Production, consumption and cost of energy for surface mining of bituminous coal

by V. Kecojevic, I. Vukotic and D. Komljenovic

Abstract ■ The objective of this research was to establish the relationship between production, consumption and energy cost in the surface mining of bituminous coal. Specific energy sources such as diesel, gasoline, electricity, explosives and bituminous coal were considered in this study. Gain in net energy, proportion of the cost of energy consumption and total energy cost relative to total revenue of extracted coal were determined, and a new energy efficiency index and a new energy-cost ratio were established. A case study on an operating surface coal mine was carried out to demonstrate the application of the newly developed method. The results of this study can be used by the mine operators in establishing strategies for the optimization of energy production and consumption, and for reducing the cost of bituminous coal extraction.

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Introduction

Bituminous coal is one of four main types of coal in the United States. It contains 45-86% carbon, 7.6-11% ash, 1-2.7% sulfur and approximately 10% moisture. The heating value is between 23 and 34 MJ/kg (9,800 and 14,600 btu/lb). It is primarily used for electricity generation, but is also employed in the industrial (iron, still) sector. The largest U.S. producers of bituminous coal are, in decreasing order, West Virginia, Kentucky and Pennsylvania. Total production of bituminous coal in 2011 was nearly 480 Mt (529 million st), which represents 48% of total coal production in the United States (EIA, 2012).

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Bituminous coal has been extracted by surface and underground mining methods. Surface mining requires a significant amount of energy, which comes from sources such as diesel fuel, gasoline, electricity and explosives. Energy is consumed in drilling and blasting, digging and loading, haulage, crushing and auxiliary operations.

The U.S. Department of Energy (DOE) has funded research and development projects related to energy efficiency in mining (DOE, 2007a; 2007b; 2004a; 2004b; 2002). These projects have established benchmarks and methods for measuring energy consumption and recommendations for energy savings. However, only two projects (DOE, 2002; 2007a) produced quantitative data for energy requirements in the mining industry.

Several authors analyzed energy consumption of specific mining equipment. Oskouei and Awuah-Offei (2013) established the relationship between energy consumption and different dragline parameters. Bogunovic and Kecojevic (2011) developed an algorithm for the calculation of "the best" fill factor for optimum energy consumption and dragline productivity. Awuah-Offei and Frimpong (2007) examined the relationship between energy and production through simulation of the energy-per-unit load of cable shovels. Cooke and Randall (1995) established energy efficiency targets and benchmarks for mining equipment used in overburden removal. Bogunovic et al. (2009) conducted a systematic analysis of energy consumption in the mining process through an integrated data monitoring system. Several research studies have shown that mine operating conditions and operators' practices significantly affect energy consumption, production and the relationship between energy and production in cable shovels and draglines (Patnayak, 2006; Widzyk-Capehard and Lever, 2004; Awuah-Offei and Summers, 2010; Oskouei and Awuah-Offei, 2013); Komljenovic et al. (2010) developed an operator performance indicator based on the ratio between energy consumption and dragline production.

Although there have been a number of studies related to energy consumption in mining operations, further investigation is needed into the relationships among energy production, consumption, and cost, as these factors relate to the extraction of a specific type of coal, i.e., bituminous coal. This study delineates several new relationships between these factors that may be beneficial to mining operators seeking to optimize them. Knowledge gained

and methods established by this study can also be applied to other types of coal.

Methods

Data for this study were collected from an operating surface bituminous coal mine in West Virginia. The mine has been active since the early 1970s. The geologic formations in the mine consist of sandstone overburden, with some shale streaks, and five coal seams of varying thicknesses interspersed between layers of interburden. The mine produces approximately 2.6 Mt (2.9 million st) of coal and approximately 32 million m^3 (42 million cu yd) of overburden per year. The operation uses diverse mining equipment, including a dragline, cable shovel, drills, bulldozers, hydraulic shovel, graders, haul trucks, front-end loaders, water trucks and various auxiliary equipment. The overburden and interburden rocks are fragmented by blasting operation using ANFO and emulsion explosives. The mine uses 46% ANFO and 54% emulsion for blasting. An average powder factor is 0.75 kg per m^3 (1.26 lb/ cu yd). Data on diesel, gasoline, electricity and explosive consumption, number of operating hours of mining equipment, and coal and overburden production were collected for a period of 12 months (January - December 2011).

