethylene oxide unit (EG/EO(U))

In the process of oxidizing ethylene to produce ethylene glycol, the oxidation of ethylene to ethylene oxide units will produce GHG emissions, and the emissions can be calculated using the carbon mass balance method. The GHG emissions of ethylene glycol/ethylene oxide production unit can be expressed in Eq. (12).

$$E_g = \sum_{j=1}^{N} \left(\left(RE_j \times REC_j - EO_j \times EOC_j \right) \times 44/12 \right) \tag{12}$$

(6) Methanol unit (MU)

According to the calculation method of production facilities for other products in the "Chinese Petrochemical Enterprises Greenhouse Gas Emissions Accounting Methods and Reporting Guidelines (Trial)," the carbon mass balance method is used to calculate the GHG emissions of methanol production facilities. The GHG emissions of the methanol production unit can be expressed in Eq. (13).

$$E_m = \left(\sum_r (AD_r \times CC_r) - \left(\sum_p (Y_p \times CC_p) + \sum_w (Q_w \times CC_w) \right) \right)$$
$$\times 44/12 \tag{13}$$

(7) Sulfur recovery unit (SRU)

At this stage, the mass balance method is used to calculate the CO_2 emissions of sulfur recovery acid gas, which can be expressed by Eq. (14).

$$R_s = (Q_{ag} \times P) \times 19.7 \tag{14}$$

1.3.3. Torch combustion phase

The torch combustion can be divided into the combustion under normal working conditions and that under accident working conditions. Since the data monitoring bases of the two types of torch gas differ, they are calculated separately. The GHG emissions of the torch combustion phase can be expressed in Eq. (15).

$$E_t = E_n + E_a \tag{15}$$

(1) The GHG emissions under normal operating conditions can be expressed in Eq. (16).

$$E_n = \sum_j \left(Q_n \times (CC_n \times OF \times 44/12 + V_{CO_2} \times 19.7) \right) \tag{16}$$

CC_n can be expressed in Eq. (17).

$$CC_n = \sum_n ((12 \times V_n \times CN_n \times 10)/22.4) \tag{17}$$

(2) The GHG emissions caused by an accident can be expressed in Eq. (18).

$$E_a = \sum_j \left(GF_{aj} \times T_{aj} \times CN_{nj} \times (44/22.4) \times 10 \right) \tag{18}$$

1.3.4. CO_2 recycling phase

Carbon capture and utilization (CCU) technologies—some of the crucial means for addressing global climate change—can help meet emissions targets while still using fossil fuels (Fan et al., 2019; Shen et al., 2020). At present, the CCU technology of petrochemical enterprises absorbs CO_2 through the ethanolamine amine (MEA) liquid chemical absorption method, then heats the steam to separate out the CO_2 under the action of a rich solvent, which is used to produce food-grade CO_2, injecting CO_2 into a well originally used to extract oil and then used for geological storage. The amount of CO_2 recycled can be expressed in Eq. (19).

$$R_C = (Q_o \times P_O + Q_i \times P_i) \times 19.7 \tag{19}$$

1.4. Lifecycle data inventory

1.4.1. Basic data

This research collected the first-hand information of four typical petrochemical enterprises in China through field investigation and analysis of environmental monitoring reports and GHG emission reports. In the field investigation, we used a combination of an on-site survey, engineer interviews and questionnaire surveys. Then we created a standardized data list for each company, including all processes, raw materials, products, emission factors, and calculation coefficients within the study boundary (Appendix A).

1.4.2. GHG emission factors

GHG emission factors and calculation coefficients are crucial for estimating GHG emissions from petrochemical enterprises. Here, GHG emissions can be divided into three categories: fossil fuel combustion, industrial processes, and torch combustion.

(1) Fossil fuel combustion phase

Due to the lack of local LCA data, the GHG emission factors and calculation coefficients during the combustion of fossil fuels followed the approach in "Accounting Methods and Reporting Guidelines for GHG Emissions of Petrochemical Enterprises in China (Trial)," hereinafter referred to as "PC GHG accounting guidelines" (Standard for Petrochemical GHG Emission Calculation, 2013), "Accounting Methods and Reporting Guidelines for GHG Emissions of Power Generation Enterprises in China (Trial)," hereinafter referred to as "PG GHG accounting guidelines" (Standard for Power Generation Enterprises GHG Emission Calculation, 2013), and the "Laboratory Information Management System (LIMS)." If the data were not available, this study used the "recommended values of national Carbon Emission Trading System help platform," hereinafter referred to as "ETS Helpdesk" (China National ETS Helpdesk, 2019), and the "recommended values of Ecoinvent 3.3 database" (Ecoinvent, 2019) to estimate GHG emissions, as shown in Table 3.

