Health Impacts of Air Pollution in Chinese Coal-Based Clean Energy Industry: LCA-Based and WTP-Oriented Modeling

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Research Article

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Abstract

The evolution of energy system occupies an important position in economic development and quality of life. Influenced by the energy endowment in China, developing the coal-based clean energy industry has been regarded as a guaranteed path to realizing the clean and efficient use of coal resources. However, an evaluation paradigm could systematically assess the health impacts of airborne pollution in this industry is still lack, which is our concern. Combining with life cycle analysis, probabilistic risk models, and health impacts models, this study proposes a series of models which are consistent enough to unite pollutant concentration, health risk, and health impact, and equip assessment results with more intuitive significance using life and economic loss. Further, case studies for three typical coal-based clean energy processing, namely, coal mining, coal-fired power generation, and coal liquefaction are presented to verify the reliability of these models. It is proved that this evaluation paradigm can help to find out the worksite, substage, and airborne pollutant with the most severe impact, and more importantly, the application of evaluation indicators with life and economic meaning is more profitable to provide references for minimizing or eliminating the health impacts, moreover, explicit the developing directions of the national energy industry.

1. Introduction

Energy is the motive power of social and economic development, the majority of energy supplies in China are composed of coal resources. As is estimated, even renewable energy is taken into full consideration, coal would still predominant in Chinese energy supply system, with the percentage of 30% by 2050 (ERI, 2009). More specifically, coal consumption in China is mainly used in electric power generation, steel, chemical and building materials production. In 2017, coal used for the power industry accounted for about 52%, and approximately 17% for steel industry, nearly 7% of coal were used in chemical production, and domestic coal occupied about 11% (CNCA, 2018). However, traditional coal utilization produces many serious problems such as extensive use pattern, low efficiency and heavy pollution. For instance, it is estimated that among the national emissions in China, nearly 85% of SO_2, 80% of CO_2, 70% of smoke dust, and 67% of NO_x are produced by coal combustion, furthermore, a significant rise of $PM_{2.5}$ concentrations is induced by coal combustion as well (Ai et al., 2021).

In the context of global climate change, the energy supply sector in the worldwide offers a multitude of options to reduce emissions, including fossil fuel switching, energy efficiency improvements and fugitive emission reduction in fuel extraction and energy conversion (Edenhofer et al., 2014; Gu et al., 2021). Amongst, with the consideration of energy endowment in China, developing clean coal technologies has been regarded as a strategic choice to ensure the balance of energy supply and demand, and achieve the harmonious development of energy, economy and environment. Correspondingly, a circular economy industry chain in Chinese coal-based clean energy industry grows up gradually, namely, “coal development–coal with high quality–clean energy–integration of coal-based materials and chemicals”, as shown in Fig. 1. Amongst, great numbers of clean coal technologies related to coal production and utilization are developed, such as greening mining, high-efficiency coal-fired power generation, and coal conversion. A good case in point is the developing of coal chemical industry, it has been revealed that China has become the largest producer of traditional coal chemical products, the yield of coke, ammonia and methanol account for about 58%, 32%, 28% of global production (Zhang et al., 2019). In brief, coal chemical industry is not only a substantial pillar industry but also drives the development of other Chinese industries.

In literature, extensive researches have been done to explore the coal-based clean energy industry, where technological details and economic outlooks receive great attention. For example, Gu et al. (2020) portrayed and explained the dynamic conditional dependencies among clean energy sector indexes, steam coal prices, and environmental conditions under the stock market volatility in China. It is proved that there is bilateral volatility spillover between the steam coal market and the clean energy stocks. Huang et al. (2019) proposed a constrained nonlinear program to optimize deployment technologies and processes of the coal chemical sector to reduce CO_2 emissions, and thus the minimum CO_2 emissions per unit output of the coal chemical industry during 2020–2050 were obtained. In Cai et al.'s research (2018), a computer simulation tool was developed to study the dynamic performance of business structure, profit and carbon emission in a traditional power generation company, which can further quantify the key operation indicators in the context of clean coal transition in China's power sector. However, according to the three dimensions of sustainable development, achieving the sustainability of energy systems, the way that must be passed is minimizing the environmental impact. To the best of our knowledge, although certain contributions have been obtained in the fields of pollutant emissions linking with clean coal technologies, the related studies mainly focus on the sources and concentrations of airborne pollutants (Song et al., 2020; Yang et al., 2020), health impacts of pollutant emissions have not been explained comprehensively. On the other hand, the propose of clean coal technologies is applying coal resources in a more efficient and environmental-friendly way. Therefore, conducting studies of health impacts in the coal-based clean energy industry, would not only help the related enterprises to control the pollutant emissions but inspect their competitiveness and effectiveness from environmental burden mitigation potential.

From what we have discussed above, health impacts issues in the clean coal industry is critical to its development, which calls for a systematic and detailed investigation targeting numerous pollutant emissions. To this aim, this study proposes a model for quantifying health impacts of pollutants emissions in the coal-based clean energy industry. The evaluation paradigm aims to: 1) identify the hot spots with the most severe health impacts, and prioritize for the future management and development of the clean coal industry; 2) help policymakers to establish feasible rules and regulations from an environmental perspective; 3) reinforce the dialectical perception of public on the development of coal-based clean energy industry in more understandable viewpoints.

2. Methodology

To help to elucidate the evaluation paradigm, Fig. 2 shows the core flow of our research with the three key methods of life cycle analysis (LCA), probabilistic risk models, and health impacts models.

2.1 Life cycle analysis

It is well known that the energy consumption structure with coal as the core is the crucial source of air pollution in China. Apart from conventional air pollutants such as NO_x, SO_2, and CO_2, other hazardous substances, e.g., dust (Tong et al., 2019a), heavy metal (Sun et al., 2019), and noise (Hasanuzzaman & Srivastava, 2018) also bring about a stubborn threat to public health in and around the coal-based energy industry. What's more, the coal-based clean energy industry is characterized by various machinery equipment and complex working environment. Therefore, there is an objective necessity to divide the manufacturing stages when investigating coal-based clean energy processing.

LCA is a method for compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, which is usually performed in four steps, goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006; ISO, 2018). Using the idea of LCA, the entire process in the coal-based clean energy industry is generally divided into substages ranging from raw coal acquisition to coal transportation, clean energy production, production distribution, and utilization. A streamlined life cycle for the coal-based clean energy industry is shown in Fig. 3.

With the utilization of the idea of LCA, two basic tasks could be accomplished. First, the entire process of the energy system is divided into several substages. On the other hand, input and output inventory should be established, which includes data such as resource inputs, pollutant emissions, number of workers, and exposure duration. Specifically, there are two major ways to collect the concentrations of airborne pollutants, namely, through scene sampling or industrial production report. Overall, LCA has made itself as an effective tool for environmental impacts exploration in the clean coal energy industry, as it can recognize the sources and levels of environmental discharging with the explicit stage division, and thus would help to find out the substages with severe contamination.

2.2 Probabilistic risk models

Using the thought of the LCA method, the types and contents of environmental pollutants throughout both product and process life cycle could be identified, substages with severe environmental impacts could be determined accordingly. However, LCA takes more notice of resource utilization and pollution issues, human health impacts cannot be vividly pictured only by exposure concentrations. Meanwhile, individuals are more concerned about the possibility and severity of suffering from health damages induced by pollutants. Therefore, a quantitative health risk assessment must be applied to elucidate risk issues the public concerned.

Quantitative health risk assessment is an indispensable approach to yield insight into the health risks of environmental pollutants, which can be divided into deterministic and probabilistic risk assessment (Tong et al., 2019b). The deterministic risk assessment assesses the health risk by adopting a single point value of parameters. However, there is a general existence of uncertainty in parameters under such complex and variable working environments. Consequently, the plain utilization of deterministic risk assessment often brings about underestimated or overrated evaluation results (Koupaie & Eskicioglu, 2015). Different from deterministic risk assessment, probabilistic risk assessment applies a probability distribution to characterize the input parameter, making the evaluation results more reliable. Besides, with the aid of Monte Carlo simulation method, sensitivity analysis can be conducted to pinpoint the crucial parameters in the evaluation process, instructing exposure people to regularize their exposure behaviors and providing suggestions for risk prevention and control.

