The Economic Potential of Electric Mining Equipment

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In response economic and regulatory pressures, interest in electric mining equipment has continued to grow. Given the ongoing development of grid/battery-electric equipment, transitioning to a fully electric mine in the near future could become a genuine opportunity for mine operators to consider. In this respect, this paper discusses some of the technical considerations that are important for the evaluation and implementation of electric mining equipment and introduces a cost driver model developed by the authors which demonstrates how implementing electric equipment could lead to reduced operating and capital costs. Based on the cost driver model, the results of an economic assessment of electric mining using a discounted cash flow model will be presented and some case studies discussed.

1. Introduction and background

As heat is the only emission produced by electric mining equipment, understanding how much they generate is critical to determining how the design of ventilation systems will change as a result of their implementation.[1] [2] As well, because heat emissions are closely related to the amount of work performed by the equipment and the amount of fuel they consume, understanding the processes by which they emit heat will also help in calculating their fuel consumption and allow a cost comparison to be made between diesel and electric power.[3] [2] Finally, because the volumes of air circulated through underground ventilation systems are closely tied to diesel exhaust emissions, implementing electric equipment may allow these volumes to be significantly reduced. Given that these air volumes are also closely related to the cost of building and operating ventilation systems, reducing them could result in substantial savings.[2]

2. Assumptions about equipment heat production

In his book *Subsurface Ventilation Engineering*, McPherson states:

> *"This heat appears in three ways each of which may be of roughly the same magnitude. One third appears as heat from the radiator and machine body, one third as heat in the exhaust gases and the remaining third as useful shaft power which is then converted to heat (less work done against gravity) by frictional processes as the machine performs its task."*[3]
>
> and
>
> *"As with other types of heat emitting equipment there is little need, in most cases, to consider peak loads. It is sufficient to base design calculations on an average rate of machine utilization. The most accurate method of predicting the heat load is on the basis of average fuel consumption during a shift."*[3]

From this we can paraphrase three conclusions:

1. All of the useful work done by equipment is converted to heat except for work converted to potential energy (e.g. work done against gravity, regenerative braking).
2. Heat emissions from equipment result from the amount of time the equipment is run (i.e. utilization)
3. And the amount of input energy consumed by the equipment during that time (i.e. fuel consumption).

In general, the common term used to relate the amount of input energy (i.e. fuel consumption) to the amount of useful output power (i.e. brake power) produced by an engine or motor is efficiency. This is defined by Merriam-Webster as: "T*he ratio of the useful energy delivered by a dynamic system to the energy supplied to it."*[4] It is also defined by SAE International as stated in Equation 1, where η is efficiency.[5]

$$\eta = \frac{Power\ Output}{Fuel\ Energy\ Input} \tag{1}$$

To summarize then, it can be stated simply that the amount of heat generated by operating equipment is based on the amount of fuel it consumes, less any work converted to potential energy. In considering how the fuel energy gets converted to heat, we can also state that equipment heat emissions are based on the work performed, the efficiency of the prime mover and the efficiency of all of the transmission systems in between the performed work and the prime mover.[2] In practice, the four equipment variables which govern heat emissions are:

- Equipment engine/motor size
- Equipment (engine/motor) utilization
- The average engine/motor load factor
- Equipment efficiency assumption (includes engine/motor and drive train)

2.1 Method for modelling the relative heat emissions of diesel and electric equipment

Given the assumption that the heat emissions from equipment are proportional to the work it performs and the efficiencies of its prime mover and transmission systems (the drive train) then a simple model to compare diesel and electric equipment can be created by making the following two assumptions:

1. Both types of equipment are of equal capacity and perform the same amount of work in a shift.
2. The transmission systems (drive trains) of both types of equipment have equal efficiencies.[2]