The energy used in the mining process (coal and overburden) was determined for each energy source (diesel, gasoline, electrical, explosives), and adequate heating values were taken into consideration. The latter was also established for the coal. The heating value of fuel is the heat obtained by burning certain quantity of fuel under particular conditions (National Biodiesel Board, 2005). There are two different heating values for the same amount of fuel, higher (gross) and lower (net) heating value. The gross value represents the amount of heat obtained when a certain amount of fuel is completely combusted. The net value is the value obtained when the vaporization heat of the water vapor is subtracted from the gross value. The heating values for gasoline, diesel and bituminous coal combustion were obtained from GREET (2010). In addition to gross and net values, average values were also determined. In order to justify use of the latter, the concept of confidence intervals was used.

The average heating values for the diesel, gasoline and coal were calculated as the average values between gross and net heating values, and the results are accurate enough for practical purposes. Further in the study, the minimum and maximum heating values refer to net and gross heating values. The confidence interval used was 95%.

Energy consumption of diesel and gasoline fuel was calculated by the following equations:

$$EC_{min} = FC \times HV_{min} \times \rho \quad (1)$$

$$EC_{max} = FC \times HV_{max} \times \rho \quad (2)$$

$$EC_{avg} = FC \times HV_{avg} \times \rho \quad (3)$$

where EC_{min}, EC_{max} and EC_{avg} represent the minimum, maximum and average monthly energy consumed by a given fuel in MJ/month, respectively; FC is monthly fuel consumption of a given fuel in L/month; HV_{min}, HV_{max} and HV_{avg} are minimum, maximum and average heating values of given fuel in MJ/kg, respectively; and ρ is density of the given fuel expressed in kg/L. The energy consumed by electrical equipment ($E_{electricity}$) was calculated by conversion from kWh to MJ, and it is expressed in MJ/month.

In order to calculate energy consumed in the blasting process, the energy of ANFO and emulsion explosives was used. This energy represents one of the properties of explosives, which shows the quantity of energy liberated in the blasting process. It is expressed in calories per gram for the particular type of explosive; and for the purpose of this study, it is converted to MJ per kg. The energy consumed by explosives in the blasting process was calculated as follows:

$$E_{explosive} = A_{ANFO} \times Q_{ANFO} + A_{emulsion} \times Q_{emulsion} \quad (4)$$

where $E_{explosive}$ represents total energy consumed in the blasting process in MJ/month; Q_{ANFO} and $Q_{emulsion}$ are energy of ANFO and emulsion explosives, respectively, in MJ/kg; and A_{ANFO} and $A_{emulsion}$ are monthly consumption of ANFO and emulsion, respectively, in kg/month.

Total energy consumed EC_{total} represents an aggregation of diesel, gasoline, electricity and explosive energy. Therefore, the equation for total energy consumption used in the process of mining bituminous coal and overburden material can be presented as follows:

$$EC_{total} = EC_{avg\ diesel} + EC_{avg\ gasoline} + E_{explosive} + E_{electricity} \quad (5)$$

The energy contained in the mined coal was determined on the basis of minimal EP_{min}, maximal EP_{max} and average EP_{avg} heating values, i.e.:

$$EP_{min} = P \times HV_{min} \times CF_{kg/t} \quad (6)$$

$$EP_{max} = P \times HV_{max} \times CF_{kg/t} \quad (7)$$

$$EP_{avg} = P \times HV_{avg} \times CF_{kg/t} \quad (8)$$

where the P represents coal production in t/month; HV_{min}, HV_{max} and HV_{avg} represent minimum, maximum and average heating value of bituminous coal, respectively, in MJ/kg, and $CF_{kg/t}$ represents the appropriate conversion factor in kg/t.

In order to compare the energy consumed in the process of coal and overburden extraction and energy gained through coal production, an energy efficiency index E_{eff} was established. This energy efficiency index was obtained by the relationship between Eqs. (8) and (5) as follows:

$$E_{eff} = \frac{EP_{avg}}{EC_{total}} \quad (9)$$

Net energy E_{net} was determined by the subtraction of energy gained by the production of coal EP_{avg} and energy consumed in the process of coal and overburden extraction EC_{total}, i.e.:

$$E_{net} = EP_{avg} - EC_{total} \quad (10)$$

The cost of each energy source used in the mining process was determined as follows:

$$C_{diesel} = FC_{diesel} \times ucd \quad (11)$$
$$C_{gasoline} = FC_{gasoline} \times ucg \quad (12)$$
$$C_{explosives} = A_{explosives} \times uce \quad (13)$$
$$C_{electricity} = E_{electricity} \times ucel \quad (14)$$

where C_{diesel}, $C_{gasoline}$, $C_{explosives}$ and $C_{electricity}$ are costs for diesel, gasoline, explosives and electricity, respectively, in \$/month; FC_{diesel} (L/month), $FC_{gasoline}$ (L/month), $A_{explosive}$ (kg/month), and $E_{electricity}$ (kWh/month) are diesel, gasoline, explosives and electricity consumption, respectively; and *ucd* (\$/l), *ucg* (\$/l), *uce* (\$/kg) and *ucel* (\$/kWh) are unit costs of diesel, gasoline, explosives and electricity, respectively.

Therefore, the total cost of energy C (\$/month) used in mining process is:

$$C = C_{diesel} + C_{gasoline} + C_{explosives} + C_{electricity} \quad (15)$$

The energy-cost ratio C_R (\$/MJ) was established in order to examine the relationship between the total cost of energy used in mining process C (\$/month) and the total energy consumed EC_{total} (MJ/month) in the same process, i.e.:

$$C_R = \frac{C}{EC_{total}} \quad (16)$$

Revenue from coal production R_{coal} (\$/month) was determined as:

$$R_{coal} = P \times spc \quad (17)$$

where P is coal production (t/month) and *spc* is the sale price of coal (\$/t).

Therefore, the proportion of total energy cost C (\$/month) used in the mining process relative to the total revenue of coal R_{coal} (\$/month) was established as follows:

$$PEC = (C/R_{coal}) \times 100\ \% \quad (18)$$

It should be noted that no thermal efficiency in the coal power plant was considered in this study. Instead, the focus was related to the mining process only. It was also decided to consider all parameters on a monthly instead of hourly basis so mine operators can analyze energy consumption in various months throughout the year. This approach may be beneficial to mine operators in order to analyze energy consumption and related costs in summer and winter periods of the year.

Results and discussion

Figure 1 shows an overview of energy obtained through the production of bituminous coal in a surface mine. The quantity of energy is presented in petajuoles (PJ). It can be seen that the highest energy production of 6.78 PJ was recorded in August, while the lowest production of 4.28 PJ was observed in July. Total energy production in the entire year was 69.19 PJ.

Figure 2 shows the values of monthly energy consumption in the mine. It includes all four energy sources: diesel, gasoline, explosives and electricity. Energy quantity is presented in terajoules (TJ). It can be seen that the highest energy consumption of 119 TJ was recorded in January, while the lowest consumption of 77.07 TJ was observed in July.

Figure 1

Monthly energy production in 2011.

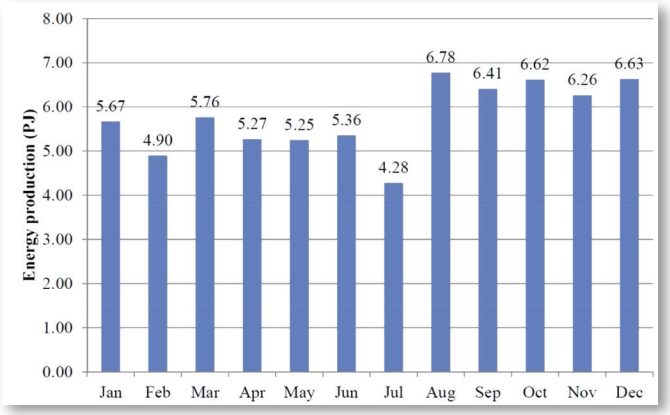


Figure 2

Monthly energy consumption for extraction of coal and overburden in 2011.