Therefore, probabilistic risk models proposed by the U.S. Environmental Protection Agency (USEPA) are applied, which are proven to be valid to assess the health risks of heavy metals (Chabukdhara & Nema, 2013), polycyclic aromatic hydrocarbons (Tong et al., 2018), and carcinogenic chemicals (Slob et al., 2014). Likewise, the model parameters for each case are determined in terms of specific production conditions and different population characteristics. Generally, four steps are included in probabilistic risk models, that is, hazard identification, dose-response assessment, exposure assessment, and risk characterization. A typical computational process of health risk via inhalation pathway is shown as (1)-(3). Based on the calculation equations, we could notice that various exposure parameters are included in this model, with the integrative consideration of individual variability and group identity. Remarkably, owing to the influence of occupational features, there is a significant difference in the time-activity patterns between workers in the coal-based clean energy industry and the public. Some exposure parameters in probabilistic risk models, such as exposure time, exposure duration, exposure frequency, and average time, cannot be straightforwardly obtained from the exposure parameter manual, thus they are investigated through the on-site questionnaire. Furthermore, acceptable risk levels proposed by different institutions present a different threshold. In this study, acceptable risk thresholds suggested by the USEPA are applied. For carcinogenic risks, if CR is less than 1.0E-06, indicating that the harm is acceptable; if CR is between 1.0E-06 and 1.0E-04, meaning that there is a potential risk; if CR is greater than 1.0E-04, denoting a serious risk; for non-carcinogenic risks, if HQ equals to or less than 1, meaning that there is no significant health damage; if HQ is greater than 1, denoting that it may result in unacceptable hazards.

$$ADD=(C\times IR\times ED\times EF\times ET)/(BW\times AT) \quad (1)$$

$$CR = ADD\times SF \quad (2)$$

$$HQ = ADD/RfD \quad (3)$$

where ADD = daily exposure dose during lifelong intake [$mg\cdot(kg\cdot d)^{-1}$]; C = pollutants concentrations ($mg\cdot m^{-3}$); IR = inhalation rate ($m^3\cdot h^{-1}$); ED = exposure duration (a); EF = exposure frequency ($d\cdot a^{-1}$); ET = exposure time ($h\cdot d^{-1}$); BW = body weight (kg); AT = average exposure time (a); CR = carcinogenic risk (unitless); SF = slope risk factor for carcinogenic pollutants ($kg\cdot d\cdot mg^{-1}$); HQ = non-carcinogenic risk (unitless); RfD = reference concentration of non-carcinogenic pollutants [$mg\cdot(kg\cdot d)^{-1}$].

2.3 Health impacts models

As mentioned above, the application of LCA and probabilistic risk models could help to evaluate the health risks of environmental pollutions with the specific division of production stages. But health risks are still not intuitive enough to reflect health impacts comprehensively. In other words, industrial development and policy formulation always rely on economic index as references. Therefore, to turn risks values into a more intuitive index, indicators of disability adjusted life year (DALY)and willingness to pay (WTP) are introduced in this paradigm.

The indicator of DALY can be divided into years of life lost due to premature mortality (YLL) and years of life lost due to disability (YLD) (Chowdhury et al., 2020), representing the years lost due to early death and healthy years lost resulting from disease and injury (Murray & Lopez, 1996). WTP is an environmental economic approach which can measure the monetary value of different impact categories, more specifically, implying the maximum amount of money an individual is prepared to give up to secure an environmental improvement or to avoid an environmental loss (ISO, 2019). In this study, health impacts models are established to associate DALY with WTP indicators, where three steps are involved, namely, categorization, characterization, and quantitative evaluation.

In categorization, with the aid of existing epidemiological researches, health damage of different pollutants is classified into various terminal diseases, the classification and the values of critical parameters are shown in Tables 1 and 2, specifically. As for characterization, the health risks we obtained through probabilistic risk models can be proportionally distributed to each terminal disease, thus the values of health risks are unified into DALY. At last, the DALY values are transformed into WTP indicators in quantitative evaluation. By doing so, the severity of various health impacts can be compared on the same scale, reflecting that it is more scientific and reliable to apply DALY and WTP values instead of single health risks. The specific formulations are listed as (4)-(6).

$$DALY = n \bullet \sum_i R \bullet Q_i \bullet W_i \bullet L_i \bullet P \quad (4)$$

$$VSLY = VSL/[(1-(1+r)^{-t})/r] \quad (5)$$

$$WTP = DALY \times VSLY \quad (6)$$

where DALY = daily exposure dose during lifelong intake [mg·(kg·d)$^{-1}$]; n = the number of occupational groups exposure (d); R = carcinogenic risk or non-carcinogenic risk (unitless); Q_i = risk factor of disease category i, namely, the proportion of risk in different disease types (unitless); W_i = effect factor of disease category i, valuing between 0 to1 (unitless); L_i = damage factor of disease category i, taking values related to “t”; P = the number of people affected by pollution; VSLY = the annual average value of a statistical life (46.96 thousand USD); VSL = value of a statistical life, estimated by the VSL of American residents with the consideration of currency inflation in the US and the Purchasing Power Parity between the US and China (969.2 thousand USD); r = the efficiency discount rate (4%); t = remaining life expectancy (a), valuing as the difference between average life expectancy and average age of Chinese residents; WTP = willingness to pay (yuan).

Table 1 Terminal diseases of different environmental pollutants (Li et al., 2010; Li et al., 2015b).

Pollutant	Terminal diseases	Pollutant	Terminal diseases
Dust	Pneumoconiosis (CWP)	SO_2	Death of CVD
	Acute respiratory infection (ARI)		COPD
	Cardio-cerebrovascular disease (CVD)		ARI
	Chronic obstructive pulmonary disease (COPD)		
NO_2	Death of CVD	CO_2	ARI
	ARI	CH_4	CVD
		N_2O	
		CO	

Table 2 Values of related factors for different terminal diseases.

Terminal disease	**Q_i (Li et al., 2015a,b)**	**W_i (Li et al., 2015a,b)**	**L_i (NBSC, 2019)**
Death	0.13	1.00	42.2
CWP	0.37	0.24	34.2
COPD	0.12	0.14	10
CVD	0.15	0.23	19
ARI	0.21	0.08	0.038

3. Case Studies

To verify the practicality and reliability of this evaluation paradigm, three representative coal-based clean energy technologies are selected as research objects, the health impacts of airborne pollutions in their processing are estimated.

3.1 Model applied to coal mining

Coal mining is one of the core industries in coal-producing countries, China is included. However, the direct and indirect negative impacts of coal mining on air quality are well known, which not only cause serious damage to the ecological environment of the mining area but also threaten the health conditions of the workers involved. Amongst, dust is a major occupational hazard, containing more than 50 chemical elements and is classified as a very dangerous fossil pollutant, leading to increased CVD, ARI, and COPD (Petsonk et al., 2013; Khaniabadi et al., 2017). Overall, given that the contradiction between ecological environment and mining activity has become a problem which urgently awaits to be solved, it is an actual need to investigate the exposure levels and health impacts of dust for coal miners.

The coal mine we researched in this study is located in Shanxi Province, where is the most influential coal production and export base in China (Li et al., 2018b). This coal mine was built in 1992, the mining area is 5.5 km long and 2.5 km wide with mining depth from + 80 to -320 m, covering an area of 13.8 km^2, and with an annual coal output of nearly 4 million tons. To investigate the health impacts of dust in its mining processing, air samples were collected from the beginning of August 2016 to the end of October 2016. The sampling process all met the requirements of the relative national standards for the determination of hazardous atmospheric substances in the workplace (Ministry of Health, 2007; 2017; 2019).

3.2 Model applied to coal-fired power generation

The plentiful supply of electricity is the foundation and key point for supporting the countries to prosper and the public to live safe. Electricity has become the most robust driving forces of China's rising industrial energy consumption from 2000 to 2018, with the contribution rate of 38% (Yue et al., 2021). Given the energy endowment of China, coal-fired power generation plays a critical role in the whole electric power sector, which is also the most important utilization pattern of coal resources. However, the relative researches have proven that pollutant emissions in coal-fired power generation pose a threat to the environment, and carbon emission is often cited as an example (Tang et al., 2017). It is reported that as the world's largest carbon emitter, the thermal power generation sector contributed to more than 40% of the total emissions in China (Li & Tang, 2016). Actually, except for carbon contamination, workers in the coal-fired power generation industry would be exposed to many other occupational hazards, representing by dust, toxic and harmful gases, and high temperatures. Therefore, no one can deny that the health impacts evaluation of environmental pollutions in coal-fired power generation would provide scientific reference for industrial development.

The coal-fired power generation plant we evaluated is SLQ thermal power industry, which is located in the southern of Zaozhuang, Shandong province. This power plant is equipped with 7 production units and has a total installed capacity of 1225 MW and a yearly electrical output of over 8 billion kWh. Further, the major coal supplier of the SLQ thermal power plant is the JZ coal mine, which is situated in the central zone of the southern mining area in Shandong province. After coal mining, the raw coal is separated and washed in a coal preparation plant, and subsequently transported to the SLQ coal-fired power generation industry. In this study, seven pollutants we investigated were divided into four categories in terms of their contamination characteristics, that is, greenhouse gases (CO_2, CH_4, N_2O, CO), PM_{10}, NO_2, and SO_2.

3.3 Model applied to coal liquefaction

Coal liquefaction is a vital approach for converting coal into desired chemicals and liquid fuels (Wang et al., 2017), as it is practical to turn the tide of coal and oil, and perk up the underdeveloped areas of the energy structure (Hao et al., 2018). In China, whose energy structure is featured as “rich in coal but poor in oil”, coal-to-liquid (CTL) technology has become a new coal chemical engineering with receiving much attention. It has been reported that CTL processing has the advantages of cost-effectiveness, high liquid recovery and low contaminations. More specifically in environmental aspect, it is demonstrated that the harmful substances such as sulfur atoms, would be removed through CTL. However, although the CTL technology could indeed reduce the pollution in its production processing, it is still controversial on the total contamination emissions as the CTL processing calling for more productive resources. Therefore, conducting an environmental assessment with the thought of life cycle for the CTL industry is essential.

