Benchmarking Energy Efficiency of Opencast Mining in India

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Abstract: Benchmarking energy consumption in industries is presently gaining importance due to the role of energy efficiency in controlling the cost of production. In this paper, a review of the energy benchmarking practices of opencast mines in worldwide is analysed and methodologies for energy benchmarking in opencast mine are proposed. The energy efficiency of five opencast mines in India for different end uses like coal, manganese and limestone are compared by statistical approach. The study resulted in minimum specific energy consumption (SEC) of 152 MJ/t for positive gradient mines and 34 MJ/t for negative gradient mine. The SEC of best practices opencast positive gradient mine in India is 123 MJ/t. A potential energy saving of at least 19\% is possible by comparing the SEC of best practice mine with present case studies. A minimum SEC of 90 MJ/t is estimated for an opencast coal mine of China. The model based approach has been discussed for mine transportation and pumping system. The result shows a fuel saving of 17\% in mine transportation using dump trucks.

Keywords: Benchmarking, energy efficiency, opencast mine, diesel, electricity.

1. INTRODUCTION

Presently India produces about 84 minerals comprising of 4 fuel, 11 metallic, 49 non metallic industrial and 20 minor minerals \cite{1}. The mining industry accounts for the 3\% of the industrial energy use in US and energy cost accounts for 15\% of the total cost of production \cite{2}. Mining and quarrying in India contribute about 1.7\% of the industrial energy usage \cite{3}. Benchmarking energy efficiency is a technical tool for comparing the energy consumption of process, equipment, industrial units and buildings etc. Energy benchmarking is gaining importance due to implementation of Kyoto Protocol in 2005 \cite{4} for national allocation of CO\textsubscript{2} emission right and trading off of CO\textsubscript{2} emission. Specific energy consumption (SEC) is mostly used as energy benchmarking indices for assessing the energy efficiency and measured as the energy consumed to the production output of a plant or process (MJ/t, kWh/t etc.). There have been limited studies on the energy benchmarking in mining. In this paper, the statistical and model based approaches have been used for benchmarking energy consumption in opencast mines.

The energy consumption in mine varies due to the variation of the mine topography, mine equipment characteristics and operational practices. The energy consumption of three large opencast mines of China has been compared by Shuzho et al \cite{5}. The SEC of the mines varies between 90-225 MJ/t \cite{5}. The SEC of total operation for seven Canadian opencast mine varies from 97-256 MJ/t \cite{6}. An energy benchmarking and bandwidth analysis for the US mining industry showed that the practical minimum energy consumption is about 0.61 billion GJ/year where as the current energy consumption is 1.31 billion GJ/year in 2006 \cite{7}. Bandwidth analysis estimates the minimum energy consumption of total mining industries including coal, metal and minerals using statistical approach. The majority of the production in mines is extracted through opencast mining method. In US, the opencast mine production varies from 65\% for coal to 96\% for industrial minerals in the year 2002 \cite{7}. In India, the opencast mining constitutes about 70\% of the total coal production \cite{8}. The process flow chart for opencast mining is shown as Fig.1 \cite{9}.
The objective of this paper is to review the existing methods available in literatures for energy benchmarking in opencast mines and propose a methodology for benchmarking in opencast mine for case studies with different end uses like coal, manganese and limestone. The specific energy consumption of five opencast mines in India with different mine topography, material and equipment characteristics are compared for benchmarking based on the statistical approach. The modelling frameworks are developed for benchmarking energy consumption of major processes like transportation and water pumping in mine.

2. REVIEW OF ENERGY BENCHMARKING

Energy benchmarking can be done by statistical methods, thermodynamic approach based on pinch analysis and model based approach. Benchmarking of energy consumption in commercial building has been done by Chung et al. [10] using a statistical approach. Omid et al. [11] and Chauhan et al. [12] have also used statistical methods for benchmarking energy for agriculture. Statistical benchmarking has been used by Boyd et al. [13] for benchmarking energy in industrial sectors. Benchmarking energy efficiency for Dutch industries has been done by Phylipsen et al [14]. Most of these benchmarking methods are based on the statistical approach. Model based energy benchmarking for glass industries has been discussed by Sardeshpande et al [15]. The statistical and model based benchmarking approach can also be used for benchmarking energy efficiency in mining sectors.

