Environmental Load of Iron Ore Transportation, Bayan Obo Mine, China

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Abstract. The Bayan Obo Mine in the Inner Mongolia Autonomous Region, China, is the largest rare earth ore deposit in the world. The Baotou Iron and Steel Group (Baotou Steel) is in charge of the exploitation. Every year, approximately 12 million tons of ore are transported from the mine to the Baotou Steel factory by rail for dressing and smelting. The transportation of these massive quantities of ore has a large environmental impact. Based on the life cycle assessment (LCA) method, this study explores the environmental impact of the railway transportation of ore from the Bayan Obo Mine. Our results indicate that the environmental impact is primarily due to the marine aquatic ecotoxicity potential (MAETP), the abiotic depletion potential of fossil fuels (ADP fossil), and the acidification potential (AP). The environmental impact of the production of raw materials is much greater than that of the railway transportation. Our sensitivity analysis indicates that environmental impact is most sensitive to changes in the amount of diesel fuel used. The annual greenhouse gas emissions is 52.22 million tons, which is approximately 0.45% of the total greenhouse gas emissions in China in 2017. In particular, the direct emission from this transportation is 1.7 million tons, which is approximately 0.0077% of the country’s total emissions and 0.3% of Inner Mongolia’s total emissions. A comparison of our study and the European Union railway demonstrates that in both cases, the environmental impacts are primarily due to MAETP, ADP fossil, and global warming potential (GWP).

Keywords: life cycle assessment; railway transportation; carbon emission; Bayan Obo; China.

1. Introduction
The Bayan Obo Mine is located 149 kilometers north of Baotou City in the Inner Mongolia Autonomous Region, China. To date, it is the world’s largest iron, bismuth, and rare earth ore deposit. The Baotou Iron and Steel Group (Baotou Steel) is in charge of the exploitation of the mine. Every year, approximately 12 million tons of ore are transported by rail from the mine to the Baotou Steel factory in a suburb of Baotou City for dressing and smelting. After they deliver the ore, the empty trains return to the mine. This railway transportation is in operation 24 hours a day year round. This method of
transportation is a massive waste of fuel resources, is extremely expensive, and has a severe environmental impact. In this study, we investigate the following questions. What specific types of pollution is this transportation method causing? Is it possible to reduce the pollution without changing the current transportation method; and if so, how?

This study uses the life cycle assessment (LCA) method and Gabi software for modeling. The life cycle assessment method assesses the entire life cycle of a product, technique, or activity in relation to its environmental impact, including the initial collection of the raw material, the production, transportation, sale, use, recycling, maintenance, and disposal of the product. First, the LCA method identifies and quantifies the consumption of energy and resources as well as any emissions to the environment. Then, it assesses the impact of these consumptions and emissions. Finally, it identifies and assesses ways to reduce these impacts (ISO 14040, 2006; ISO 14044, 2006). The life cycle assessment method is an advanced method used to determine the comprehensive environmental impact of a process. It has been widely applied as an advanced method in modern environmental management. The LCA method has been used in several studies to investigate the fundamental theory (Guinée et al., 2001; Guinée et al., 2002; Guinée et al., 2011), research methodology (Cappuyns and Kessen, 2012; Von et al., 2017), research objects (De Feo and Ferrara, 2017), and resource and energy consumption of processes (Hong et al., 2017). However, few studies have focused on transportation (Li and Yan, 2011; Yang et al., 2013; Wu and Wang, 2013; Song et al, 2014; Chen et al., 2016). In particular, the LCA method has not previously been applied to the railway transportation of ore; and in particular, it has not been applied to the transportation of ore from the Bayan Obo Mine.

