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An LCA study of an electricity coal supply chain

Chao Wang, Dong Mu

School of Economics and Management, Beijing Jiaotong University (China)
chaowang.hn@gmail.com, mudong.bjtu@gmail.com

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Abstract:

Purpose: The aim of this paper is to provide methods to find the emission source and estimate the amount of waste gas emissions in the electricity coal supply chain, establish the model of the environmental impact (burden) in the electricity coal supply chain, detect the critical factor which causes significant environmental impact, and then identify the key control direction and reduce amount of environmental pollution in the electricity coal supply chain.

Design/methodology/approach: In this context, life cycle inventory and life cycle assessment of China's electricity coal were established in three difference stages: coal mining, coal transportation, and coal burning. Then the outcomes were analyzed with the aim to reduce waste gases emissions' environmental impact in the electricity coal supply chain from the perspective of sensitivity analysis.

Findings: The results and conclusion are as follow: (1) In terms of total waste gas emissions in electricity coal supply chain, CO_2 is emitted in the greatest quantity, accounting for 98-99 wt% of the total waste gas emissions. The vast majority of the CO_2, greater than 93%, is emitted from the power plant when the coal is combusted. (2) Other than CO_2, the main waste gas is CH_4, SO_2 and so on. CH_4 is mainly emitted from Coal Bed Methane (CBM), so the option is to consider capturing some of the CH_4 from underground mines for an alternative use. SO_2 is mainly emitted from power plant when the coal is combusted. (3) The environmental burden of coal burning subsystem is greatest, followed by the coal mining subsystem, and finally the coal transportation subsystem. Improving the coal-burning efficiency of coal-fired power plant in electricity coal supply chain is the most effective way to reduce the environmental impact of waste gas emissions. (4) Of the three subsystems examined (coal mining, coal transportation, and coal burning), transportation requires the fewest resources and has the lowest waste gas emissions. However, the energy consumption for this subsystem is significant (excluding the mine mouth case), and transportation distance is found to have a substantial effect on the oil consumption and non-coal energy consumption. (5) In electricity coal supply chain, the biggest environmental impact of waste gas emissions is GWP, followed by EP, AP, POCP and ODP, and regional impact is greater than the global impact.

Practical implications: The model and methodology established in this paper could be used for environmental impact assessment of waste gas emissions in electricity coal supply chain and sensitivity analysis in China, and it could supply reference and example for similar researches. The data information on life cycle inventory, impact assessment and sensitivity analysis could supply theory and data reference for waste gas emissions control in electricity coal supply chain.

Originality/value: To the best of our knowledge, this is the first time to study the environmental influence of electricity coal supply chain by employing a LCA approach from life cycle of electricity coal.

Keywords: life cycle assessment; electricity coal supply chain; sensitivity analysis

1. Introduction

According to the official data from the National Bureau of Statistic (CSY, 2013), in 2012, the velocity of national electric power grows overwhelmingly in the recent years in China. And 81% of the electricity was produced from the coal-fired power plant (IEA, 2010). Therefore, coal plays a dominant role in China economic growth. Coal accounts for almost 90% of China’s primary energy storage (Qiu, 2013) and accounts for about 70% of China’s primary energy production and consumption (Yan, 2006). Because of its abundance in proven reserves and its stability in supply, coal will continue to be a key component of primary energy mix in China at least over the next few decades (Li & Leung, 2012). However, coal also accounts for a large share of CO_2 emissions generated by anthropogenic activities, and based on Miao (2009) over 70% of total SP, 90% of SO_2, 67% of NO_x, 85% of CO_2 produced by fossil fuels come from coal now. Therefore, in this carbon-constrained global world, understanding the environmental implications of producing electricity from coal life cycle is an important component of any policy to reduce total pollutants emissions.

Electricity coal life cycle involves coal-mining, transportation and coal-burning process (Liu & Zhao, 2011) which is also called electricity coal supply chain. It has seriously adverse effects on natural environment and human society. Main waste gas emissions includes CO_2, SO_2, NO_x and smoke dust, which could cause acid rain, ozonosphere damage and global warming after emission. Coal-mining process can result in overburden waste and slag heaps, mine fires (Mann & Spath, 2001). The combustion of fuel for the coal transportation can result in air pollution, water pollution, traffic hazards etc. SO_2, NO_x and particulate matters are released from the power plant in coal-burning process. However most researchers only give rise to the growing concern of the discharges and control methods of pollutants in coal burning process, not from the perspective of coal lifecycle, because of the high consumption of coal and high levels of waste emissions. Therefore, various measures have been taken to achieve better use of resources and energy as well as implement more sustainable practices in the coal-electricity system. Bates (1995), Uchiyama (1996), Restrepo, Miyake, Kleveston and Bazzo (2012) and Liang, Wang, Zhou, Huang, Zhou and Cen (2012) aimed at power plants in U.K, Japan, Brail and China respectively, studied the power plants' influence on environment with a Life Cycle Assessment (LCA) method. Pacca and Horvath (2002) calculated Global Warming Potential (GWP) of coal, gas, solar power and wind energy power plants. Hondo (2005) calculated greenhouse gas emission in eight power plants' construction, operation and retirement processes in Japan, using LCA method, process analysis and input-output analysis method. Kannan, Leong, Osman and Ho (2007) studied on five power plants and their influence on environment in Singapore from the point of power generation technology with LCA and LCC methods.

Lave and Freeburg (1973) found that comparison with petroleum and gas, coal has the most significant impact on environment in mining process, transportation process, as well as coal-burning process. Hence, it is necessary to study the environmental influence of electricity coal from cycle life point. However, the literature on this aspect is rare. Pan and Mu (2011) compared the influence of nuclear power supply chain and electricity coal supply chain on health, environment and climate in China, with radiation effect from natural radioactive nuclides in coals as a indicator. Some researchers studies the environmental performance from natural gas (Korre, Nie & Durucan, 2012), forestry (Björk, Erlandsson, Häkli, Jaakkola, Nilsson, Nummila et al., 2011), biofuel (You, Tao, Graziano & Snyder, 2012). This paper studies an electricity coal supply chain by employing a LCA approach. The remainder of the present paper is organized as follows. Section 2 gives a brief introduction of a specific electricity coal supply chain in China. Section 3 studies this electricity coal supply chain with LCA. Methods of sensitivity analysis are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. The case study

The electricity coal supply chain involves the coal mining process, coal transportation process and coal burning process, all based in China. The goal of coal mining is to remove coal from the ground. After coal preparation/cleaning, coal is moved to the coal-fired power plant by barge, rail or truck. This paper presents a thorough case study of the environmental impact of waste gas emissions in an electricity coal supply chain, where the coal is mined by an underground colliery- Jiangzhuang Coal Mine (JZCM) of Zaozhuang Coal Mining Group Co.,Ltd. and is transported 93 Km by heavy-truck and then burned at Shiliquan Plant (SLQP) of Zaozhuang which is a coal-fired power plant.

2.1. Coal mining process

Underground mining operations include: cutting, drilling, blasting, loading, and hauling. Auxiliary operations include ventilation, drainage, power, communications, and lighting. Roof support is another task which is considered to be a unit operation. The raw coal output of JZCM was 3.4 million tons in 2012. In the same year, it used 1.81 million m^3 fresh water, 0.44 thousand tons of diesel oil, 0.086 thousand tones of petrol, 9.87 thousand tons of steel, 19.7 thousand tons of cement and 1.74 thousand m^3 of timber. The energy consumption includes 7.23 million kWh of electricity and 13.2 thousand tons of coal. It produced waste comprising 0.461 million tons of coal gangues, 0.235 million tons of washed gangue, 0.168 million tons of coal slurry, 1.78 million tons of mining wastewater and other waste. Table 1 gives the underground mining equipment fuel and material requirement, and Table 2 gives a breakdown of the electrical details. The research result of Clean Production Standard in Coal Washing and Processing Industry (2010) shows that electricity consumption of raw coal production in state-owned key coal mines usually ranges between 15 kWh/t and 25 kWh/t, and the rock bottom electricity consumption reaches 4.4 kWh/t.