By making these assumptions the heat emissions of both diesel and electric equipment can be stated as seen in Equations 2 and 3, respectively, where W is the work performed, H is the heat emitted and η is the efficiency of their prime movers.[2]

$$H_D = W/\eta_D \tag{2}$$

$$H_E = W/\eta_E \tag{3}$$

Since the work performed is also assumed to be equal, one equation can be substituted into the other and the ratio of heat emissions from electric equipment compared to be diesel can be stated as seen in Equation 4.[2]

$$H_E/H_D = \eta_D/\eta_E \tag{4}$$

3. Important values for specifying heat emissions of underground mining equipment

3.1 Typical efficiencies of diesel engines

For mining trucks using the C18 ACERT engine like the 45 tonne AD45B from CAT, documents published online concerning their fuel consumption suggest that they have an average efficiency of ~37%, and this can be seen in Figure 1.[2]

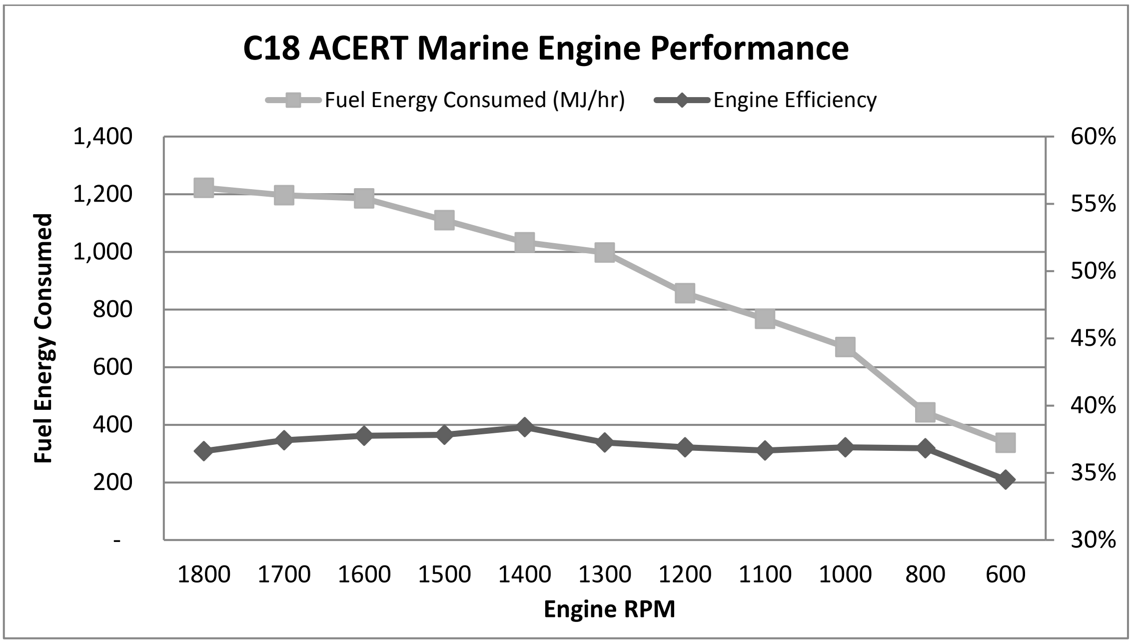

Figure 1: C18 ACERT energy consumption and efficiency at various RPMs [2].

When compared to a range of typical fuel consumption values for diesel engines published by SAE International, as seen in Table 1, it can be seen that 37% seems to be a valid approximation.[5] The values published in the table represent the best of the range observed during the engine testing, and they show the efficiency of diesel engines can range from 35% to above 50% in the largest, most efficient installations.

Engine Type	Specific Fuel Consumption (g/kWh) up to	η (%) up to
Small engines (two-stroke)	350	25
Motorcycle engines	270	32
Car SI engines	250	35
Indirect injection car diesel engines	240	35
Turbocharged DI car diesel engines	200	42
Turbocharged truck diesel engines	190	45
Crosshead engines (two-stroke diesel)	156	54

Table 1: Engine fuel consumption and efficiency values.[5]

3.2 Typical efficiencies of electric motors and the heat emissions of electric equipment relative to diesel

Using typical motor efficiencies published by the US Department of Energy as seen in Table 2, it can be seen that for motors larger than 37 kW operating at or above 50% of their name plate capacity, an assumed average efficiency of 92% could be considered representative.[6] [2] Given the assumptions outlined in Sections 2.1, 3.1 and 3.2, it can be calculated using Equation 4 that electric equipment will produce only about 40% of the heat produced by diesel equipment.[2]

