A white paper from Epiroc

Grid Integration of Smart Electric Mining Machines

Enabled with Grid Communication & Automation

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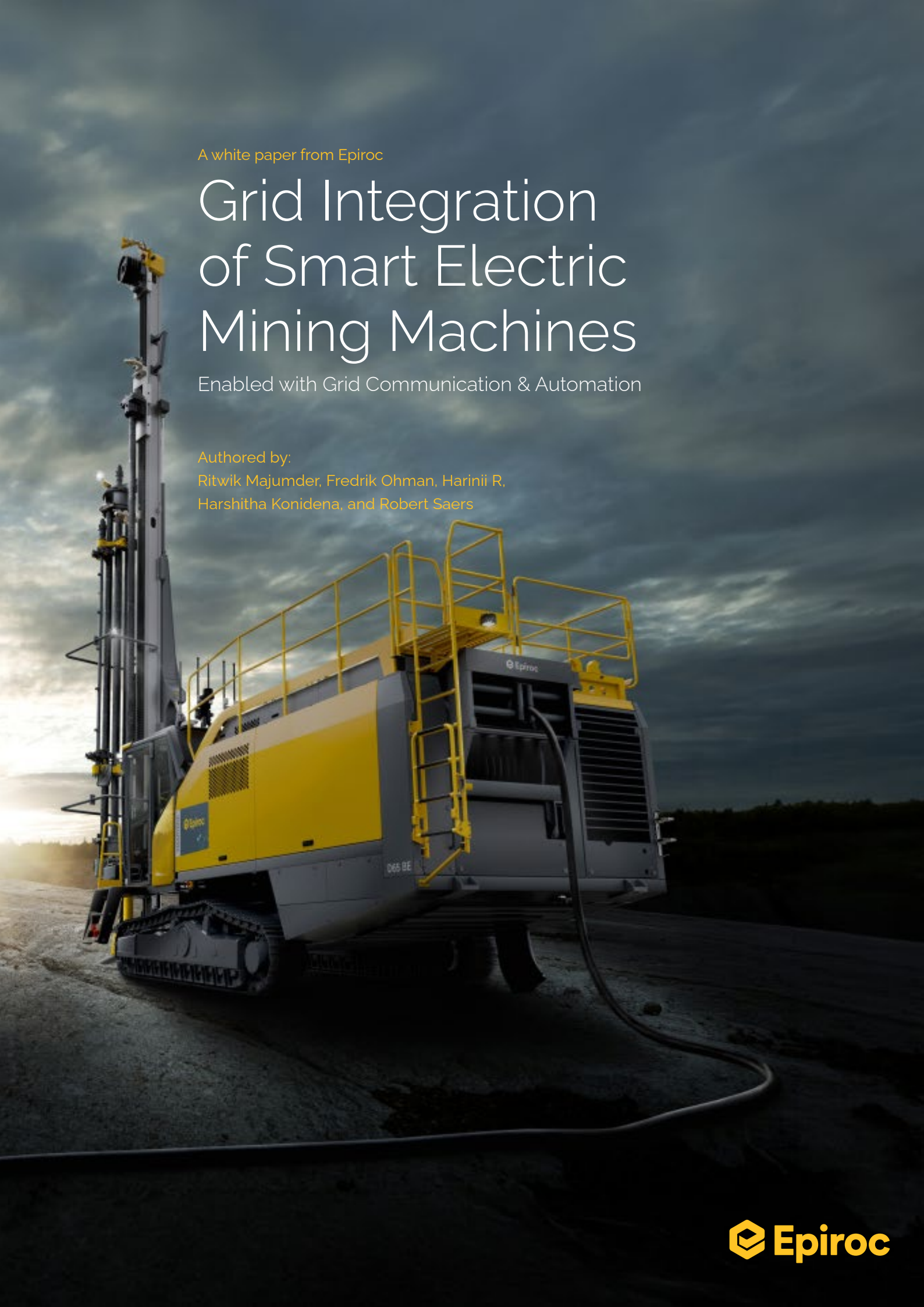

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Executive summary

The electrification of mining integrates surface mining machines into the electric grid. While essential, this integration creates infrastructure challenges, including weak grids, remote grids, and grid contingencies, resulting in considerable stress on the grid.