Fuel/material	Application amount	Unit	Fuel/material	Application amount	Unit
Electricity	2.13E+01	KWh	Petrol	2.54E-05	t
Coal	3.88E-03	t	Steel	2.90E-03	t
Fresh water	5.32E-01	m^3	Cement	5.65E-03	t
Diesel oil	1.30E-04	t	Timber	5.11E-04	m^3

Table 1. Underground mining equipment fuel and material requirement (Unit: /t of raw coal)

Equipment	Total(kW)	Hours used/day	Load (kW)	Electrical consumption	
				MWh/day	kWh/day/Mt coal
Longwall unit	1860	16	1860	29.76	21.4
Continuous miner	890	10	890	8.90	6.1
Loading machine	245	10	245	2.45	2.9
Shuttle car	423	10	423	4.23	3.1
Roof bolter	85	12	85	1.02	0.8
Ratio feeder	196	10	197	1.96	1.8
Triple-rock duster	70	12	70	0.84	0.7
Auxiliary fan	25	18	25	0.45	0.4
Supply car	209	12	209	2.51	1.7
Conveyor	596	16	596	9.54	7.3
Ventilation fan	375	24	375	9.00	6.9
Pumps, bolting	315	10	315	3.15	3.0
Lighting	N/A	24	268	6.43	4.8

Table 2. Underground mining electrical requirements

In this case, coal preparation/cleaning is a part of coal mining process in JZCM. Coal preparation normally involves size reduction of the mined coal, the removal of ash-forming materials and rocks, as well as the removal of very fine coal. Coal preparation methods include the gravity method, floatation, magnetic separation and electro-separation. The JZCM uses the gravity method. The coal and detrimental impurities can be separated by weight differences of the coal and the waste in both water and air. In this process, the coal floats on the surface and the detrimental impurities submerge to the bottom. And then coal is shipped to coal-fired power plants, while the waste are used for filling. The coal preparation process includes screening, crushing, separating, dewatering, storing and loading. Screening is to identify the constitution of different raw coal particles. Crushing is to grind the mined coal blocks into coal power. Separating is to classify coal particles according to their size, and to separate mineral particles from the coal. Dewatering is to remove water from the coal. Storing and loading is to store the cleaned coal, load it and then ship it to the coal-consuming enterprises. The preparation process and coal preparation equipment requirements are shown in Table 3, and the coal preparation fuel and material requirements are presented in Table 4. According to Clean Production Standard in Coal Washing and Processing Industry (2010), energy demand for washing 1 ton of coal in large coal preparation plant is less than 10 kWh, and the lowest energy consumption is less than 5 kWh.

Techniques Process	Equipment
Screening	Screen grader
Crushing	Crusher
Jig washing	Jigger, heavy-media separator, heavy medium cyclone
Dewatering	Dewatering centrifuge
Loading	Truck, crane

Table 3. Coal preparation equipment requirements

Fuel/material	Requirement	Unit
Coal	1.31	ton
Electricity	32.4	MJ
Water	1278	Kg
Manganese (Mn)	1.593	Kg

Table 4. Coal preparation fuel and material requirement (Unit: /of ton MAF raw coal)

2.2. Coal transportation process

In China, the main transportation methods are railways, highways and waterways. In the coal transportation process, this paper only considers coal that is transported from the coal mine to the power plant. Ammonium nitrate and other blasting materials which are transported to the coal mine, and ammonia (NH_3), hydrogen chloride (HCl), sodium hydroxide (NaOH), calcium carbonate ($CaCO_3$), etc, which are transported to the power plant are not included in the LCA. According to the investigation, from JZCM to SLQP, the coal is shipped by steyr-king heavy duty trucks which have a loading capacity of 24 tons. The distance is 93 Km, the total diesel fuel consumption is 36L, and the transportation routing is presented in Figure 1.

Figure 1. Transportation routing of the electricity coal supply chain

2.3. Coal burning process

The burning process occurred in coal-fired power plants, and data collected from SLQP are as show below. The total installed capacity is 1225 MW, and the power generation is 8.39 billion kW. In 2012, SLQP consumed 1.91 million tons of raw coal, 1.62 million tons of coal gangue, 2.76 million tons of coal slurry, and 58.30 million tons of fresh water. The power plant inventory includes energy and non-energy (material) demand (See Table 5).

Number of generators	4	Raw coal	227 (g/KWh)
Installed capacity	1225 (MW)	Diesel	194 (g/KWh)
Installation time	Apr. 1995	Fresh water	6.94E-03 (g/KWh)
Efficiency	32%	Electricity	1.16E-01 (KWh)
Fuel type	Lean coal	Water consumption	33595 (t/day)
Ammonia water	N/A (g/KWh)	Cooling water	56000 (t/h)
Coal slurry	329 (g/KWh)	Power capacity	8.29 (GWh)
Coal gangue	192 (g/KWh)	Pollution control system	ESP
Middlings	65.4 (g/KWh)	Generator life expectancy	30 (year)
Pollution control equipment	ESP	Generator type	Pulverized coal boiler
Fuel properties	Low Calorific Value =22675KJ/Kg，Sulf concent=1.24%，ash concent=26.82%		

Table 5. Power plant inventory

3. Life cycle analysis of the electricity coal supply chain

An LCA approach is adopted to investigate the cumulative environmental burden produced by the supply chain generating 1 kWh of electricity (reference flow).

3.1. Goal and scope definition

The overall objectives of the LCA study are to:

- Demonstrate the usefulness of the LCA method in measuring the environmental impacts of a defined electricity coal supply chain system.
- Provide an overall understanding of an electricity coal supply chain and the associated environmental burden involved in the main processes of the supply chain.
- Seek quantitatively the most effective way to reduce the environmental burden of waste gas emissions.

- Highlight important areas for future research (further LCA studies concerning coal cinder utilization and the cost factor).

The scope of the LCA study (system boundary) is defined as follows: The system starts with the mining of coal and ends with electricity as the product. The main processes are the coal mining process, coal transportation process and coal burning process. The power plant which supplies energy to the supply chain is included in the system.

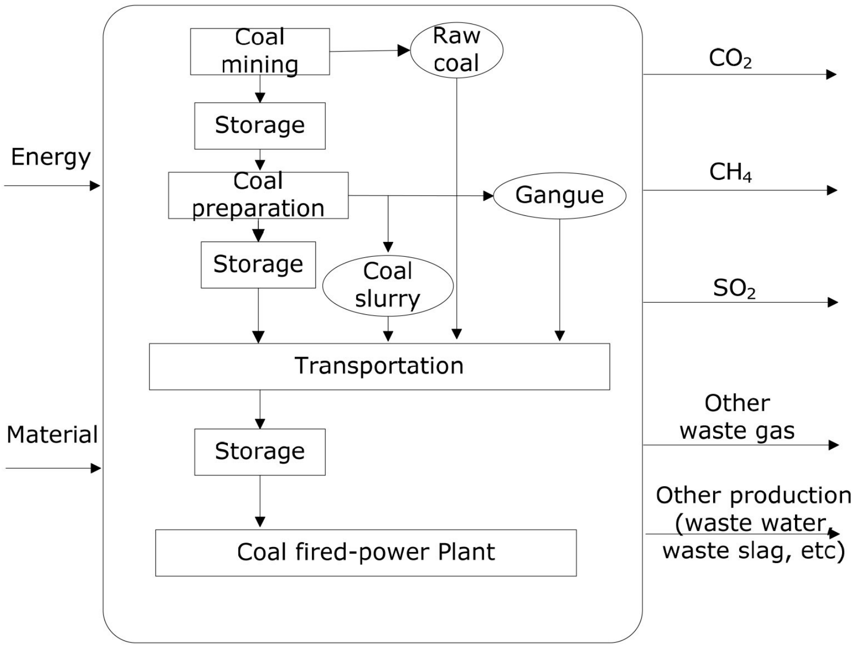

Figure 2. System boundary of the electricity coal supply chain

Based on the scope of the LCA, the supply chain model is displayed in Figure 2. The model represents a "Mining to Products (MTP)" system as distinct from a "Cradle to Grave" system. This means that coal's end of life (recycling) is not included in the study.