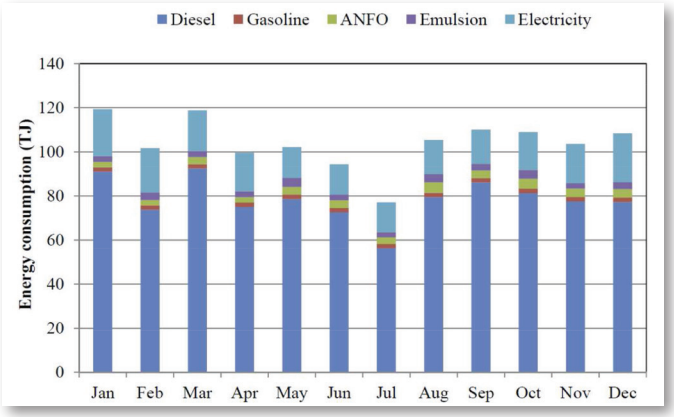
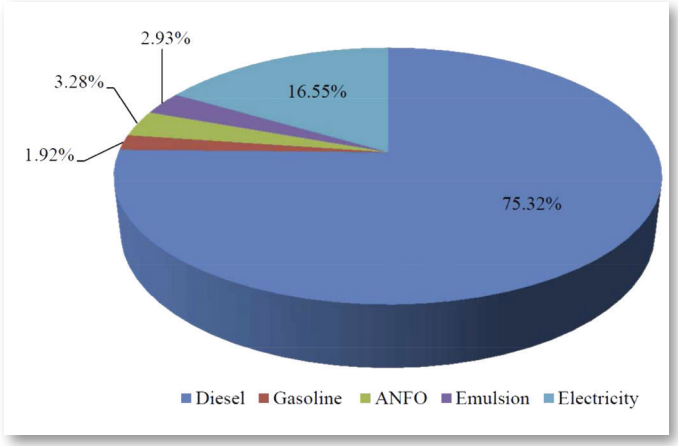


Figure 3

Proportion of energy sources in total energy consumption.



Total energy consumption in the entire year was 1,249 TJ or 1.249 PJ. The highest proportion of energy consumption was recorded for diesel, followed by electricity, explosives (ANFO and emulsion) and gasoline. Figure 3 shows that diesel fuel was 75.32% over the 12-month period, electricity was 16.55%, ANFO was 3.28%, emulsion was 2.93% and gasoline was 1.92%. It should be noted that the variation of the total

Figure 4

Energy efficiency index in 2011.

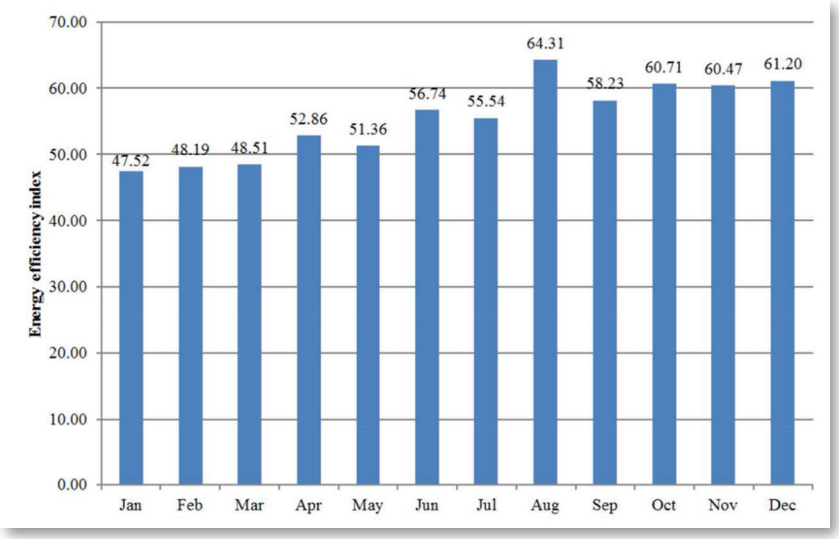


Figure 5

Net energy obtained in the process in 2011.

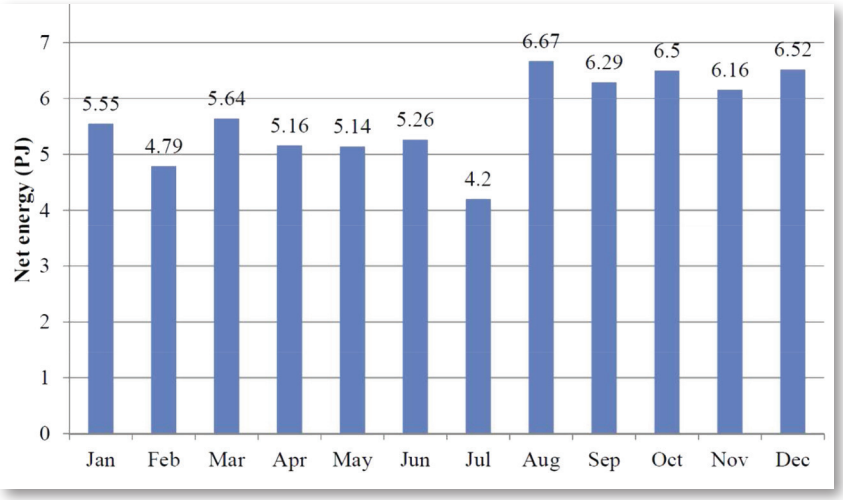


Table 1

Basic statistics for consumed and produced energy.