These challenges intensify as sites expand, and mixed fleets add further complexity. In this paper, we argue that the fleet and its machines must communicate with the grid and with one another. At the heart of this is the use of smart electric machines that communicate with the grid through SCADA systems.

We examine the SCADA integration architecture, including the fleet manager (providing operational planning for machines) and the machines for grid communication. We show how this facilitates the exchange of data and control signals between the grid controller and the machine fleets to ensure stability, capacity, power quality, and safety.

And we look at how Epiroc's OEM-agnostic fleet-automation platform, LinkOA, plays an important role in integrating mixed fleets to unify operations and optimize grid-adaptive power consumption while balancing productivity.

And, done right, grid-adaptive operations carry two massive financial benefits:
- around/up to 20 % reduction in infrastructure costs
- around/up to 10 % improvement of production efficiency

Introduction

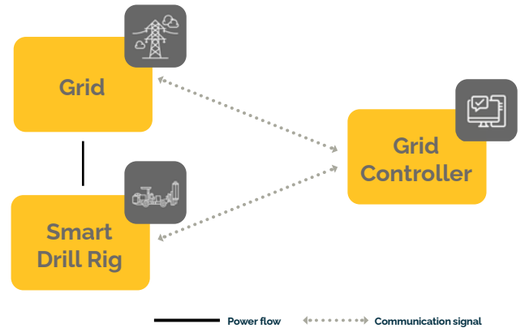
Without smart electric machines, electrification in mining is running blindly.

There are many challenges when it comes to electrification in mining, such as power and energy with mixed fleets and different types of machines. To solve them, we need a standardized approach to avoid everyone using inferior, home-made solutions.

This white paper discusses how an important step in the right direction is enabling grid communication so that Epiroc's smart electric machines can connect to SCADA for grid adaptation. However, our vision is to optimize this at the fleet level, combined with grid-adaptive functions at the machine level. This involves the fleet controller exchanging information bidirectionally with the grid on current and forecasted grid power and energy availability, as well as the flexibility of individual machines to adapt their operations.

The primary goal is to balance the production target with the available energy and power to prevent grid contingency failures. To achieve this, we believe the most effective way to operate mining equipment is to supervise all machines and equipment from a fleet-level controller, such as Epiroc's LinkOA, which helps coordinate and optimize the entire fleet. LinkOA aims to modify these drill plans to meet productivity targets, forecast and predict power consumption patterns, and enable grid-adaptive machine functions when integrated with SCADA.

Electrification requires a clear plan and coordination between the production target and available power or energy. Without these, you'll be unsure of when, where, or how to use the equipment effectively. This can result in the system using more power than it has, leading to shutdowns and costly outages. Since many mines operate in areas with weak, remote, unreliable, or insufficient grids, it's essential to mitigate these risks.



Integration of smart Epiroc electrified equipment with grid control

Proper use of smart electric machines and grid communication is essential, offering a wide range of benefits, including load shifting, power balancing, preventing costly power peaks and downtime, and enabling smart interactions with external grids. The smart electric machines' grid adaptive functionalities not only provide much needed energy/power flexibility but also grid support during startups of other machines and operational contingencies like reactive power support. Recognizing this and acting will be a game-changing moment for electrification efforts in the mining industry. The main goal is to balance production targets and optimize power and energy utilization.

Business-critical for mines, an absolute necessity for the world

This issue is more than just a matter of critical importance to individual businesses. Still, it's essential that we support electrification efforts and give them a better chance of success, as that will persuade others to take the leap. Creating success stories and credible business cases is always better than simply being rational and presenting theoretical facts.

