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Mine Electrification and Power Electronics

The roles of wide-bandgap devices.

IN THE RUGGED TERRAINS OF TRADITIONAL mining, a revolutionary shift is taking place, driven by the desire to achieve net-zero targets and respond to multiple challenges, primarily health issues and operational inefficiencies. The electrification of mining operations depends upon the integration of advanced power electronics (PEs) and wide-bandgap (WBG) devices, which serve as the enabling technology by efficiently converting and controlling electrical power, ensuring not only energy savings and reduced emissions but also robust, reliable systems. In the meantime, the mining sector is evolving into a key player in grid modernization, driven by an increase in distributed energy resources (DERs), the need for energy efficiency, and the growing interconnectedness and digitization of power systems. This modernization is critical for ensuring grid resiliency and security, particularly in the face of potential cyberthreats. As mining operations move toward full electrification, elements such as renewable energy, energy storage, microgrids, electric mobility, and digitization play a central role, with autonomous dc microgrids emerging as a viable solution to ensure reliability and safety in both the power grid and mining sites. Therefore, WBG device-based PEs are pivotal in mining transition by offering advanced control, energy management, and protection required for efficient grids, devices, and machineries. In addition, WBG devices' exceptional characteristics, such as high-efficiency, high-power, and high-frequency capabilities and higher

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temperature tolerance are ideal for mining applications, specifically in large-scale mining machinery that demands significant electric energy. The outcome is reduced energy consumption, enhanced reliability, and the development of more compact machinery designs with less waste heat, diminishing the need for extensive cooling systems.

Introduction

Over the last decade, the electric power grid and its associated components have undergone significant transformations. These changes have been driven primarily by a series of factors including technological readiness, policy directives aimed at achieving net-zero emissions, and environmental considerations. However, there is a complex interplay among these elements: technological advancements enable policy changes, which in turn further encourage technological innovation.

Moreover, the technological advancements have opened up opportunities for enhancing the efficiency, reliability, and environmental sustainability of power systems. For example, the rapid improvements and adoption of renewable energy technologies, such as solar and wind, have encouraged the development of complementary technologies including batteries, fuel cells (which will boost the use of hydrogen as a fuel), and smart grid technologies equipped with intelligent sensors and advanced metering infrastructure that are all driven by the digitization. As a result, electrification has become the standard in a number of transportation sectors, covering a wide range of vehicles from domestic cars to large mining trucks and from airborne to deep-sea mining vehicles.

As is well known, PEs serve as the most pivotal enabling technology within this transformation, playing a critical role in electrification. As reported by the International Energy Agency (IEA), PEs used in motors,

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drives, and other applications account for around 30% of global electricity consumption in 2017. This percentage is projected to surge to 80% by 2030, also primarily driven by electrification.

It is worth noting that when renewable energy penetration increases, the need for the ac grid diminishes. Although the existing infrastructure of power network still accommodates ac microgrids, dc microgrids can offer various unique and unparalleled benefits against ac systems. In addition, as PEs become the primary enabling technology, there will be a paradigm shift toward the dc sources (such as wind, solar, fuel cells, and batteries) and dc loads (such as batteries and every conceivable electrical device).

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Furthermore, we are witnessing drastic electricity-associated other technological trends in all areas of digitization, electrification, and energy efficiency. Digitization is now visible to all with an ever-increasing level of data storage and relevant applications, which demand faster processing and faster transmission of data. Interestingly, this development is also tied to efficient power supply applications through PEs, as evident in data centers.

Mining sites are likely to accelerate the adoption of grid transformation and efficiency enhancements due to their unique operational requirements, the imperative for cost-effectiveness, and the pursuit of sustainable energy practices. The advanced control capabilities offered by PEs make them an ideal solution for managing the complex and demanding energy needs of modern mining operations in the form of an autonomous microgrid. In addition, mining operations also face pressure to reduce carbon emissions in the coming decades while requiring efficiency improvements in all aspects of mining processes. Note that an effective efficiency analysis requires a comprehensive understanding of each application (mining machinery) and the related industrial process.