3.2. Life cycle inventory (LCI)

3.2.1. Main processes

The LCI of the waste gas emissions released by the system are shown in Appendix A. All the results are based on the reference flow of 1 kWh of electricity.

3.2.1.1. Coal mining process

In the coal mining process, a lot of waste gases will be released. For example, greenhouse gases like CO_2 and CH_4 will be released during the coal mining process, and gases like CO_2, SO_2, CO and H_2S will be spontaneously released from coal gangues. The mining process has great effects on the regional ecological environment, with the major sources of waste gases being the mine ventilation process, coal gangue, and the coal preparation process. All emissions of waste gases in the mining process are listed in Appendix A.

3.2.1.2. Coal transportation process

The atmospheric environmental problems arising in the coal transportation process are mainly caused by the burning of transport fuels, spontaneous combustion of coal in the process of transportation and coal dust pollution near the transport route. Main waste gases consist of HC, CO, NO_x, SO_2 and H_2S. Considering the coal transport from JZCM to SLQP by heavy duty trucks, all emissions of waste gases in the coal transportation process are listed in Appendix A.

3.2.1.3. Coal burning process

The coal-fired power plants in coal burning process often burn large quantities of low grade coal with high sulfur and high ash, even coal gangues, and are adjudged as the greatest sources of waste gases in China. Waste gases from burning mainly contain CO_2, SO_2, CO and NO_x. The direct consequence is that smoke dust and SO_2 emissions are dominant among emissions from industrial various sectors in China (Zhao, Wang, Nielsen, Li & Hao, 2010). In fact, the emissions of SO_2 from coal and electricity account for more than 59% of the emissions in Controlled Zones for Acid rain and Sulfur Dioxide (Lu, Streets, Zhang, Wang, Carmichael, Cheng et al., 2010). All emissions of waste gases in the coal burning process are listed in Appendix A.

3.2.2. Interpretation of LCI

Appendix A represents waste gas emissions in the coal mining process, coal transportation process and coal burning process in the electricity coal supply chain. It is seen that:

- In terms of total air emissions, CO_2 is emitted in the greatest quality, accounting for 98.8% wt% of the total air emissions for all processes examined. The vast majority of CO_2, about 93.6%, is emitted from the power plant when the coal is combusted. (See Table 6)

- Excluding the CO_2, the main waste gases emissions in the electricity coal supply chain are displayed in Table 6. The largest proportion of the main waste gases is CH_4, because JZCM is a high gas mine which releases 200m^3 CH_4 from CBM in producing one ton of coal. SO_2 mainly comes from the coal burning process. Because there is no denitrification process in SLQP, the percentage of NO_x in the burning process, mining process and transportation process is 66.5%, 28% and 5.56% respectively.

Process in electricity supply chain	CO_2		Other mainly waste gas		
			CH_4	SO_2	NO_x
	(g/KWh)	(%)	(g/KWh)	(g/KWh)	(g/KWh)
Coal mining process (g/KWh) (a)	50.328	5.17	3.58E+00	4.01E-01	3.67E-01
Coal transportation process (g/kWh) (b)	11.981	1.23	1.93E-04	7.98E-02	2.64E-03
Coal burning process (g/KWh) (c)	910.22	93.6	3.72E+00	9.54E-01	8.20E-01
Sum (g/KWh)	972.53	100	7.30	1.43	1.19

Note:
(a) Mining process is the underground mining process of JZCM;
(b) Transportation process is that coal is transported 93Km by truck from JZCM to SHQP;
(c) Burning process is that coal is burned by SHQP.

Table 6. Main waste gas emissions

3.3. Impact assessment and discussion

GaBi 4 Education software (PE Intentional, 2011) is used to carry out the impact assessment stage of the case study. Gabi 4's CML 2001 is adopted to calculate the following environmental impacts: (i) Global Warming Potential (GWP), (ii) Eutrophication Potential (EP), (iii) Photochemical Oxidants Creation Potential (POCP), (iv) Acidification Potential (AP), (v) Ozone Depletion Potential (ODP). The impact assessment method consists of three steps: characterization, normalization and final weighted scores.

3.3.1. Characterization

In this step, the LCI data are sorted into ''classes'' or environmental impact categories according to the effect they have on the environment. For example, CO_2 will be classified under Global Warming Potential. Within each ''class'', the emissions are aggregated to produce an effect score.

3.3.1.1. Global Warming Potential

Global Warming Potential (GWP) is derived by summing the emissions of the GHG multiplied by their respective GWP factors. The gases that contribute to Global Warming Potential are mainly CO, CO_2, CH_4, and N_2O. GWP in the electricity coal supply chain is calculated in Table 7. In the coal life cycle, GWP mainly occurs in the coal burning process. So reducing the emissions of CO_2 and N_2O in the coal burning process is the main approach to decrease GWP in the electricity coal supply chain.

	Mining Process			Transportation Process			Burning Process		
Stressors	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Amount	50.33	3.58	0.00	11.98	0.19	0.00	910.22	0.04	0.04
Normalization g CO_2 -Equiv.	50.33	89.38	0.22	11.98	4.83	0.09	910.22	93.07	11.72
Normalization g CO_2 -Equiv. (Process)	139.93			16.90			922.87		
Normalization g CO_2 -Equiv. (Electricity Coal Supply Chain)	1079.71								

Note: Data in above table rounded off to two decimals.

Table 7. GWP of waste gases in electricity coal supply chain (g/KWh)

3.3.1.2. Eutrophication Potential

Eutrophication Potential (EP) is defined as the potential of nutrients to cause over-fertilization of water and soil which in turn can result in increased growth of biomass. EP in the electricity coal supply chain is calculated in Table 8. In the coal life cycle, EP mainly occurs in the coal burning process. So reducing the emissions of NH_3 and NOx in the coal burning process is the main approach to decrease EP in the electricity coal supply chain.

	Mining Process		Transportation Process		Burning Process	
Stressors	NH_3	NO_x	NH_3	NO_x	NH_3	NO_x
Amount	2.50E-04	4.01E-01	0.00E+00	7.98E-02	6.31E-03	9.54E-01
Normalization g Phosphate -Equiv.	8.75E-05	5.22E-02	0.00E+00	1.04E-02	2.21E-03	1.24E-01
Normalization g Phosphate -Equiv. (Process)	5.23E-02		1.04E-02		1.26E-01	
Normalization g Phosphate -Equiv. (Electricity Coal Supply Chain)	1.89E-01					

Note: Data in above table rounded off to two decimals.

Table 8. EP of waste gases in electricity coal supply chain (g/KWh)

3.3.1.3. Photochemical Oxidants Creation Potential

Photochemical Oxidants Creation Potential (POCP) is related to the potential for VOCs and oxides of nitrogen to generate photochemical or summer smog. It is usually expressed relative to the POCP classification factor for ethylene. POCP in the electricity coal supply chain is calculated in Table 9. In the coal life cycle, POCP mainly occurs in the coal mining process. So reducing the emissions of CH_4, CO and NMVOC in coal mining process is the main approach to decrease POCP in the electricity coal supply chain.

	Mining Process			Transportation Process			Burning Process		
Stressors	CH_4	CO	NMVOC	CH_4	CO	NMVOC	CH_4	CO	NMVOC
Amount	3.58 E+00	1.11 E-01	3.24 E-02	1.93 E-01	1.90 E-02	3.21 E-03	3.72 E-02	1.68 E-01	2.35 E-02
Normalization g Ethene -Equiv.	2.15 E-02	3.01 E-03	1.18 E-02	1.16 E-03	5.14 E-04	1.17 E-03	2.23 E-04	4.53 E-03	8.57 E-03
Normalization g Ethene -Equiv. (Process)	3.63E-02			2.84E-03			1.33E-02		
Normalization g Ethene -Equiv. (Electricity Coal Supply Chain)	5.24E-02								

Note: Data in above table rounded off to two decimals.