2. Life Cycle Assessment

2.1. Purpose and scope

We chose the transportation of 1 t·km as the functional unit. The main purpose of this study is to quantitatively analyze the consumption of resources and energy and the environmental emission due to the railway transportation of ore from the mine to the factory; and therefore, to provide evidence for the development of a program for energy conservation and emission reduction. The railway transportation system includes the production of train, construction of the railway infrastructure, upstream power and fuel production, train operation, and the maintenance and scrapping of the railway infrastructure and trains. Given the lack of data on the production of the trains, the construction of the railway infrastructure, construction and operation of railway stations, and maintenance and scrapping of the trains, our study focuses on two phases: the upstream power and fuel production and the train operation. In this study, we assume that the train does not malfunction during operation and that it receives normal and regular maintenance.

2.2. Inventory

We collected data on material consumption, energy consumption, transportation distance, transportation volume, the train’s technical parameters, and the amount and type of gases emitted during the train’s operation.

The Bao-Bai special line is used to transport ore from the Bayan Obo Mine to the Baotou Steel factory. It is an industrial and mining railway line connecting the mine to the factory. The line extends 146.8 km from the Baotou west station in the south to the Bayan Obo station in the north. To guarantee safe and efficient operation of the trains, strict specifications are followed concerning the type of diesel, engine oil, cooling water, and quartz sand used.

Sulfur is an important measure of the quality of diesel. The combustion of diesel fuel that contains too much sulfur results in atmospheric and environmental pollution. According to China’s nationwide diesel fuel standard (GB19147-2016), the sulfur content of diesel fuel must not exceed 100 ppm.

With the development of biodiesel technologies, some diesel production enterprises add biodiesel to petrochemical diesel to reduce the cost (the basic component of biodiesel is fatty acid methyl esters). However, biodiesel is not comparable to petrochemical diesel in terms of their performances. Therefore,
diesel fuel standard GB19147-2016 specifies the limitation of fatty acid methyl esters in locomotive diesel fuels. The fatty acid methyl ester content (volume fraction) must not exceed 1.0%. Thus, we used data for diesel fuel with 100 ppm sulfur and 0.23% of biodiesel.

The engine oil used for modern railway diesel locomotives contains a large number of additives. The performance of the engine oil depends on the quality and quantity of these additives and the compound formulation technology used to produce the oil (Wang et al., 1992). According to standard GB17038-1997, two types of engine oil can be used for locomotives: oil with zinc and oil without zinc. Zinc-containing engine oil contains an anti-oxidation, anti-corrosion, and anti-wear additive called zinc dialkyl dithiophosphates (ZDDP). Non-zinc-containing engine oil contains no ZDDP. Instead, it contains ashless antioxidant, corrosion-resistant, and anti-wear composite additives. The DF4-model diesel locomotives used in the railway transportation of ore from the Bayan Obo Mine use zinc-containing engine oil. Therefore, we used ZDDP engine oil data.

Diesel locomotives require high quality cooling water. According to the TB/T 1750-2006 standard for diesel locomotive coolants released by The Ministry of Railways, China, locomotive coolants must use deionized water. Therefore, we used data for deionized cooling water produced using the ionic membrane exchange technique.

In diesel locomotives, quartz sand is primarily used to increase the friction between the locomotive and the track. The specific quality requirements for this sand are as follows: quartz content > 90%, water content < 0.5%, granularity of 1–2 millimeters, no impurities, and no dust. Therefore, we used data for quartz sand that meets these specifications.

Figure 1 illustrates the system boundary of the LCA and the inventory data for the railway transportation of the ore from the Bayan Obo Mine.

Note: "Others" include combined governor oil, tachometer oil, worm bearing oil, controller oil, regulation gearing, gear oil, antifriction bearing oil, worm gear ring oil. The consumption of mentioned above is little, so we can ignore them.

NMVOC: non-methane volatile organic compounds; PM2.5: particulate matter2.5

![Figure 1](image.png)

Figure 1. The system boundary of the LCA and the inventory data for the railway transportation

3. Results

3.1. Classification of environmental impact
We used the CML2001 environmental impact assessment method developed by the Environmental Science Center of Leiden University, Netherlands.

