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Energy performance of loading and hauling operations in opencast mines

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Abstract:

Loading and hauling machines accounts for significant share of the total energy usage in large opencast mines. Major share of power is consumed in electric shovels used for loading operations and accounts for 32% of the total electricity usage in mine. Diesel is also used for operating hauling machines (dump trucks) in opencast mine and accounts for 56% of the total diesel consumption. In this paper, a methodology is proposed for calculating overall energy consumption in major energy intensive mining processes such as loading and hauling operations of the coal mine. Statistical approach has been used to estimate minimum SEC of a specific mine based on the annualized data. A linear regression method has been used to develop a mine specific model for estimating SEC by the correlation between SEC and composite production. A case study of an Indian opencast mine is presented to illustrate the results. Minimum SPC of electric shovels is calculated as 0.15 kWh/cum whereas the best operating SDC values of dump trucks operating in same mine is 0.47 l/cu.m. The overall SEC of loading and hauling operations calculated for the same opencast mine is 17.76 MJ/Cu.m and SEC of total operation in mine is 27.2 MJ/Cu.m. The best practices opencast mine without dragline from the literature is 26.3 MJ/cu.m.

Keywords:

Energy performance, Statistical approach, Loading, Hauling, Opencast mine, Specific energy consumption

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1. Introduction

Dump trucks are used worldwide for handling of ore and waste in most of the opencast mines. It is considered as one of the versatile heavy earth moving equipment. The diesel consumption in dump trucks accounts for about 56 % of the total diesel consumption in opencast mine [1]. Dump trucks are used for material handling in opencast mines using shovel- truck combination. The transportation network of mine includes a fleet of dump trucks moving between crushers/dumping stations and shovels. The diesel consumption in dump trucks depends on the speed, material handling rate and distance between loading and unloading point. Benchmarking and optimization models are generally used for calculating minimum energy consumption. An energy benchmarking model is developed by Sardeshpande et al. for calculating minimum energy consumption in glass furnace [2]. Most of the exercises on optimization in transportation are based on linear programming approach for reducing cost. Energy efficiency of dump trucks operating in opencast mine has been rarely analyzed. The optimization of loading and transport system in opencast mine has been done to optimize number of trucks required serving at loading point, number of trips per hour and theoretical output of dump trucks [3]. Optimization of journey schedule of high capacity dump truck has been done by Vasil'ev et al. to reduce the travel time of dump truck [4]. Fuel consumption depends on the inherent resistances such as gradient resistance, drag force and rolling resistance. Fuel consumption rate is taken as objective function and solved by Langrage's multiplier method with constraint of total time. Solving the optimization problem shows that fuel consumption is minimum by keeping speed profile constant for level, ascending and descending gradient [5]. The results of study made Tolouei et al confirmed that fuel consumption increases as mass increases and is different for different combination of fuel and transmission type [6]. A benchmarking model was developed by Sahoo et.al. for optimization of specific fuel consumption for dump trucks [7]. Specific diesel consumption (SDC) can be used as energy performance indicators to assess and compare the energy performance of hauling operations in operating mine.

Electric shovels dominate the electrical energy consumption in opencast coal mine and consume 32% of the total electrical energy usage [8]. Energy efficiency indices have been used by researchers to assess energy efficiency in mining process. Specific power consumption (SPC) has been used previously to describe the

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performance of digging equipment and operators. Energy benchmarking using statistical approach has been done for commercial building [9]. Past studies showed that operator's proficiency plays a significant role in the productivity of shovels [10-13]. Energy efficiency of loading and hauling operations depends on the equipment, operating conditions, mine planning and operator's performance [10]. Specific energy consumption (SEC) is used as energy benchmarking index and is measured as the energy consumed to the production output (MJ/t, kWh/t etc.). Oskouei et al. revealed that the operator's skill affect the energy efficiency of the mining machinery [11]. The study done by Karpuz et al. revealed that there is an increase in digging power consumption with the increase in the cutting depth and operator's performance [12]. The results of simulation experiments conducted by Awuah-Offei, K. et.al revealed that an operator operating near optimal levels with a 44 cu.m bucket capacity can save over $114,000/- in electricity costs for digging cycle alone as compared to an average operator [13].

From the literature review it is concluded that limited literature addresses benchmarking of specific energy consumption for loading and hauling operations in opencast mine using statistical approach. In this paper a methodology is developed for benchmarking of specific energy consumption for loading and hauling operation and validated with energy performance for best operating mine.