Table 9. POCP of waste gases in electricity coal supply chain (g/KWh)

3.3.1.4. Acidification Potential

Acidification Potential (AP) is based on the contributions of SO_2, NO_x, HCl, NH_3 and HF to the potential acid deposition in the form of H+ (protons). Appendix A shows that SO_2, NOx, HCl, HF and NH_3 mainly come from coal mining process and transportation process, and emissions of HCl, HF and NH_3 relative to emissions of SO_2 and NO_x are negligible. AP in the electricity coal supply chain is calculated in Table 10. In the coal life cycle, AP mainly occurs in the coal burning process. So reducing the emissions of SO_2 and NO_x in the coal burning process is the main approach to decrease AP in the electricity coal supply chain.

	Mining Process		Transportation Process		Burning Process	
Stressors	NO_x	SO_2	NO_x	SO_2	NO_x	SO_2
Amount	4.01E-01	3.67E-01	7.98E-02	2.64E-03	9.54E-01	8.20E-01
Normalization g SO_2 -Equiv.	2.81E-01	3.67E-01	5.59E-02	2.64E-03	6.68E-01	8.20E-01
Normalization g SO_2 -Equiv. (Process)	6.48E-01		5.85E-02		1.49E+00	
Normalization g SO_2 -Equiv. (Electricity Coal Supply Chain)	2.19E+00					

Note: Data in above table rounded off to two decimals.

Table 10. AP of waste gases in electricity coal supply chain (g/KWh)

3.3.1.5. Ozone Depletion Potential

Ozone Depletion Potential (ODP) indicates the potential for emissions of chlorofluorocarbon (CFC) compounds and other halogenated hydrocarbons to deplete the ozone layer. ODP in the electricity coal supply chain is calculated in Table 11. In the coal life cycle, ODP mainly occurs in the coal burning process. So reducing the emissions of CFC-11, R114, R12 and R22 in the coal burning process is the main approach to decrease ODP in the electricity coal supply chain.

	Mining Process				Transportation Process				Burning Process			
Stressors	R11	R114	R12	R22	R11	R114	R12	R22	R11	R114	R12	R22
Amount	8.27 E-08	8.47 E-08	1.78 E-08	1.94 E-08	0	0	0	0	4.88 E-07	5.00 E-07	1.05 E-07	1.15 E-07
Normalization g R11-Equiv.	8.27 E-08	7.20 E-08	1.46 E-08	6.60 E-10	0	0	0	0	4.88 E-07	4.25 E-07	8.61 E-08	3.91 E-09
Normalization g R11-Equiv. (Process)	1.70E-07				0				1.00E-06			
Normalization g R11-Equiv. (Electricity Coal Supply Chain)	1.17E-06											

Note: Data in above table rounded off to two decimals.

Table 11. ODP of waste gases in electricity coal supply chain (g/KWh)

Based on the above analysis, GWP, EP, POCP, AP and ODP in the coal mining process, coal transportation process and coal burning process are shown in Table 12.

Classification	Mining Process	Transportation Process	Burning Process	Electricity Coal Supply Chain	Unit
GWP	1.40E-01	1.69E-02	9.23E-01	1.08E+00	kg CO_2-Equiv.
EP	5.23E-05	1.04E-05	1.26E-04	1.89E-04	kg PO_4^{3}-Equiv.
POCP	3.63E-05	2.84E-06	1.33E-05	5.24E-05	kg C_2H_4-Equiv.
AP	6.57E-04	5.85E-05	1.51E-03	2.22E-03	kg SO_2-Equiv.
ODP	1.70E-10	0.00E+00	1.00E-09	1.17E-09	kg R11-Equiv.

Table 12. Impact assessment of each process in electricity coal supply chain

3.3.2. Normalization

A normalization step is performed to provide the relative size of each environmental impact. Each of the total characterized scores is benchmarked against the known total effect (usually based on the country's average) for their respective "class". Currently there are many life cycle impact assessment (LCIA) methods such as CML 2001, Eco-Indicator 95 (Goedkoop, Demmers & Collignon, 1995), Eco-Indicator 99 (Goedkoop & Spriensma, 2001), EDIP 1997 (Wenzel, Hauschild, Alting & editors, 1997), EDIP 2003 (Dreyer, Niemann & Hauschild, 2003), IMPACT 2002+ (Jolliet, Margni, Charles, Humbert, Payet, Rebitzer et al., 2003), Ecological Scarcity (UBP Method) (Frischknecht, Steiner & Jungbluth, 2009) and so on. However, the shortcomings of these methods are that most indicators, normalization factors and weighting factors are based on the data of Netherlands, Denmark, and the European Union. Because these normalization factor and weighting factors depend on the actual conditions of a particular country or region, they cannot be used to process the data of the Chinese electricity coal supply chain. Thus, this paper uses Chinese normalization factors and weighting factors given by the Environment Research Center in Chinese Academy of Science and Technical University of Denmark (Yang, Cheng & Wang, 2002). Table 13 illustrates that in the electricity coal supply chain, the biggest environmental impact of waste gas emissions is GWP, followed by EP, POCP, AP and ODP.

3.3.3. Final weighted scores

It is assumed that the relative importance of various impacts is the same. However, in fact, the relative importance of various impacts is different, which on the one hand depends on the characteristics of the environment itself, while on the other hand this reflects the current understanding of human society and its degree of concern. In the final stage, the normalized scores are multiplied by a weighting factor representing the relative importance of the total environmental impact. The environmental impacts of GWP, EP, POCP, AP and ODP after weighting are shown in Table 13. It is seen that the coal burning process has the biggest environmental impact, followed by the coal mining process and the coal transportation process.

Table 13 presents that the biggest environmental impact in the electricity coal supply chain is GWP, then followed by EP, AP, POCP and ODP. The global environmental burden of the electricity coal supply chain is 1.03E-04 man·a, and the regional environmental burden of the electricity coal supply chain is 1.58E-04 man·a., so the regional impact is greater than the global impact. The environmental burden of the electricity coal supply chain is 2.61E-04 man·a.

Classification		Step	Mining process	Transportation process	Burning process	Electricity coal supply chain	Category	Environmental burden
Global	GWP	Normalization	1.61E-05	1.94E-06	1.06E-04	1.24E-04	1.03E-04	2.61E-04
		Weighting	1.34E-05	1.61E-06	8.81E-05	1.03E-04		
	ODP	Normalization	8.50E-10	0.00E+00	5.00E-09	5.85E-09		
		Weighting	2.30E-09	0.00E+00	1.35E-08	1.58E-08		
Regional	AP	Normalization	1.88E-05	1.67E-06	4.31E-05	6.34E-05	1.58E-04	
		Weighting	1.37E-05	1.22E-06	3.15E-05	4.63E-05		
	EP	Normalization	2.84E-05	5.65E-06	6.85E-05	1.03E-04		
		Weighting	2.07E-05	4.13E-06	5.00E-05	7.50E-05		
	POCP	Normalization	4.78E-05	3.74E-06	1.75E-05	6.89E-05		
		Weighting	2.53E-05	1.98E-06	9.28E-06	3.65E-05		
Sum		Weighting	7.31E-05	8.94E-06	1.79E-04	2.61E-04		

Table 13. Impact assessment in electricity coal supply chain (Unit: man·a)

4. Sensitivity analysis

A sensitivity analysis was conducted to determine the parameters that had the largest effect on the results and to determine the impact of estimated data as well as variations in data on the conclusions. One variable may affect several factors and thus several process steps, or it may affect only one process in the overall life cycle assessment. For instance, changing the coal-burning efficiency can affect the amount of coal required at the plant, which in turn affects the coal mining and transportation requirements. However, varying the transportation distance affects only the emissions associated with the coal transportation process. These effects were taken into account automatically in the LCA model. The base case assumed transportation to the average user (QLQP) by truck. The following are abbreviations used in the different sensitivity analyses: A means base case; B means CH_4 utilization ratio is 30%; C means nearest user; D means farthest user; E means increase coal-burning efficiency by 5 points; F means decrease coal-burning efficiency by 5 points.

