



Electrification of Loaders and Trucks – A Step Towards More Sustainable Underground Mining

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Abstract. Metal mining at great depths is associated with a high demand for fresh air required to cool down mine openings, evacuate noxious gases and contaminants, as well as to provide sufficient amounts of oxygen for miners. Diesel powered load-haul-dump (LHD) machines, trucks and other mobile equipment used extensively by modern mines not only emit exhaust gases and diesel particulate matters (DPM), but constitute also an additional source of heat. As mine regulations get steadily more stringent with regard to air quality, the use of diesel engines has an increasingly adverse impact on ventilation costs. In this context, this paper examines electric drives (mainly those commercially available) as possible alternatives for diesel power trains. They are reviewed with regards to their principles, required infrastructure, as well as technical and operational issues. Their practicality and economic viability are also addressed. Moreover, their benefits and potential for implementation in the conditions of deep metal mines are discussed. The paper concludes with a resume of current and short-term potential of electric loading and haulage equipment as alternative to diesel-powered vehicles in deep metal mines. It underlines the growing interest in their application as means to improve sustainability of underground mining.

Key words

Underground mines, electric drives, diesel engines, load-haul-dump machines, trucks, sustainable mining.

1. Introduction

Operation of modern underground metal mines depends heavily on the use of mobile equipment powered predominantly by internal combustion engines (ICE) running on diesel fuel. Diesel ICE emits exhaust gases, diesel particulate matters (DPM) and a considerable amount of heat. Combustion products, such as CO, NO_x, and H₂S, are noxious and together with DPM are harmful to human workers' health. With regard to health and

safety concerns, mine regulations all over the world specify the fresh air flow required to dilute diesel emission below acceptable limits, carry away hazardous contaminants and provide necessary levels of oxygen for the miners. With time, these regulations become more and more stringent. Diesel engines are also an important source of heat loading (hot exhaust gases and hot external engines parts). These problems become more acute in very deep mines operating at depths in excess of 2000 m, whose number around the world is on the rise, as shallower, more easily accessible ore deposits get depleted. In such mines, high virgin rock temperatures require more intense ventilation, and, in some cases, even air-conditioning to maintain ambient temperature at the level acceptable for the miners. In such conditions, the extensive use of diesel engines puts additional strain on ventilation systems and affects adversely a production costs. Despite the achievements of engine and mining equipment manufacturers in reducing pollutants, there would always be a percentage of emissions that must be strictly monitored, diluted and vented to the surface, as well as the engine-generated heat be evacuated. Last but not least, exhaust gases contain CO₂ and other greenhouse gases (GHG) leaving an environmental footprint.

In such context, it is worthwhile to look at other power sources as potential alternatives to diesel. Electric drives are the most advanced technically and, fairly probably, the most promising option. This paper is focused on technical, operational, cost and environmental aspects of these drives in comparison to diesel power trains and their potential as a viable alternative to power loading and haulage vehicles in underground mining environment.

2. Diesel vs. Electric Drives for the Case of Loading and Haulage Equipment

Mobile loading and haulage trackless equipment in underground mines includes predominantly load-haul-dump (LHD) machines and haul trucks. LHD is an articulated loader, equipped with a bucket and capable of travelling (tramping) in both directions (see Fig. 1 in section 3). Bucket capacities reach 25 tonnes. LHD loads a broken ore or waste rock into the bucket, hauls it to a dumping point or fills trucks or rail cars. Economic LHD tramping distances are usually below 200 m one-way. Underground trucks are a low profile, articulated, usually four-wheel-drive vehicles, equipped with a suspended chassis for the prime mover as well as for the rear car (see Fig. 2 in section 3) with carrying capacities usually between 20 and 60 tonnes. Underground trucks operate at distances from several hundred meters up to several kilometers.

With regards to the nature of work that LHDs and trucks carry out, diesel engines are versatile power plants. They offer essentially unlimited operating range, high quantity of energy per mass of energy storage material (from now on referred to as “specific energy”) around 13 kWh/kg of fuel, advantageous power to gross vehicle weight ratio (approximately 5,6 kW/t), relatively low capital cost, rapid and easy refuelling, etc. However, apart from exhaust gases’ emission and heat generation mentioned above, they have other drawbacks including:

- Relatively low energetic efficiency (about 30-35%).
- Low overload capacity.
- Substantial maintenance required and high skills demanded from mechanics.
- Significant operating costs that tend to rise with oil prices.
- High level of noise and vibrations.
- Possibility of fog formation.