There have been few studies carried out on energy benchmarking in mining sectors based on the statistical methods. Energy use benchmark for opencast coal mine is discussed by Cooke and Randal [16]. A range of energy efficiency benchmark and targets have been established based on studies undertaken at number of coal mines in Hunter valley. The benchmark target and present level for mines with and without dragline are presented in Table 1 considering the total energy consumed for overburden removal in bank cubic meter. An energy efficiency improvement of 24.7% is indicated based on the current best practices.

<table>
<thead>
<tr>
<th>Benchmark indices</th>
<th>Opencast mines with drag line</th>
<th>Opencast mines without drag line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy consumption (SEC)</td>
<td>18.6 MJ/m³</td>
<td>14 MJ/m³</td>
</tr>
</tbody>
</table>

The energy benchmarking of Canadian opencast mines is assessed for seven participated opencast mines based on the comparison of specific energy consumption [6]. The material handled for each mine (ore and waste) varies between 20 Mt/y to 120 Mt/y and the stripping ratio (ore: waste) varies considerably between 0.04 to 6.05. The stripping ratio of the mine has significant effect on the specific energy consumption of the mine. The SEC of the total operation in mine varies from 97 to 256 MJ/t of ore. The weighted average SEC is 128 MJ/t. The potential saving in energy cost is about 36% based on the benchmarking. An energy bandwidth analysis [7] was conducted by US Department of Energy (DOE) under the Industrial technologies program (ITP) to calculate the theoretical minimum and practical minimum energy for coal, metal, mineral mines to assess energy saving potential. The practical minimum energy consumption for coal, metal and
mineral mines are calculated as 0.26 billion GJ/y, 0.22 billion GJ/y and 0.123 billion GJ/y. The SEC for diesel powered equipment for a 3 Mt/y opencast coal mine is 73.5 MJ/t. The current energy consumption of opencast coal mine, metal mine and minerals are 164 MJ/t, 178 MJ/t and 34.8 MJ/t. The practical minimum energy requirement for coal, metal and mineral mining are 85.67 MJ/t, 78.7 MJ/t and 18.3 MJ/t. The energy saving potential is estimated from the difference between the current energy consumption and practical minimum energy consumption. The study conducted at hypothetical opencast coal mine of 3 Mt/y at Interior US shows the SEC of 81.5 MJ/t whereas the SEC estimated for an opencast coal mine of capacity 8.3 Mt/y at Western US is 58.4 MJ/t [17]. The energy requirement of 1.8 Mt/y limestone opencast mine is 25.3 MJ/t [17]. The energy requirement of coal and lime stone mine is calculated using SHERPA software.

Benchmarking of opencast coal mines of India has been discussed by Reddy et al. [18] using the data envelope analysis (DEA). This paper establish the benchmarking of the opencast coal mines of Southern Collieries Company Limited (SCCL) of Coal India Limited (CIL) using input oriented Constant Return to Scale (CRS) model for 15 opencast coal mines. DEA identifies a set of efficient coal mines that can be utilised as benchmark for improvement of the performance and productivity. The efficiency of coal mines is defined as ratio of the weighted sum of all outputs to the weighted sum of all inputs. The linear programming formulation has been used to maximize the production. The efficiency score of opencast mines varies from 39.68% to 100%. Six mining units that scores 100% are taken as benchmark units. The other opencast mining units are compared with these units to identify the scope for improvements. The result shows that there is a significant scope for improvement after benchmarking and comparing to efficient mines.

There have been few studies on energy benchmarking in opencast mine based on the statistical data. In this work a framework for statistical approach of benchmarking for opencast mining sector is given and model based approach is proposed for opencast mining processes.

3. PROBLEM STATEMENT

The energy in form of diesel or electricity is used in various opencast mining processes like mine transportation, excavation, water pumping and crushing of the ore. The energy consumption in mine varies with mine topography, material handled and operating parameters of the processes. The objectives of this work are as follows.