The grid transformation process is well underway, as demonstrated by several global mining operations incorporating electrification, predominantly in mining electric vehicles (EVs) and microgrids. However, this article seeks to highlight an equally vital, even though secondary, technological progression. This evolution is expected to be driven by innovative solid-state WBG devices that have the ability to revolutionize PEs.

Grid Modernization and Transition in Mine Sites

The grid transition cannot be considered in isolation from the power systems of energy-intensive industries like mining. Moreover, mining electric and autonomous vehicles have to be reliable and connected to a flexible electricity supply as many mine sites are already becoming prosumers (consumers and generators). Furthermore, as a key player, the mining industry should prioritize whether they are connected to the major grid or decentralized, flexible, and digitized.

The key drivers for the grid transition include an increase in DERs (such as solar panels, wind turbines, battery storage systems, EVs as load/generators, and hydrogen fuel cells), aging legacy systems, rising electricity demand, and the changing climate. Additionally, advancements in PE technology, growing physical threats and cyberthreats, regulatory changes, and the inefficiency of legacy systems escalating energy costs all play significant roles in this transformation.

In general, the process of grid modernization can be characterized by the degree of DER integration, which is influenced by technological advancements, local energy resources, government policies and regulatory support, acceptance of related technologies, environmental considerations, economic factors, and the capabilities of the existing infrastructure. Therefore, the levels of DERs can be defined under four groups, which are somewhat similar to the levels of autonomy defined in automotive applications:

- level 1 (DER-agnostic grid), a traditional, centralized grid not designed for DERs
- level 2 (DER-aware grid), which recognizes DERs but does not fully utilize them and where PEs interface DERs with the grid
- level 3 (DER-leveraging grid), in which DERs are actively used to optimize grid operations, assisted by advanced PEs and control systems
- level 4 (DER-dependent grid), in which DERs are integral to operations, potentially replacing centralized generation, and advanced PEs, control, communication, and cybersecurity systems are critical.

Note that level 3 has already been a norm in data center systems, which are fully dc, and level 4 can be achieved when the dc network is established with dc-enabled loads. Note that as we progress toward level 4 grids, the role of PEs will only become more critical, given the expected increase in the penetration of DERs and the growing need for advanced control and management strategies.

The grid transition is expected to follow the aforementioned order, altering the grid architecture and transitioning from an ac grid to a pure dc PE grid. An image of the principal components of the electrified mine and a rough time line of the transformation is visualized in Figure 1. Within the next few decades, it is predicted that high-PE devices will play a major role in transforming almost every part of the power system, from generation to consumption.

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As is known, improving energy efficiency is a crucial component in the transition to a net-zero carbon future. This involves using less energy to achieve the same output, thereby reducing the demand for energy and the associated carbon emissions. In terms of its contribution to reaching net zero, the specific percentage can vary depending on the source and context. As of the last update in September 2021, the IEA stated in its "Net Zero by 2050" roadmap that about 40% of the required carbon emissions reductions to achieve net zero by 2050 can come from energy efficiency improvements across all sectors (buildings, industry, and transport).

With the increasing digitization and interconnectedness of modern power systems and smart grids, the domains of power system security and cybersecurity have also become deeply intertwined. However, such systems, while providing benefits like remote monitoring and control, optimized performance, and integrated data analysis, also open up new vectors for potential cyberthreats. For instance, the 2015 Ukrainian power grid cyberattack demonstrated the potential of such threats. Therefore, it is likely that autonomous and multiple dc microgrids will essentially ensure the reliability and safety of the future power grid in the face of potential cyberthreats, which is seamlessly applicable to the mine sites and mine operation as well.

In conclusion, the transformation of mining grids will be significantly driven by key factors such as decentralization, digitization, grid resiliency, and security. The incorporation of electrification, electric mobility, renewable energy, and energy storage into mining operations will additionally aid in achieving the full electrification of future mine sites. These collective advancements will bring about a new era in mining infrastructure, optimizing efficiency and greatly reducing the environmental impact.