These and other aspects will be used as references while reviewing electric drives’ options.

Electric drives have been employed in the mining industry for over 100 years, actually longer than diesel engines. They have a few substantial advantages over diesel drives:

- Much higher energy efficiency (about 90%);
- Constant torque (including high torque at low speeds), quick response to the load and better overload capacity.
- No exhaust fumes and therefore no mine air pollution and no fog formation.
- They generate only a third of the heat emitted by a diesel having the same power.
- Hourly electric energy cost lower than hourly fuel cost for diesels.
- Less maintenance required.
- Low noise and vibration level.

These features make electric drives an attractive alternative to diesel power trains, but their actual benefits and drawbacks depend considerably on how electric energy is supplied to vehicle’s motors. For this reason,

different categories of electric loading and haulage equipment will be discussed separately.

3. Power Alternatives for Underground Electric LHDs and Trucks

There are five principal categories of electric LHDs and trucks depending on the way electric energy is provided to the motors:

- From onboard battery pack.
- Through umbilical power cable.
- From an overhead trolley line.
- Using hybrid electric drive.
- From fuel cells.

This paper focuses mostly on three first categories, but it discusses briefly hybrid electric drives as well.

A. Battery-powered equipment

The main advantages of the equipment running on batteries are their versatility, power efficiency, good tractive effort (including high torque at low speeds), good overload capacity and relatively little maintenance required. Unfortunately, their autonomy is limited due to low batteries’ energy storage capacity. Specific energy is low: for the lead batteries is only about 40 Wh/kg, whereas for more efficient lithium iron phosphate (LiFePO₄) or LFP batteries it barely reaches 90 – 110 Wh/kg, a meagre fraction of that of diesel fuel. More efficient lithium-ion batteries have specific energy of up to 250 Wh/kg [1], but they are not yet applicable for vehicles. Limited autonomy, high weight of suitable battery packs and their cost (it is estimated that storing 1 Wh costs about 1€) are still serious hurdles in the development of electric passenger cars [1]. These problems are even more acute in the case of highly powerful mining equipment working under much heavier loads than passenger cars. Despite this, there is a vivid interest in applying this technology to underground mine vehicles, not only small service ones, or personnel carriers, but also heavier mobile loading and haulage machines.

To the best knowledge of the authors, the only models of battery-powered LHDs and trucks have been commercialized by a Canadian company RDH Mining Equipment. A 2 m³ Muckmaster 300EB LHD and a 20-tonne Haulmaster 800-20EB truck are powered by LFP batteries [2]. In late summer 2013, four Muckmasters and one Haulmaster were working in the Macassa gold mine (Kirkland Lake, Ontario, Canada) [3]. Main advantage of battery-powered loaders and trucks is their “zero-emission” (no noxious or GHG gases) and their mobility (not linked to any permanent infrastructure). Concerning the drawbacks of such vehicles, low energy density has a negative impact on the ratio between a useful load and an empty vehicle weight (“tare weight”): For Muckmaster and Haulmaster it is 0,26 and 0,7 respectively, whereas for similar size diesel LHDs and trucks it is 0,31 and 0,98 respectively [2, 4]. Low energy storage capacity of batteries has another negative consequence: relatively short working time between consecutive charges.

Following the information from RDH [2, 3], LFP batteries allow an LHD and a truck to operate on average for 4 hours. This is less than the duration of a normal workshift (usually between 8 and 12 hours), so the battery pack must be changed at least once during the shift. Even though an experienced crew could accomplish battery change in approximately 15 minutes [3], frequent battery changes affect adversely equipment availability.

All in all, despite some significant progress in battery technology, they still lag far behind diesel fuel in specific energy. For this reason, battery-powered LHDs and trucks do not yet constitute a fully viable alternative for diesel powertrains. Nevertheless, whenever ventilation demand and heat are a serious concern for mine operators, these vehicles may become a justifiable choice. Also, with a constant progress in the battery technology one may expect an increase in their specific energy enhancing their attractiveness for mine applications.