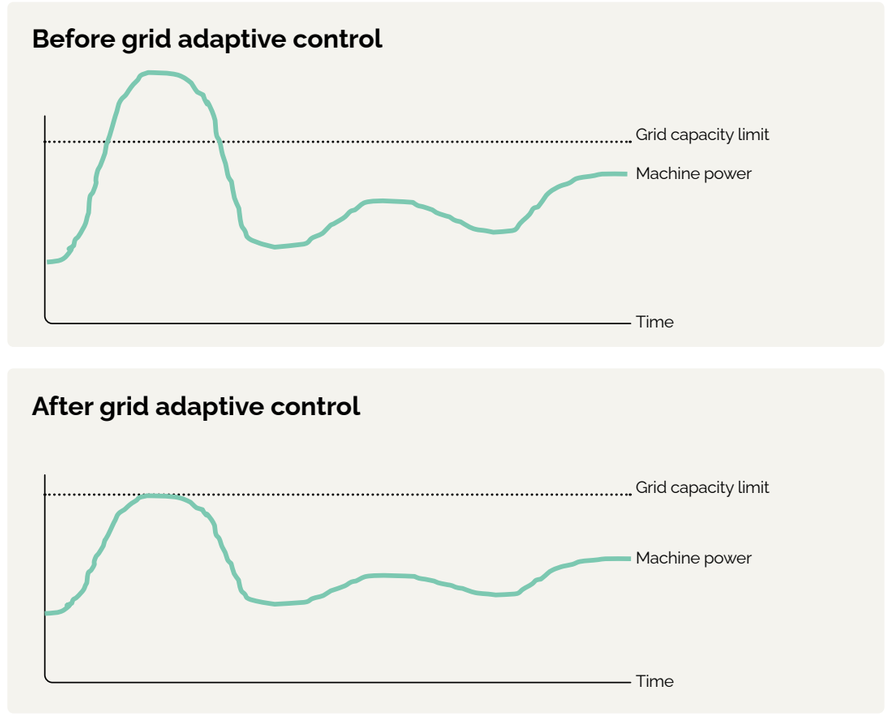
On a global level, we need the green transition to move away from fossil fuels and support decarbonization efforts. Currently, several factors, including regulatory pressures, energy cost fluctuations, and geopolitical concerns, drive electrification efforts. At the same time, there are constraints. Partial or unsuccessful electrification projects can cause people to doubt the benefits of going electric. Additionally, there are concerns that electrification is more than just replacing equipment; it also introduces system-level complexity. And complexity is expensive.

Still, that can be turned into an opportunity to improve system reliability and the utilization of machine flexibility through a well-structured system-level approach that controls the assets and balances production targets with available power/energy.

This white paper argues that helping individual actors run better businesses can be achieved by adopting electric solutions. It also suggests that, if we embrace this shift, we can support a necessary, industry-wide transition away from fossil fuels. The key in both cases is using smart electric machines with added grid-adaptive functionality and then optimizing their behavior at the fleet controller level, while individual machine operational changes take place at the machine rig control level.

And that integration should include grid information (through SCADA systems) and production planning from mine planning. Succeeding with this will simply prove that electrification benefits business, which is a sure way to accelerate the transition. To clarify, we can summarize this as:

The grid-adaptive behavior of a fleet of machines results from combining optimized efforts at the fleet level with primary, functional changes at the rig level.



An example of peak power support with and without grid-adaptive behavior.

Global electrification starts at home – and our grids need help to cope

There is no doubt that electrification is crucial for the mining industry, and there is no turning back. However, while the financial and environmental benefits are substantial, bottlenecks and challenges remain that we need to address to move more quickly. This is especially true because many mines face grid issues, including remote, unreliable, and contingent grids.