Motor Size hp (kW)	Motor Load Level in Percent			
	100% (% Eff.)	75% (% Eff.)	50% (% Eff.)	25% (% Eff.)
50 (37)	91.6	91.8	91.1	86.3
100 (74)	92.3	92.1	91.4	85.5
150 (111)	93.3	93.1	92.2	86.7
200 (148)	94.2	94.0	93.1	87.8
250 (185)	93.8	94.2	93.5	89.4
300 (222)	94.5	94.4	93.3	89.9

Table 2: Average efficiency values for 1800 rpm, TEFC standard efficiency electric motors.[6] [2]

3.3 The types of equipment which are the heaviest users of underground ventilation systems

Data presented in a thesis examining the economics of electric mining equipment show that an operating mine in northern Ontario has over 100 pieces of diesel powered equipment which together have a nameplate engine capacity of approximately 20 MW.[2] However, after utilization is taken into account, the active brake power in operation is closer to 10 MW and therefore the total airflow requirements at the site according to regulations in Ontario are approximately 570 m^3/s.[2] After taking into account equipment utilization it can be seen in Figure 2 that the three types of equipment which are by far the heaviest users of the ventilation system are haul trucks, personnel carriers and LHDs. These accounted for 47%, 22% and 19% of airflow requirements respectively, or almost 90% of ventilation requirements when taken together.[2]

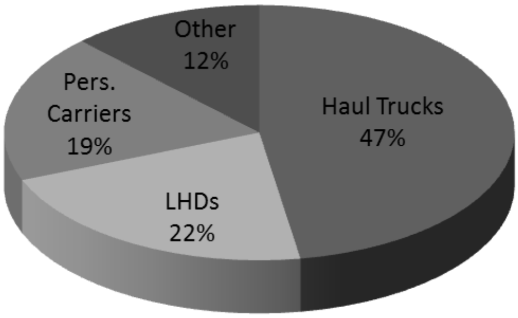

Figure 2: Airflow demand by equipment type.[2]

3.4 Proposed load factors and utilization rates of specific underground equipment

For the three types of equipment which were seen to be the heaviest users of the ventilation system, the same thesis on the economics of electric mining equipment presented data which suggested that the load factor and utilization values presented in Table 3 could be considered representative.

Parameter	Haul Trucks	LHDs	Personnel Carrier
Average engine load factor	49%	66%	10%
Utilization	62%	58%	45%

Table 3: Load factor and utilization values for the apparent heaviest users of underground ventilation systems.[2]

4. Discussion on adequate airflow rates per brake kilowatt of engine/motor power

It has previously been calculated that diesel equipment can require airflow rates higher than those required by Ontario regulations in order to adequately dissipate heat, i.e. 0.075 vs 0.06 m^3/s per bkW.[1] However, the proposed higher rate of airflow was calculated instantaneously at 100% load and so does not recognize that heat loads would be lower in practice due to utilization rates and engine load factors below 100%.[2]

Regardless, the 0.075 m^3/s per bkW is still useful in determining airflow rates, so long as they are adjusted after the fact to account for how the equipment is used in the field. Similarly, based on Section 2.1 a preliminary airflow rate for electric equipment can be calculated by adjusting the 0.075 m^3/s per bkW rate according to the ratio of heat emissions discussed in Section 3.2. Therefore a preliminary airflow rate required to dissipate heat from electric equipment can be estimated at (0.075 x 40%) 0.03 m^3/s per bkW.[2]

Aside from needing to adjust airflow estimates made using these rates for utilization and engine load factors, airflows calculated for electric equipment will also need to take into account the fact that their motors can be significantly smaller than the engines found on diesel equipment of an equal capacity, as has been recognized previously.[7] [8] [2] This fact is important due to Assumption 1 made in Section 2.1, i.e. that both types of equipment (of equal size/capacity) are assumed to do the same amount of work in a shift. For example, assume that the airflow rates discussed above are applied to equal capacity pieces of diesel and electric equipment that have engine and motor sizes of 100 kW and 70 kW respectively, as summarized in Table 4.