PEs: Past and Future

Past

After the invention of electricity, the most technological advancements have been driven by the first solid-state power switches, silicon (Si)-based thyristors from about 70 years ago (see Figure 2). This has formed the primary enabling

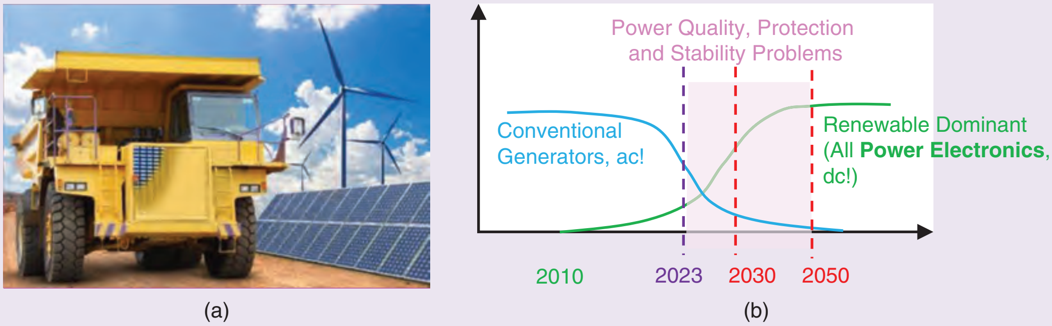

Figure 1. (a) Mining sites lead grid transformation with DERs and electrified trucks. (b) A rough time line of an intuitive prediction of the grid transformation from ac to dc grid.

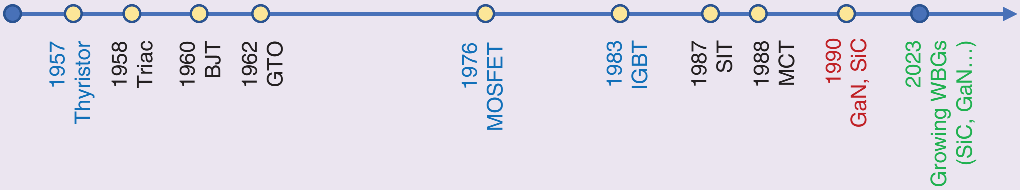

Figure 2. The historical time line in PE switches. BJT: bipolar junction transistor; IGBT: insulated gate bipolar transistor; MCT: MOS-controlled thyristor; SIT: static induction transistor; GTO: gate turn-off thyristor.

technology in human history, PEs. However, the search for ideal switches continued by the enhancement of the performance of Si-based MOSFETs around 1970s and the Si-based insulated gate bipolar transistors in 1983 followed by static induction transistors and MOS-controlled thyristors near the end of 1980. In addition, the first commercial WBG devices emerged around the 1990s with an exponential growth in recent years. It is worth noting that currently, more than 70% of electric power is processed through some form of PE circuit primarily using Si-based devices.

> ***Considering the trend and the commitments of the industrial and emerging world, it is clear that WBG devices will play a significant role in mine electrification efforts.***

PEs are employed in every sector, including e-mobility, consumer electronics, telecommunication, military and aerospace, industrial, energy, and power. In addition, every embedded modern generation source (such as solar photovoltaic [PV], wind, fuel cell, supercapacitor, flywheel, microturbine, and battery) involves PE converter topologies that are either coupled to an ac grid or operated in a dc network. Furthermore, environmental concerns regarding fossil fuels, rapid urbanization, and economic growth in emerging regions are all major factors that are contributing to the PE market growth. Therefore, the global renewable energy market itself is expected to reach to US$1.1 trillion by 2027 (from US$0.613 trillion in 2020).