In compliance with the actual demand for energy transformation, China has built the most active CTL programs in the world through its research, development, and demonstration efforts. Herein, as one of two main CTL technologies, the direct coal-to-liquid (DCL) project might be given as a good example. The 1.08 million tons/year DCL plant locates in Erdos, Inner Mongolia, which is constructed by the China Shenhua Energy Company Limited and is the world's first and largest DCL plant (Rong & Victor, 2011). In this study, it is planned to conduct the health impacts assessment for this DCL plant, to clarify its effectiveness from the perspective of environmental damage. Notably, the contaminants we considered include dust, SO_2, and NO_2, which are all the conventional pollutants in the CTL industry.

The definition of stages division and functional unit for three case studies are shown in Table 3, the life cycle stages of the coal-based clean energy industry were divided in consideration of the actual generation conditions and emission features. Notably, for the case study of coal liquefaction, this study mainly focuses on discussing the health impacts of environmental pollutions during the DCL's productive process, and it has been reported that the objective results could be obtained if the assessment systematically begins with coal mining processing in the CTL industry (Zhu et al., 2018). Therefore, the downstream processes of CTL are outside the analyzed system boundary, its life cycle stages were subsequently divided into three parts: coal mining and processing, coal transportation, and coal liquefaction.

Table 3 Definition of stages division and functional unit for three case studies.

Case study	Stages division	Functional unit
Coal mining	Construction stage-Production stage-Reconstruction stage-Disposal stage	1ton product coal
Coal-fired power generation	Coal mining-Coal transportation-Coal combustion-Slag disposal	1kWh electric power generation
Coal liquefaction	Coal mining and processing-Coal transportation-Direct liquefaction	1ton product oil

4. Results And Discussions

To better depict the evaluation paradigm and reveal the superiority of these methods, the assessment results are unified and discussed in the below.

4.1 Discussion on life cycle analysis method

Data collection is a key procedure in LCA, where plenty of data needs to be collected, such as energy inputs, raw material inputs, atmospheric emission factors and so on. To ensure the accuracy of this assessment, two types of data are collected. For the case studies of coal-fired power generation and coal liquefaction, their energy efficiency and emission factors are mainly collected from the report issued by the authority and the related mature researches. For the basic data of coal mining, its energy consumption and emission data are chiefly collected from the investigated coal mine. Detailedly, a total of 582 dust samples were collected in the coal mine along with the division of four workplaces, that is, coal face (140 samples), heading face (168 samples), shotcrete point (124 samples), and transshipment point (150 samples). The dust concentrations in these various workplaces are shown in Table 4. Meanwhile, the mass of pollutants emitted from four substages in coal-fired power generation are illustrated as an example, as shown in Table 5. As for coal liquefaction, its related evaluation parameters were collected as well, as illustrated in Table 6.

In brief, the application of LCA could help to ascertain the quantitative polluting condition in different production processing, and thus clarify the worksites and occupants which need to be protected in priority. Such examples might be given easily, as shown in Table 4, the concentrations of dust in the four workplaces during coal mining can be defined, with the range of 3.34–16.85, 2.24–20.28, 1.29–17.38, and 3.69–12.53 mg/m^3 for coal face, driving face, shotcreting point, and transshipment point, respectively. It could be found that the concentrations of coal dust are all higher than the occupational exposure limit in each workplace, namely, 4 mg/m^3 (Ministry of Health, 2019). As for silica dust, the most serious contamination occurred at driving face with the concentration of 20.28 ± 3.17 mg/m^3, which is 20.28 times the occupational exposure limit for silica dust in the workplace (1 mg/m^3). Therefore, it is suggested that during coal mining, attentions of pollutant control should be centered on coal dust more than silica dust. Given the prevention and control technologies differ from various pollutants, it would be more cost-saving and effective with shooting the arrow at the target.

Table 4 Dust concentrations and health risks in various workplaces for coal mining.

Workplaces	Work types	Dust	Number of samples	Concentrations (mg/m^3)
Coal face	Shearer operator	Coal dust	24	16.85±4.19
		Silica dust	16	3.38±1.02
	Hydraulic pump worker	Coal dust	13	9.67±1.46
		Silica dust	10	4.93±1.34
	Support worker	Coal dust	21	14.39±2.36
		Silica dust	7	4.54±0.71
	Coal digger	Coal dust	17	16.25±3.47
		Silica dust	12	5.89±0.62
	Scraper conveyor driver	Coal dust	9	10.28±0.24
		Silica dust	11	3.34±0.16
Driving face	Roadheader driver	Coal dust	12	3.97±0.27
		Silica dust	26	14.36±1.24
	Driller	Coal dust	10	4.62±1.25
		Silica dust	19	18.95±2.16
	Muck loader driver	Coal dust	11	2.24±0.38
		Silica dust	23	16.54±0.71
	Belt driver	Coal dust	14	2.73±0.47
		Silica dust	18	14.31±0.62
	Blaster	Coal dust	11	3.62±1.08
		Silica dust	24	20.28±3.17
Shotcreting point	Gunite worker	Silica dust	11	4.92±0.45
		Cement dust	14	17.38±0.14
	Drilling machine operator	Silica dust	8	10.09±1.35
		Cement dust	14	2.91±0.19
	Mixer and feeder driver	Silica dust	10	1.29±1.67
		Cement dust	15	16.56±1.33

	Loading and unloading workers	Silica dust	12	2.72±0.12
		Cement dust	17	14.41±0.73
	Support worker	Silica dust	9	7.83±1.15
		Cement dust	14	12.64±1.03
Transshipment point	Scraper conveyor driver	Coal dust	9	8.07±1.13
		Silica dust	12	7.32±0.24
	Cage driver	Coal dust	15	5.61±3.24
		Silica dust	21	9.03±1.14
	Belt driver	Coal dust	15	4.26±2.35
		Silica dust	9	4.52±1.76
	Transfer conveyor driver	Coal dust	8	10.72±1.49
		Silica dust	13	6.34±1.65
	Repairman	Coal dust	8	8.78±0.85
		Silica dust	16	3.69±1.06
	Coal caving worker	Coal dust	10	12.53±2.41
		Silica dust	14	5.31±0.81

Table 5 The total mass of airborne pollutants emitted from coal-fired power generation (unit: kg).

		Substage classification			
		Coal mining	Coal transportation	Coal combustion	Slag disposal
Pollutant types	CO_2	2.05E+08	4.47E+07	9.89E+09	5.16E+06
	CH_4	4.36E+06	3.34E+03	6.68E+04	3.85E+02
	N_2O	3.58E+02	1.20E+03	2.66E+04	1.38E+02
	CO	9.94E+05	7.43E+04	1.12E+06	8.57E+03
	PM_{10}	4.18E+05	7.29E+04	7.84E+05	3.62E+04
	NO_2	2.80E+05	4.98E+05	5.44E+06	5.75E+04
	SO_2	7.29E+05	7.29E+05	2.41E+06	3.21E+03

Table 6 Evaluation parameters for the life cycle of coal liquefaction.

Parameter				Value	Unit	Source
Consumption	Coal mining and processing	Comprehensive energy		30.2	kgce/t	Wang, 2014
		Electricity		25.8	kWh/t	
	Coal transportation	Energy intensity		240	kJ/(t•km)	Zhou et al., 2017
		Fuel mix and percentage	Diesel	55%	–	
			Electricity	45%		
		Transport distance		72.30	km	Production data
	Coal liquefaction	Raw coal		2.89	tce/t	Du, 2016
		Water		5.84	t/t	Production data
		Electricity		692.80	kWh/t	
Production	Main product		Diesel	0.66	t/t	Production data
			Liquefied gas	0.095		
	Byproduct		Naphtha	0.23		
			Phenol	0.0033		
Population of the project sites per unit area				24	people/km^2	BSOC, 2018
Gross area of the city where project sites locate				86752	km^2	
Key parameters for the calculation of emissions	Coal mining and processing	SO_2	Direct emission	1200	kg/t	Production data
			Indirect emission	740.4		
		NO_2	Direct emission	1665		
			Indirect emission	4.858E + 08		
		Dust	Direct emission	130.70		
			Indirect emission	1506		
	Coal transportation		SO_2	51.36		
			NO_2	14.75		
			Dust	64.48		
	Coal liquefaction		SO_2	934		Chen, 2016

Parameter		Value	Unit	Source
	NO_2	1900		
	Dust	46900		

4.2 Discussion on probabilistic risk models

Exposure assessment is an important procedure in probabilistic risk models, where exposure level, exposure route, and the frequency of the human body exposed to pollutants need to be defined. Although it is researched that the pathways of people exposed to environmental pollution are classified into inhalation, oral intake, and dermal intake. However, the workers in the coal-based clean energy industry are usually equipped with staff uniforms that leave a tiny area of bare skin. Furthermore, behaviors such as drinking and eating are prohibited in the working periods, thus preventing the oral intake of environmental emissions to a great extent. Therefore, the probabilistic risk assessment in this study only considers the inhalation pathway. In the following, the probabilistic risks assessment for the case study of coal mining is selected as a sample to discuss. Table 7 presents the exposure parameters reflecting the features of workers at coal mining plant, the probabilistic risks can be accordingly assessed with the application of formulas (1)-(3).