Energy Source	Consumed (TJ)			Produced (PJ)
	Diesel	Explosives	Electricity	Coal
Mean	78.42	6.47	17.23	5.76
St. deviation	9.44	1.17	2.91	0.78
CV (%)	12.04	18.16	16.89	13.54

energy consumption is mostly related to the total amount of extracted coal and overburden, but seasonal variations also play a role (summer consumption seems slightly lower).

Values for the energy efficiency index E_{eff} are shown in Fig. 4. It can be observed that the highest value of 64.31 was recorded in August, and the lowest value of 47.52 in January.

Values of net energy obtained in the process are shown in Fig. 5. These values range from a minimum of 4.2 PJ in July to a maximum of 6.67 PJ in August. It can be observed that the highest monthly values of net energy in Fig. 5 correspond to the highest energy production months in Fig. 1.

Table 1 shows the values of mean, standard deviation, and coefficient of variation for monthly energy consumption of diesel, explosives and electricity, and energy produced by bituminous coal. Values for gasoline consumption are omitted from this table since they are very low and nearly the same for every month. It can be noted that the highest standard deviation is seen in diesel fuel, while the least variable is explosives. However, the highest relative variability is seen in explosives, which means that the data for explosives significantly varies, even though they have the lowest monthly standard deviation. Electricity and coal follow explosives by the value of relative variability.

Diesel consumption is more variable in the first half of the year, with maximum energy consumption in this period. Electricity consumption gradually decreases from January to July, when it is the lowest, and gradually increases from July to December, when it is the highest. Explosives show higher energy consumption in the second half of the year.

Based on the values presented in Table 1, a Monte Carlo simulation of 5,000 trials has been conducted. Results of the simulation presented in Fig. 6 and Table 2 show a very close match with the actual mine data.

It should be noted that the simulation covers a larger confidence interval and, thus, the minimal and maximal simulated values are inferior and superior, respectively, compared to the actual values in Table 2. Meanwhile, the mean value and standard deviations are almost identical, which confirms that the simulation provides valid results. Considering a confidence interval at 95%, the lower and upper limits of the simulation results are 4.1 and 7.16 PJ per month, respectively.

Figure 7 shows the proportion of the energy consumption cost for each energy source. Diesel was 40.53%, emulsion was 28.64%, ANFO was 21.43%, electricity was 8.33% and gasoline was 1.07%. It should be noted that following unit costs were considered: \$0.87/L for diesel, \$0.82/L for gasoline, \$1.05/kg for ANFO, \$1.32/kg for emulsion, and \$0.079/kWh for electricity.

Figure 8 presents energy and cost proportions for each energy source. It can be observed that diesel, gasoline and electricity are higher in energy consumption proportion than cost proportion. However, ANFO and emulsion are higher in cost than in energy consumption proportion. The total amount of energy generated with explosives is 6.22% of total energy consumption; however, it accounts for 50% of total energy costs. Figure 9 indicates the ratio between energy and

Table 2

Comparison between actual data and simulation results for net energy.

Parameter	Observed (PJ)	Simulation (PJ)
Mean:	5.66	5.63
Std. Dev:	0.78	0.78
Minimum	4.20	2.83
Maximum	6.67	8.36
Confidence interval at 95%		
Lower limit		4.10
Upper limit		7.16

Figure 6

Distribution of net energy.