1.1. Mining process

Drilling and blasting is the first process of surface mining for fragmentation of overburden and coal seams. An efficient blasting result in lower cost of extraction as the particle size and density of material affects the energy consumption of an opencast mine. Excavators/Hydraulic backhoe, shovels are used for loading material in to dump trucks. Dump trucks are then used to transport coal and overburdens to the specified dumping stations. The fuel consumed in heavy earth moving machines operating in mines varies with mine topography, distance, material handled and the capacity utilization. Pie charts showing the fuel consumption and power consumption of Dipka opencast mine of South Eastern Coalfields Ltd (SECL) is shown in Fig.1a and Fig 1b. From the Fig. 1a, dump trucks consume about 56% of total diesel consumed in opencast mine.

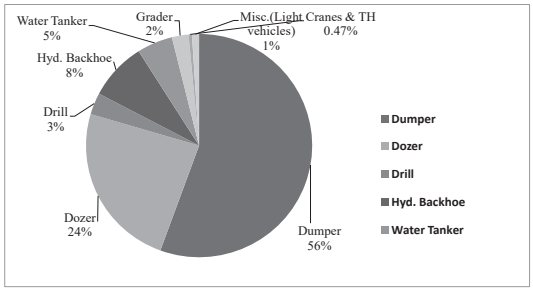

Fig 1a Diesel consumption profile in opencast mine of SECL

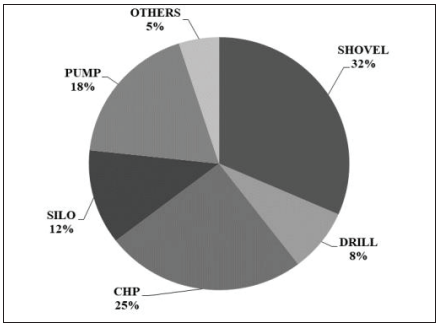

Fig 1b Power consumption in opencast mine of SECL

1.2. Objective

Diesel is used as fuel for operating heavy earth moving machines (HEMMs) such as dump trucks, dozers and drills etc. in an opencast mine. The diesel consumption in haul trucks used for hauling operation consume 32% of total energy consumed in an opencast coal mine and varies with mine topography, bulk density of coal and overburdens and operating practices of haul trucks. Similarly loading operation consume significant energy consumption. Electric shovel consumes 32% of total electrical energy consumption in opencast mine. Hence, these two operations such as loading and hauling consume significant energy in opencast mine. The objectives of the paper are given as follows.

1) Evaluate the energy performance of loading and hauling operations
2) Propose a method for energy benchmarking of shovels and sump trucks
3) Study the variation of SDC of hauling operations with composite production
4) Study the variation SPC of loading operation with composite production
5) Compare the benchmark SEC with best practices mines.

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2. Methodology for Energy Benchmarking

2.1. Statistical Benchmarking

Statistical approach has been applied by many researchers for benchmarking energy consumption of commercial buildings, agriculture and industrial sectors. Benchmarking energy consumption in commercial building has been done by Chung et al. using a statistical approach [14]. Chauhan et al., and Omid et al. have also used statistical methods for benchmarking energy for agriculture [15,16]. Benchmarking energy efficiency for Dutch industries has been done by Phylipsen et al.[17]. These approaches are defined as statistical energy benchmarking. The loading and hauling machines in opencast coal mines can implement the idea of energy benchmarking. A study was conducted in a large opencast coal mine in India by author to apply statistical benchmarking methodology [18]. In present paper, the statistical approach has been applied for benchmarking energy consumption for two major operation:

- Loading operations using electric shovel
- Hauling operations using dump trucks

The statistical benchmarking can quickly estimate the minimum energy required per cubic meter of composite coal production in an opencast mine. The statistical benchmarking approach uses specific diesel consumption (SDC) as energy performance indicator for dump trucks, specific power consumption (SPC) for electric shovels and specific energy consumptionn(SEC) for overall energy consumption in loading and hauling operations in opencast mine. The SEC of the best performing year is considered as the energy benchmark target from the annualized data for the specific mine equipment. The monthly data is not appropriate due to seasonal variations of energy performance of mining equipment during rainy and off rainy season. In case of benchmarking mine quipment of different coal mines, multiple mine equipment of different capacities are compared to evaluate the minimum SEC. The specific energy consumption (SEC) of the mine is calculated from the aggregate energy consumption of both loading and hauling operations for electric shovels and dump trucks.