Future: WBGs

The electronvolt is used to define the major characteristics of semiconductors and quantify their proximity to an ideal switch (which should act as an ideal insulator when off and should act like a zero-resistor metal, ideal short circuit when on). Although Si has been the most preferable material, it falls short in handling the higher voltages and power levels required for emerging applications such as battery EVs, high-power fast chargers, and renewable energy systems, military, and mine applications. The common semiconductor materials and their electronvolt levels are given in Table 1.

TABLE 1. Electronvolt levels of some typical solids.

Solids	Electronvolt Level	Remarks
Germanium (Ge)	0.67 eV	Pure semiconductor
Silicon (Si)	1.1 eV	Pure semiconductor
Gallium arsenide (GaAr)	1.42 eV	Compound semiconductor
Silicon carbide (SiC)	3.3 eV	Compound (doped) semiconductor, WBG
Gallium nitride (GaN)	3.4 eV	Compound semiconductor, WBG
Gallium oxide (GaO)	5 eV	Compound semiconductor, ultra-WBG
Dimond (C)	5.5 eV	Pure semiconductor, ultra-WBG
Aluminum nitride (AlN)	6.2 eV	Compound semiconductor, ultra-WBG
Glass	>4.4 eV	Insulator ! (very high resistivity and very low conductivity)

As listed, WBG and ultra-WBG solid materials are compound semiconductors, which have considerable potential for high-voltage, high-power applications due to their large bandgap, high carrier mobility, and high electrical and thermal conductivities. Their properties also enable devices with higher switching frequency, lower conduction drop, higher junction temperature, higher switching speed, higher efficiency, and greater power density compared with silicon devices.

Two of the WBG devices are emerging, SiC and GaN. Currently, SiC is preferred over GaN for high-temperature applications, while GaN is likely to achieve high voltage values soon. High-power SiC devices with superior thermal performance are required for applications such as HVdc and wind energy systems, solid-state transformers, and high-power motor drives. In addition, both devices are becoming commonplace in renewable energy, EVs, battery storage, and a very wide range of power supply applications.

Mine electrification commonly refers to the process of replacing diesel-powered equipment in mines with electric alternatives, which primarily aims to reduce greenhouse gas emissions, improve worker safety and health, and increase efficiency and productivity in mining operations. Considering the trend and the commitments of the industrial and emerging world, it is clear that WBG devices will play a significant role in mine electrification efforts.

Although transitioning to WBG devices presents a few technical challenges, as well as supply chain and manufacturing challenges due to the scarcity and geographical distribution of raw materials, in 2022, the market for SiC and GaN power devices was valued at US$1.022 billion. However, it is projected that the SiC and GaN market will expend to US$4.368 billion by 2028, exhibiting a compound annual growth rate of 33.7% during the forecast period from 2023 to 2028.

As compiled and summarized in Table 2, SiC and GaN manufacturing facilities are surging globally, which showcases a spectrum of WBG device activities that span the entire range of PE applications (domestic, transportation, industrial, power supplies, communications, consumer electronics, etc.). In addition, the significant financial investments committed by a number of companies provide a clear snapshot of the promising future of WBG technology and underscore their strategic vision for the evolution of the legacy Si-switch-based PEs. It is worth noting that although Table 2 highlights the trends in the United States, Europe, Japan, and South Korea, three major SiC manufacturers in China have also allocated a total of US$4 billion for capital expenditures for SiC development from 2022 onward, excluding the significant SiC-based start-ups.

The Specific Roles of WBG-Based PEs in Mine Electrification

Improvements in high-performance power converters using WBG devices will have far-reaching implications, from EVs to data centers and power supplies. Using WBG devices, it is possible to achieve a number of improvements while reducing the converter cost 50%. In summary, the prime benefits of WBG devices compared with conventional Si-based PEs can be summarized as follows: enhanced power/energy efficiency (flat power efficiency that is predictable), improved thermal management (hence operating under high temperature), increased power density (volumetric and gravimetric, desirable in mobile mining equipment and vehicles), higher switching frequencies (reduction of component sizes and allowing higher speeds in motors), and greater system reliability and robustness (increasing the uptime of mining equipment). Table 3 summarizes the roles of PEs primarily in mining electrification, which aims to expose the utilization of the new semiconductor devices, WBG devices.