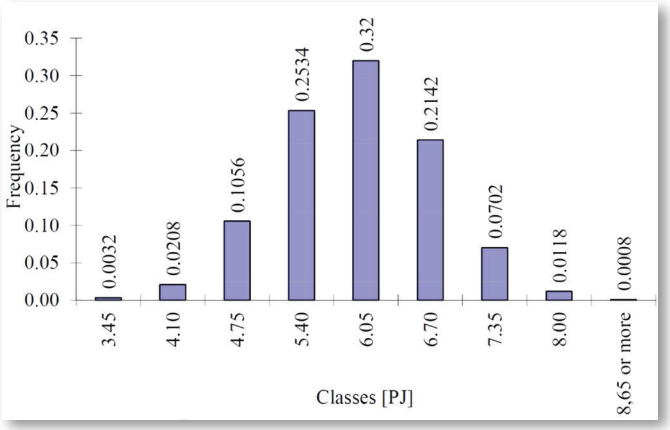


Figure 7

Proportion of the energy consumption cost for each energy source.

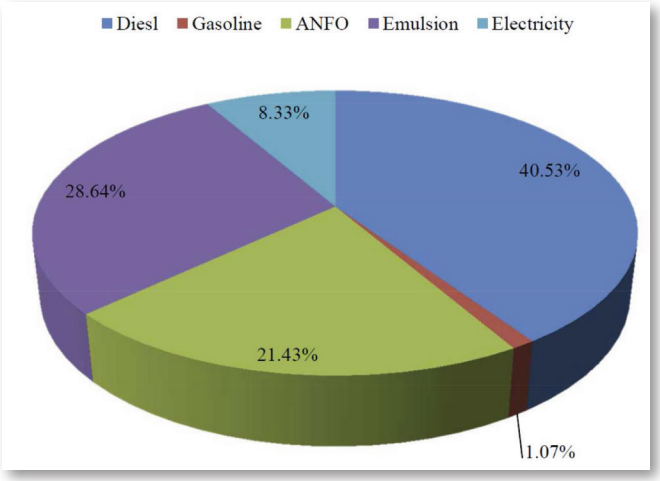


Figure 8

Energy and cost proportions for each energy source.

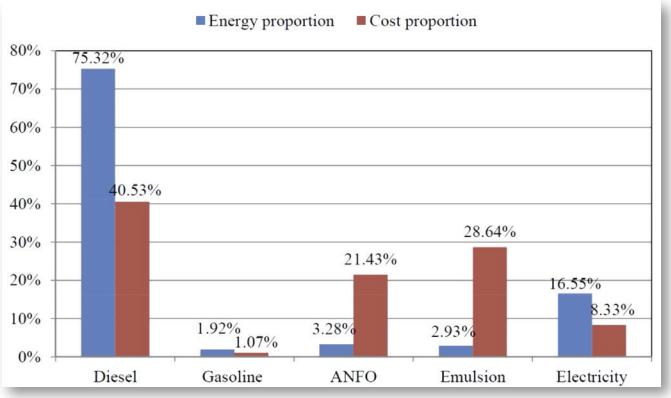


Figure 9

Ratio of energy per cost for different energy sources

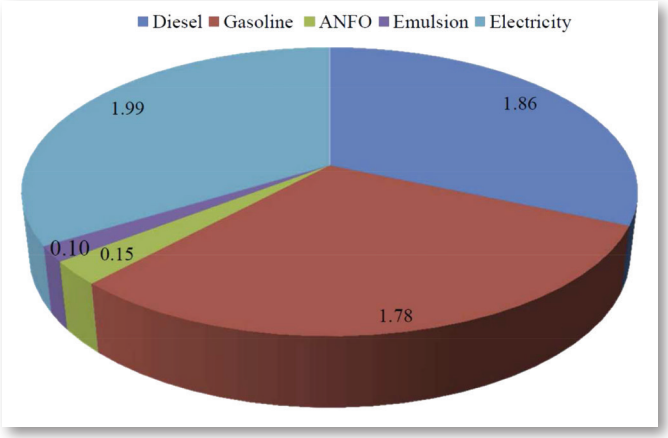
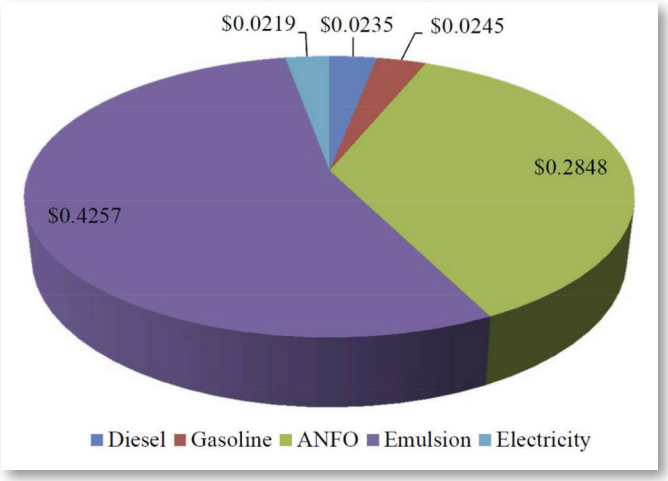