The GHG emission factors for electricity and heat followed the "Average GHG Emission Factors for China's Regional Power Grids in 2011 and 2012" (Baseline emission factors of China's regional power grid, 2013) and the "PC GHG accounting guidelines" (Standard for Petrochemical GHG Emission Calculation, 2013), as shown in Table 4.

(2) Industrial production phase

The emission factors and calculation coefficients in the industrial process mainly came from the "PC GHG accounting guidelines" (Standard for Petrochemical GHG Emission Calculation, 2013), "LIMS," and the internal measured values of the enterprises, as shown in Table 5. When calculating carbon content based on element conservation, molecular formula, and substance purity, the purity of ethylene raw material is 99.98%, the purity of ethylene oxide is 100%, the purity of CO_2 is 100% and the purity of methanol is 99.99%.

(3) Torch combustion phase

The emission factors and calculation coefficients during the torch combustion process are CC_n, OF, V_{CO_2}, and CN_n. Due to the lack of local LCA data, OF and CN_n use the default values in the "PC GHG accounting guidelines" (Standard for Petrochemical GHG Emission Calculation, 2013). The CC_n in DLP and KP uses the default values in the "PC GHG accounting guidelines" (Standard for Petrochemical GHG Emission Calculation, 2013). However, CC_n and V_{CO_2} of DSP will be measured, as shown in Table 6.

Table 3 – Main GHG emission factors and calculation coefficients during fossil fuel combustion.

Use	Type		Value	Unit	Data sources
Petrochemical	Crude oil		0.227	tons CO$_2$e/ton	Ecoinvent 3.3
	NCV	Natural gas	389.310	GJ/ten thousand Nm^3	Accounting Methods and Reporting Guidelines for GHG
		Refinery dry gas	46.05	GJ/ton	Emissions of Petrochemical
		Diesel - mobile source	43.33	GJ/ton	Enterprises in China (Trial) (PC
		Gasoline - mobile source	44.8	GJ/ton	GHG accounting guidelines)
	OF	Fuel oil	98	%	
		Natural gas	99	%	
		Refinery dry gas	99	%	
		Diesel - mobile source	98	%	
		Gasoline - mobile source	98	%	
		Analytical gas	99	%	
		Bituminous coal	98	%	Carbon Emission Trading System help platform (ETS Helpdesk)
	CC	Fuel oil	0.021	tons C/GJ	PC GHG accounting guidelines
		Natural gas	0.015	tons C/GJ	
		Refinery dry gas	0.018	tons C/GJ	
		Diesel - mobile source	0.020	tons C/GJ	
		Gasoline - mobile source	0.019	tons C/GJ	
		Analytical gas	0.014	tons C/GJ	Laboratory Information Management System (LIMS)
		Bituminous coal	0.034	tons C/GJ	ETS Helpdesk
Thermal power plant	CC	Bituminous coal-DSP	0.020	tons C/GJ	LIMS
		Bituminous coal-KP	0.026	tons C/GJ	ETS Helpdesk
		Bituminous coal-UP	0.034	tons C/GJ	
		Natural gas	0.015	tons C/GJ	Accounting Methods and
		Refinery dry gas	0.018	tons C/GJ	Reporting Guidelines for GHG
	OF	Bituminous coal	98	%	Emissions of Power Generation
		Natural gas	99	%	Enterprises in China (Trial) (PG
		Refinery dry gas	98	%	GHG accounting guidelines)

Table 4 – Main GHG emission factors for electricity and heat.

Use		Value	Unit	Data sources
Electricity	DLP	0.7769	tons CO$_2$e /MWh	Average GHG emission factors of Northeast China Power Grid in 2011 and 2012
	DSP UP KP	0.6671		Average GHG emission factors of Northwest China Power Grid in 2011 and 2012
Heat		0.11	tons CO$_2$e /GJ	PC GHG accounting guidelines

2. Results

2.1. *Fossil fuel combustion phase*

GHG emissions per unit is an important index for energy conservation and GHG emission reduction (Zhou et al., 2014). As shown in Table 7, DSP had the highest unit GHG emissions (1.20 tons CO$_2$e/ton), followed by UP (0.89 tons CO$_2$e/ton),

DLP (average 0.40 tons CO$_2$e/ton) and KP (average 0.38 tons CO$_2$e/ton). The main reason for the high unit GHG emissions may be the high proportion of bituminous coal consumption, which accounts for 55.49% and 34.19% of the total emissions in DSP and UP, respectively. It is worth noting that the unit GHG emissions of DSP and UP are significantly higher than those of DLP and KP, a result that may be related to the target products. As the operating status of fuel-chemical enterprises (DSP and UP) is frequently affected by the nature of upstream

Table 5 – Main GHG calculation coefficients during industrial processes.