It should be emphasized here that auxiliary systems such as heating, ventilation, and air conditioning play a crucial role in maintaining the safety and liability of mine sites and adjacent mining towns. For example, heating systems in mining operations and associated towns, particularly in colder climates, can be responsible for a large portion of energy consumption. Moreover, ventilation systems in mines are essential for ensuring worker safety by maintaining air quality and removing

TABLE 2. The status of the recent WBG devices and chips manufacturing and financial commitments within the next decade.

Companies	Location	Remarks
Wolfspeed (Old Cree Inc.), SK Siltron, Onsemi, United Silicon Carbide (USCi), TSMC, SkyWater Technology, Samsung, Navitas (+ GeneSiC), II-VI Incorporated	USA	• To produce 6-in SiC wafer and to expand to 8-in wafers, packaged SiC devices, and GaN power IC, 1,700-V SiC Schottky rectifier • Targeting EV market, data centers, and solar PV applications • Over US$205 billion investments between 2022 and 2030 and 11,800 job opportunities
ST Microelectronics	Italy, Sweden, France	• To produce 200-mm and 300-mm SiC wafers, • Over €8 billion investments between 2024 and 2030
Rohm Semiconductor. Toshiba	Japan	• SiC manufacturing and SiC wafer fab • US$860 million investment to increase production capacity by 10 times by 2025
Infineon	Malaysia, Germany, Austria	• €8.6 billion investment for SiC and GaN modules and for 300-mm thin wafers • For industrial power supply, photovoltaic, transportation, drives, automotive, and EV charging • For analog, mixed-signal, and power semiconductors
VisIC Technologies	Israel	• US$35 million funding in 2021 • 650-V GaN transistors for motor drives
Soitec	France, Singapore	• Energy-efficient wafers, using silicon-on-insulator, GaN, piezoelectric-on-insulator, and SiC • €1.1 billion capital expenditure by 2026
Texas Instruments, Efficient Power Conversion, MACOM, GaN Systems, Transphorm, Analog Devices, NXP Semiconductors, Panasonic Corporation, Fujitsu Limited, Broadcom Inc., Northrop Grumman Corporation, Sumitomo Electric Industries, Raytheon Technologies Corp.		• GaN power devices
Anvil Semiconductors, Microchip Technology, UnitedSiC, GeneSiC Semiconductor, Littelfuse, Mitsubishi, Renesas Electronics Corp., Hitachi, Sanken Electric Co.		• SiC devices

hazardous gases. However, these systems often operate continuously and therefore consume substantial amounts of energy. Utilizing PEs to intelligently manage and optimize ventilation, such as on-demand ventilation that only operates when and where necessary, can result in significant energy savings.

In addition, electrification in mining targets three major vehicles and machineries, including battery EVs, hydrogen-powered fuel cell EVs, and heavy machinery and equipment (such as for excavation, drilling, loading, and transportation tasks). Note that in the context of mining, with the help of WBG devices, PE converters offer five primary advantages: reduced or zero local emissions, energy efficiency, reduced maintenance, and improved performance, as well as noise reduction.

TABLE 3. The roles of PEs in mining operations.