3.2. Characterization
We conducted a characterization analysis of the collected inventory data using the CML2001 characterization model. The analysis results were converted into environmental impact type parameters expressed in a unified unit. Table 1 lists the specific results.
Table 1. The characterization results of railway transportation LCA

| Category  | Unit  | Diesel  | Engine Oil | Cooling Water | Quartz Sand | Transportation | Total     |
|-----------|-------|---------|------------|---------------|-------------|----------------|-----------|
| GWP       | kg CO₂-Equiv. | 1.83E-03 | 1.35E-04 | 2.41E-04 | 1.11E-03 | 6.54E-05 | 3.38E-03 |
| AP        | kg SO₂-Equiv. | 1.10E-05 | 8.93E-07 | 4.53E-07 | 1.59E-06 | 9.30E-05 | 1.07E-04 |
| EP        | kg Phosphorus-Equiv. | 8.54E-07 | 3.95E-08 | 1.09E-07 | 2.67E-07 | 2.42E-05 | 2.55E-05 |
| ODP       | kg R11-Equiv. | 3.31E-16 | 1.51E-17 | 5.08E-15 | 3.96E-15 | 0.00E+00 | 9.39E-15 |
| ADP elements | kg Sb-Equiv. | 4.96E-10 | 1.48E-11 | 2.05E-09 | 4.50E-10 | 0.00E+00 | 3.02E-09 |
| ADP fossil | MJ      | 1.94E-01 | 5.21E-03 | 2.75E-03 | 1.22E-02 | 0.00E+00 | 2.14E-01 |
| FAETP     | kg DCB-Equiv. | 1.34E-04 | 3.89E-06 | 6.58E-07 | 1.23E-06 | 8.83E-07 | 1.41E-04 |
| HTP       | kg DCB-Equiv. | 4.97E-04 | 2.89E-05 | 7.67E-06 | 6.55E-05 | 2.28E-04 | 8.28E-04 |
| MAETP     | kg DCB-Equiv. | 3.14E-01 | 1.35E-02 | 2.25E-02 | 9.91E-02 | 1.75E-07 | 4.49E-01 |
| POCP      | kg Ethene-Equiv. | 1.15E-06 | 7.16E-08 | 3.73E-08 | 1.31E-07 | 8.86E-06 | 1.02E-05 |
| TETP      | kg DCB-Equiv. | 4.71E-06 | 4.58E-07 | 2.24E-07 | 6.40E-07 | 1.01E-07 | 6.13E-06 |

3.3. Normalization

The total equivalent amount of the world environmental load refers to an annual sum of consumed resources, energy, and pollution emissions. To compare different environmental impact parameters, a standardization process of the characterization results based on the world environmental load in 2000 is called normalization. Table 2 lists the results.

Table 2. The Normalization results of railway transportation LCA

| Category  | Diesel  | Engine Oil | Cooling Water | Quartz Sand | Transportation | Total     |
|-----------|---------|------------|---------------|-------------|----------------|-----------|
| GWP       | 4.33E-17 | 3.20E-18 | 5.70E-18 | 2.63E-17 | 1.55E-18 | 8.01E-17 |
| AP        | 4.60E-17 | 3.74E-18 | 1.90E-18 | 6.67E-18 | 3.89E-16 | 4.47E-16 |
| EP        | 5.40E-18 | 2.50E-19 | 6.92E-19 | 1.69E-18 | 1.53E-16 | 1.61E-16 |
| ODP       | 1.46E-24 | 6.65E-26 | 2.24E-23 | 1.75E-23 | 0.00E+00 | 4.13E-23 |
| ADP elements | 1.37E-18 | 4.10E-20 | 5.69E-18 | 1.25E-18 | 0.00E+00 | 8.35E-18 |
| ADP fossil | 5.57E-17 | 1.37E-17 | 7.24E-18 | 3.21E-17 | 0.00E+00 | 5.63E-16 |
| FAETP     | 5.70E-17 | 1.65E-18 | 2.79E-19 | 5.20E-19 | 3.74E-19 | 5.98E-17 |
| HTP       | 1.93E-16 | 1.12E-17 | 2.97E-18 | 2.54E-17 | 8.85E-17 | 3.21E-16 |
| MAETP     | 1.61E-15 | 6.92E-17 | 1.15E-16 | 5.08E-16 | 8.98E-22 | 2.30E-15 |
| POCP      | 3.13E-17 | 1.95E-18 | 1.01E-18 | 3.56E-18 | 2.41E-16 | 2.78E-16 |
| TETP      | 4.32E-18 | 4.20E-19 | 2.05E-19 | 5.87E-19 | 9.22E-20 | 5.62E-18 |