Sample	Type		Value			Unit	Data sources
			2016	2017	2018		
DLP	CF_j	Catalytic (II)	93.46	91	#	%	Internal estimates
		Catalytic (III)	93.3	93.8	#	%	
		Catalytic (IV)	92.94	92.94	#	%	
	CF_{bj}	Reformer (600,000 tons)	3.3	5.31	#	%	Catalyst test of reformer in enterprise
		Reformer (2,200,000 tons)	4.12	4.67	#	%	
	CF_{aj}	Reformer (600,000 tons)	0.05	0.18	#	%	
		Reformer (2,200,000 tons)	0.05	0.05	#	%	
	OF (char)		98	98	#	%	PC GHG accounting guidelines
	CC_r (liquid hydrocarbons) - HPU		85	85	#	%	Device design parameters
DSP	$Con_{CO2,j}$		#	1.0289	#	%	LIMS
	$Con_{CO,j}$		#	0.000368	#	%	
	REC_j		#	0.857	#	tons C/ton	Calculated
	EOC_j		#	0.5455	#	tons C/ton	
	CC_r (natural gas) - MU		#	5.4284	#	tons C/ton	PC GHG accounting guidelines
	CC_r (methane) - MU		#	0.75	#	tons C/ton	Calculated
	CC_p (CO_2) - MU		#	0.2727	#	tons C/ton	
	CC_p (methanol) - MU		#	0.375	#	tons C/ton	
	P (new area)		#	3.05	#	%	LIMS
	P (old area)		#	13.42	#	%	
UP	CF_j		#	#	100	%	PC GHG accounting guidelines
	OF (char)		#	#	98	%	
KP	CF_j		100	100	100	%	PC GHG accounting guidelines
	OF (char)		98	98	98	%	
	CF_{bj}		3	4	3.9	%	Analytical test
	CF_{aj}		0.01	0.08	0.092	%	
	CC_r (natural gas) - HPU		5.956	5.956	5.956	tons C/ten thousand Nm^3	PC GHG accounting guidelines
	P		0	21.18	20.77	%	Sulfur recovery unit acid gas detection data table

means that the data is unpublished.

raw materials and the demand for downstream products, unnecessary losses will be generated during the adjustment of operating parameters. These results indicated that it is most important to improve the energy transformation efficiency of fossil fuels and CCU from the gas stream, before combustion, for minimizing the direct GHG emissions.

2.2. Industrial production phase

The GHG emission intensity in the industrial production phase mainly refers to the GHG emissions from coke burning and raw material consumption (liquid hydrocarbon, ethylene, methane, etc.). As can be seen in Table 7, DLP had the highest unit GHG emissions (average 0.13 tons CO_2e/ton), followed by UP (0.10 tons CO_2e/ton), DSP (0.07 tons CO_2e/ton) and KP (average 0.03 tons CO_2e/ton). The main reason for the high GHG emission intensity may be too much coke burning in the production plant. Coke burning occurs mainly in CCU and CRU. CCU, especially, has the largest GHG emission intensity, accounting for more than 69% of the total emissions in all the enterprises except DSP. In DSP, the ECU has the highest GHG emission intensity, which mainly refers to the excessive residence time of the material in the furnace tube, and to increased coking. It can be seen that choosing high-efficiency

Table 6 – Main GHG calculation coefficients during torch combustion.

Category	Sample		Value	Unit	Data sources
CC_n	DLP		16.07	tons C/ten thousand Nm^3	PC GHG accounting guidelines
	DSP	Low-pressure flare gas	2.352	tons C/ten thousand Nm^3	LIMS
		Acid gas flare gas	0.023	tons C/ten thousand Nm^3	In-plant analysis of data
	KP		5.956	tons C/ten thousand Nm^3	PC GHG accounting guidelines
OF	All Petrochemical		98	%	
V_{CO_2}	Low-pressure flare gas		0.23	%	LIMS
	Acid gas flare gas		1.46	%	In-plant analysis of data
CN_n	Refining system		5		PC GHG accounting guidelines
	Chemical system		3		

Table 7 – Lifecycle GHG emission intensity of four typical petrochemical enterprises (tons CO_2 e/ton).