2.1. 1. Energy benchmarking for loading operations

Energy benchmarking of loading operations is the minimum SPC of electric shovels operating in the mine from best operating value. A benchmark SPC of the electric shovels is calculated by comparing progressive SPC based on the aggregated annualized data of power consumption and material handled. A mine specific model of benchmarking has been developed using linear regression analysis by correlating the SPC and composite production. The model helps in predicting the SPC of the mine equipment.

Electric shovels are used for loading materials in to the dump trucks in large opencast mines and consume significant quantity of electrical energy. Smaller opencast mines use diesel operated excavators for loading operations. Depending on the production requirement the machines are deployed by production supervisors. The SPC of electric operated shovel is obtained from the ratio of annualized energy consumed in shovel to the annual material handled and is given as:

$$SPC_j = \frac{\sum_{i=1}^{12} E_{c,ij}}{\sum_{i=1}^{12} Q_{t,ij}} \quad (1)$$

2.1. 2. Energy benchmarking for hauling operations

Specific diesel consumption (SDC) is an energy performance index to assess energy efficiency of heavy earth moving machines (HEMMs) operating in an opencast mine. Dump trucks consume major share of diesel consumption in mine. Therefore, SDC should be monitored regularly for targeting and minimizing diesel consumption in mine. The methodology for practical benchmarking approach for calculating SDC has been discussed in this section. The specific diesel consumption of single dump truck is defined as the ratio of diesel consumed during field trial period (t) to the material handled. The material handled is determined as the product of shovel bucket capacity, actual numbers of buckets filled, number of trips of truck and fill factor.

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$$SDC_1 = \frac{m_f(t)}{C_b n_b(t) x_d(t) C_f} \quad (2)$$

Dump trucks are used for transportation of coal and OB from shovels to CHP or OB dumping stations in opencast mine and consume significant quantity of diesel for its operation. Dump trucks are generally accommodated in the workshop of the mine from where it goes to mine site for operation as per the planning and requirement of production supervisors. Diesel is filled once a day at diesel filling station located near the workshop. Diesel is issued to dump trucks of different capacity ($i = 1,2,3$) for example 240t, 120t, 100t trucks.

If 'Q' is material handled by different capacity dump trucks, the benchmark SDC (SDC_{BM}) of multiple dump trucks is obtained using following formula for rainy as well as off rainy season. Minimum SDC is considered as benchmark for same capacity dump trucks operating in same roots. For different roots, average value is taken.

$$SDC_{BM} = \frac{Min\sum_{i=1}^{n} SDC_i Q_i}{Q} \quad (3)$$

Where,

$$Q = \sum_{i=1}^{n} Q_i \quad (4)$$

Average SDC of dump trucks for of dump trucks for rainy/off rainy season is estimated as:

$$SDC_{Avg} = \frac{Avg\sum_{i=1}^{n} SDC_i Q_i}{Q} \quad (5)$$

Eq (3) to Eq (5) are used for calculating benchmark SDC.

3. Case study of large coal mines

A case study of Dipka opencast coal mine of M/s South Eastern Coalfields Ltd (SECL), Bilaspur has been presented for assessing the practical benchmark SDC [18]. Dipka opencast mine of M/s. SECL lies in the latitude 22^0 18'59" – $22^0$19'43" and longitude 82^0 30'47" - $82^0$33'34" and bears the toposheet No. 64J/11 in the *Survey of India* and is located in Korba district of Chattisgarh, India. The installed production capacity of the mine is 25 MTPA with average stripping ratio of the mine is 1 m^3/Te of coal. Diesel is used for operating different HEMMs including dump trucks. Dump trucks consume about 56% of the total diesel consumption. The minimum SDC of the mine from past 4 years data is 0.81 l/cu.m. whereas the benchmark of the mine by comparing with five operating mines of different production capacity is 0.66 l/cu.m. Dump trucks used in hauling operation consume major share of diesel consumption and therefore the benchmarking has been done to evaluate minimum SDC based on statistical approach using methodology given above in para 2.1.2.

Dump trucks of different capacity (240t, 120t, 100t) and model of BEML/Caterpillar/Terex are operating in mine for transporting overburden (OB) and coal from different levels of mine to coal storage/ OB dumping stations. BEML dump trucks uses Cummin's engine whereas Caterpillar has its engine of the own make. Engine performance is very important for fuel economy in mine. Selection of dumper with a fuel-efficient engine helps in reducing SDC of the dump trucks. The engine specifications of dump trucks are given in Table 1.