Item	Remarks
dc power grid	As power grids evolve, dc grids, facilitated by PEs based on WBG devices, will replace traditional ac distribution systems and will eliminate multiple ac/dc conversions as well as power system stability.
Efficient motor drives	PEs manage and optimize motor operations, thereby reducing energy consumption. The enhancement in efficiency will involve converter, motor, and operation.
Energy recovery systems	PEs can enable significant energy recovery during the operation of mine machineries when electrified, which can be fed back to the mine grid.
Energy storage systems	PEs are key in managing energy storage systems such as batteries, supercapacitors, etc., which can optimize energy use and reduce costs.
Auxiliary systems	PEs used in heating, ventilation, and air conditioning play a crucial role in maintaining the safety and liability of mine sites, as well as adjacent remote mining towns.
DER integration	PEs facilitate effective use of renewable energy sources and other emerging DERs such as flywheels and hydrogen fuel cells, which potentially lower the energy cost.
Smart grids and microgrids	PEs play a crucial role in the implementation of smart grids and microgrids, which can also improve reliability of electricity supply in mining operations. Such systems can manage multiple energy sources and quickly balance supply and demand.
Data analytics and optimization	PEs can collect and analyze data about energy usage in real time, which can be used to identify inefficiencies, predict maintenance needs, and optimize energy use across the entire mining operation, enabling more informed decision-making.
Smart loads	The electrified machinery and DERs encompass the integration of PEs with digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and machine learning, which will also enable capabilities for communication, self-diagnosis, and autonomous decision-making, all for enhancing efficiency, safety, and productivity.
Communication	Digitization and future devices will allow a fully interconnected local network among the entire mine machinery. Data obtained via PEs will enable real-time monitoring and control of all devices from a centralized system or even remotely.
Self-diagnosis and maintenance	PE-integrated smart mining machinery will monitor its own health and predict and report faults before leading to failures. WBG-based PEs will also involve miniaturization of power supplies in advanced sensors used in such processes.
Safety and security	PE-integrated future devices will have advanced safety features (such as emergency stop functions, collision avoidance systems, and protective barriers), and cybersecurity will have robust measures needed to protect against threats.
Autonomous operation	AI and machine learning technologies will enable mining machinery to operate autonomously or semiautonomously. PE-enabled autonomous electrified haul trucks and loaders will optimize routes and schedules to maximize efficiency and safety.
Localized data centers	The localized data centers or “edge computing” will have significant implications for the electrified and autonomous mines, offering timely real-time decision making, effective bandwidth utilization, improved local data privacy and security, improved reliability by minimizing external connectivity, and facilitation of effective digitization for AI, machine learning, and IoT in mining operations.
User-friendly interfaces	For setup, control, and troubleshooting, the smart loads need to be designed with intuitive interfaces including voice control, AI, or augmented reality systems. PEs will seamlessly integrate these features.

The application of WBG-based PE technologies spans nearly all industrial products, extending to electrical network systems of any scale. This shift and transition are already being followed by numerous leading companies that are developing products in support of mine electrification. While a handful of academic institutions are at the forefront of research regarding the various components of mine electrification, the uptake of mine electrification in the industry to date is summarized in Table 4. This information confirms imminent activities, which are set to surge exponentially with the aid of WBG-based PEs. Additionally, although not officially disclosed as of yet, a substantial number of companies are presently working on, and will continue to work on, the development of products for high-power fast chargers, energy storage systems, and hydrogen-powered fuel cell technologies for mining vehicles.

> ***Utilizing PEs to intelligently manage and optimize ventilation, such as on-demand ventilation that only operates when and where necessary, can result in significant energy savings.***

The Immediate Directions for Innovations in Mine Electrification

The global drive toward sustainable and efficient mining has also amplified the significance of research on mine electrification, with WB devices in PEs playing a crucial role, which includes a number of interconnected directions. For example, increasing energy storage capacity with the development of a new class of PE converters, driven by WBG devices, will enable mining operations to continue uninterrupted during periods of peak demand.

In addition, high-power microwaves, powered by efficient WBG-enabled PEs, could play a pivotal role in the rock-breaking process while improving efficiency in the process. Even more ambitiously, fusion power plants may provide a virtually limitless source of clean energy in the future, which could revolutionize the energy landscape of mining operations. On a smaller scale, micro-electromechanical systems (MEMSs) for cooling PE converters can enhance the longevity and reliability of these crucial components, ensuring uninterrupted operations. Finally, data centers, which are integral for managing the vast amounts of information generated in modern mining operations, can also benefit from WBG PEs, improving efficiency and reducing their environmental footprint. Table 5 was compiled to summarize some of the immediate research directions in mine electrification.