Parameter	Diesel	Electric	Unit
Airflow as per regulations	0.060	n/a	m^3/s per brake kW
Airflow to dissipate heat	0.075	0.03	m^3/s per brake kW
Brake power	100	70	kW

Table 4: Some assumptions about adequate airflow rates and equipment engine/motor sizes.[2]

It can subsequently be seen in Table 5 that because the engine and motor sizes are different, that for any given diesel load factor the implied load factor for the electric motor will be higher, even though the work performed is equal. Also apparent in Table 5 is that by adjusting the preliminary airflow rate of 0.03 m^3/s per kW according to the load factor, it is then not possible to give one set airflow per bkW of nameplate motor capacity as it is different in each scenario. Finally, it can also be seen that in each scenario the amount of air required to dissipate heat emissions from electric equipment are far below what would be required by Ontario regulations for diesel equipment, as measured both on a per bkW and volume basis.

Diesel load factor	70%	60%	50%	40%	Units
Implied electric LF	100	86	71	57	%
Consumed power	70	60	50	40	kW
Airflow required to remove heat	2.1	1.8	1.5	1.2	m^3/s
Flow rate per nameplate kW	0.030	0.026	0.021	0.017	m^3/s
% below regulation rate	50	57	64	71	%
% below regulation volume	65	70	75	80	%

Table 5: How adequate airflow rates per bkW can vary according to the engine/motor load factor and between diesel and electric equipment.[2]

5. Other sources of underground heat that need to be accounted for in ventilation planning and recommended targets for airflow reductions

Although Table 5 implies that in some situations airflows could be reduced by up to 80%, in practice this is unrealistic. A major impediment to such large reductions in airflow is heat loading from other sources, which are numerous. A comprehensive breakdown of these heat sources can be found in Figure 3, which was adapted from a list originally published by McPherson.[3] [2]

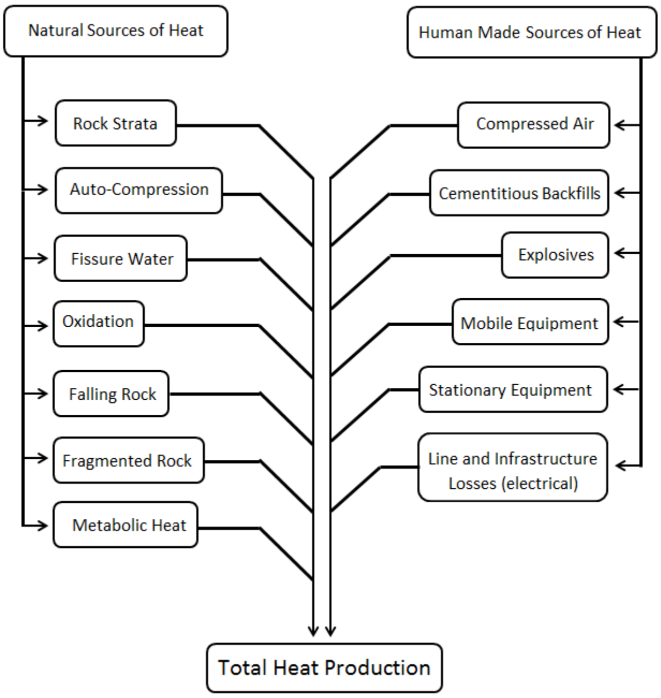

Figure 3: Comprehensive breakdown of u/g heat sources.[2] [3]

Aside from other sources of heat loading which should be considered in ventilation planning, other possible concerns with reducing airflows too much include increased blast clearance times and increased concentrations of airborne dust. However, opposing the need to provide adequate airflows is the opportunity to reduce power requirements by reducing them by as much as possible.