1) Analyse the energy consumption and cost in opencast mining processes
2) Propose generic methodologies and modelling frameworks for energy benchmarking in opencast mine.
3) Identify the best practices opencast mine

The methodologies include statistical benchmarking for mine and model based benchmarking for mining process. For statistical benchmarking, the energy efficiency of different opencast mines of different mine topography are compared to obtain the minimum energy consumption. Model based approach are discussed for specific mining process like mine transportation and pumping system of the mine.

4. ENERGY CONSUMPTION IN MINING PROCESS

4.1 Input energy profile and energy cost

The electricity and diesel are major energy sources used in opencast mines. The electricity and diesel consumption pattern of a dragline operated coal mine and a conventional coal mine with dump truck – excavator are shown as Table 2 and Table 3. The electrical energy contributes to 55% of the total energy in a dragline operated opencast coal mine whereas diesel consumption accounts for about 64% of the total energy in conventional mine. The energy cost accounts for about 8-11% of the total energy consumption for manganese mines [22].
### Table 2 Input energy profile for dragline operated coal mine [19, 20]

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Annual energy consumption</th>
<th>Eq. energy in GJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Electricity</td>
<td>18000 MU</td>
<td>216000</td>
<td>55</td>
</tr>
<tr>
<td>Diesel</td>
<td>5000 kl</td>
<td>178500</td>
<td>45</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>394500</td>
<td>100</td>
</tr>
</tbody>
</table>

### Table 3 Input energy profile for conventional opencast coal mine [21]

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Annual energy consumption</th>
<th>Eq. energy in GJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Electricity</td>
<td>8203 MU</td>
<td>98760</td>
<td>36</td>
</tr>
<tr>
<td>Diesel</td>
<td>5019 kl</td>
<td>179195</td>
<td>64</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>277955</td>
<td>100</td>
</tr>
</tbody>
</table>

*Note: The equivalent primary energy is calculated considering 30% conversion efficiency*

#### 4.2 Energy consumption in process

The diesel or electricity are used for operating dump trucks, excavators, shovels, draglines, crushers, conveyors and pumps. The energy consumption in mining processes depends on the material handling rate, mine topography and operating practices. The energy consumption in mining equipment including the diesel and electricity usage pattern for dragline operated mine [19,20] is given in Fig. 2.

- a. Energy consumption
- b. Diesel consumption
- c. Electricity

![Fig. 2 Energy consumption in opencast mining equipment](image)

#### 5. ENERGY BENCHMARKING FOR OPENCAST MINE

The energy benchmarking methods for opencast mining sector is classified as:

- Statistical energy benchmarking
- Model based energy benchmarking

The opencast mining sector should implement the idea of energy benchmarking across the whole mining sector i.e., coal, metal and mineral mines to improve their energy efficiency by comparing the energy performance of similar type of mine. This approach is called statistical energy benchmarking. The model based approach consider the process parameters for developing an analytical model for energy benchmarking of individual mining processes like transportation, pumping etc.
5.1 Statistical benchmarking approach

The statistical benchmarking approach uses specific energy consumption (SEC) for comparison amongst mines. The SEC of the best performing mine is considered as the energy benchmark target in a sample of $N$ similar mines and other mines are compared to minimise their energy consumption. The specific energy consumption of the mine is calculated from the energy usage in fuel (diesel) consuming equipment like dump trucks, excavators, dozers, drill etc and electrical energy consuming equipment like pumps, crushers etc. The flow chart of statistical benchmarking is given in Fig. 3.

The total energy consumed in $i^{th}$ mine is given as:

$$E_i = E_{elect,i} + E_{fuel,i} \quad (i = 1,2,3,\ldots,N) \quad (1)$$

$$SEC_i = \frac{E_i}{Q_i} \quad (i = 1,2,3,\ldots,N) \quad (2)$$

$$S_i \text{ (% saving)} = \frac{100(SEC_i - SEC_{b,i})}{SEC_i} \quad (3)$$

5.1.1 Comparison of SEC of Indian opencast mines

The specific energy consumption of five opencast mines in India have been taken from the technical reports and personal communications with industries for comparison of the energy efficiency of opencast mines. The SEC for five opencast mines of India from the energy audit studies conducted by CIMFR is given in Table 4.