B. Cable-powered equipment

Powering an electric LHD through a trailing cable is an interesting option that makes empty vehicle's weight more favorable than in the case of battery-powered LHDs. This advantage comes however at a certain price: due to the limited size of a cable reel located on the moving machine (regardless whether it is placed horizontally or vertically), vehicle's operating range is limited to less than a double of a total cable length that can be stored on the reel. In practical terms, it means that a one-way operating distance for bigger LHDs does not exceed approximately 700 m (less for smaller LHDs), even for the most advantageous match of a cable diameter and a reel diameter. Therefore, this technical solution is impractical for trucks, so only cable-powered LHDs (Fig. 1) have been commercialized.

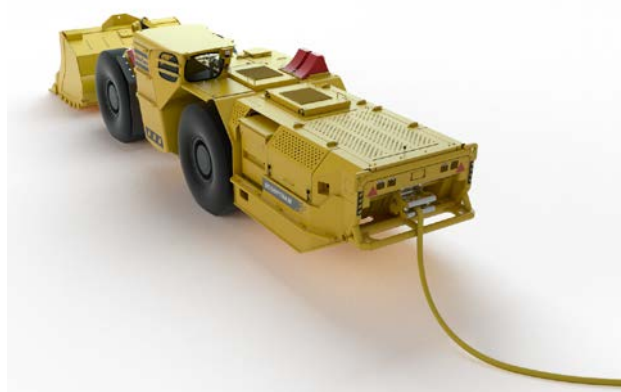


Fig. 1. EST-1030 - Electric LHD powered through a trailing cable (Courtesy of Atlas Copco)

Several electric models with tramming capacities ranging from 2 to 25 tonnes are commercially available. Actually, the world's most powerful LHD, Sandvik's LH 625E is a cable-powered machine. Due to higher efficiency of electric drives, these LHDs may be equipped with the motors of a lesser power than their diesel counterparts, while offering similar performances. In relation to this, electric loaders have more favourable ratio between

tramming capacity and the machine's installed power than corresponding diesel units. For a 10-tonne and 14-tonne LHDs from Sandvik, the ratio between the tramming capacities and propulsion motor power for tethered machines is about twice of that for diesel ones. [5]. At the same time, for the loaders of a similar bucket load, the capital and overall operational hourly cost for diesel and electric machines is similar [6], whereas operating cost alone may be even 10 – 30% lower, depending, among others, on the price of diesel fuel and electricity. Energy cost alone accounts for about 15% of the total hourly operation cost for diesel loaders, and only about 5% for electric loaders [6].

Unfortunately, tethered vehicles have reduced flexibility in operation since loader's operating range is limited. Moreover, their mechanical availability is adversely affected by frequent cable damages (risk of cutting at sharp drift corners, or while run over) and cable replacement cost is significant. A price of such cable is roughly 60€/m. For the very same reason, in order to avoid entanglement of trailing cables or running over them only one such loader may operate in a certain area. LHDs require also specific infrastructure including electric substations, transformer boxes, sockets, etc. When loading and haulage operations need to be moved to another area of the mine and it is not possible to plug the loader all the way, towed diesel generators must be used. Moving cable-powered LHDs may then affect operational flexibility and availability. With regards to these shortcomings, cable-powered electric LHD is not a viable alternative for every mine.

Nevertheless, tethered electric LHDs offer good performance in the areas of repetitive trams, where the same path is relatively short and well enough defined to enable the use of the umbilical cord and associated handling facilities. Such is the case of some mining methods such as block caving or sublevel caving. Contrary to diesel machines, these loaders do not need refueling, which helps increase their utilization and thus productivity. Successful application of electric 25-tonne loaders in the Kiruna iron ore mine in Northern Sweden for over 25 years confirms that in favourable conditions these machines outperform their diesel counterparts. Moreover, similarly to battery-powered equipment, they are too "zero-emission" vehicles with a very limited environmental footprint.

C. Trolley-powered equipment

Powering electric rail or trackless vehicles from an overhead cable is a concept that has been applied even in underground mines for more than hundred years. However, its applicability for trackless loading and haulage equipment is limited. Given the character of the work of load-haul-dump machines, it is totally impractical, but constitutes an attractive alternative for mine trucks, particularly for those working in long ramps (up to a few kilometers). Up to now, there exists only one commercialized design of a trolley-powered underground mine truck, known as "Kiruna Truck". It is currently manufactured and marketed by Atlas Copco. The

company offers two models: a 35-tonne and a 50-tonne trucks, labeled EMT-35 (Fig. 2) and EMT-50 respectively.