The electrification of mining equipment can lead to significant energy efficiency improvements. For example, electric dump trucks and diggers can be more energy efficient than their diesel counterparts, particularly if they

TABLE 4. The companies involved in mine electrification and efficiency improvements.

Company	Product Range/Initiatives
Sandvik Group	Manufacturers of electric mining equipment, such as loaders and trucks, have delivered over 600 units of electric equipment and are actively developing self-swapping battery technology for their machines.
ABB	ABB has developed the ABB Ability eMine portfolio of technologies and methodologies to make the all-electric mine possible. In addition, they have collaborated with Perenti on projects to support net-zero emissions targets for underground and open pit mines.
Perenti	Perenti is focused on developing and deploying low-emissions technology and working to implement projects that improve energy efficiency.
FLSmidth, Amazon Web Services, MEDATech, Liebherr	Working with ABB in the mining industry to develop solutions to decarbonize mining operations.
Electric Mine Consortium	To accelerate progress toward the fully electrified zero CO_2 and zero particulates mine, involving Gold Fields, South 32, OZ Minerals, IGO, Barminco, Evolution Mining, Newcrest Mining Limited, Blackstone Minerals, Iluka, MMG, Sandfire, Ampcontrol, Dassault Systemes, Epiroc, 3ME Technology, Zero Automotive, Mets Ignited, Deswik, Nukon, and Amazon Web Services.
Caterpillar	In battery technology, hybrid drive systems and trolley-assist technology.
Komatsu	Development of hybrid and electric dump trucks and electric forklifts.
Epiroc	Development of electric drill rigs, loaders, and trucks.

use regenerative braking to recover energy. A fully electric mine could potentially achieve energy savings of up to 40% compared with a traditional mine.

In the context of mining electrification, a similar system indicates the transition from traditional, fossil-fuel-reliant operations to fully electrified, renewable-energy-powered, and autonomous mining operations. This classification helps to guide advancements toward more sustainable and efficient mining practices.

> ***A fully electric mine could potentially achieve energy savings of up to 40% compared with a traditional mine.***

Conclusions

The ongoing power grid transformation, driven by technology advances, environmental and health concerns, and economic considerations, is promoting decentralization, resilience, and digitization, integral to the larger shift toward a sustainable, efficient energy system. This is propelling mine electrification, recognized as a priority transformation in the mining sector. With an expected 60% of next-generation mines being entirely electric and powered by renewable sources, the evolution toward dc microgrids underlines the importance of advanced PEs, particularly WBG devices. These offer control, protection, and energy management for efficient dc grid operation, playing a critical role in mining machinery and microgrids.

Leveraging WBG devices' high-power and high-frequency capabilities can result in more efficient, compact mining machinery with lower energy consumption and waste heat. This evolution reduces the

TABLE 5. Some of the immediate research directions in mine electrification, which can utilize WBG PEs.