4.1. Coal mining process - utilization ratio of CH_4 sensitivity analysis

CH_4 emissions in the electricity coal supply chain is mainly caused by the emissions of CBM in the coal mining process, which accounts for 94% of the total CH_4 emissions in the electricity coal supply chain. So the reduction of CH_4 emissions mainly focuses on the coal mining process, and the utilization of CH_4 as an alternative mode of power generation. At present, the utilization of mine gas is mainly based on civil and industrial use; this percentage has already reached 80% (Zhuo, Lin & Wang, 2008). The gas chemical industry also has wide market prospects, and gas power generation is a leading direction of development. Methane-power generation (heat supply) is used in many large industries. Methane power generation is a mature technology, with the main technologies being gas turbine power generation, steam turbine power generation, gas-fired generator power generation, combined cycle system power generation and CHER power generation.

The coal seam in JZCM has low air permeability and the coal bed is soft, so recovery and utilization of CBM is quite difficult. In addition, without data about power consumption of CH_4 recovery equipment, the waste gas emissions from the equipment is ignored. Thus, this paper considers the environmental impacts caused by waste gas emissions in the electricity coal supply chain based on the assumption that the utilization ratio of CH_4 can reach 30%. The results are shown in Table 14 and a comparative analysis of impact assessment is made in Table 15.

Classification	Environmental burden	Normalization factor	Normalization	Weighting factor	Weighting
GWP	1.05E+00 kg CO_2-Equiv.	8700 Kg CO_2 eq./(man·a)	1.21E-04 man·a	0.83	1.00E-04 man·a
EP	1.89E-04 kg PO_4^3-Equiv.	1.84 Kg PO_4^3- eq./(man·a)	1.03E-04 man·a	0.73	7.52E-05 man·a
POCP	4.85E-05 kg C_2H_4-Equiv.	0.76 Kg C_2H_4 eq./(man·a)	6.38E-05 man·a	0.53	3.38E-05 man·a
AP	2.22E-03 kg SO_2-Equiv.	35 Kg SO_2 eq./(man·a)	6.34E-05 man·a	0.73	4.63E-05 man·a
ODP	1.17E-09 kg R11-Equiv.	0.2 Kg R11 eq./(man·a)	5.85E-09 man·a	2.7	1.58E-08 man·a

Table 14. Normalization and weighting analysis (utilization rate of CH4 is 30%)

<table>
<tr><th colspan="2" rowspan="2">Classification</th><th colspan="3">Final weighted scores</th><th colspan="3">Category</th><th colspan="3">Environmental burden</th></tr>
<tr><th>A</th><th>B</th><th>Changing rate</th><th>A</th><th>B</th><th>Changing rate</th><th>A</th><th>B</th><th>Changing rate</th></tr>
<tr><td rowspan="2">Global</td><td>GWP</td><td>1.03E-04</td><td>1.00E-04</td><td>-2.91%</td><td rowspan="2">1.03 E-04</td><td rowspan="2">1.00 E-04</td><td rowspan="2">-2.91%</td><td rowspan="5">2.61 E-04</td><td rowspan="5">2.55 E-04</td><td rowspan="5">-2.30%</td></tr>
<tr><td>ODP</td><td>1.58E-08</td><td>1.58E-08</td><td>0.00%</td></tr>
<tr><td rowspan="3">Regional</td><td>AP</td><td>4.63E-05</td><td>4.63E-05</td><td>0.00%</td><td rowspan="3">1.58 E-04</td><td rowspan="3">1.55 E-04</td><td rowspan="3">-1.90%</td></tr>
<tr><td>EP</td><td>7.52E-05</td><td>7.52E-05</td><td>0.00%</td></tr>
<tr><td>POCP</td><td>3.65E-05</td><td>3.38E-05</td><td>-7.40%</td></tr>
</table>

Table 15. Comparative analysis of impact assessment in electricity coal supply chain (Unit: man·a)

Under the assumption that the utilization ratio of CH_4 is 30% in the coal mining process, Table 15 gives the global environmental burden, regional environmental burden and total environmental burden of waste gas emissions in the electricity coal supply chain change as 2.91%, 1.9% and 2.3%, respectively. So the environmental burden caused by waste gases emissions is not sensitive to the change of CH_4 in the coal mining process and utilization of CH_4 is not an effective method to reduce the environmental burden in the electricity coal supply chain.

4.2. Coal transportation process - transportation distance sensitivity analysis

This section analyzes sensitivity of transportation distance and studies the environmental impact of transportation distance on waste gas emissions in the electricity coal supply chain. According to the investigation of JZCM, the fastest user is Yangzhou power plant, and the nearest user is JZ plant, mine mouth power plant. Detailed data are shown in Table 16.

Scenario	Vehicles	Path	Distance
Base case	Truck	Jiangzhuang coal mine--->Shiliquan power plant	Highway 93Km
Nearest user	Truck	JZ power plant	Highway 2Km
Farthest user	Barge and truck	Jiangzhuang coal mine--->Zaozhuang port--->Jinghang canal --->Yangzhou port--->Yangzhou power plant	Highway 89Km, Waterway 427Km

Table 16. Comparison of three scenarios

Table 17 gives the change of input index (standard coal, diesel, electricity consumption and non-coal energy) and Table 18 presents the change of output index (GWP, EP, POCP, AP and ODP), in order to assess the environmental impact of three different of transportation distances. And it shows that change of transportation distance has a great influence on diesel and non-coal energy.

Input index	Quality	Unit	C	A	D
Standard coal	Mass	g	-0.01%	438.171	0.03%
Diesel	Mass	g	-48.96%	12.1	243.31%
Electricity consumption	Energy (gross calorific value)	MJ	-2.41%	0.0325	7.01%
Non-coal energy	Energy (gross calorific value)	MJ	-33.62%	0.7239	112.97%

Table 17. Impact of electricity coal supply chain on transportation distance (Input index)

Table 18 illustrates POCP is most sensitive to fluctuations of transportation distance compared with GWP, ODP, AP, EP, because large amounts of CO are released in the coal transportation process. Therefore an oxidation catalyst on the vehicles is recommended to oxidize the carbon monoxide into carbon dioxide.

Classification		Final weighted scores			Category			Environmental burden		
		A	C	Changing rate	A	C	Changing rate	A	C	Changing rate
Global	GWP	1.03E-04	1.01E-04	-1.85%	1.03 E-04	1.01 E-04	-1.83%	2.61 E-04	2.51 E-04	-3.70%
	ODP	1.58E-08	1.58E-08	0.00%						
Regional	AP	4.63E-05	4.54E-05	-2.02%	1.58 E-04	1.50 E-04	-4.92%			
	EP	7.52E-05	7.52E-05	-0.01%						
	POCP	3.65E-05	2.97E-05	-18.71%						
Classification		**Final weighted scores**			**Category**			**Environmental burden**		
		A	**D**	**Changing rate**	**A**	**D**	**Changing rate**	**A**	**D**	**Changing rate**
Global	GWP	1.03E-04	1.09E-04	6.31%	1.03 E-04	1.10 E-04	6.33%	2.61 E-04	2.84 E-04	8.89%
	ODP	1.58E-08	1.58E-08	0.00%						
Regional	AP	4.63E-05	4.88E-05	5.41%	1.58 E-04	1.75 E-04	10.55%			
	EP	7.52E-05	7.52E-05	0.03%						
	POCP	3.65E-05	5.06E-05	38.76%						

Table 18. Impact of electricity coal supply chain on transportation distance (Output index)

4.3. Coal burning process - coal-burning efficiency sensitivity analysis

Both a decrease and an increase in the coal-burning efficiency were examined. The base case efficiency for the average is 37%. The coal-burning efficiency is changed by plus or minus five percentage points for each system, i.e., 32% and 42% for the Average system. Changing the coal-burning efficiency had a large effect on the energy efficiency and energy ratios defined in Table 19.