Phase	Item	DLP 2016	2017	Mean	DSP 2017	UP 2018	KP 2016	2017	2018	Mean
Fossil fuel combustion	Crude oil	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
	Fuel oil	0.07	0.07	0.07	2.57×10^{-4}	2.10×10^{-3}	0	0	0	0
	Refinery dry gas	0.10	0.11	0.10	0.05	0.12	0.08	0.08	0.08	0.08
	Natural gas	0	0	0	0.04	0.07	0.01	0.01	0.01	0.01
	Analytical gas	0	0	0	0.13	0	0	0	0	0
	Bituminous coal	0	0	0	0.76	0.47	0.04	0.05	0.09	0.06
	Diesel	5.09×10^{-5}	6.34×10^{-5}	5.72×10^{-5}	0	1.51×10^{-4}	5.11×10^{-6}	4.05×10^{-6}	9.22×10^{-7}	3.36×10^{-6}
	Gasoline	5.09×10^{-5}	6.34×10^{-5}	5.72×10^{-5}	0	1.51×10^{-4}	5.11×10^{-6}	4.05×10^{-6}	9.22×10^{-7}	3.36×10^{-6}
	Total	0.40	0.41	0.40	1.20	0.89	0.37	0.37	0.40	0.38
Industrial production	CCU	0.09	0.09	0.09	0.02	0.07	0.03	0.03	0.03	0.03
	CRU	1.66×10^{-4}	2.06×10^{-4}	1.86×10^{-4}	0	0	9.22×10^{-5}	1.22×10^{-4}	1.49×10^{-4}	1.21×10^{-4}
	HPU	0.03	0.04	0.04	0.01	0.03	3.76×10^{-3}	2.45×10^{-3}	1.39×10^{-3}	2.54×10^{-3}
	ECU	0	0	0	0.04	0	0	0	0	0
	EG/EO(U)	0	0	0	1.79×10^{-3}	0	0	0	0	0
	MU	0	0	0	4.47×10^{-4}	0	0	0	0	0
	SRU	0	0	0	6.74×10^{-4}	0	0	0	0	0
	Total	0.13	0.13	0.13	0.07	0.10	0.03	0.03	0.03	0.03
Torch combustion	Normal	2.95×10^{-4}	3.41×10^{-4}	3.18×10^{-4}	0	0	4.48×10^{-4}	4.52×10^{-4}	4.98×10^{-4}	4.66×10^{-4}
	Accident	2.57×10^{-3}	4.14×10^{-3}	3.36×10^{-3}	9.65×10^{-4}	2.24×10^{-3}	0	0	0	0
	Total	2.87×10^{-3}	4.49×10^{-3}	3.68×10^{-3}	9.75×10^{-4}	2.24×10^{-3}	4.48×10^{-4}	4.52×10^{-4}	4.98×10^{-4}	4.66×10^{-4}
Whole life stage		0.57	0.58	0.58	1.17	1.08	0.49	0.50	0.52	0.50

catalysts and improving processing equipment to reduce coke production are the keys to reducing the GHG emissions in the industrial production phase.

2.3. Torch combustion phase

The GHG emissions intensity from the torch combustion of these four typical petrochemical enterprises in China is shown in Table 7. On the whole, DLP had the highest GHG emission intensity (average 3.68×10^{-3} tons CO_2e/ton), followed by UP (2.24×10^{-3} tons CO_2e/ton), DSP (9.75×10^{-4} tons CO_2e/ton) and KP (average 4.66×10^{-4} tons CO_2e/ton). Obviously, torch combustion under accident conditions resulted

in the primary GHG emissions. Besides KP, the contribution rates of GHG emission in the other three enterprises under accident conditions were more than 90%, and that of UP even reached 100%. Under normal operating conditions, burning is only used for igniting the pilot burner, and a very small gas volume can satisfy the needs of combustion, which will generate relatively lower GHG emissions. However, under accident conditions (where the situation is different), tank roof gas needs to be discharged into the torch for emergency pressure relief. This leads to more GHG emissions. It is particularly important to improve the process plan, identify and evaluate the corresponding risks, and reduce the burning time of the accident torch.