Directions	Remarks
Increasing energy storage capacity	High power density and stationary energy storage are vital for seamless 24/7 mining operations. Methods like regenerative braking and underground gravity energy storage offer potential solutions, storing energy when demand is low for use in high-demand periods. Additionally, controlled water heating can serve dual purposes, storing energy and providing heating for mining towns and industrial processes.
Development of new class of PE converters	Resonant converters and innovative circuit topologies benefit from WBG devices' high-frequency switching, improving components in electrified transportation. Additionally, a new high-power (500-kW), bidirectional onboard converter for fast charging of electric mining vehicles and transforming infrastructure enables vehicle-to-dc grid or vehicle-to-vehicle/machinery energy transfer.
Improving system and operational efficiency	Ventilation and air conditioning, consuming up to 30%–50% of the total electrical energy in underground mines, are significant energy users. WBG devices provide a distinct advantage in PE converters, sustaining constant power loss across diverse conditions for predictable, high efficiency.
Optimization of mining operation	PE systems boost mining efficiency via strategic scheduling and optimization. This includes streamlining crushing and grinding processes, utilizing autonomous trucks, and implementing electrically controlled conveyors. Other strategies include ventilation management, process control, smart blasting, operator training, and tire management.
Using high-power microwaves	WBG PEs can use renewable energy to selectively heat specific minerals in ore with microwaves. This eases ore crushing and grinding, reducing energy consumption in these demanding mining steps. The process improves grindability, liberates valuable minerals efficiently, and increases the particle surface area, leading to significant energy savings.
Hydrogen fuels for high-power vehicles or machinery	PEs are crucial in hydrogen generation and usage stages, including green (generated by electrolyzing water with renewable energy), brown, gray, and blue hydrogen production. Using fuel cells in mining vehicles allows zero emissions at the point of use, higher energy density than batteries, and quick refueling.
Fusion power plants	As a potential alternative energy source, it requires efficient, high-power electrical drivers for plasma heating, compression and control, which can accommodate WBG PEs.
MEMSs for cooling PE converters	Thermal management is key in electrical devices. MEMSs offer localized, active cooling, a compact form, improved energy efficiency, and smart cooling based on conditions, optimizing performance and reliability, and extending the life span of PEs.
Data centers	Cooling in data centers is a significant energy consumer, accounting for up to 30%–40% of total energy usage. With the rising demand for data centers and the development of advanced hardware, the power needed by processors is expected to increase, leading to a higher power density within these centers, which require high power density and efficiency PEs aligning with the emerging standard of dc grid operations.

TABLE 6. A proposed framework to classify mining electrification.

Driving Levels	Remarks
Level 0 (traditional mining)	Mining operations rely solely on diesel or other fossil fuels for power, and equipment, vehicles, and facility operations have no electric components.
Level 1 (partial electrification)	Some aspects of the mining operations, such as lighting or specific machinery, are powered by electricity, while the primary sources of energy remain fossil fuels.
Level 2 (hybrid electrification) (started around 2020 and likely to continue next decade)	Electricity is mainly sourced from the ac grid, with charging infrastructure in place for electric equipment. Renewable energy sources are also used. Numerous electric/battery-powered mining machinery is in operation. In both open pit and underground settings, gravity energy storage is considered. Ventilation, air conditioning, water heating, and heat pumps are considered.
Level 3 (full electrification)	All mining operations are powered by electricity. The electricity is primarily sourced from the grid, and ac and dc, ac/dc, and dc/ac options may coexist.
Level 4 (smart electrification)	There is a dc grid only, and mining operations are powered by locally produced renewable energy sources. Grid power is used as a backup or supplementary source, and there are some capabilities for energy storage and demand response.
Level 5 (fully autonomous electrification)	Smart and autonomous grid technologies are fully integrated to optimize energy use and ensure reliability, which can include AI. The operations are powered by a self-regulating, fully renewable, and autonomous energy system that maximizes efficiency, minimizes environmental impact, and can operate independently of the grid by demand forecasts and real-time data. Note that autonomy will be driven by power system and cyberspace security.

The blue text indicates the current status of the technology.

need for extensive cooling systems, achieving further savings. Additionally, the integration of autonomous systems and artificial intelligence into mining will necessitate local data storage and processing powered by WBG-based dc power networks. This, along with energy and load forecasting, will significantly improve operational efficiency and reliability.

In the next decade, "mine electrification" will become a more common term, alongside concepts like autonomous microgrid, e-mobility, e-mining, digitization, and power system security. WBG devices are poised to be key enablers in PEs, driving this transformation.

The framework outlined in Table 6 provides a systematic approach to transitioning toward fully autonomous and sustainable mining operations. It delineates the growing complexity from a hybrid system to pure electrification. Each level's actual capabilities may vary significantly, depending on specific technologies and mining practices. Furthermore, each stage integrates a level of autonomy and intelligence, offering insight into present states and future trajectories.

For Further Reading

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