Figure 10

Dollars per MJ of energy consumed by various sources.



cost proportions for each energy source. It can be observed that electricity and diesel have the lowest unitary energy cost per MJ, with ratios of 1.99 and 1.86, respectively, whereas the emulsion has the highest unitary energy cost, with a ratio of 0.10, followed by ANFO with 0.15. It should be noted that the higher values of this ratio represent a lower per unit energy cost.

Figure 10 shows the energy-cost ratio, which represents the relationship between the total cost of energy used in the extraction process and total energy consumed in the same process. This figure represents, in dollar terms, the values in Figs. 8 and 9. It can be seen that explosives account for

Figure 11

Total revenue from coal production in millions of dollars per month in 2011.

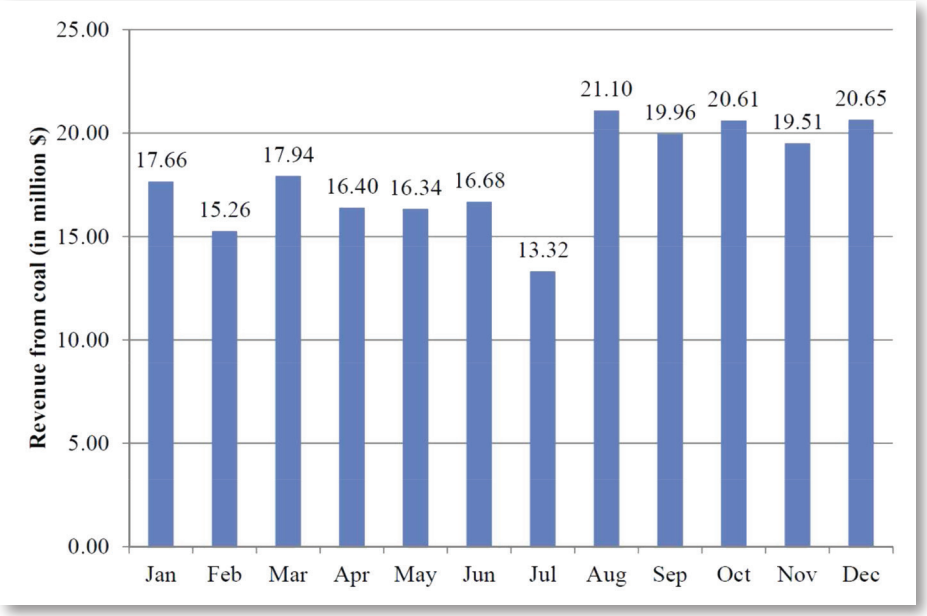
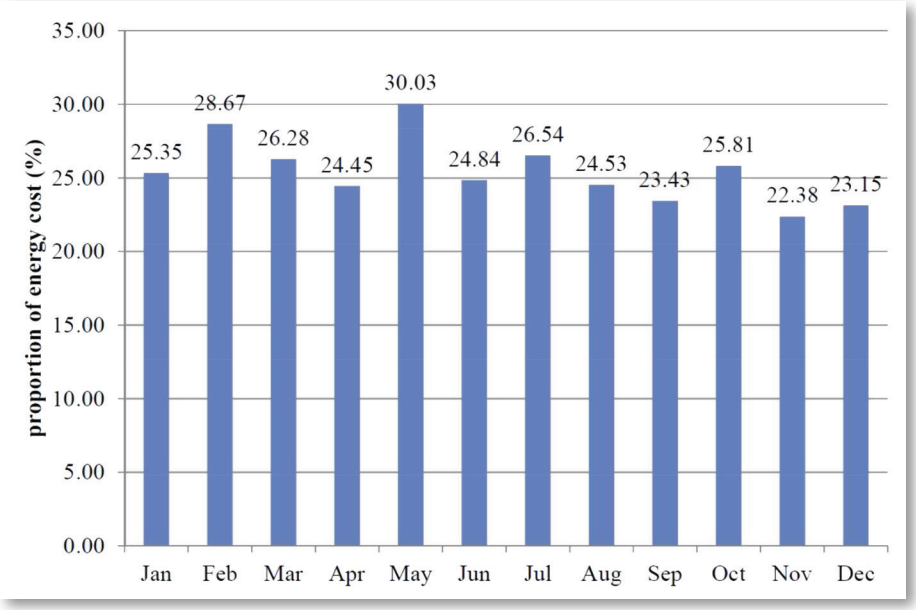


Figure 12

The proportion of total energy cost relative to total coal revenue in 2011.