Table 1 Engine specification of dump trucks

PARAMETERS	CAT 793D (240t)	CAT777 (100t)	BH 100 (100t)	MK 30 /MT 3000 (120t)
Make	Caterpillar	Caterpillar	BEML/Cummins	Detroit diesel
No of cylinders	16	12	12	16
Bore & stroke	170mm x 215mm	145mm x162mm	140mm x165mm	130mm x 150 mm
Displacement	78 lits	32.1 lits	37.7 lits	32 lits
Gross power	1801 kW,2415 hp	765 kW,1025 hp	783 kW, 1050 hp	898 kW

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Max torque	9553 N-m	5286 N-m	4629 N-m	-
Engine speed	1800 rpm	1750 rpm	2100 rpm	1900 rpm
Gear ratio	28.1:1	17.49:1	22.21:1	28.8:1
Payload	240 tons	100 tons	91.5 tons	108.8t
Volumetric capacity	96 m^3	41 m^3	41.5 m^3	49.4 m^3
Heaped capacity	129 m^3	60.1m^3	61 m^3	69.4 m^3

P & H electric shovels operating in Dipka opencast coal mine of M/s South Eastern Coalfields Ltd (SECL), Bilaspur, India has been presented in this paper for energy performance assessment using statistical approach. The annual electrical energy consumption of the mine is 49.3 GWh/y in 2014-15. The connected load of the electrical machinery in mine is 38.49 MW. The electric shovels (four numbers of 10 cu.m. and two numbers of 42 cu.m.) consume 32% of the total electrical energy. The power rating for hoist motors, crowd motor, swing motor and propel motors of electric shovel is 1887 kW, 547 kW, 746 kW and 716 kW respectively. The connected of electric shovel is 7235 kW (2 hoist motors, 1 crowd motor, 2 swing motors and 2 propel motors). The physical parameters of P & H electric shovel are given in Table 2. Five dump trucks were allocated to the shovel at the pit for hauling operation. The loading cycle of shovel include five different operations; digging, swinging, unloading, swing back and positioning/waiting time.

Table 2 Physical parameters of P & H electric shovel

Parameters/Model	Value	Unit
Model	4100C	
Nominal dipper capacity	45.9	cu.m.
Nominal Payload	81.6	t
Rated suspended load	154.2	t
Bucket fill factor	0.80	(assumed)

4. Results and Discussions

The variation of SDC with material handled for sample dump trucks during field measurement is shown in Fig.2a. From the analysis of results, SDC of dump trucks decreases with increase in material handling rate. The minimum SDC of 0.47 l/cu.m. is shown for maximum material handling rate of 348 cu.m./h for dump trucks with lead varies from 2.2 km to 2.97 km. The variation of SDC with monthly composite production shows non-linear trend and is shown in Fig 2b. Statistical approach of benchmarking considers minimum SDC of past 3 years progressive data to benchmark diesel consumption in mine. The analysis of annual progressive SDC showing monthly minimum and maximum value is shown in Table 3.

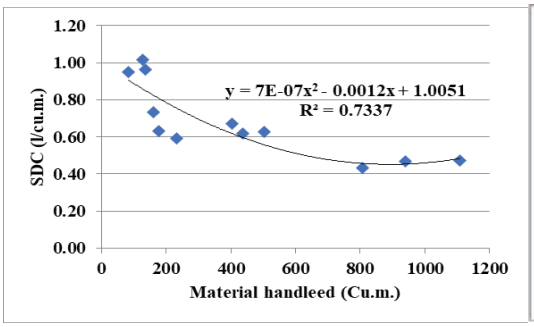

Fig 2a: Variation of SDC with total material handled

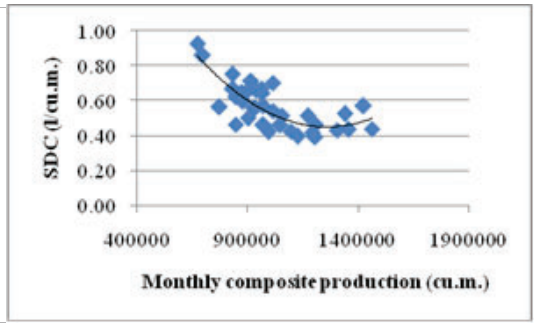

Fig.2b Variation of SDC of dump trucks with monthly material handled

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Table 3 Analysis of progressive SDC of dump trucks for an opencast coal mine of SECL