3.4. Weighting

The normalized environmental impact potential data cannot directly indicate the extent of environmental pollution. Therefore, weights need to be assigned to the various environmental impact potentials to derive the final environmental load indices. We assigned CML2001 environmental impact weights to the normalization results and derived the quantitative results of the overall environmental impact. Table 3 lists the results.

Table 3. The weighted calculation results of railway transportation LCA

| Category  | Diesel  | Engine Oil | Cooling Water | Quartz Sand | Transportation | Total     |
|-----------|---------|------------|---------------|-------------|----------------|-----------|
| GWP       | 4.03E-16 | 2.98E-17 | 5.30E-17 | 2.45E-16 | 1.44E-17 | 7.45E-16 |
| AP        | 2.81E-16 | 2.28E-17 | 1.16E-17 | 4.07E-17 | 2.37E-15 | 2.73E-15 |
| EP        | 3.57E-17 | 1.65E-18 | 4.57E-18 | 1.11E-17 | 1.01E-15 | 1.06E-15 |
| ODP       | 9.05E-24 | 4.13E-25 | 1.39E-22 | 1.08E-22 | 0.00E+00 | 2.56E-22 |
| ADP elements | 8.79E-18 | 2.63E-19 | 3.64E-17 | 7.99E-18 | 0.00E+00 | 5.35E-17 |
| ADP fossil | 3.57E-15 | 9.60E-17 | 5.07E-17 | 2.25E-16 | 0.00E+00 | 3.94E-15 |
| FAETP     | 3.87E-16 | 1.12E-17 | 1.90E-18 | 3.53E-18 | 2.54E-18 | 4.06E-16 |
| HTP       | 1.37E-15 | 7.95E-17 | 2.11E-17 | 1.80E-16 | 6.28E-16 | 2.28E-15 |
| MAETP     | 1.09E-14 | 4.71E-16 | 7.85E-16 | 3.45E-15 | 6.11E-21 | 1.57E-14 |
| POCP      | 2.04E-16 | 1.27E-17 | 6.58E-18 | 2.31E-17 | 1.56E-15 | 1.81E-15 |
| TETP      | 2.94E-17 | 2.86E-18 | 8.93E-17 | 3.99E-18 | 6.27E-19 | 3.82E-17 |
4. Discussion

4.1. Environmental impact

Figure 2 illustrates the overall environmental impact of the Bayan Obo Mine derived from the weighting results. In particular, the environmental impact of the MAETP, which is more than half of the total impact, is the largest.

![Figure 2. The calculation results of railway transportation life cycle inventory](image)

Figure 2. The calculation results of railway transportation life cycle inventory

Figure 3 illustrates the proportions that are caused by the material consumption, the energy consumption, and the transportation process. The largest environmental impact is from the MAETP, which is primarily caused by the diesel fuel production process and is secondarily caused by the quartz sand production process. This is due to the massive emission of Dichlorobenzene during these two processes. The second highest is from the ADP fossil, which is primarily caused by the pollution produced from chemical energy sources, e.g., hard coal and crude oil, in the production of diesel fuel. The third largest is from the AP. This is primarily due to the emissions of SO2 and NOx (nitrogen oxides) during the transportation process and the emission of HCl, HF, and NH4+ during the production of diesel fuel. The fourth largest is from the HTP, This is primarily caused by toxic substances entering the air, water, and soil during the production of diesel fuel. The fifth largest is from the POCP. This is primarily due to the emission of NMVOC during the transportation process. The sixth largest is from the EP. This is primarily due to the emission of NO during transportation. The seventh largest is from the GWP. This is primarily due to the massive emission of CO2, NO2, CH4, CFCs, and CH3Br during the production of diesel fuel and quartz sand; and secondarily due to the emission of pollutants during transportation. In addition, the environmental impacts of the production of the cooling water and engine oil account for a small proportion of the overall environmental impact during the railway transportation life cycle.