2.4. CO_2 recycling phase

The CO_2 emissions intensity in DLP increased from -1.94 × 10^{-3} tons CO_2e/ton in 2016 to -2.07 × 10^{-3} tons CO_2e/ton in 2017, and all the recovered portions were sold outside the enterprise for the production of food-grade soft drinks. The CO_2 recovered intensity in DSP is -1.68 × 10^{-3} tons CO_2e/ton. All of the recovered portions are for self-use: most are used as a raw material in the methanol plant, and a very small amount is used for acid and alkali neutralization adjustment in the sewage tank of the glycol plant. Due to the lack of any CO_2 recovery process in KP and UP, CO_2 is directly discharged into the atmosphere. The results show that the effective recovery of this CO_2 would be a good way to reduce GHG emissions.

2.5. Lifecycle phase

2.5.1. GHG emission intensity
The key to reducing emissions in the petrochemical industry is to reduce the intensity of GHG emissions, thereby controlling the growth rate of GHG emissions. It can be seen from Table 7 that over the whole life cycle, DSP has the highest GHG emission intensity (1.17 tons CO_2e/ton), followed by UP (1.08 tons CO_2e/ton), DLP (average 0.58 tons CO_2e/ton) and KP (average 0.50 tons CO_2e/ton). The main reason for this sequence may be that DSP's coal-based energy structure has not undergone fundamental changes. Among the total primary energy consumption values, coal has the largest GHG emission coefficient, and an energy consumption structure dominated by coal is the main reason for the increase in GHG emissions. Besides, due to different target products, the unit GHG emissions of the fuel-chemical enterprises (DSP and UP) are significantly higher than those of the fuel-lubricant enterprises (DLP and KP), mainly because the operating status of fuel-chemical enterprises' equipment is frequently affected by the nature of upstream raw materials and the demand for downstream products. Therefore, unnecessary losses will be generated in the process of adjusting operating parameters.

2.5.2. GHG emissions throughout the lifecycle phases
Fig. 2a shows the total GHG emissions and environmental benefits of the sample enterprises during the life cycle phases. It can be seen from the results that DLP reduced its GHG emissions during the whole life cycle from 9518 kton CO_2e in 2016 to 7627 kton CO_2e in 2017, with an annual decline rate of about 20%. Although the crude oil processing capacity of DLP is much higher than that of DSP, the GHG emissions of DSP are higher than those of DLP, reaching 8649 kton CO_2e. The crude oil processing capacity of UP is only 8.5 million tons, but its GHG emissions reach 6832 kton CO_2e. The GHG emissions of KP have remained basically stable. It is noted that the CO_2 recycling stage has a "negative value", indicating that it could generally bring some environmental benefits from CO_2 recycling. Given the current situation, if no effective measures are carried out for DSP and UP, the GHG emissions of these petrochemical enterprises will continue to increase.

Fig. 2b shows the contributions of the sample enterprises to total GHG emissions at different life cycle stages. (Here, only GHG emissions are considered; the GHG emission reduction from CO_2 recovery and external power supply is ex-

cluded). The results show that fossil fuel combustion has the largest GHG emissions, accounting for 77.31%–94.27% of the total GHG emissions, followed by the industrial production phase (5.64%–22.18%) and the torch combustion phase (0.08%–0.77%). Therefore, when considering effective measures to reduce GHG emissions in the future, priority should be given to GHG emissions in the fossil fuel combustion and industrial production phases.

3. Discussion

3.1. Scenario analysis for GHG emission reductions

According to the results of field investigation, the average heating furnace thermal efficiency of advanced petrochemical enterprises in China is about 92.3%. However, the sample enterprises in this study are generally lower than 91%. At the same time, the working efficiencies of the other equipment in the enterprises have not also reached the designed value. After consulting the process engineer in the sample enterprises, this study determined the emission reduction ratio under four different scenarios and the future development trends of the enterprises. According to the above research, GHG offsets should focus on "improving the thermal efficiency of the heating furnace, reducing the use of bituminous coal, cutting down on the amount of coking, decreasing torch combustion (under accident conditions), and raising CO_2 recovery rates". This study identifies the factors affecting the emission reduction of petrochemical enterprises through scenario analysis, and then formulates four scenarios (baseline, conservative, moderate, and ideal) for current changes, to evaluate the GHG emission reduction potential of the sample enterprises. Table 8 shows the assumptions at various stages of the life cycle. The method of setting scenario parameters is as follows: this study selects 2017 as the base year for DLP and DSP, and 2018 as the base year for KP and UP, to achieve emission reduction by strengthening the parameters applicable to the current production conditions. In the scenario analysis, the emission reduction ratios under the four different scenarios were determined by considering the present environmental conditions and the process status of the sample enterprises.