Input index	Quality	Unit	E	A	F
Standard coal	Mass	g	-12.91%	438.171	17.43%
Diesel	Mass	g	-12.91%	12.1	17.43%
Electricity consumption	Energy (gross calorific value)	MJ	-12.91%	0.0325	17.43%
Non-coal energy	Energy (gross calorific value)	MJ	-12.91%	0.7239	17.43%

Table 19. Impact of electricity coal supply chain on coal boiler efficiency (Input index)

Table 20 shows the base case as well as the results for increasing and decreasing the coal-burning efficiency. So improving the coal-burning efficiency of a coal-fired power plant in the electricity coal supply chain is the most effective way to reduce the environmental burden of waste gas emissions.

Classification		Final weighted scores			Category			Environmental burden		
		Base case	E	Changing rate	Base case	E	Changing rate	Base case	E	Changing rate
Global	GWP	1.03E-04	8.97E-05	-12.91%	1.03 E-04	8.97 E-05	-12.90%	2.61 E-04	2.27 E-04	-12.90%
	ODP	1.58E-08	1.38E-08	-12.91%						
Regional	AP	4.63E-05	4.03E-05	-12.91%	1.58 E-04	1.38 E-04	-12.91%			
	EP	7.52E-05	6.55E-05	-12.91%						
	POCP	3.65E-05	3.18E-05	-12.91%						
Classification		Final weighted scores			Category			Environmental burden		
		Base case	F	Changing rate	Base case	F	Changing rate	Base case	F	Changing rate
Global	GWP	1.03E-04	1.21E-04	17.43%	1.03 E-04	1.21 E-04	17.45%	2.61 E-04	3.07 E-04	17.44%
	ODP	1.58E-08	1.86E-08	17.43%						
Regional	AP	4.63E-05	5.44E-05	17.43%	1.58 E-04	1.86 E-04	17.43%			
	EP	7.52E-05	8.83E-05	17.43%						
	POCP	3.65E-05	4.29E-05	17.43%						

Table 20. Impact of electricity coal supply chain on coal boiler efficiency (Output index)

5. Conclusion

LCA results help to pinpoint several tangible strategies to decrease the environmental impact in the coal life cycle, from coal mine to coal-fired power plant. The results show that the environmental burden of the coal burning process is greatest, followed by the coal mining process, and finally the coal transportation process. In the electricity coal supply chain, the biggest environmental impact of waste gas emissions is GWP, followed by EP, AP, POCP and ODP, and the regional impact is greater than the global impact. Improving the coal-burning efficiency of a coal-fired power plant is the most effective way to reduce the environmental burden of waste gas emissions in the electricity coal supply chain.

While there are certain limitations in the LCA supply chain case study in its current ‘‘cradle-to-gate’’ approach, in future research a full LCA study will incorporate a ‘‘cradle-to-grave’’ scheme including recycling, re-use and/or various disposal methods. And a cost factor will be integrated with LCA methods.

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References

Bates, J. (1995). *Full life cycle atmospheric emissions and global warming impacts from UK electricity generation*. London.

Björk, A., Erlandsson, M., Häkli, J., Jaakkola, K., Nilsson, Å., Nummila, K., et al. (2011). Monitoring environmental performance of the forestry supply chain using RFID. *Computers in Industry,* 62(8), 830-841. http://dx.doi.org/10.1016/j.compind.2011.08.001

Clean Production Standard in Coal Washing and Processing Industry. (2010). *HJ 446-2008.* China Department of the environment.

CSY. (2013). *China Statisitcal Yearbook 2012*. Beijing.

Dreyer, L.C., Niemann, A.L., & Hauschild, M.Z. (2003). Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. *The international journal of life cycle assessment,* 8(4), 191-200. http://dx.doi.org/10.1007/BF02978471

Frischknecht, R., Steiner, R., & Jungbluth, N. (2009). *The Ecological Scarcity Method-Eco-Factors 2006-A method for impact assessment in LCA* (Methode der ökologischen Knappheit–Ökofaktoren 2006-Methode für die Wirkungsabschätzung in Ökobilanzen).

Goedkoop, M., Demmers, M., & Collignon, M. (1995). *The eco-indicator 95.* PRé Consultants Amersfoort (NL).

Goedkoop, M., & Spriensma, R. (2001). *The eco-indicator99: A damage oriented method for life cycle impact assessment: Methodology report*.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy,* 30(11), 2042-2056. http://dx.doi.org/10.1016/j.energy.2004.07.020

International Energy Agency, IEA (2010). *Electricity Information 2010*. In OECO (Ed.). Paris.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., et al. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *The international journal of life cycle assessment,* 8(6), 324-330. http://dx.doi.org/10.1007/BF02978505

Kannan, R., Leong, K., Osman, R., & Ho, H. (2007). Life cycle energy, emissions and cost inventory of power generation technologies in Singapore. *Renewable and Sustainable Energy Reviews,* 11(4), 702-715. http://dx.doi.org/10.1016/j.rser.2005.05.004

Korre, A., Nie, Z., & Durucan, S. (2012). Life Cycle Assessment of the natural gas supply chain and power generation options with CO 2 capture and storage: Assessment of Qatar natural gas production, LNG transport and power generation in the UK. *Sustainable Technologies, Systems & Policies(CCS Workshop)*, 11.

Lave, L.B., & Freeburg, L.C. (1973). Health effects of electricity generation from coal, oil, and nuclear fuel. *Nuclear safety, 14(5),* 409-428.

Li, R., & Leung, G.C.K. (2012). Coal consumption and economic growth in China. *Energy policy,* 40(0), 438-443. http://dx.doi.org/10.1016/j.enpol.2011.10.034

Liang, X., Wang, Z., Zhou, Z., Huang, Z., Zhou, J., & Cen, K. (2012). Up-to-date life cycle assessment and comparison study of clean coal power generation technologies in China. *Journal of cleaner production,* 39(0), 24-31. http://dx.doi.org/10.1016/j.jclepro.2012.08.003

Liu, Z., & Zhao, Q. (2011). Research on the Scale-Planning Model for the Coal Logistics Center Based on Coal Logistics Network Planning. *Journal of System and Management Sciences,* 1(1), 59-69.

Lu, Z., Streets, D., Zhang, Q., Wang, S., Carmichael, G., Cheng, Y., et al. (2010). Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000. *Atmospheric Chemistry and Physics,* 10(13), 6311-6331. http://dx.doi.org/10.5194/acp-10-6311-2010

Mann, M., & Spath, P. (2001). A life cycle assessment of biomass cofiring in a coal-fired power plant. *Clean Products and Processes,* 3(2), 81-91. http://dx.doi.org/10.1007/s100980100109

Miao, Y.X. (2009). Exploration and Analysis of 5,000,000 t/a coal washing technology. *Hebei Chemical Engineering and Industry,* 32(6), 45-47(In Chinese).

Pacca, S., & Horvath, A. (2002). Greenhouse gas emissions from building and operating electric power plants in the Upper Colorado River Basin. *Environmental Science & Technology,* 36(14), 3194-3200. http://dx.doi.org/10.1021/es0155884

Pan, B., & Mu, D. (2011). *Research on CDM projects in electricity coal supply chain*. Paper presented at the International Conference on Information, Services and Management Engineering (ISME2011).

PE Intentional. (2011). www.gabi-software.com/america/index/.

Qiu, Z. (2013). On the analysis of building a public information platform based on e-Commerce for coal logistics. *Journal of Industrial Engineering and Management,* 6(4), 986-995. http://dx.doi.org/10.3926/jiem.746

Restrepo, Á., Miyake, R., Kleveston, F., & Bazzo, E. (2012). Exergetic and environmental analysis of a pulverized coal power plant. *Energy,* 45(1), 195-202.

http://dx.doi.org/10.1016/j.energy.2012.01.080

Uchiyama, Y. (1996). *Life cycle analysis of electricity generation and supply systems.* A paper in the technical document: IAEA-SM-338/33, 279-291.