The entire life cycle of the railway transportation of ore from the Bayan Obo Mine includes the production of diesel fuel, engine oil, cooling water, and quartz sand and transportation phase of ore. Figure 4 illustrates the environmental impact of the production processes of these four materials and transportation phase of ore. The environmental impact of the production of the purchased raw materials and the energy to transport these materials accounts for 80.52% of the overall impact. The environmental impact of the production of diesel fuel is the largest; and it is far greater than that of the transportation of diesel fuel. Therefore, an improvement in the production process of various raw materials and a green procurement can effectively reduce the negative environmental impact.
Figure 3. The environmental impact proportion of each inventory unit in different environmental impact category

Figure 4. The environmental impact of the production processes of these four materials and transportation phase of ore

Over the entire life cycle of the railroad transportation of ore from the Bayan Obo Mine, the MAETP caused by diesel fuel production accounts for 38.11% of the overall environmental impact. This is the largest environmental impact factor. In other words, as a single index in a single phase, the MAETP contributes most to the overall environmental impact. The second largest environmental impact is from the ADP fossil caused by the production of diesel fuel, which accounts for 12.42%. The third largest environmental impact is from the MAETP caused by the production of quartz sand, which accounts for 12.03%. The overall environmental impact of the railway transportation of ore is primarily caused by the four indices related to the AP, POCP, EP, and HTP (Figure 5).
4.2. Sensitivity

Based on the environmental impact life cycle results, we conducted a sensitivity analysis on the input of various raw materials in the railway transportation of ore from the Bayan Obo Mine. This calculation used a value range of materials input between -10% and +10%. Table 4 lists the sensitivity analysis results for the various environmental impact indices.

Table 4. Sensitivity analysis on raw materials and energy corresponded to potential values of environmental impacts

| Category   | Standard Deviation |
|------------|--------------------|
|            | Diesel     | Engine Oil | Quartz Sand | Cooling Water |
| GWP        | 5.16%      | 0.38%      | 3.55%       | 0.74%         |
| AP         | 1.03%      | 0.08%      | 0.15%       | 0.04%         |
| EP         | 0.34%      | 0.02%      | 0.11%       | 0.04%         |
| ODP        | 0.35%      | 0.02%      | 4.22%       | 5.41%         |
| ADP elements | 0.00%    | 0.00%      | 0.00%       | 0.00%         |
| ADP fossil | 0.00%      | 0.00%      | 0.00%       | 0.00%         |
| FAETP      | 9.53%      | 0.28%      | 0.09%       | 0.05%         |
| HTP        | 6.01%      | 0.35%      | 0.79%       | 0.09%         |
| MAETP      | 6.99%      | 0.30%      | 2.21%       | 0.50%         |
| POCP       | 1.13%      | 0.07%      | 0.13%       | 0.04%         |
| TETP       | 7.68%      | 0.75%      | 1.04%       | 0.37%         |

As shown in Table 4, in the railway transportation of ore, the input of the raw materials has no effect on the results of the ADP elements or the ADP fossil indices. The reason for this is that the two indices are related to the production of the raw materials. The FAETP, TETP, MAETP, and HTP environmental impact indices are highly sensitive to diesel fuel compared to other materials. All of these indices have a low sensitivity to engine oil. The ODP, GWP, and MAETP environmental impact indices are highly sensitive to quartz sand. The ODP environmental impact index is the only index that is highly sensitive to cooling water.