According to the above data and the scenario assumptions in Table 8, the potential GHG emission reduction scenarios can be estimated, as shown in Fig. 3. This study makes a horizontal comparison of the emission reduction rates of the sample enterprises. In a conservative scenario, the emission reduction rate ranges from 1.91% to 6.87%, while the rate is between 3.83% and 10.77% under moderate scenarios. In an ideal scenario, the emission reduction rate reaches 5.63%–15.26%.

In order to achieve in practice the goals set forth in the scenario analysis, some effective measures should be taken. In the fossil fuel combustion stage, high-efficiency heat exchangers should be replaced to recover waste heat from flue gas, reduce flue gas temperature, and improve both the thermal efficiency of devices and the utilization efficiency of bituminous coal so as to reduce its consumption, thereby achieving the maximum level of recycling. At the same time, the process itself should be reformed to cut down on the coke generation rate of the catalytic cracking unit. During the torch combus-
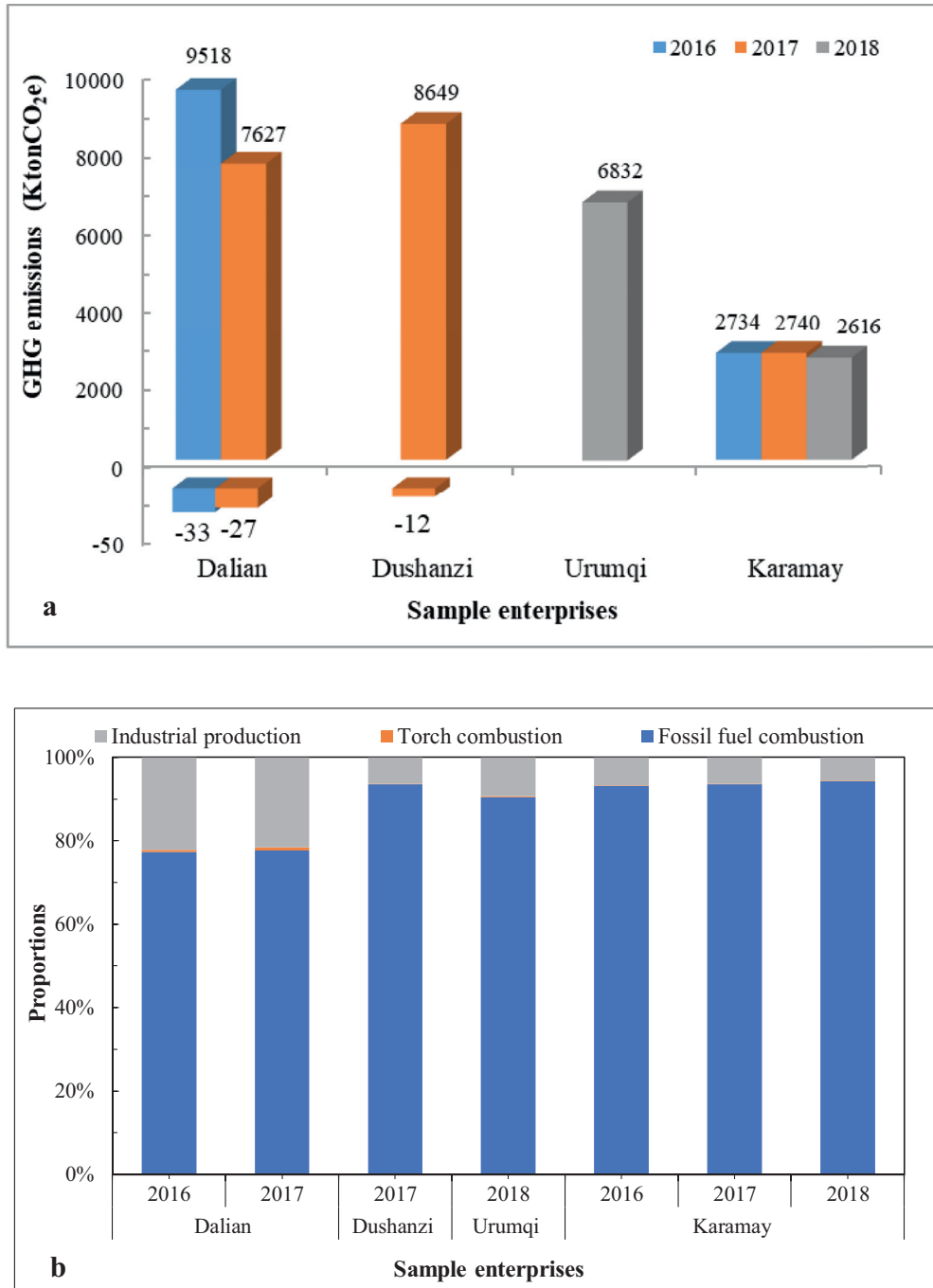
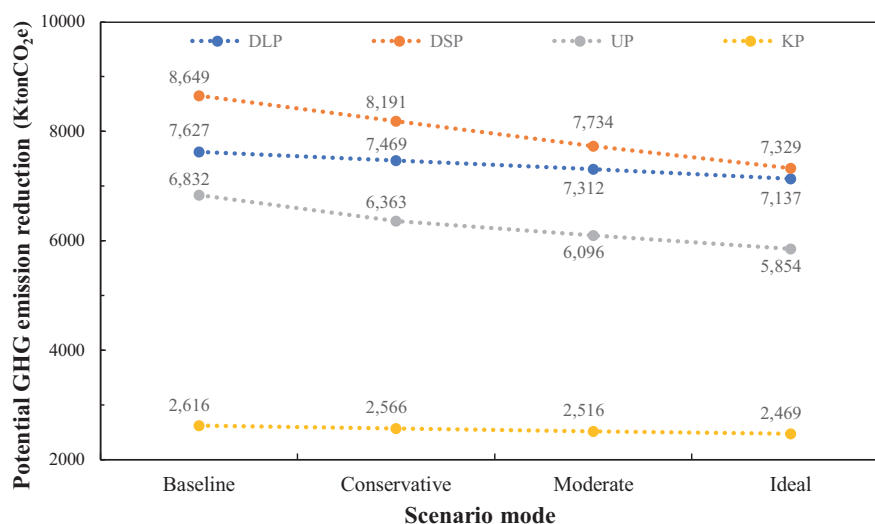Fig. 2 – (a) GHG emissions during the whole life cycle and (b) proportions of the different phases.