Wenzel, H., Hauschild, M., Alting, L., & editors. (1997). *Environmental assessment of products.* Vol. 1. London, UK: Chapman & Hall.

Yan, L.H. (2006). *Japanese post-war energy security strategy and implications for China*. Beijing, University of International Business and Economics (In Chinese).

Yang, J.X., Cheng, X., & Wang, R.S. (2002). *Methodology and application of life cycle assessment*. Beijing: China Meteorological Press (In Chinese).

You, F., Tao, L., Graziano, D.J., & Snyder, S.W. (2012). Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input–output analysis. *AIChE Journal,* 58(4), 1157-1180. http://dx.doi.org/10.1002/aic.12637

Zhao, Y., Wang, S., Nielsen, C. P., Li, X., & Hao, J. (2010). Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants. *Atmospheric Environment,* 44(12), 1515-1523. http://dx.doi.org/10.1016/j.atmosenv.2010.01.017

Zhuo, C., Lin, B. Q., & Wang, L. (2008). CBM utilization and problem of underground coal mine in China. *Natural gas industry,* 28(7), 23-26 (In Chinese).

Appendix A

Waste gases emissions in electricity coal supply chain (g/KWh)

Emission to air		Coal supply chain	Underground mining	Transport	Power plant
Heavy metals to air	Antimony	3.21E-05	2.28E-05	0.00E+00	9.22E-06
	Arsenic (+V)	6.82E-05	1.77E-05	0.00E+00	5.06E-05
	Arsenic trioxide	2.22E-12	9.25E-13	0.00E+00	1.29E-12
	Cadmium (+II)	8.34E-06	3.46E-06	0.00E+00	4.88E-06
	Chromium (+III)	1.11E-08	8.31E-10	0.00E+00	1.03E-08
	Chromium (unspecified)	2.34E-05	1.05E-05	0.00E+00	1.30E-05
	Cobalt	1.78E-05	1.30E-05	0.00E+00	4.81E-06
	Copper (+II)	1.41E-05	5.30E-06	0.00E+00	8.79E-06
	Heavy metals to air (unspecified)	2.18E-09	6.04E-12	0.00E+00	2.17E-09
	Hydrogen arsenic (arsine)	1.84E-10	7.68E-11	0.00E+00	1.07E-10
	Iron	1.95E-06	7.21E-07	0.00E+00	1.23E-06
	Lanthanides	4.91E-10	2.54E-10	0.00E+00	2.38E-10
	Lead (+II)	1.39E-04	4.69E-05	0.00E+00	9.23E-05
	Manganese (+II)	7.08E-05	1.40E-05	0.00E+00	5.68E-05
	Mercury (+II)	2.04E-05	1.13E-06	0.00E+00	1.92E-05
	Molybdenum	7.79E-08	4.05E-08	0.00E+00	3.74E-08
	Nickel (+II)	3.90E-05	2.73E-05	0.00E+00	1.17E-05
	Palladium	3.73E-16	8.58E-17	0.00E+00	2.87E-16
	Rhodium	3.60E-16	8.28E-17	0.00E+00	2.77E-16
	Selenium	2.16E-04	6.02E-05	0.00E+00	1.56E-04
	Silver	1.25E-15	1.01E-15	0.00E+00	2.39E-16
	Tellurium	1.48E-09	1.11E-10	0.00E+00	1.37E-09
	Thallium	1.08E-08	7.45E-10	0.00E+00	1.01E-08
	Tin (+IV)	6.26E-05	2.44E-06	0.00E+00	6.02E-05
	Titanium	3.84E-08	1.27E-08	0.00E+00	2.56E-08
	Vanadium (+III)	1.10E-04	9.23E-05	0.00E+00	1.79E-05
	Zinc (+II)	3.25E-04	1.15E-04	0.00E+00	2.09E-04
Inorganic emissions to air	Ammonia	6.56E-03	2.50E-04	0.00E+00	6.31E-03
	Ammonium	1.34E-10	4.99E-13	0.00E+00	1.33E-10
	Ammonium nitrate	7.75E-11	1.05E-11	0.00E+00	6.69E-11
	Barium	1.82E-04	7.66E-05	0.00E+00	1.06E-04
	Beryllium	1.41E-06	7.00E-07	0.00E+00	7.13E-07
	Boron compounds (unspecified)	1.80E-03	1.85E-04	0.00E+00	1.62E-03
	Bromine	1.00E-03	2.21E-04	0.00E+00	7.81E-04
	Carbon dioxide	9.73E+02	5.03E+01	1.20E+01	9.10E+02
	Carbon dioxide (biotic)	1.47E+00	7.50E-01	0.00E+00	7.20E-01
	Carbon disulphide	1.81E-08	1.19E-09	0.00E+00	1.69E-08
	Carbon monoxide	2.98E-01	1.11E-01	1.90E-02	1.68E-01
	Chloride (unspecified)	1.82E-05	9.86E-06	0.00E+00	8.38E-06
	Chlorine	3.82E-09	1.72E-10	0.00E+00	3.65E-09
	Cyanide (unspecified)	3.80E-07	2.00E-07	0.00E+00	1.81E-07
	Fluoride	1.10E-05	5.20E-06	0.00E+00	5.78E-06
	Fluorine	4.24E-10	1.19E-10	0.00E+00	3.05E-10
	Helium	2.19E-06	1.26E-06	0.00E+00	9.26E-07
	Hydrogen	4.77E-04	4.46E-06	0.00E+00	4.72E-04
	Hydrogen bromine (hydrobromic acid)	2.66E-08	1.96E-10	0.00E+00	2.64E-08
	Hydrogen chloride	1.43E-02	6.31E-03	0.00E+00	7.97E-03
	Hydrogen cyanide (prussic acid)	3.38E-08	2.25E-09	0.00E+00	3.15E-08
	Hydrogen fluoride	3.45E-03	1.75E-03	0.00E+00	1.70E-03
	Hydrogen iodide	2.91E-11	1.14E-13	0.00E+00	2.90E-11
	Hydrogen phosphorous	1.20E-11	9.32E-12	0.00E+00	2.65E-12
	Hydrogen sulphide	8.93E-05	2.45E-05	0.00E+00	6.48E-05
	Lead dioxide	1.31E-11	1.06E-11	0.00E+00	2.50E-12
	Nitrogen (atmospheric nitrogen)	9.99E-02	2.38E-02	0.00E+00	7.62E-02
	Nitrogen dioxide	5.06E-14	0.00E+00	0.00E+00	5.06E-14
	Nitrogen monoxide	1.80E-09	1.26E-10	0.00E+00	1.67E-09
	Nitrogen oxides	1.43E+00	4.01E-01	7.98E-02	9.54E-01
	Nitrous oxide (laughing gas)	4.04E-02	7.47E-04	2.99E-04	3.93E-02
	Oxygen	9.78E-02	6.03E-02	0.00E+00	3.75E-02
	Scandium	1.97E-10	1.27E-10	0.00E+00	7.00E-11
	Steam	1.67E-03	4.70E-04	0.00E+00	1.62E-03
	Strontium	8.78E-09	5.06E-09	0.00E+00	3.72E-09
	Sulphur dioxide	1.19E+00	3.67E-01	2.64E-03	8.20E-01