Table 7 Exposure parameters for assessing inhalation health risks.

Parameter	Distribution	Value	Source
IR	T	0.95, 1.90, 2.85	MEEC, 2013
ED	T	5, 20, 33	This study
EF	T	229, 274, 332	
ET	T	3, 5.2, 8.5	
BW	N^2	66.32 ± 4.88	
AT	T	1825, 7300, 12045	

With the application of this evaluation paradigm, the dust-induced health risks in coal mining were quantified. To go into greater details, 21 types of workers involved in the life cycle of coal mining were determined, and the health risks for them are illustrated in Fig. 4. As mentioned in Sect. 2.2, the acceptable range of health risks proposed by the USEPA is 1.0E-06 to 1.0E-04, suggesting that the health risks induced by respirable dust are in the tolerable scope in most cases. Perhaps most remarkable, roadheader driver at driving face suffered from the highest risk caused by silica dust, with the average risk of 5.60E-06. What's more, the total health risks of four workplaces were 1.44E-05, 2.41E-05, 1.43E-05, and 2.28E-05 for coal face, driving face, shotcreting point, transshipment point, respectively. And the transshipment point had the highest health risks level of dust, it can be attributed that this worksite takes on the task of underground coal transportation. More specifically, there are vertical drops between transshipment points, leading dust spread to surrounding circumstances from coal flow and thus causing greater dust pollution.

From what we have discussed above, we could easily find that with the utilization of probabilistic risk models, the health risks caused by contamination substances can be characterized in unified and comprehensible indicators. In doing so, it would be more evidence-based for the related enterprises and departments when controlling the pollutants discharging. Meanwhile, the occupants in the coal-based clean energy industry would be much clearer about the damaging degree of their worksites, and further instruct them to adopt standard protective measures.

4.3 Discussion on health impacts models

Compared with single health risk values, indicators of life loss and economic loss are often easier to understand for employees and companies when perceiving the damage extent. The third part of this evaluation paradigm, namely, health impacts models consequently play the role in transforming health risk values into more understandable indexes.

For the case study of coal mining, the probability distribution of dust-induced health impacts is illustrated in Fig. 5, suggesting that the coal mine dust had different influences on occupants in different workplaces. The highest health impacts took place at driving face, with the maximum value of 2.50 a, and following a lognormal distribution of 1.76 ± 0.14 a. As for the second high-impact worksite, the dust health impacts values at coal face ranged from 1.50 to 1.92 a, suggesting a high potential health effect. By way of contrast, the health impacts levels of coal mine dust in transshipment point and shotcreting point were slightly smaller, with the mean values of 1.24 and 0.99 a, respectively. In other words, the dust in these two places would not result in a significant hazard to human bodies, but the health impairments are still nonnegligible. Consequently, countermeasures should be taken in priority at driving face and coal face to decline the adverse health effect of dust.

As for coal-fired power generation, to present detailed results from more perspectives, comparison on the assessment results of four substages, ten terminal disease, and seven airborne pollutants were clarified. Firstly, the life loss induced by airborne pollutants in different production stages were illustrated in Fig. 6. It can be seen that the substage of coal combustion exposed to the highest health impact, following by coal mining, coal transportation, and slag disposal, with the life loss values of 118.85, 30.90, 4.14, and 0.91 a, respectively. Specifically, the total health impacts of four processing substages can be partitioned into more details. Firstly, the contribution to the total health impacts of seven pollutants is illustrated in Fig. 7(a). It is found that although the economic losses caused by various pollutants were generally different from four substages, there were still regular patterns can be summarized. On the one hand, SO_2, NO_2, and PM_{10} were always the three pollutants with the highest health impacts throughout the four processing stages. On the other hand, among the remaining four pollutants, CO_2 always brought about higher damage than the other three harmful substances. For instance, during coal combustion, the WTP values of SO_2, NO_2, and PM_{10} were 1.79E + 07, 6.45E + 06, and 2.57E + 06, respectively; CO_2 contributed nearly 6.71E + 05 yuan of health impacts, while N_2O, CO, and CH_4 only induced health impacts of 6.19E + 02, 1.99E + 02, and 1.08E + 02, severally. Furthermore, the assessment results can be explained in terms of terminal diseases as well. Notably, the terminal diseases of CH_4, CO_2, N_2O, and CO were summarized as global warming-related diseases, and for the other four substances, their corresponding diseases were divided into two kinds, circulatory system damage and respiratory system damage. As shown in Fig. 7(b), respiratory system damage was the most serious damage type throughout the life cycle of coal-fired power generation, with the WTP values of 8.06E + 07; while circulatory system damage and global warming-related diseases contributed less, valuing as 9.10E + 06 and 7.18E + 05, respectively.

For the third case study, its health impacts induced by dust, SO_2, and NO_2 in the whole life cycle of coal liquefaction were assessed as well. As depicted in Fig. 8, substage of coal mining and processing contributed to the most of the economic loss, with the values of 4.28E + 04, following by coal liquefaction and coal transportation, valuing as 1.34E + 03 and 1.85E + 00, respectively. Further, for the specific airborne pollutant, the health impacts of dust were greater than SO_2 and NO_2 in most cases. However, during coal mining and processing, the economic loss of NO_2 was bigger than dust, which enlightens us to pay attention to the NO_2 pollution in this substage. To go into details, the life loss of dust and toxic and harmful gases were illustrated separately. The terminal diseases caused by dust pollution are presented in Fig. 9(a), it could be easily found that the life loss of four diseases followed the order of CWP > COPD > CVD > ARI. What's more, as shown in Fig. 9(b), the most serious damage of toxic and harmful gases occurred in coal mining and processing, where NO_2 contributed the most with the life loss value of 2.83E-01.

From what have been discussed above, it can be concluded that the health impacts models could aid to identify the terminal disease which occupies the most serious impairment. On the other hand, the evaluation indicators of DALY and WTP have meanings of life and economic loss, respectively. There is no doubt that compared with the pollutant concentrations and health risks, enterprises and workers would be more sensitive to these two indexes, and could provide references for the policy formulation on environmental taxes and health subsidies.

4.4 Comparative analysis

Keeping paces with the development of coal-based clean energy industry, the related environmental pollution issues have recently been a hot topic in academia, and many contributory studies are conducted. In this section, we work on reviewing the research methods mainly applied in the related studies.

After taking close insight into the related researches in this area, the authors found that these publications can be partitioned as three hot topics. Firstly, to investigate the relationship between coal consumption and environmental contamination, most studies apply the dataset of pollutants concentration and the distribution of coal consumption (Xie et al., 2020). Herein, establishing the exposure-response relationship between different air pollution and health effect ends is a research focus.

For instance, with the established exposure-response relationship, Li et al. (2018a) measured the number of different health effect ends caused by $PM_{2.5}$ emissions of coal consumption under various emission scenarios. Secondly, simulation physical models are commonly utilized to simulate air conditions during clean coal energy processing. Such examples might be given easily, Xiu et al. (2020) established a highly simulated physical model of the goaf and multiple dust-removal air flow rates in the roadway, to investigate the dust pollution characteristics during coal mine production. Likely, Chen et al. (2020b) employed a three-dimensional nested air quality condition model with source apportionment to analyze the environmental impacts of coal-fired power plants. Amongst, it is noteworthy that the majority of researchers have recognized the processing of coal-based clean energy industry includes numerous resource consumption and emission inventories. Therefore, the idea of LCA, which can evaluate environmental pollution burden from “cradle-to-grave” process of a product or service, is often used (Wu et al., 2017; Zhang et al., 2018; Ghadimi et al., 2019). Thirdly, as it is a common knowledge that the road to sustainable development is only attainable if it is built on the simultaneous development among environment, economic, and social. Correspondingly, when discussing pollutant discharging and its health impacts in the coal-based clean energy industry, many researchers combine with the considerations of economic and technical analysis (Cui et al., 2018; Zhao et al., 2019; Yang et al., 2020). Meanwhile, increasing numbers of studies start to adopt economic cost and health benefits as the final assessment indicators, to turn the assessment results more intuitive and understandable. For example, Chen et al. (2020a) estimated the impacts on public health and the related economic loss of $PM_{2.5}$ pollution produced by coal consumption using the Poisson regression model.

As a whole, many kinds of innovative and effective methods have emerged to explore the contamination issues in the coal-based clean energy industry. However, there are still some gaps that need to be filled. On the one hand, pollution data in dataset usually report the statistical condition, scene sampling would be more correct to reflect the contamination at specific worksites. On the other, although the ideologies of life cycle and economic indexes are used extensively, they often serve to technical assessment and isolate from environmental evaluation. Correspondingly, the evaluation paradigm we proposed could assess environmental impacts from the perspectives of life and economic loss, and the idea of LCA was combined. It is believed that this paradigm could fill the gap and provide references for academia and industrial development to some extent.

5. Conclusion And Policy Implications

5.1 Conclusion

The development of coal-based clean energy industry takes an important role in China’s energy stability. Although a circular chain including green and intelligent mining, clean energy conversion and production has emerged and put into production, concerns on the related contamination issues still exist, as it has a genuine impact on the developing directions of the national energy industry. Therefore, evaluations for health impacts of environmental pollution in the coal-based clean energy industry is often required.