Fig. 2. Trolley powered EMT-35 truck (Courtesy of Atlas Copco)

These low-profile articulated, four-wheel-drive mining trucks are powered from an overhead 3-phase 690V AC supply line. The latter is composed of three 50 mm copper tubes and two square section guide rails (see Fig. 3).

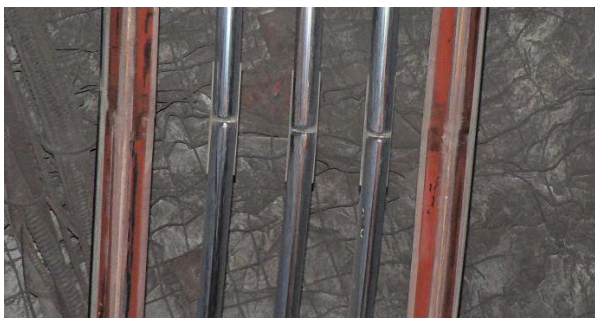


Fig. 3. Tri-phase supply line for electric trucks (photo: courtesy of the Coleman mine, Vale)

In order to provide sufficient manoeuvrability, the truck is equipped with a diesel generator set enabling the truck to be loaded, operated and dumped while not connected to the power line. As the auxiliary diesel engine is relatively small compared to the main electric motors (72 kW vs. 2x200 kW in EMT-35, and 107 kW vs. 2x355 kW in EMT-50), ventilation needs for these trucks are much lower than for conventional vehicles using diesel engines. EMT-50 requires only about 17% of the air indispensable to dilute and evacuate exhaust gases and fumes emitted by a similar 50-tonne diesel truck.

The most important advantage of these trucks is their high overload capacity and very good gradeability. On a 14% ramp the speed for the electric truck running up is almost double when compared to a similar diesel unit. Due to this, their production rate is on average 20% higher and a smaller truck fleet is needed to meet certain production targets. Electric trucks also have a favorable ratio between useful load and empty vehicle weight (1,06 and 1,1 for EMT-35 and EMT-50 respectively), similar to diesel-powered trucks. It is estimated that for the same ramp haulage system and production rate, electric trucks will use only 24% of the energy per tonne hauled as compared to a diesel fleet. This means that application of electric trucks can generate economies stemming not only from a lower ventilation cost, but also from substantially smaller energy cost. Of course, the scale of

savings on energy depends on a ratio between the price of diesel fuel and electric energy. At the same time, trolley-powered trucks generate far less GHG, so, although they are not “zero-emission vehicles”, their negative impact on environment is almost unfelt.

The weakest point of this technology is its limited mobility and operational flexibility as well as high capital cost. Complex design of the power supply trolley line (see Fig. 3) and the infrastructure cost per truck is said to be about 75% of the truck price. Trolley-powered trucks require also slightly higher or wider mine openings than the equivalent diesel machines.

In the last 30 years or so, Kiruna Trucks have been implemented with a various degree of success in different mines in Sweden, Canada, Australia, Spain, USA and Kazakhstan. At present three mines: two in Canada and one in the USA use this equipment. Vale’s Coleman mine near Sudbury (Ontario, Canada) has 18 years of experience with electric trucks. It now operates a fleet of five 50-tonne vehicles running on the longest trolley line ever built (cumulative length of 6200 m). Based on a current and past experience, it may be stated that trolley-powered trucks may be a quite interesting alternative for existing mines going deeper that have a reasonable life expectancy. It seems that the best results can be achieved in the case of ramp haulage over distances exceeding 1500 m, particularly when the haul road is to be used for several years and the volume of ore and/or waste hauled is in excess of 500 000 tonnes per year. Also, new operations with mine lives of more than seven years may benefit from the implementation of electric trucks.

D. Hybrid electric vehicles

A hybrid electric vehicle (HEV) combines a conventional propulsion system with an on-board rechargeable energy storage system (RESS) to achieve better fuel economy than a conventional vehicle without being hampered by range from a charging unit like a battery electric vehicle. Regular HEVs most commonly use an internal combustion engine (ICE) and electric batteries to power electric motors. The ICE in an HEV can be smaller, lighter, and more efficient than the one in a conventional vehicle, because it can be sized for slightly above average power demand rather than peak demand. The high torque of the diesel engine combined with hybrid technology, may offer substantially improved mileage. Modern HEVs prolong the charge on their batteries through regenerative braking. The ICE drives an electric generator to either recharge the battery or directly feed power to an electric motor that drives the vehicle. Main benefits of the hybrid electric design include:

1. Lower fuel consumption through:
 - a) Less wasted energy during idle/low output, generally by turning the ICE off.
 - b) Recapturing waste energy through regenerative braking.
 - c) Reducing the size and power of the ICE, and hence inefficiencies from under-utilization, by using the added power from the electric motor

to compensate for the loss in peak power output from the smaller ICE.