A sensitivity analysis of the input of raw materials cannot intuitively reflect the changes in the overall environmental impact. Therefore, a weighting calculation of all of the environmental impacts was conducted; and a change interval was set. The sensitivity of the overall environmental impact to the changes in the input of the various raw materials was derived. Table 5 lists the results of this analysis.
Table 5. The total sensitivity of environmental impact about each material

| Materials         | Variation Range | Reduction Amplitude |
|-------------------|-----------------|---------------------|
| Diesel            | ±10%            | 5.51%               |
| Engine Oil        | ±10%            | 0.26%               |
| Quartz Sand       | ±10%            | 1.61%               |
| Cooling Water     | ±10%            | 0.36%               |

Note: Normalization used the database "CML2001-Jan. 2016, World, year 2000, incl biogenic carbon"; Weighting used the database "thinkstep LCIA Survey 2012, Global, CML 2016, incl biogenic carbon (global equivalents weighted)".

As shown in the results, the overall environmental impact is most sensitive to the consumption of diesel fuel. The environmental impact is secondarily sensitive to quartz sand. The environmental impact is least sensitive to the cooling water and engine oil. Therefore, a reduction in the use of diesel fuel should be the major goal of energy conservation and emission reduction efforts. This would enhance transportation efficiency, reduce the empty train ratio, increase the train traction tonnage, and enhance the environmental protection awareness of the drivers. Due to the fact that the Bayan Obo Mine is located to the north of Baotou city, with an elevation difference of 576 meters, it is a cold tundra plateau (about 1600 meters above sea level) (Tan and Shen, 2011). To make the train climb steadily, quartz sand is used to increase the friction between the wheels and the track. Therefore, an effective use of quartz sand and an improvement of the drivers’ operation, as well as a green procurement would reduce some of the environmental impact caused by the quartz sand. Minimizing the use of cooling water and engine oil would also cause a smaller environmental impact. However, they must still be used, but more conservatively. During the regular maintenance, if the sand and cooling water supplies have not significantly decreased, the frequency with which they are replaced can be reduced.

4.3. Uncertainty

This study uses the Monte Carlo method. The method randomly selects data from each data set at a pre-defined uncertainty interval and conducts the calculation. The calculation results are saved; and the process is repeated. If the process is repeated n times; n sets of results will be derived. All of these results combined form an uncertainty distribution. The lower the standard error of the calculated means, the more reliable the corresponding calculation results are. This study conducted 3000 calculations. The standard error of all of the indices formed a normal distribution within the confidence interval. Thus, our results are reliable. Table 6 lists the results.

Table 6. The Monte Carlo analysis of environmental impact indicator

| Category | Standard deviation |
|----------|--------------------|
| GWP      | 2.00%              |
| AP       | 1.00%              |
| EP       | 0.34%              |
| ODP      | 2.73%              |
| ADP elements | 0.00%         |
| ADP fossil | 0.00%             |
| FAETP    | 2.29%              |
| HTP      | 2.88%              |
| MAETP    | 1.04%              |
| POCP     | 1.00%              |
| TETP     | 2.54%              |
| Integrated Impact | 1.52%       |

5. Conclusion

(1) The LCA of the Bayan Obo Mine conducted in this study indicates that from the highest to lowest, the environmental impact potentials are the MAETP (54.52%), the ADP fossil (13.72%), the AP (9.50%), the HTP (7.93%), the POCP (6.30%), the EP (3.71%), the GWP (2.59%), the FAETP (1.42%), the ADP...
elements (0.19%), the TETP (0.13%), and the ODP (0.00%). Overall, the environmental impact of the production of the purchased raw materials is much higher than that of the transportation process.

(2) The sensitivity analysis results show that in the transportation process, the environmental impact is the most sensitive to the consumption of diesel fuel; and secondarily to quartz sand. The environmental impact is the most insensitive to the cooling water and engine oil. Therefore, a reduction in the use of diesel fuel and quartz sand should be the major goal in any energy conservation and emission reduction efforts in railway transportation.

(3) The uncertainty analysis results show that the standard error levels of all of the indices formed a normal distribution within the confidence interval. Thus, our results are reliable.

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