However, numerous processing technologies and substages, and environmental pollutants are included in this industry, an assessment paradigm is still scarce, which is our concern. To fill this gap, evaluation models were proposed in our study, in which health impacts caused by environmental pollution can be signified using health risks, life loss and economic loss. Last but not the least, three representative clean coal industries are explored as case study to demonstrate the broad applicability of the proposed models. Results show that during coal mining, the worksite and pollutant need to be monitored in priority were driving face and coal dust, respectively. For coal-fired power generation, the health impacts of different substage induced by seven pollutants followed the order of coal combustion, coal mining, coal transportation, and slag disposal. As for coal liquefaction, the substage of coal mining and processing contributed to the greatest part of total health impact, and the related economic loss of dust were bigger than SO_2 and NO_2 in most cases.

The main limitation of the analysis conducted in this paper is that it only estimates the health impacts of three clean coal technologies. Correspondingly, in the future studies, this proposed evaluation paradigm would be applied in other industries to demonstrate its wider applicability, such as coal-to-olefin (Shen et al., 2020), coal gasification (Sutardi et al., 2019), and coal-to-methanol (Puig-Gamero, et al., 2021). Meanwhile, as complex and diverse pollutants involve in energy processing, it is an urgent need to conduct health impacts assessment of other contaminations, such as volatile organic compounds (VOCs) and heavy metals (Chang et al., 2016). Herein, it is reported that in Chinese coal, the concentration of Hg is 0.15–0.22 $mg \cdot kg^{-1}$, and more than 99% of Hg would emit during coal combustion (Zhou et al., 2015). Therefore, the health impacts evaluation of Hg should be focused in the following studies.

5.2 Policy implications

Overall, linking the results mentioned above with practical significance, it is suggested that the proposed evaluation paradigm would be useful for social mobilization promoting, policy making, and environmental pollution prejudging.

At first, sufficient and stable energy supply is a prerequisite for the sustained development of industrialized society. Developing the coal-based clean energy industry has become a key success factor for economic growth in China, as it could meet wider societal needs. The enhancing attentions on Industrial Symbiosis call for cooperation between traditionally separate industries and public service infrastructure (Marchi et al., 2017). And a community-integrated energy supply system combined with production, provision, sales, and transportation is developing, which needs cooperation between different sectors. Accordingly, the formation and updating of public consciousness on coal-based clean energy industry undoubtedly play a vital role in the industry chain of the circular economy. On the other hand, it is an impressing task to alter the intrinsic stylized cognitions on coal utilization, as when it comes to coal use, environmental pollution would come to the public's mind.

This study can evaluate the damaging degrees of environmental pollutions in the coal-based clean energy industry. More importantly, indexes that the public is more sensitive, namely, life losses are introduced to explain the health impacts results. For instance, it is estimated that in the four worksites of coal mining, the total life loss of all workers involved was about 5.60 a. Correspondingly, these results could provide data support for the general public to clarify that comparing with traditional coal use, whether the clean coal industry is more environment-friendly or not. Therefore, it is believed that this study could help to promote the convergence of the energy industry and related public service system, and for the cognitions update on new-type coal clean and efficient use.

Secondly, to achieve the emission-reducing objectives and the transition to new energy systems, the Chinese government has proposed and implemented several relevant measurements in recent years, which include laws, regulations, and policies. Herein, the "Air Pollution Prevention and Control Action Plan" was issued in 2013, where coal control is a critical part. The promulgation of this action plan is also a vital milestone in China's war on pollution (Wu et al., 2020). Meanwhile, with the publication of "Law of the People's Republic of China on Coal", the strategic area of clean coal energy has been emphasized; administrative regulations and ministerial rules such as "Energy Development 'Thirteenth Five Year Plan'", "Action Plan for Clean and Efficient Use of Coal", and "Modern Coal Chemical Industry Innovative Development Layout Plan" have formulated the development directions and key points of coal-based clean energy technologies.

However, it is proposed that these policies lack economic incentives and detailed mandatory requirements, which inhibits clean coal technologies in actual development (Tang et al., 2015). Specifically, the environmental performance of different technologies substantially differs, implying that the related policies are not always compatible with one another, especially those policies surrounding financial support and tax regime. Further, the clean coal industry has the characteristics of high investment costs, long payback date, and high investment risk, determining it depends strongly on policy subsidies (Fang et al., 2020). Therefore, subsidy policies should be formulated in combination with the sound policy framework, where supervisory policies and profit evaluation policies are included. In this study, WTP values representing the economic losses were applied, which could provide references for the formulation of environmental taxes and health subsidies. Taking coal-fired power generation as an example, it is evaluated that the WTP values were 6.16E + 07, 1.04E + 06, 2.76E + 07, and 2.12E + 05 for coal mining, coal transportation, coal combustion, and slag disposal, respectively. Meanwhile, we believe that these results would help the related departments to judge the environment-economic effectiveness of each processing plant.

Last, as emphasized in sustainable development, energy should be applied in a sustainable pattern without future generations being harmed by the overexploitation of finite natural resources (Heffron & McCauley, 2017). Therefore, clarifying contamination conditions in and around the coal-based clean energy plants, not only help to diminish the health impacts to workers and residents, but also provide references on the development trend of the national energy market. Herein, what matters is prejudging the environmental change in processing, as it could help to avoid the health damages preliminary. Moreover, in the case where environmental policies are sophisticated, the intensity of environmental regulation is a critical factor influencing emission behaviors of industrial production, as well as the changes of residents' cognitions on environmental standards (Du & Li, 2020). Notably, environmental attention and pollution management investment are inextricably linked to the intensity of environmental regulation, whereas these two factors are finite and need to be allocated reasonably.

With the aid of life cycle idea, this study could show the comparisons of environmental impacts in different substages and occupants, which would help the stakeholders to appropriately allocate the attention and investments on industrial environmental management. For example, in coal liquefaction, the WTP values of coal mining and processing were 4.28E + 04, followed by coal liquefaction and coal transportation, with the values of 1.34E + 03 and 1.85E + 00, respectively. Furthermore, among three airborne pollutants, the health impacts level of dust was greater than SO_2 and NO_2. Therefore, in the pollution management of coal liquefaction, more attention should be paid to the substage of coal mining and processing, and the pollutant of dust. By doing so, it is expected that the environmental pollution control in the coal-based clean energy industry can get the highest benefit with the lowest cost. These practical implications mentioned above are profitable not only for China, but also for other countries who go through in a period of energy transition.

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Authors' contributions:

Boling Zhang: Data curation, Formal analysis, Methodology, Software, Writing – original draft.

Xiaoyi Yang: Investigation, Writing – review & editing, Validation, Visualization.

Ruipeng Tong: Conceptualization, Funding acquisition, Methodology, Resources.