Therefore a balance should be found between savings in power consumption and the proper functioning of the ventilation system. A recent thesis on the economic potential of electric equipment takes these factors into account and concludes that airflows could potentially be decreased by 50% in order to strike the right balance between cost savings and adequate ventilation. However, the thesis also suggests that the optimum reduction could range between 40% and 60%.[2]

6. A model of the main cost drivers affected by a transition to electric mining equipment and how they are impacted by the mine design process

It is proposed that there are 5 main cost drivers which would be affected by the implementation of electric mining equipment.[2] These include:

- The power consumption of auxiliary fans
- The power consumption of the main fans
- Conditioning of the mine air (heating/cooling)
- Diesel fuel consumption and
- Infrastructure costs (drifts and ventilation system)

The main cost drivers, as well as their direct inputs and how they are all impacted by the mine design process can be seen in Figure 4.[2] In the model main cost drivers are coloured dark grey and their direct inputs are light grey. It can also be seen in the model that the mine design process starts at the top left and works toward the main cost drivers in the bottom right. Most of the main cost drivers also significantly contribute to a mine's CO_2 emissions (also grey) and so one of the benefits of implementing electric equipment will be reducing these emissions significantly. For a more detailed discussion of the cost driver model and how the mine design process is expected to impact the main cost drivers, one can be found in the original thesis.[2]

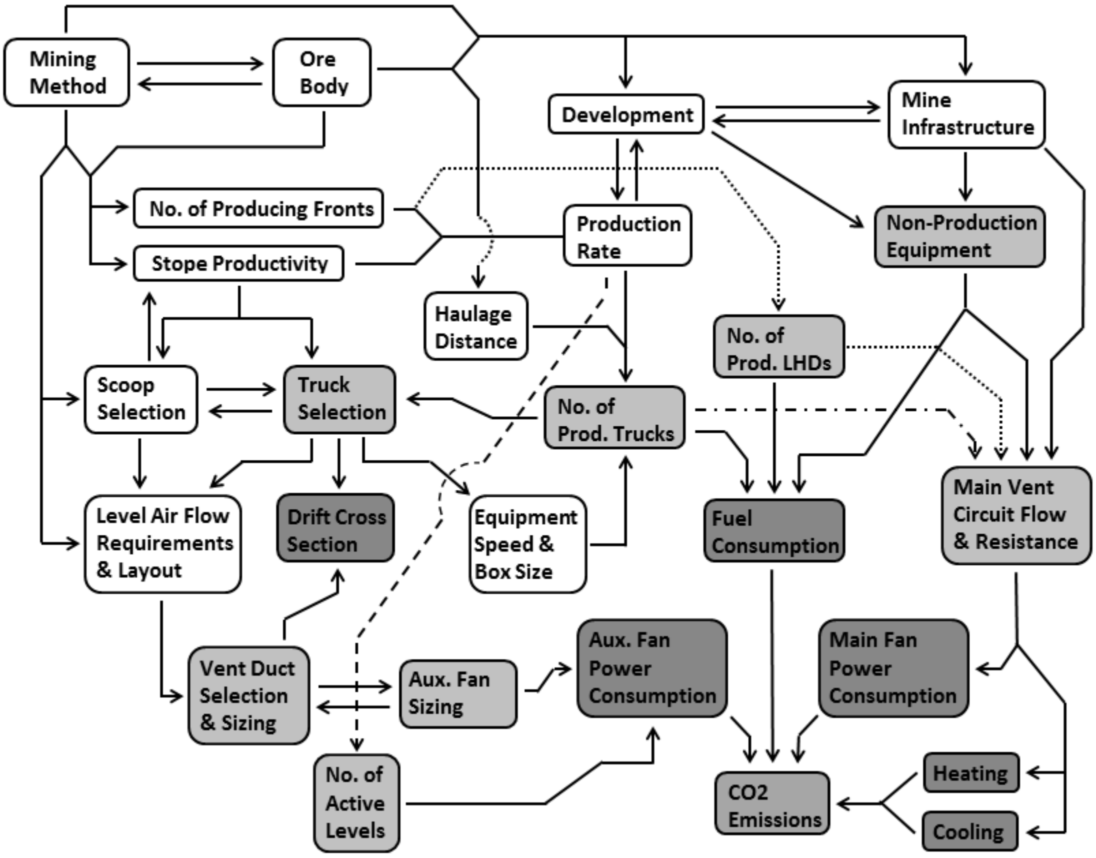

Figure 4: A model of the cost drivers which would be affected by electric mining equipment.[2]

7. The results of an economic evaluation of electric mining equipment

In order to evaluate the economic potential of electric mining equipment, models were built in Excel that reflected development and production activities at both a new mine and an existing mine. The purpose of the models was to determine how specific operating costs would change in different scenarios and to ultimately calculate annual cash flows and complete a Discounted Cash Flow (DCF) analysis for each scenario.