The specific energy consumption of five opencast mines in India varies between 152-207 MJ/t for positive gradient mine. The SEC of negative gradient opencast mine is 34 MJ/t. The variation of SEC is due to the variation in mining technology, mine equipment characteristics and the mine topography. The SEC of dump trucks varies between 32-85 MJ/t for positive gradient mine and 7 MJ/t for negative gradient mine. The fuel consumption for negative gradient mine is less than the positive gradient mine due to assistance of gradient.

Table 4 Analysis of energy efficiency of opencast mines of India

<table>
<thead>
<tr>
<th>Mine Specification/Year</th>
<th>End use</th>
<th>Production (Million t/y)</th>
<th>Diesel equipment SFC (l/t)</th>
<th>Diesel consumption in dump truck (l/t)</th>
<th>Electrical equipment SEC (kWh/t)</th>
<th>Mine SEC (MJ/ton)</th>
<th>SEC of Dump trucks (MJ/t)</th>
<th>Mine topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine D [19,20],1997-98</td>
<td>Coal</td>
<td>2.59</td>
<td>1.92</td>
<td>1.23</td>
<td>6.94</td>
<td>152</td>
<td>44</td>
<td>Positive gradient</td>
</tr>
<tr>
<td>Mine E [21], 2010-11</td>
<td>Coal</td>
<td>1.34</td>
<td>3.75</td>
<td>2.39</td>
<td>6.09</td>
<td>207</td>
<td>85</td>
<td>Positive gradient</td>
</tr>
<tr>
<td>Mine F [22],2000-01</td>
<td>Manganese</td>
<td>0.093</td>
<td>3.90</td>
<td>0.91</td>
<td>4.9</td>
<td>198</td>
<td>32</td>
<td>Positive gradient</td>
</tr>
<tr>
<td>Mine G [22],2000-01</td>
<td>Manganese</td>
<td>0.135</td>
<td>3.82</td>
<td>1.30</td>
<td>2.05</td>
<td>161</td>
<td>46</td>
<td>Positive gradient</td>
</tr>
<tr>
<td>Mine H [23],2007-08</td>
<td>Limestone</td>
<td>6.47</td>
<td>0.53</td>
<td>0.20</td>
<td>1.25</td>
<td>34</td>
<td>7</td>
<td>Negative gradient</td>
</tr>
</tbody>
</table>

5.1.2 Energy benchmarking and saving

The comparison of the SEC for positive gradient mines including best practices mines of India (Mine C, Mine D, Mine E, Mine F, Mine G) and few mines of other countries (Mine A and B) taken from the literature is shown in Fig. 3. The
mine B is identified as the best operating mine. The energy saving for each mines A to G comparing to the benchmark mine B are shown in figure. From the trend line, the SEC decreases with production rate. The SEC of the larger mines with higher production rate are less than the smaller mines. Hence, large mines are more energy efficient than smaller mines. The variation of the SEC is mostly due to the variation of the energy consumption in dump trucks since the diesel consumed in dump trucks varies with distance, speed and payload. The SEC of dump trucks are also compared to assess the minimum energy consumption in mine transportation. The SEC of dump trucks varies between 32 MJ/t to 85 MJ/t and the minimum SEC is 32 MJ/t. The energy saving in mines in comparison to the SEC of best performing mine varies between 26 to 56%.

5.1.3 Best practices mine
The energy consumption of a best practices opencast coal mine (Mine A) shown in Fig. 3 - (b) has been taken from the unit profile for energy conservation award submitted to the Bureau of Energy efficiency (BEE), Ministry of power, Govt. Of India. The SEC of the mine is 123 MJ/t for production of 5.96 Mt/y in 2006-07 [24] in captive opencast coal mine of Jindal Steel and Power, Raigarh. Hence the SEC of 123 MJ/t can be used as energy benchmark for Indian opencast mines. The specific energy consumption of the best operating opencast mine can be taken as energy benchmark for targeting and assessing the energy saving potential in opencast mining sector. A potential energy saving of at least 26 % is possible by comparing the SEC of the benchmark mine among seven opencast mines.