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Figures

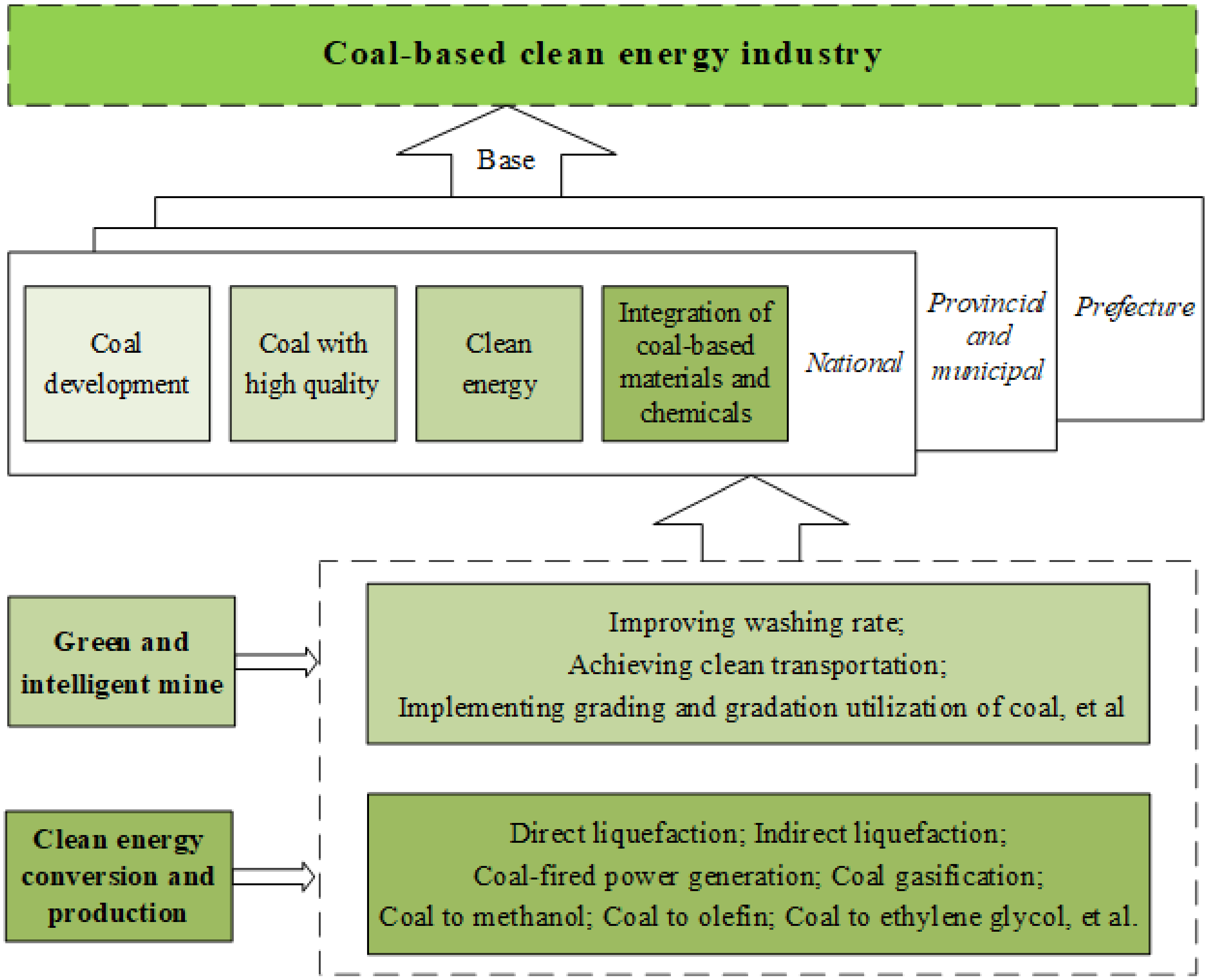

Figure 1

Definition of coal-based clean energy industry.

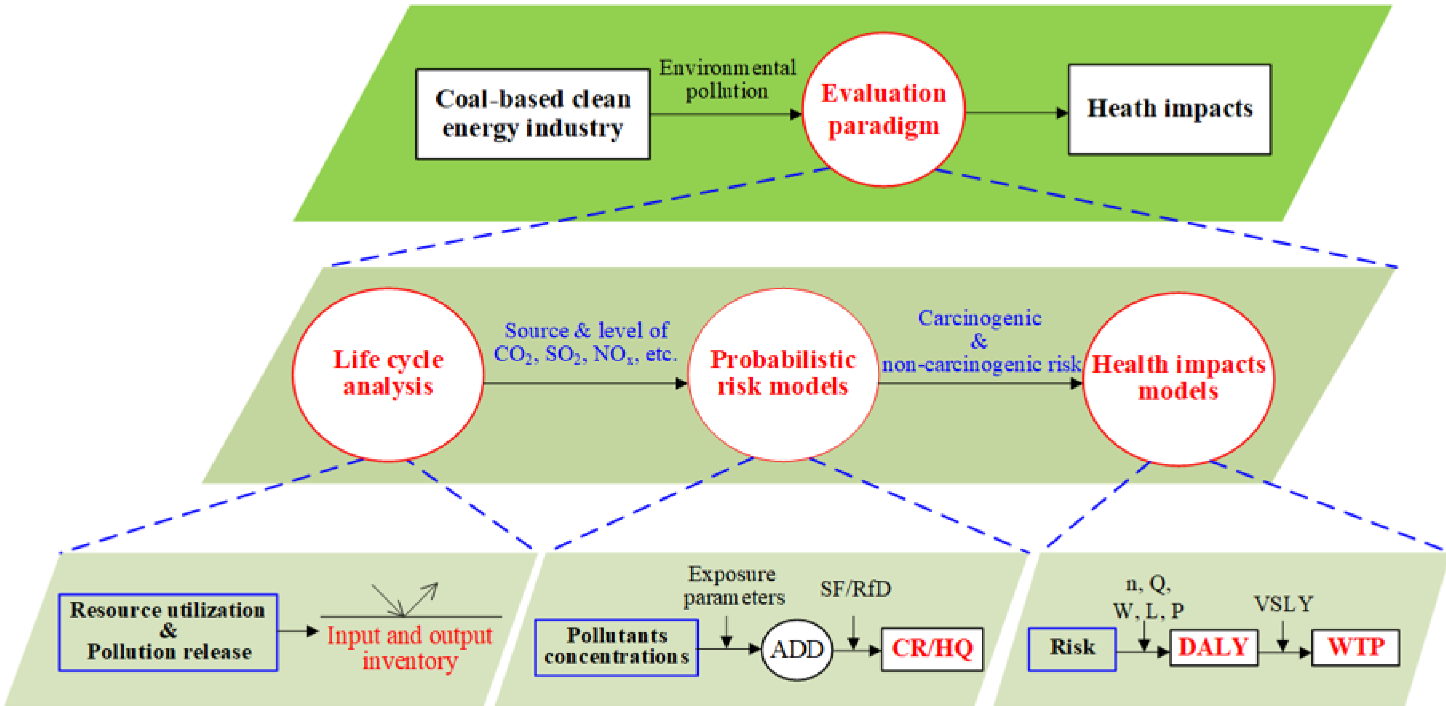

Figure 2

Flowchart for evaluating health impacts in the coal-based clean energy industry.

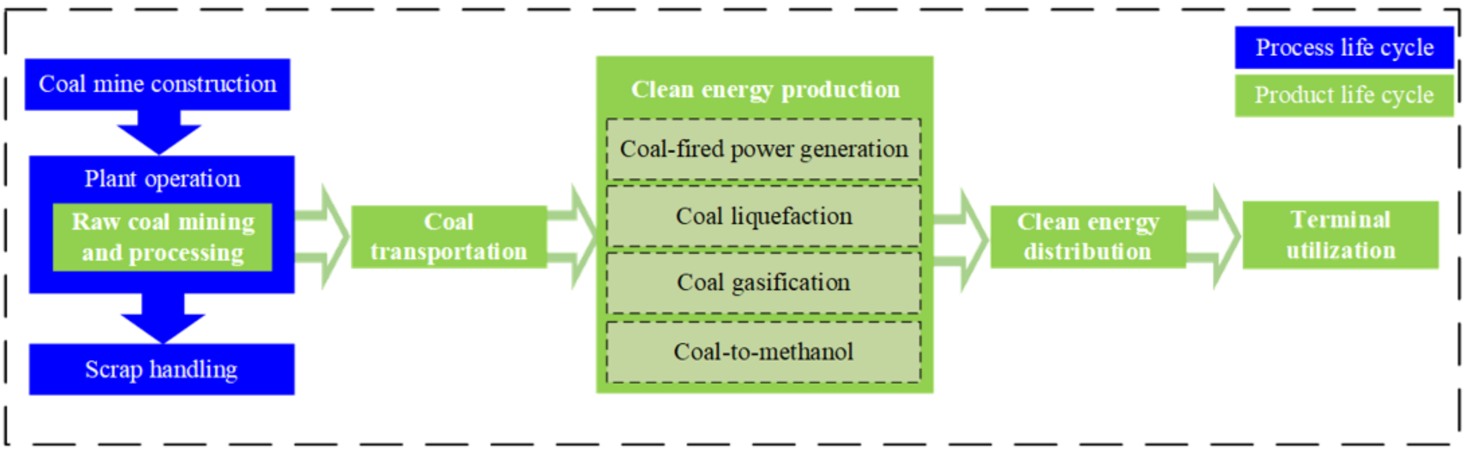

Figure 3

The streamlined life cycle for the coal-based clean energy industry.

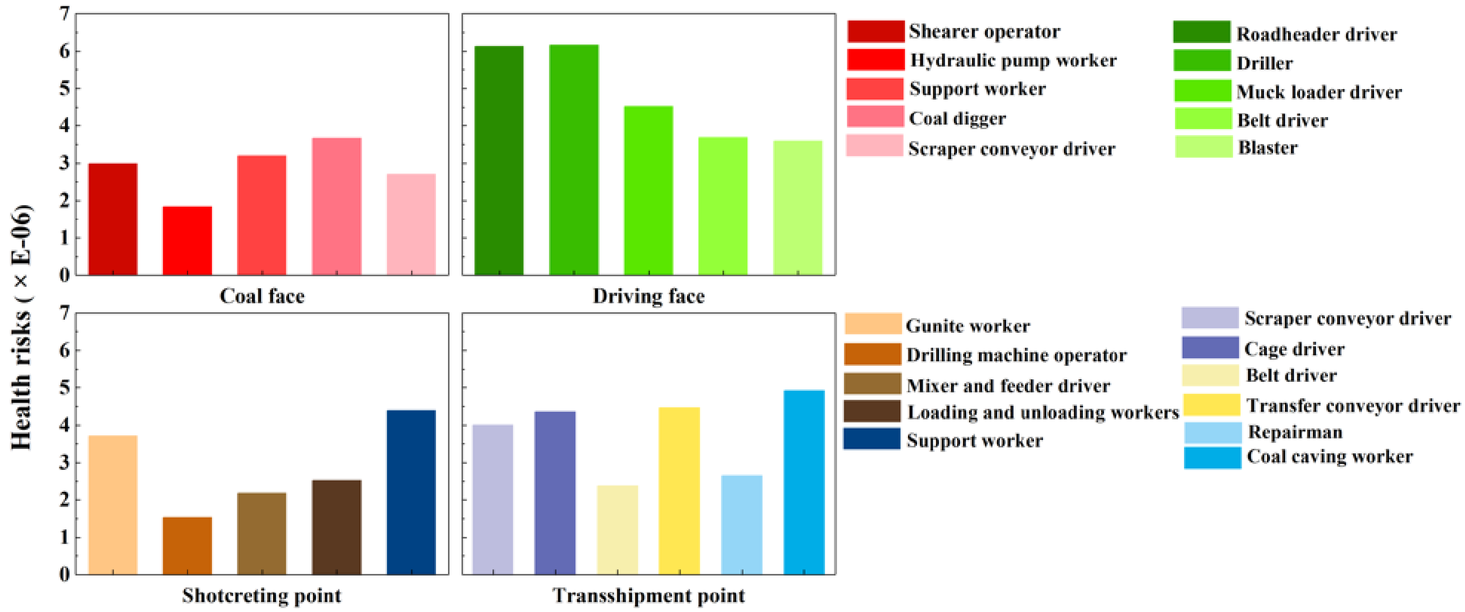

Figure 4

Health risks of dust for various workers in coal mining.