The models were all populated using data from operating mines and from reliable industry sources so that the quantity of consumables and the cash flows calculated for each year would be convincing and provide meaningful results. One major component of each scenario was to determine how airflows in the mine and the main and auxiliary ventilation systems might change given the implementation of different amounts of electric equipment. For each different scenario fan diameters, fan motor sizes and fan blade angles were all specified. In considering the implementation of electric mining equipment at a new 200 koz per annum operation, 12 different scenarios, or cases, were considered and an Excel model was built for each one. These were broken up into two sets of six scenarios and the mix of equipment considered in the first six scenarios can be seen in Table 6.[2]

Case	HT	LHD	PC	BE Maintenance
1	D	D	D	-
2	T	D	B	-
3	T	T	B	-
4	B	B	B	+25%
5	B	B	B	Equal
6	B	B	B	-30%

Table 6: Equipment types and maintenance cost assumptions considered in each of the first 6 scenarios.[2]

In the table the headings HT, LHD and PC stand for Haul Truck, Load-Haul-Dump unit and Personnel Carrier. In these columns of the table the letters D, T and B stand for Diesel, Trolley-electric and Battery-electric respectively. These letters indicate what mix of equipment was considered in each of the six cases. Based on the data summarized in Figure 2, all other types of equipment were left as diesel and did not have a large impact on the results. It can also be seen that in this evaluation Case 1 is meant to be the base-case scenario as all of the equipment is diesel. It is also important to explain that the column to the right of the table shows what assumption was made in each scenario about the cost of maintenance for battery-electric equipment. In Case 4 it was assumed that maintenance costs for electric equipment would be 25% higher than for diesel equipment, in Case 5 they were assumed to be equal, and in Case 6 they were assumed to be 30% lower.

Finally, it should be noted that the second set of six scenarios, i.e. Cases 7-12 were the same as Cases 1-6 except that they also considered the cost of rebuilding and replacing the equipment as it wore out. This was important to consider and evaluate because some equipment manufacturers are expecting electric equipment to have longer lifetimes than diesel equipment.[2] All of the results from the economic evaluation of each scenario representing the implementation of electric mining equipment at a new operation can be found in Table 7.

	Total Investment	Percent Change	Net Present Value	Percent Change	CO_2 Emissions	Percent Change	Drop in Cash Costs	Percent Change	IRR	Haul Trucks	LHDs	Person. Carrier	Support Equip.
Case 1	$418M	N/A	$286M	N/A	131.5 kt	N/A	N/A	N/A	N/A	D	D	D	D
Case 2	$410M	-2%	$283M	-1%	72.8 kt	-45%	$6/oz	-1%	13%	T	D	B	D
Case 3	$394M	-6%	$273M	-5%	40.2 kt	-69%	$18/oz	-3%	36%	T	T	B	D
Case 4	$387M	-8%	$264M	-7%	38.5 kt	-71%	$24/oz	-4%	1478%	B	B	B	D
Case 5	$365M	-13%	$250M	-12%	38.5 kt	-71%	$41/oz	-7%	N/A	B	B	B	D
Case 6	$339M	-19%	$233M	-18%	38.5 kt	-71%	$61/oz	-11%	N/A	B	B	B	D
Case 7	$455M	+9%	$307M	+8%	131.5 kt	-	-$28/oz	+5%	N/A	D	D	D	D
Case 8	$445M	-2%	$303M	-1%	72.8 kt	-45%	$8/oz	-1%	22%	T	D	B	D
Case 9	$419M	-8%	$287M	-7%	40.2 kt	-69%	$28/oz	-5%	49%	T	T	B	D
Case 10	$407M	-11%	$276M	-10%	38.5 kt	-71%	$37/oz	-7%	1503%	B	B	B	D
Case 11	$385M	-15%	$262M	-15%	38.5 kt	-71%	$54/oz	-10%	N/A	B	B	B	D
Case 12	$359M	-21%	$245M	-20%	38.5 kt	-71%	$74/oz	-13%	N/A	B	B	B	D