2. The above leads to a substantial reduction of the emission of noxious gases and DPM. In the underground mines it would contribute to major improvement of air quality and, consequently, significant reduction of the ventilation demand.
3. Durability: reduced wear on the engine, particularly from idling with no load and reduced wear on brakes from the regenerative braking system use.
4. Reduced noise emissions resulting from substantial use of the electric motor at idling and low speeds.

Following the successful implementation of hybrid electric automobiles, trucks, buses and military vehicles, there has been a growing interest in employing this concept in underground mining vehicles. A Canadian R&D consortium has developed the world's first hybrid diesel-electric LHD prototype [7, 8], an intermediate and economical solution between zero emission and diesel vehicle. The 1,2 m³ loader built by a Canadian company MTI (Sudbury, Ontario) was based on the LT-270 model. Its power train compared to the conventional unit is shown on the Figure 4.

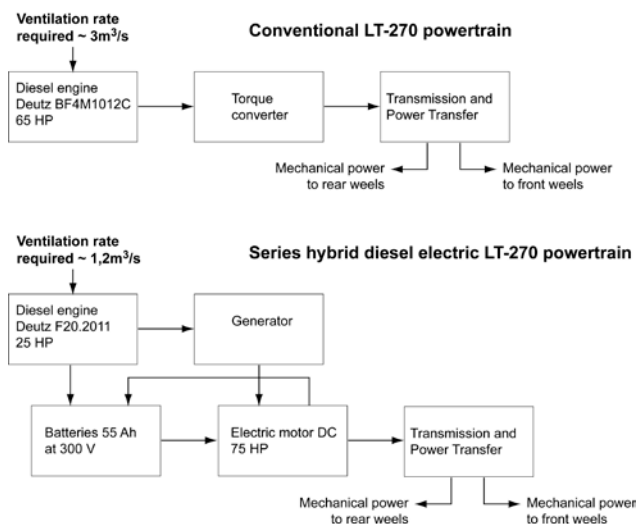


Fig. 4. Conventional and hybrid LT-270 LHD power trains (after MTI Ltd., Canada)

The results of the prototype testing released in 2010 [8] indicate that the emissions particularly those of DPM had decreased by 12 – 64%. Fuel consumption was reduced by 10%, which was below the expected value of 40%.

Some other problems encountered during testing were:

- Battery capacity (need to stop for recharge).
- Electrical system ‘challenges’ (grounding problem, now solved).
- Engine to generator mechanical connection (coupling failures, load characteristics).

Future actions were to be focused on the following issues [8]:

- Improve battery (longer run time).
- Improve powertrain efficiency (reduce losses).
- Improve hydraulic system efficiency.

However, there has not been any further information on future developments of this project, and it seems it has

been put on a backburner. To the best knowledge of the authors, there has been no other R&D work on hybrid diesel-electric underground loaders or trucks reported in the technical and/or scientific literature in the recent years. Also, neither of key equipment manufacturers contacted by the authors has manifested any particular interest in this technology. In all, contrary to some success and growing recognition of hybrid vehicles in the market of passenger cars, at this point nothing indicates that this solution will be implemented in underground mines in a near future.

4. Conclusion

As mine production all over the world comes from deposits whose depth is steadily increasing, and, at the same time, the widespread use of diesel equipment becomes more problematic (health hazards, increasingly demanding mine regulations, high ambient temperatures, etc.), mine operators are looking for other power plant alternatives for their mobile production equipment. Different options of electric drives may provide at least a partial answer to these needs. The fact, that electric vehicles are in principle “zero-emission vehicles”, or have a very low emission of hot and noxious exhaust gases (the case of trolley powered trucks equipped with a low power auxiliary diesel engine), as well as no or very little of DPM brings several benefits:

- Safer working environment for mine workers.
- There is no additional source of heat loading underground – very significant advantage in deep mines.
- With no or little exhaust gases and much less heat emitted, much less ventilation is required which helps reduce capital and operating cost.
- Almost no negative impact on environment (very little or no GHG gases released to the atmosphere).