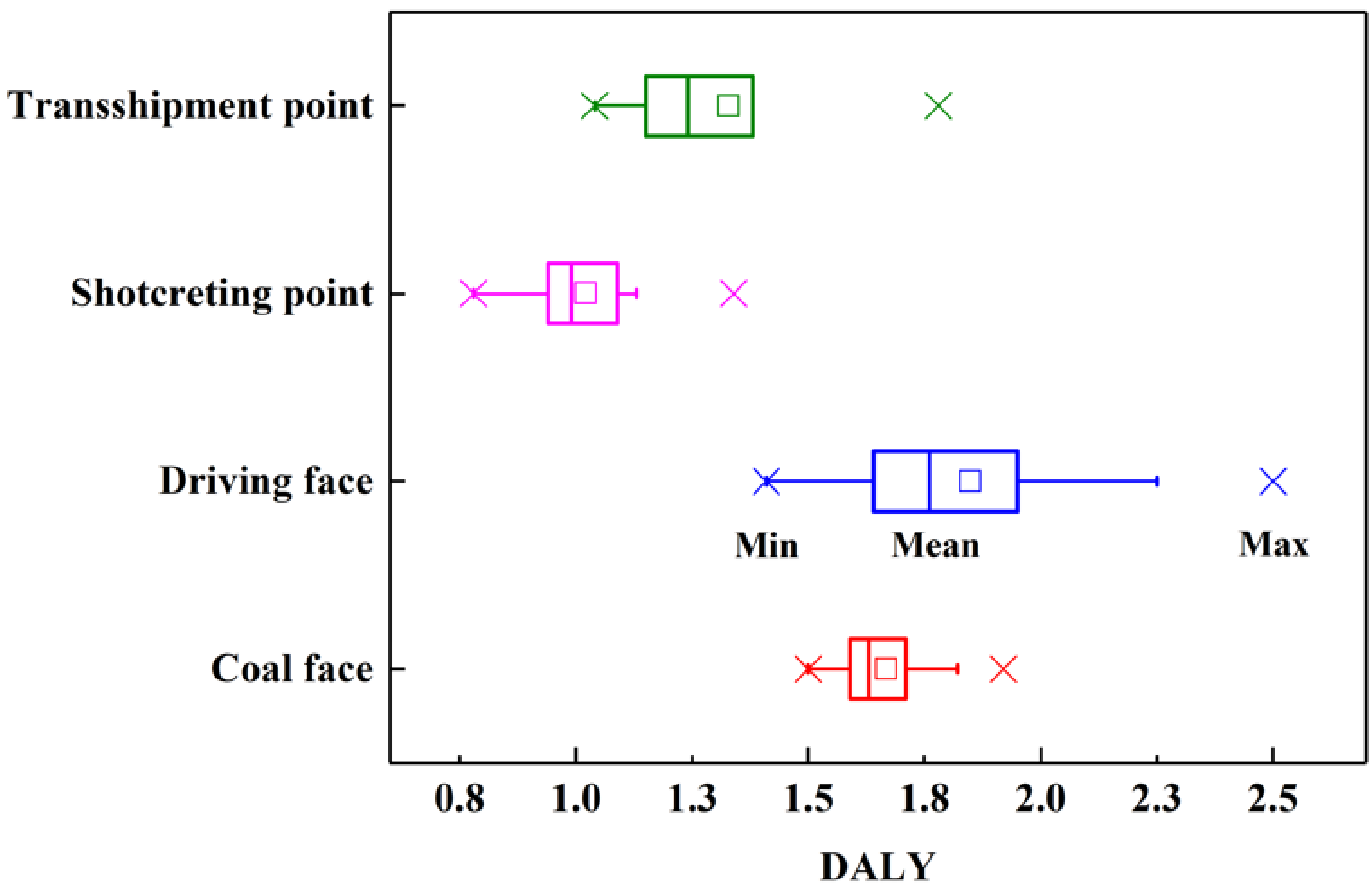

Figure 5

Health impacts of dust at different worksites in coal mining.

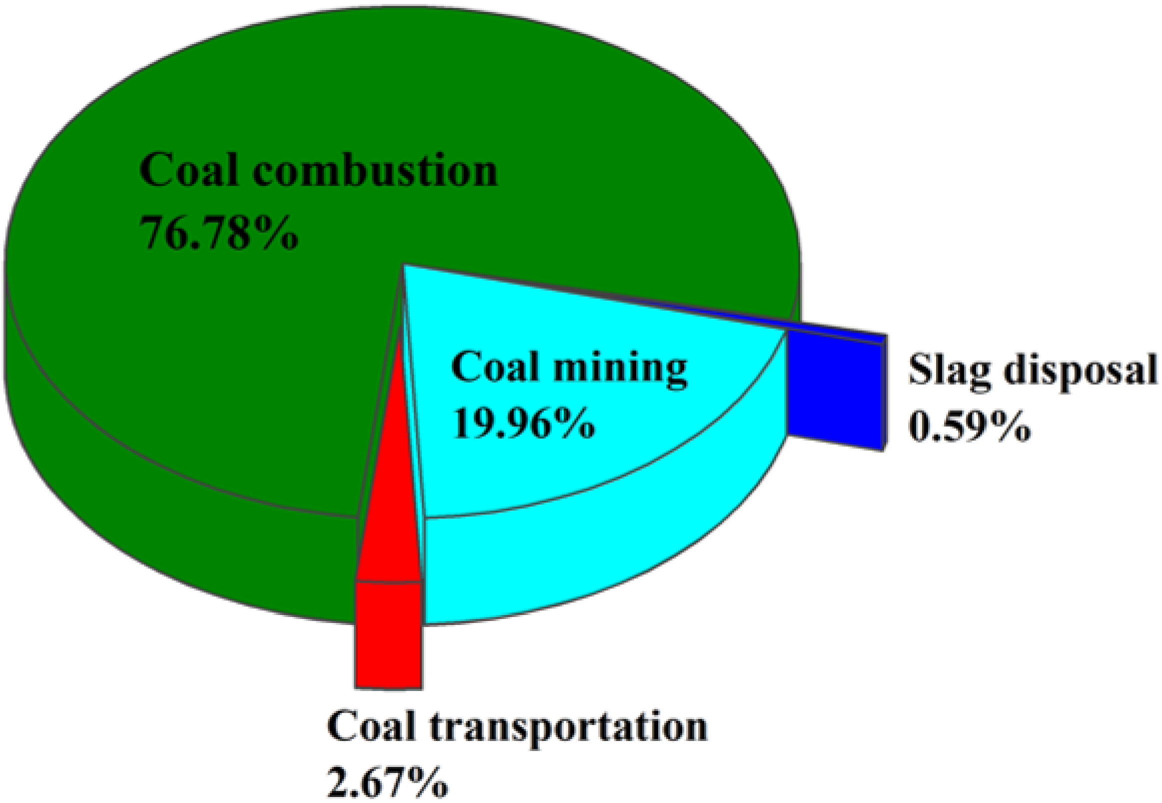

Figure 6

Total health impacts of different substages in coal-fired power generation.