5.2 Model based benchmarking
Model based benchmarking approach provides the minimum energy required for each process of mining considering the operating parameters of the mining process. The minimum energy required is taken as the energy benchmark target to minimise the energy consumption. The optimisation of energy consumption of a shovel has been done for optimal crowd arm and hoist rope speed [25]. Modelling framework works have been developed for benchmarking the energy consumption in opencast mine transport and pumping system based on the optimisation.
5.2.1 Mine transport model
The optimisation of the specific fuel consumption in dump trucks for transport system in opencast mining has been done using vehicle dynamics, engine and mine characteristics [9, 26]. The generic model input parameters are shown for the modelling framework of the energy benchmarking in Fig. 4.

![Fig 4 Schematic of energy benchmarking for dump trucks in mine](image)

5.2.2 Water and energy models for pumping
The input parameters of the water and energy models for pumping are shown in Fig. 5. The modelling framework is used to benchmark energy consumption by optimising the energy consumption in pumping for a given water removal demand.

![Fig 5 Input parameters of energy benchmarking for pumping in opencast mine](image)

6. RESULTS
The minimum energy consumption for opencast mine is 123 MJ/t for Indian opencast mine and 90 MJ/t for opencast mines including few mines of the World with specified mine topography, production and the mining area. The base line shown in Fig. 3 indicates minimum energy consumption of the sample mines. The trend line for the energy consumption of the mine and the mine transport using dump trucks are compared. The result shows that difference in the total energy consumption in mines from the best operating mine is mainly due to the variation of the energy consumption in dump trucks and the production rate. The difference between the minimum to maximum energy consumption in opencast mining sector is estimated as 56%.

The model based benchmarking approach for mine transportation has been illustrated with the case study of a limestone mine in Rajasthan (India) [26]. The minimum specific fuel consumption of 89 g/t is estimated for multiple dump trucks.
(52t, 65t) operating between two crushers and three excavators for a material handling demand 10.4 Mt/y. A potential fuel saving of 17% is estimated based on the monthly specific fuel consumption of dump trucks for optimal speed profile.

7. CONCLUSION

In the present study, generic methodologies for statistical and model based benchmarking are proposed to calculate the minimum energy consumption in opencast mines. The energy efficiency of seven opencast mines has been compared to assess the minimum energy consumption by statistical method. The modelling frameworks have been proposed for mine transportation and water pumping using model based approach.

The energy efficiency of five opencast mines of different end usage like coal, manganese and limestone in India has been compared. Result shows that the specific energy consumption of Indian opencast mine varies between 152-207 MJ/t for positive gradient mines. The specific energy consumption of negative gradient mine is about 34 MJ/t. The comparison of the specific energy consumption of two opencast coal mines with and without dragline operation shows that the dragline operated mines are more energy efficient than the conventional opencast mines without dragline. The SEC of dragline operated mine is 152 MJ/t and that of conventional mine is 207 MJ/t. The dragline operated mines are 27% energy efficient than the conventional mines. The minimum energy consumption of positive gradient mines in India is 123 MJ/t including the best practices mine. The energy saving potential of atleast 19% is estimated in sample of mines in comparison to the best practices opencast mine in India. The minimum energy consumption of opencast mines including two mines of World is 90 MJ/t. The modelling framework for mine transportation using dump trucks result in potential fuel savings of 17% for a negative gradient limestone mine.

The benchmarking methods for opencast mines using statistical and model based approach can be used to set energy benchmark target for mining sector as well as mining processes.

8. UNITS AND SYMBOLS

\[ E_i \quad \text{Total energy consumption in } i^{th} \text{ opencast mine (MJ)} \]
\[ E_{\text{elect},i} \quad \text{Energy consumption for electrical equipment for } i^{th} \text{ mine (MJ)} \]
\[ E_{\text{fuel},i} \quad \text{Energy consumption for fuel (diesel) consuming equipment for } i^{th} \text{ mine (MJ)} \]
\[ Q_i \quad \text{Production output of } i^{th} \text{ opencast mine (Mt)} \]
\[ SEC_i \quad \text{Specific energy consumption in } i^{th} \text{ opencast mine (MJ/t)} \]
\[ SEC_b \quad \text{Specific energy consumption of best operating opencast mine (MJ/t)} \]
\[ S_i \quad \text{Energy saving in } i^{th} \text{ opencast mine (}) \]

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10. REFERENCES