tion phase, corresponding risk identification and evaluation should be carried out to reduce the torch burning time (under accident conditions). As for the thermal power plant, the enterprise should implement internal production and reuse procedures, instead of purchasing electricity and heat from outside the plant. Renewable energy sources such as solar power should also be considered for this internal power generation. It is worth mentioning that developing the CO_2 recovery rate is an important step toward achieving environmental benefits, although the environmental benefits of recycling CO_2 currently remain somewhat obscure.

3.2. Policy implications

Under the goal of achieving "carbon neutrality" by 2060, petrochemical enterprises will have both opportunities and challenges for low-carbon development in China. Formulating low-carbon development policies for enterprises and making full use of technological innovation and energy structure adjustment are inevitable. According to the above-mentioned energy consumption structure, it can be seen that long into the future, the energy structure of petrochemical enterprises

Table 8 – Parameter setting for scenario analysis in the sample enterprises.

| Sample | Type | Scenario mode | | | |
		Baseline	Conservative	Moderate	Ideal
DLP	Furnace efficiency	0	2%	4%	6%
	Coke burning amount		-8%	-16%	-25%
	Torch combustion (under accident conditions)		-30%	-60%	-100%
	CO_2 recovery		5%	7%	10%
DSP	Furnace efficiency		2%	4%	6%
	Bituminous coal		-7%	-14%	-20%
	Coke burning amount		-8%	-16%	-25%
	Torch combustion (under accident conditions)		-30%	-60%	-100%
	CO_2 recovery		5%	7%	10%
UP	Furnace efficiency		2%	4%	6%
	Bituminous coal		-7%	-14%	-20%
	Coke burning amount		-8%	-16%	-25%
	Torch combustion (under accident conditions)		-30%	-60%	-100%
KP	Furnace efficiency		2%	4%	6%
	Bituminous coal		-7%	-14%	-20%
	Coke burning amount		-8%	-16%	-25%

Fig. 3 – Potential GHG emission reduction under the different scenarios.

may still be dominated by coal. Therefore, combining the needs of process characteristics and the analysis of technical and economic effects, appropriately increasing the proportion of clean energy such as natural gas, and reducing dependence on coal, are important for achieving low-carbon development in petrochemical enterprises. In addition, increasing the scale of renewable energy use and cultivating it as a competitive advantage in the petrochemical industry will also promote the optimization and adjustment of the energy consumption structure.

Building a collaborative and innovative system for energy-saving and low-carbon technologies in the petrochemical industry will remove the bottleneck in energy-saving technologies. For example, the establishment of technology centers, research centers and key laboratories and other research and development platforms can create good technical reserves. For emerging low-carbon technologies which may occupy the commanding heights of future technology, this approach forms an innovative system of "industry-university-research cooperation" with enterprises as the main body, and can result in the selective development of low-carbon energy technologies. More focus on the research and development of clean conversion technologies, for example, can promote the development and application of low-carbon technologies.