Sample size:36 (monthly SDC); 03 (Annualized data of SDC) SDC (l/cum)			
Year	Monthly Minimum	Monthly Maximum	Progressive
2012-13	0.60	0.93	0.69
2013-14	0.42	0.65	0.52
2014-15	0.39	0.66	0.47
Average	0.47	0.75	0.56

From statistical analysis, the minimum SDC of dump truck is 0.47 l/cu.m and average SDC is 0.56 l/cu.m. The progressive yearly variation of SDC is shown as Fig. 3a whereas the variation of SDC with material handled per hour is shown in Fig.3b from the actual measurement. The result of practical benchmarking is close to that by statistical approach. However, sometimes due to dynamic condition such as change of the haul road distance, material handles and operational practices statistical approach may not give accuracy in calculating the benchmark SDC. The disadvantage of statistical benchmarking is that it does not consider present operating conditions.

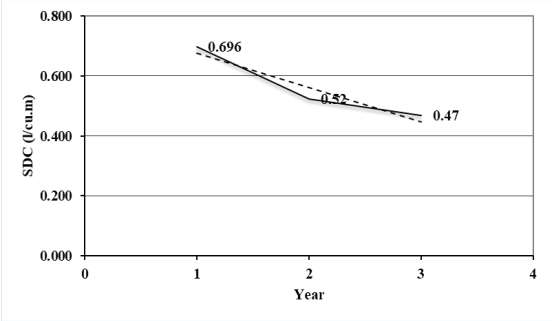

Fig 3a: Variation of progressive SDC

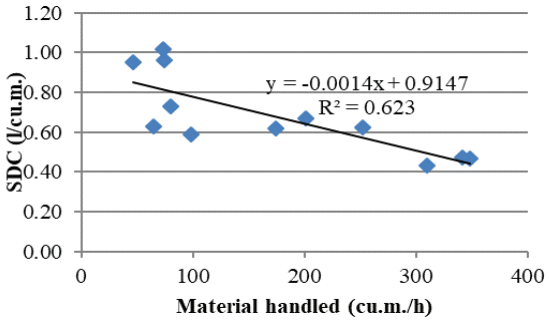

Fig.3b Variation of SDC of hauling with material handled

Statistical approach of benchmarking has also been applied for loading operation using electric shovel in large opencast mine. The annualized energy consumption and production data are used to calculate progressive SPC of the shovels operating in mine. Fig 4a shows the variation of SPC with composite production. The overall minimum SEC is then calculated to calculate benchmarking target for loading and hauling operation. Fig 4b shows the variation of overall SEC with composite production. Table 4 shows the minimum specific energy consumption of the loading and hauling operations. The minimum SEC is calculated as 17.76 MJ/cum in the year 2013-14.

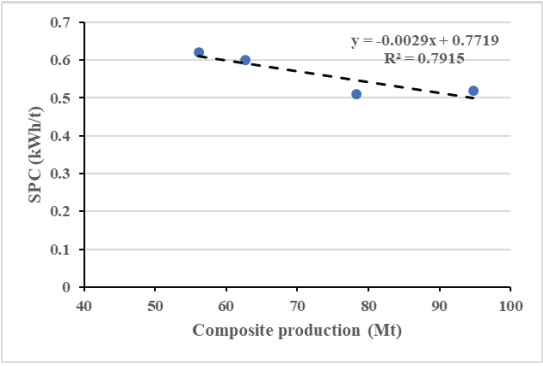

Fig 4a: Variation of progressive SPC with production

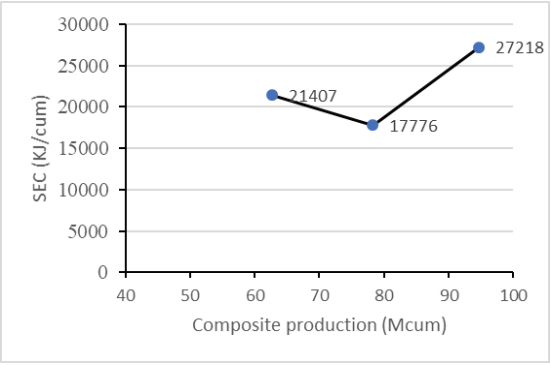

Fig.4b Variation of SEC of loading and hauling

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Table 4 Analysis of progressive SDC and SPC of an opencast coal mine of SECL