$0.426 per MJ and $0.285 per MJ for emulsion and ANFO, respectively, which is significantly higher than all of the other energy sources. The energy cost ratio of diesel, gasoline and electricity is between 2.2-2.5 cents/MJ of generated energy.

Figure 11 shows total revenue from coal production. The sale price of coal was considered to be $85.96/t. Figure 12 depicts the proportion of total energy cost relative to total revenue of coal. It can be seen that the lowest proportion of energy cost of 22.38% was recorded in November, while the highest proportion of 30.03 % was recorded in May.

Based on the results obtained in this study, a Monte Carlo simulation with 10,000 trials has been conducted in order to analyze the variation of the total energy cost with regard to total coal revenue. Figure 13 and Table 3 present the results of the simulation.

It can be observed that the simulation gives a range of energy cost proportion between 18% and 34.29% of total revenue, with a mean of 25.39% and standard deviation of 2.24%. Taking into account a confidence interval at 95%, the lower and upper limits are approximately 21% and 30%, which are quite comparable to actual observed minimum and maximum values. Compared to actual mine data, the results show that the simulation provides valid information regarding the proportion of energy cost. These values may be helpful for mine operators in estimating this parameter more accurately, while taking into account associated uncertainties.

Figure 13

Distribution of the proportion of energy costs.

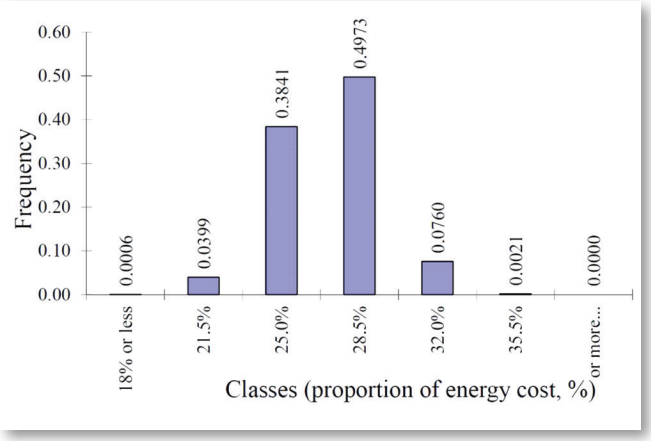


Table 3

Comparison between actual data and simulation results for the proportion of energy cost.

Parameter	Observed (%)	Simulation (%)
Mean:	25.46	25.39
Std. Dev:	2.22	2.24
Minimum	22.38	18.00
Maximum	30.03	34.29
Confidence interval at 95%		
Lower limit		21.00
Upper limit		29.78

Conclusions

There have been a number of studies analyzing energy consumption in mining operations. However, the objective of this study was to establish the relationships among energy production, consumption and cost, as these factors relate to the extraction of a specific type of coal, i.e., bituminous coal. This study establishes several new relationships between these factors that may be beneficial to mining operators seeking to optimize them. A significant amount of energy from sources such as diesel, gasoline, electricity and explosives is consumed in the extraction process of bituminous coal and overburden. The results of this study indicate that diesel contributed to approximately 75% of total energy consumed in the coal and overburden extraction process at a specific surface coal mining operation. However, almost 50% of total cost is related to explosives, while they account for only for 6.22% of total energy consumption. The study showed that explosives have the highest unitary energy costs ($/MJ), whereas diesel and electricity have the lowest. The proportion of net revenue relative to total coal revenue with regard to the total energy consumption cost is approximately 76%, with a coefficient of variation of 3%. Considering a confidence interval of 95%, this proportion varies within a range of 70-79%. Thus, this study shows that total energy costs are at a high of approximately one-fourth of total mine revenue for bituminous coal. The results obtained in this study may be used by mine operators to develop strategies for improving energy efficiency and reducing extraction costs for this type of coal. A similar study may be performed for other coal types. ■

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