Implementing a low-carbon development strategy for petrochemical enterprises and building a complete carbon-emission management system are important means for companies to save energy and reduce carbon emissions. Petrochemical enterprises should introduce modern management ideology, establish a management system covering the entire

process of energy utilization and carbon emissions, formulate a reasonable carbon asset management plan, and use market-based means to promote the establishment of a long-term mechanism for energy conservation and carbon reduction.

3.3.   Limitations and uncertainty analysis

Although many efforts had been made to characterize GHG emissions by the LCA method in this study, there are still some limitations and uncertainties:

(1) Firstly, the analysis in this study focused only on GHG emissions, ignoring other environmental impacts, such as eutrophication, acidification, and human toxicity. In future research, more types of environmental impacts should be evaluated to fully understand the environmental characteristics of petrochemical enterprises.
(2) Some parameters used in the calculations are uncertain. For example, most of the chemicals involved in the chemical processes are mixtures. If only a single carbon content is used, the result will be very uncertain.
(3) Due to limited data availability, some data from relevant accounting methods and reporting guidelines can only estimate GHG emission factors and calculation coefficients; exact results are hard to determine.
(4) Although many raw materials are used in the industrial production process, this study focused on the main materials and ignored some exhaust gas treatment materials and carbon capture materials; including these would also have caused some deviation from the obtained results.
(5) Since the products of the four petrochemical enterprises in this study differ somewhat, some deviations may appear in the comparison together, causing some additional uncertainty in the results.

4.   Conclusions

With the development of the social economy and the improvement of living standards, energy consumption related to petrochemicals has become a major source of GHG emissions in China. Based on original data and information from four typical petrochemical enterprises in China, this study quantitatively analyzed the GHG emissions throughout the life cycle stages of petrochemical production in these enterprises.

The results show that DLP, which has a processing capacity of 20.5 million tons of crude oil, has dropped its GHG emissions during the life cycle stages from 9518 kton CO_2e in 2016 to 7627 kton CO_2e in 2017, with an annual decline rate of about 20%. DSP, with a processing capacity of 10 million tons of crude oil, produced GHG emissions of 8649 kton CO_2e in 2017. The crude oil processing capacity of UP is only 8.5 million tons, but its GHG emissions have reached 6832 kton CO_2e. In 2016–2018, the GHG emissions of KP, which has a processing capacity of 6 million tons of crude oil, were 2616–2740 kton CO_2e, revealing no significant changes in emissions. From the perspective of GHG emission intensity, DSP has the highest intensity (1.17 tons CO_2e/ton), followed by UP (1.08 tons CO_2e/ton), DLP (average 0.58 tons CO_2e/ton) and KP (average 0.50 tons CO_2e/ton) over the whole life cycle.

During the fossil fuel combustion phase, GHG emissions were the largest contributor to the whole life cycle, accounting for about 77.31%–94.27% of the total emissions, followed by the industrial production phase (5.64%–22.18%) and the torch combustion phase (0.08%–0.77%). In the fossil fuel combustion phase, DSP had the highest per-unit GHG emissions (1.20 tons CO_2e), followed by UP (0.89 tons CO_2e), DLP (average 0.40 tons CO_2e/ton) and KP (average 0.38 tons CO_2e/ton). In the industrial production phase, DLP had the highest unit GHG emissions (average 0.13 tons CO_2e/ton), followed by UP (0.10 tons CO_2e/ton), DSP (0.07 tons CO_2e/ton) and KP (average 0.03 tons CO_2e/ton). In the torch combustion phase, torch burning under accident conditions is the main source of GHG emissions. From the perspective of the whole life cycle, bituminous coal usage and coke burning amount will become the two key points for sample enterprises to reduce GHG emissions. It is worth noting that CO_2 recovery has "negative value" (environmental benefits). While the current environmental benefits of recycling CO_2 remain somewhat obscure, developing the CO_2 recovery rate is an important step in achieving environmental benefits. According to our scenario analysis, the GHG emissions of the sample enterprises can be diminished by 5.63%–15.26% under the ideal scenario.

Overall, the results of this study lay a basis and guidelines for Chinese petrochemical enterprises to reduce GHG emissions, and provide a useful reference for other cities and countries to transform/upgrade low-carbon petrochemical systems.

Acknowledgments

Appendix A. Supplementary data

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jes.2021.05.031.

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