Table 7: Net present value and CO_2 emissions of each case.[2]

Depending on the scenario, the potential savings from implementing battery-electric equipment ranged from marginal, to as much as 20% of the alternative (diesel equipment). Savings ranged from a few million dollars to as much as $60 million in present value terms or $95 million in undiscounted cash flow over 10 years. Savings could be as high as ~$75 per ounce of gold produced. In addition to the cash savings, it was found that implementing electric equipment could result in up to 70% fewer CO_2 emissions compared to the diesel alternative.[2]

The implementation of electric equipment at an existing mine was also evaluated and it was found that overall savings were similar but slightly less favourable on a percentage basis. However, it was also seen that total savings increased with the size of the operation, and at a 300 koz per annum operation, the present value of the savings approached $80 million and the undiscounted savings over 10 years were over $120 million.[2]

8. Case studies

Two top-tier mining companies are currently considering the full scale implementation of electric equipment at prospective mining projects in Ontario. One is a greenfield project currently in permitting and evaluating the implementation of either grid-electric, or battery-electric equipment. The other is a brownfield project currently at the feasibility stage and seriously considering battery-electric equipment.[2]

This project anticipates a significant reduction in infrastructure, and even after factoring in the cost of the charging infrastructure and assuming a 40% premium for purchasing battery-electric equipment it expects to reduce pre-production capital spending by $15 million. In addition to this they expect an annual savings of approximately $8 million, before accounting for savings on diesel fuel.[2]

The one operation located in Ontario which has embraced electric equipment more than any other has already transitioned a significant portion of its equipment fleet to battery-electric. This decision was based on a comparison between the cost of the new equipment and the cost of a new ventilation shaft which reportedly was priced out at $300 million.[9] [2] Currently they have 25 pieces of battery-electric equipment in operation with over 100,000 operating hours accumulated.[10] [2]

Finally, several other operations in Ontario are currently trialling battery-electric personnel carriers which have undergone rapid development in recent years. One of these operations is in the process of building an economic case for transitioning the majority of its underground personnel carrier fleet to the new battery-electric carriers.[2]

9. Summary, conclusions and future work

It is proposed that one of the most important criteria for determining the potential cost savings from implementing electric equipment is the amount of heat they generate, as this is the only emission produced by electric equipment.[2]

Using data from government and industry, it is reasonable to assume that the efficiencies of diesel engines and electric motors can be approximated at 37% and 92% respectively. Furthermore, if potential differences in the drivetrain efficiencies of electric equipment and diesel equipment are ignored, it possible to calculate that electric equipment will produce approximately 40% of the heat that diesel equipment will.[2]

Using their relative heat emissions, it is also possible to conclude that if diesel equipment require 0.075 m^3/s of air per bkW in order to address heat emissions before adjusting for engine load and utilization, then electric equipment will only require 0.03 m^3/s of air per bkW under similar conditions to achieve the same effect.[2] However, it is also important to note that there are potentially many other sources of heat underground and that providing only enough air for the equipment likely will not be sufficient. Accordingly, it has been proposed that airflows could realistically be reduced by 40% to 60%, with a 50% reduction seemingly optimal.[2]

Given these assumptions about electric and diesel equipment, it is proposed that there are 5 main cost drivers that will be positively affected by the implementation of electric equipment. When savings from the cost drivers are considered alongside the other potential costs or savings resulting from equipment maintenance and equipment life it is found that electric equipment could be anywhere from 1% to 20% less costly than diesel equipment over a 10 year period. When the possibility of reductions in large infrastructure spending as seen in the examples given in Part 8 are also considered, it is possible to conclude that for a favourable mining project electric equipment may significantly reduce both operating and capital costs over the life of the project.

In the future more work could be done looking at the drivetrains of diesel and electric equipment to determine if their efficiencies have a significant impact on the assumed heat emissions of the equipment discussed. As well, as electric equipment is more widely implemented operating and cost data should be used to test the proposed assumptions and framework put forward by this paper and to validate the proposed economic model.

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