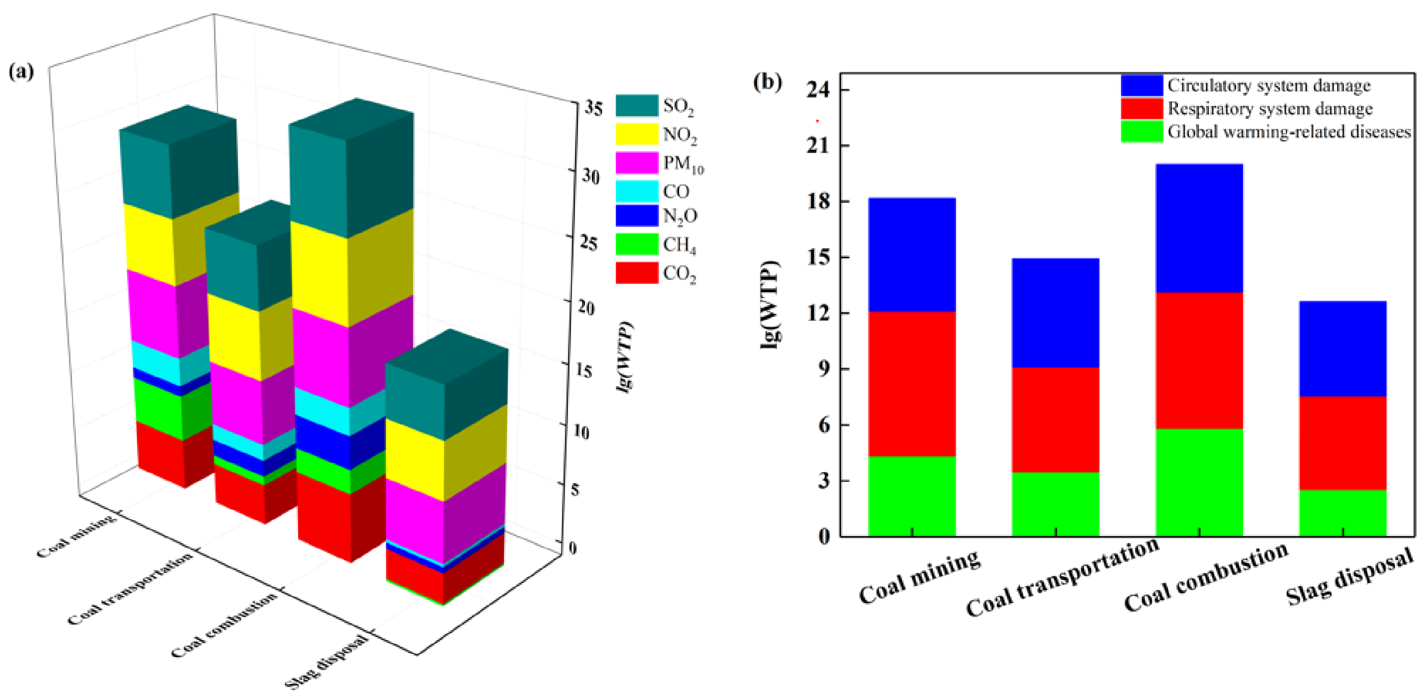

Figure 7

Health impacts of different airborne pollutants or processing stages.

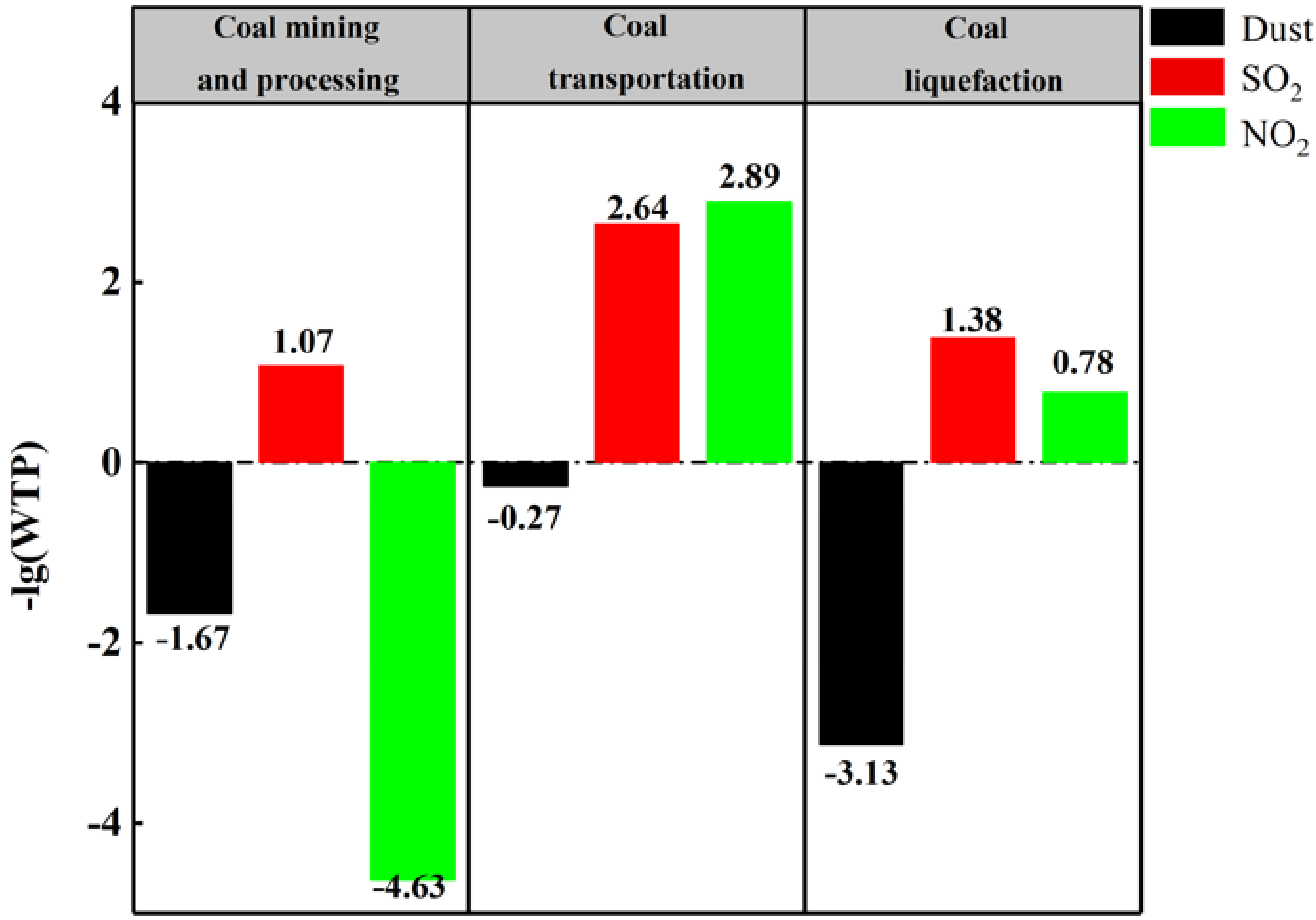

Figure 8

Economic loss of airborne pollutants in the life cycle of DCL.

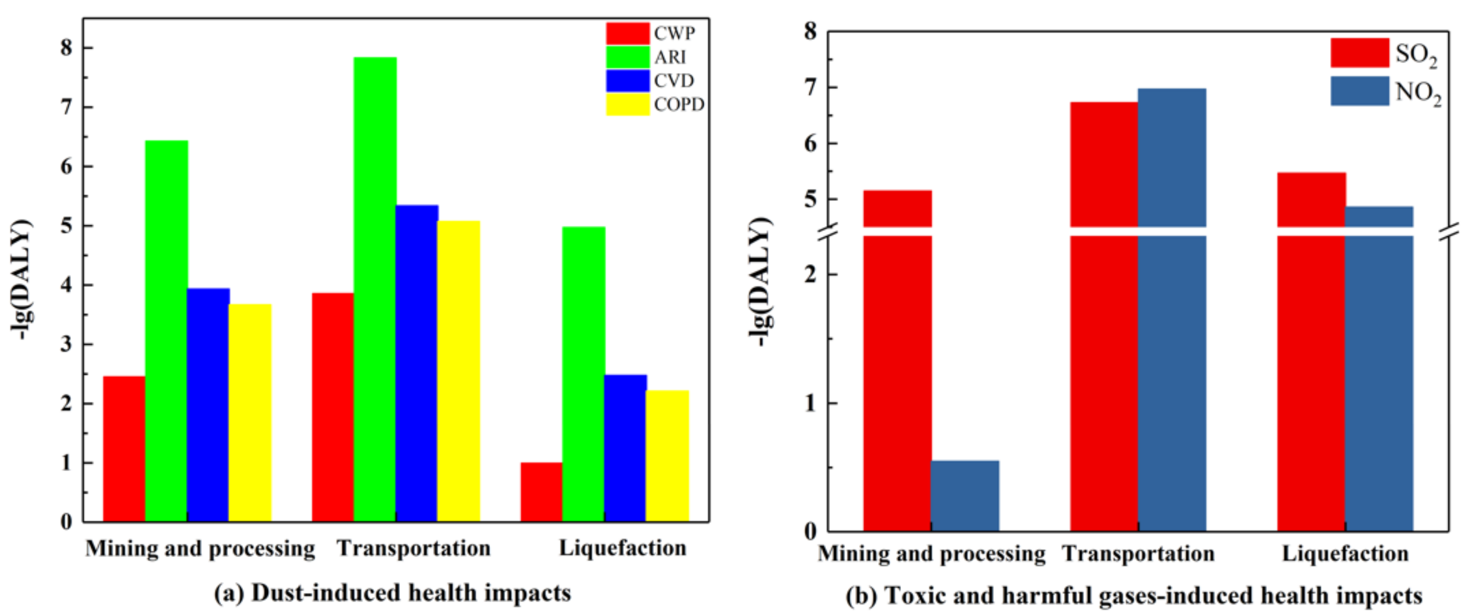

Figure 9

Life loss of airborne pollutants in the life cycle of DCL.