Electric drives have also much better efficiency, which translates into lower energy consumption, and thus energy cost. The scale of savings however, depends greatly on availability and cost of electric energy and diesel fuel. Electric vehicles also offer another advantage to equipment operators in terms of less noise and less exposure to vibrations. These and other features generate an increasing interest of mine operators. The importance of making loading and haulage operations “greener” have been recognized by major equipment manufacturers. For example, Atlas Copco has recently launched a “Green Line” of electric loaders and trucks.

Unfortunately, despite all the merits they deserve, electric loaders and trucks currently available on the market, as well as those at an advanced stage of development are definitely not, at least yet, a universal alternative to diesel engines. Each of the technical solutions described above has its shortcomings that limit their applicability or effectiveness. LHDs and trucks powered from batteries are quite versatile in operation, as they are not permanently “plugged” to any stationary infrastructure. But, as every battery-powered vehicle, they suffer from low specific energy of the batteries themselves. Due to

the magnitude of work charge and its variability, exceeding by far that of passenger cars, this problem is much more severe for heavy mining equipment. Low specific energy results in an excessive tare weight of the machines (low “useful load-to-empty vehicle weight” ratio) and limited operating time (still much less than the duration of a work shift). Unavoidable and frequent battery changes affect equipment’s operational availability and productivity. These shortcomings limit severely the applicability of battery-powered loaders and trucks, making them an interesting option only for very particular mining conditions. Nevertheless, this concept remains quite promising and it will definitely get more interest if the battery technology progresses significantly.

Cable-powered loaders have proven to be effective in several mining scenarios and they get more recognition in several countries. Sandvik offers four cable-powered loaders with tramming capacities from 3,5 to 25 tonnes). In the last couple of years, Atlas Copco has added two electric loader models (10-tonne EST-1030 and 14-tonne EST-14) to two smaller models offered before (EST-2 and EST-3,5). It is also claimed that electric LHDs are more advantageous when it comes to automation of loading operations that receive more and more attention of mine operators in developed countries. Unfortunately, their drawbacks such as limited operating range, vulnerability of power cables and inability to operate more than one loader in a given mine area are unlikely to vanish in the future. So, their applicability will remain limited to some particular mining scenarios in which they may outperform diesel machines.

Trolley-powered trucks constitute a solution that has not yet received adequate recognition it merits. The example of the Coleman mine in Canada, where Kiruna Trucks have been successfully used for the last 18 years and whose performance is fully satisfactory to mine management proves that full commitment of both the mine and the OEM makes this concept a winning solution. Electric trolley-powered trucks definitely merit more consideration in the cases of future and existing mines with truck haulage through long ramps. Again, this solution is not a universal one, but it has the potential to be beneficial in some particular applications. Any potential application should be thoroughly studied and analysed to maximize chances for a success.

Concerning hybrid diesel-electric vehicles, this technology, seemingly progressing in road transportation, has not yet been a success in underground mines. It is hard to predict whether it may become truly competitive, even in a middle-term horizon, with regards to diesel and existing electric power trains discussed in this paper.

Regarding the environmental impact of electric vehicles, it is definitely smaller than in the case of diesel engines, but it depends on the way electric energy is generated. If it comes from renewable sources such as wind or solar radiation, it is negligible. In France, where 80% of electricity comes from nuclear power stations, CO₂ emissions linked to the use of an electric car is ten times less than that from internal combustion engines [1], but

GHG emissions will increase dramatically if electricity is generated in coal-fired power stations. Implementation of electric vehicles however, is not evident in the mines situated in remote locations, with no access to power grid. Whenever electricity is provided by diesel generators, the environmental or economic viability of burning fossil fuel to power electric vehicles becomes disputable, but it may depend, among others, on operating depths and geothermal gradient at a particular mine site.

All in all, although they are definitely not a universal alternative to diesel-powered loaders and trucks, electric vehicles, even with all of their drawbacks, offer important benefits, particularly in what concerns health, safety and environmental aspects, making deep underground mining more sustainable. As the technology progresses in several related fields, the attractiveness of such vehicles should increase, particularly if their acquisition and operating costs are further reduced.

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