	Energy performance values	
Mining operations		SEC (KJ/cum)
Hauling (SDC)	0.56	19756.8
Loading (SPC)	0.16	1651
SEC_{LH} (Year1)		21407.8
Hauling (SDC)	0.47	16228.8
Loading (SPC)	0.15	1548
SEC_{LH} (Year 2)		17776.8
Hauling (SDC)	0.7	24696
Loading (SPC)	0.44	2522
SEC_{LH} (Year 3)		27218

The result shows that both SDC and SPC decreases with increase in composite production in opencast mine whereas the overall energy consumption though increases with production, the minimum specific energy consumption target is assessed for lower production rate due variation in energy inputs and operating strategies for loading and hauling machines.

4.1. Best practices in opencast mines

The specific energy consumption of the best operating opencast coal mine for overburden handling taken from the literature is 26.9 MJ/cu.m.[12]. From the present benchmarking study the SDC of best operating coal mine with 92% overburden handling is 0.66 l/cu.m. for a large opencast mine and is equivalent to 25.4 MJ/cu.m. The present energy benchmark level of 25.4 MJ/cu.m. for Gevra opencast mine can be further minimized by improving operational practices and procurring new energy efficienct heavy earth moving machines like 240t dump trucks and optimising the number of dump trucks corresponding to the total numbers and capacity of electric shovels deployed in the coal mine. The benchmarking can be used for targeting and assessing the energy saving potential in opencast mining sector. A potential fuel saving of atleast 16 % is possible by comparing the minimum SEC with average SEC of the specific mine.

4.2. Energy saving potential

The fuel saving potential in the mine is estimated by comparing the minimum SEC and average SEC of the mine using Eq. (6) for bechmarking of a specific mine.

$$E_s = \frac{SEC_{avg} - SEC_{BM}}{SEC_{avg}} \quad (6)$$

The minimum SDC of 0.66 l/cu.m (25.4 MJ/cu.m) is obtained by comparing SDC of five opencast coal mines of different installed capacity. The capacity of the mines is variable and can be increased by increasing number of machines depending on the coal reserve of the mine. The diesel saving potential by comparing minimum SDC with average SDC is 16 %.

5. Conclusion

In the present paper, a statistical approach of benchmarking has been applied for calculating specific energy consumption (SEC) and is used as energy performance indicator for loading and hauling operations. The overall minimum SEC for loading and hauling operation is calculated as 17.7 MJ/cu.m.The benchmark SDC for of hauling operations is 0.47/cu.m whereas the benchmark SPC obtained for electric shovel is calculated as 0.15 kWh/cu.m. The mine specific model for benchmarking has been developed using linear regression method. There is a significant scope of diesel and power saving by use of this method in mine. A diesel saving potential of 16 % is estimated by comparing with benchmarking value and the overall saving potential of 19% is estimated on both loading and hauling operations in opencast coal mine. Though the result of

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practical benchmarking is close to that by statistical approach, due to dynamic condition of mine operation such as haul road distance, material handling and operational practices statistical approach may not give accuracy in estimating the benchmark target. The disadvantage of statistical benchmarking is that it does not consider present operating conditions.

The statistical approach helps in quick estimation of benchmarking target for coal mines from the past data of diesel consumption, electrical energy consumption as well as composite production data of the mine. The benchmarking method can help in setting energy benchmarking target of the mine for continuous productivity improvement and energy saving in mine.

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Nomenclature

C_b	Shovel bucket capacity, cum
C_f	Fill factor
E_c	Monthly energy consumption, kWh
SEC_{BM}	Benchmark specific energy consumption, KJ/kg
SEC_{LH}	Specific energy consumption, (Loading and Hauling), KJ/kg
SEC_{avg}	Average specific energy consumption, KJ/kg
SPC_{shovel}	Specific power consumption of shovel
$m_f(t)$	Mass of fuel consumption of dump truck, lit
n_b	number of buckets
$x_d(t)$	number of dump truck trips
$.Q$	Composite production, cu.m.
SDC_{BM}	Benchmark SDC for coal mine, l/cu.m.
SDC_{avg}	Average SDC of the coal mine, l/cu.m.
SDC_i	SDC of the coal mine for i^{th}mine, l/cu.m.
SDC_{min}	Minimum SDC of the coal mine, l/cu.m.
SDC	Specific diesel consumption, l/cu.m.

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