	Emission to air	Coal supply chain	Underground mining	Transport	Power plant
	Sulphur hexafluoride	8.92E-10	7.21E-10	0.00E+00	1.71E-10
	Sulphuric acid	5.78E-08	7.34E-09	0.00E+00	5.05E-08
	Tin oxide	1.14E-12	9.20E-13	0.00E+00	2.17E-13
	Zinc oxide	2.27E-12	1.84E-12	0.00E+00	4.34E-13
	Zinc sulphate	3.88E-09	1.62E-09	0.00E+00	2.26E-09
Organic emissions to air (group VOC)	Anthracene	2.67E-10	1.12E-10	0.00E+00	1.55E-10
	Benzo{a}anthracene	1.34E-10	5.64E-11	0.00E+00	7.80E-11
	Benzo{a}pyrene	6.37E-08	5.23E-09	0.00E+00	5.84E-08
	Benzo{ghi}perylene	1.20E-10	5.03E-11	0.00E+00	6.95E-11
	Benzofluoranthene	2.40E-10	1.01E-10	0.00E+00	1.39E-10
	Chrysene	3.30E-10	1.39E-10	0.00E+00	1.91E-10
	Dibenz(a)anthracene	7.47E-11	3.14E-11	0.00E+00	4.33E-11
	Indenopyrene	8.92E-11	3.74E-11	0.00E+00	5.18E-11
	Naphthalene	2.80E-08	1.18E-08	0.00E+00	1.63E-08
	Phenanthrene	8.81E-09	3.70E-09	0.00E+00	5.11E-09
	Polycyclic aromatic hydrocarbons (PAH)	1.27E-05	1.58E-06	0.00E+00	1.11E-05
	Dichloromethane (methylene chloride)	5.21E-15	1.20E-15	0.00E+00	4.01E-15
	Halogenated hydrocarbons (unspecified)	2.86E-15	8.30E-16	0.00E+00	2.03E-15
	Polychlorinated biphenyls (PCB unspecified)	3.96E-10	1.40E-10	0.00E+00	2.56E-10
	Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD)	5.20E-11	1.91E-12	0.00E+00	5.01E-11
	R 11 (trichlorofluoromethane)	5.71E-07	8.27E-08	0.00E+00	4.88E-07
	R 114 (dichlorotetrafluoroethane)	5.84E-07	8.47E-08	0.00E+00	5.00E-07
	R 12 (dichlorodifluoromethane)	1.23E-07	1.78E-08	0.00E+00	1.05E-07
	R 13 (chlorotrifluoromethane)	7.70E-08	1.12E-08	0.00E+00	6.59E-08
	R 22 (chlorodifluoromethane)	1.34E-07	1.94E-08	0.00E+00	1.15E-07
	Tetrafluoromethane	3.69E-09	1.17E-09	0.00E+00	2.52E-09
	Vinyl chloride (VCM; chloroethene)	6.69E-08	3.09E-08	0.00E+00	3.60E-08
	Acetaldehyde (Ethanal)	4.41E-06	3.05E-06	0.00E+00	1.36E-06
	Acetic acid	1.71E-05	1.11E-05	0.00E+00	6.04E-06
	Acetone (dimethylcetone)	4.30E-06	3.01E-06	0.00E+00	1.29E-06
	Acrolein	1.88E-09	7.91E-10	0.00E+00	1.09E-09
	Aldehyde (unspecified)	3.93E-07	2.11E-07	0.00E+00	1.82E-07
	Alkane (unspecified)	3.73E-03	3.56E-04	0.00E+00	3.37E-03
	Alkene (unspecified)	3.72E-03	3.46E-04	0.00E+00	3.37E-03
	Aromatic hydrocarbons (unspecified)	1.44E-06	1.07E-06	0.00E+00	3.70E-07
	Benzene	2.47E-05	7.81E-06	0.00E+00	1.69E-05
	Butadiene	1.32E-10	3.66E-13	0.00E+00	1.32E-10
	Butane	7.37E-04	3.64E-04	0.00E+00	3.74E-04
	Butane (n-butane)	3.58E-04	3.37E-05	0.00E+00	3.24E-04
	Cyclohexane (hexahydro benzene)	4.15E-07	2.73E-08	0.00E+00	3.88E-07
	Diethylamine	3.35E-15	1.25E-17	0.00E+00	3.33E-15
	Ethane	2.73E-03	1.04E-03	0.00E+00	1.70E-03
	Ethanol	7.62E-06	5.43E-06	0.00E+00	2.18E-06
	Ethene (ethylene)	2.39E-07	1.11E-07	0.00E+00	1.29E-07
	Ethyl benzene	3.72E-03	3.45E-04	0.00E+00	3.37E-03
	Fluoranthene	8.70E-10	3.65E-10	0.00E+00	5.05E-10
	Fluorene	2.76E-09	1.16E-09	0.00E+00	1.60E-09
	Formaldehyde (methanal)	1.04E-03	1.04E-04	0.00E+00	9.38E-04
	Heptane (isomers)	2.33E-05	1.26E-05	0.00E+00	1.07E-05
	Hexamethylene diamine (HMDA)	7.76E-12	2.15E-14	0.00E+00	7.74E-12
	Hexane (isomers)	3.53E-05	1.88E-05	0.00E+00	1.66E-05
	Mercaptan (unspecified)	8.83E-07	4.09E-07	0.00E+00	4.74E-07
	Methanol	7.23E-06	5.38E-06	0.00E+00	1.85E-06
	NMVOC (unspecified)	5.59E-02	3.24E-02	0.00E+00	2.35E-02
	Octane	1.28E-05	6.94E-06	0.00E+00	5.90E-06
	Pentane (n-pentane)	2.65E-03	3.45E-04	0.00E+00	2.30E-03
	Phenol (hydroxy benzene)	9.95E-11	5.67E-11	0.00E+00	4.27E-11
	Propane	4.09E-03	1.81E-03	0.00E+00	2.27E-03
	Propene (propylene)	3.38E-04	3.14E-05	0.00E+00	3.06E-04
	Propionic acid (propane acid)	5.52E-10	2.67E-10	0.00E+00	2.84E-10
	Styrene	4.59E-10	3.03E-11	0.00E+00	4.29E-10
	Toluene (methyl benzene)	1.69E-03	1.57E-04	0.00E+00	1.53E-03
	Trimethylbenzene	1.11E-11	8.96E-12	0.00E+00	2.12E-12
	Xylene (dimethyl benzene)	1.55E-02	1.44E-03	0.00E+00	1.41E-02
	Methane	3.81E+00	3.58E+00	1.93E-01	3.72E-02
	Organic chlorine compounds	3.88E-11	5.27E-12	0.00E+00	3.35E-11
	VOC (unspecified)	3.95E-03	2.02E-06	3.94E-03	3.28E-06

Emission to air		Coal supply chain	Underground mining	Transport	Power plant
Other emissions to air	Exhaust	3.80E-03	1.27E-03	0.00E+00	3.68E-03
	non used primary energy from wind power	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Unused primary energy from solar energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Used air	2.68E+00	2.77E-01	0.00E+00	2.41E+00
	Waste heat	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Particles to air	Dust (PM10)	1.06E-02	5.90E-03	0.00E+00	4.72E-03
	Dust (PM2,5 - PM10)	1.38E-03	0.00E+00	1.38E-03	0.00E+00
	Dust (PM2.5)	8.51E-02	4.79E-02	0.00E+00	3.72E-02
	Dust (unspecified)	1.49E-01	7.90E-02	0.00E+00	7.04E-02
	Metals (unspecified)	3.81E-10	2.99E-10	0.00E+00	8.20E-11
	Wood (dust)	4.20E-10	3.40E-10	0.00E+00	8.02E-11
Radioactive emissions to air	Antimony (Sb124)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Argon (Ar41)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Carbon (C14)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cesium (Cs134)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cesium (Cs137)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cobalt (Co58)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cobalt (Co60)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Hydrogen (H3)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Iodine (I129)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Iodine (I131)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Krypton (Kr85)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Krypton (Kr85m)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Plutonium (Pu alpha)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Radon (Rn222)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Uranium (total)	7.25E-07	1.02E-07	0.00E+00	6.23E-07
	Uranium (U234)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Uranium (U235)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Uranium (U238)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Xenon (Xe131m)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Xenon (Xe133)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Xenon (Xe133m)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Xenon (Xe135)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Xenon (Xe135m)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Xenon (Xe137)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Xenon (Xe138)	0.00E+00	0.00E+00	0.00E+00	0.00E+00

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