All these issues create uncertainty, which can be paralyzing and prevent mines from moving away from fossil fuels. This is further exacerbated by the fact that mining operations test the grid. When machines start, there is an inrush of current during energization, resulting in a voltage sag due to the massive reactive current demand. For anyone considering switching to fully electric operations, we must convince them that this can be done with the available capacity in their grid. Also, the power consumption of the mining machine varies during the operation cycle, which demands a continuously changing power demand at the primary substation.

This is evident when grids are weak or unreliable, but even strong and dependable grids face similar issues. In fact, these grids can also experience peaks and may face capacity problems without proper management. To be blunt, if all machines operate at maximum capacity at the same time, no economically built grid can handle such scenarios.

Without proper management, machines run blindly and fail to see the grid's limitations until it's too late. The result? Major issues such as power outages, costly standstills, and losses in productivity and revenue.

We should also recognize that electrification requires massive investments in infrastructure and grid upgrades worldwide. This poses financial challenges for poorer countries, while other markets face regulatory obstacles and lengthy approval processes. We also need to be modest about how investments should be partly covered by companies, as societies cannot shoulder the entire cost. This is problematic because many mining companies face stiff competition and must mine deeper, which is challenging for profitability. All these factors can lead to delays in necessary investments or indefinite postponements. Additionally, it emphasizes the importance of maximizing the use of existing grid capacity for electrification to keep progressing and to gain more traction.

This again underscores how it's crucial to:

- *Balance the production target*
- *Optimize energy usage*
- *Maintain peak power*
- *Avoid overload/trips*

And to succeed here, we need a system-level control rather than that of individual machines.

Better grid communication is key to electrification success

Grid strength refers to a mine's power grid's available power capacity. This can be related to the ability to provide fault current, ensure acceptable voltage sensitivity, or deliver power. Equally significant is the power flow, or how effectively that capacity is used for active and reactive power.

Smarter operations lead to improved overall power flow, minimized power peaks, and the avoidance of voltage collapse, while utilizing power capacity. Therefore, actors must understand how their equipment performs to maximize its effectiveness.

This can be achieved only collectively at the fleet level by efficiently leveraging each machine's capabilities.

Failing to do so leads to operational complexities, including load balancing across fleets, charging logistics, downtime, and variable energy demand.

There are also interoperability and fragmentation issues arising from mixed fleets, a lack of standardized communication protocols, and data silos. All these challenges must be managed to ensure seamless communication.

Grid communication is the exchange of data and control signals among power system components, such as generators, substations, controllers, and loads, via communication networks to enable monitoring, protection, coordination, and real-time control of the electrical grid. With this setup, actors can benefit from six major advantages.

1

Coordinated operations – fewer instances of multiple heavy starts occurring simultaneously, which weakens the grid.

2

Optimized energy and power use – adjustments to consumption patterns based on available grid energy and power and reduced peak load stress.

3

No overloading or voltage drops below the threshold – machines adapt to the available grid capacity based on priority, ensuring the necessary ride-throughs.

4

Better stability – improved grid stability through local adjustments to active and reactive power demand that collectively improve the situation at the substation.

5

Reactive power support – collective and smart operations improve the substation's reactive power demand to maintain voltage profiles, prevent low-voltage trips, optimize reactive power flow, and minimize loss.

6

Better safety during faults – thanks to grid communication, machines that shut down wait for confirmation before restarting, enabling smooth recoveries.

Overall, this improves energy and power management in mines. These operations are non-linear, with power peaks and periods of low demand. There are also challenges like battery charging and peak-shaving strategies. It's a different world from fossil fuels, where each machine had its own tank; now, all equipment shares a single tank and must use it efficiently to maximize its effectiveness.

Finally, for many mines, energy costs make up 30–50 percent of total operating expenses. Electrification aims to reduce these costs, especially compared with fossil fuels, because BEVs are much more energy-efficient. However, electrification also requires high upfront capital costs, so it's crucial to optimize operations to deliver these benefits and achieve a faster, better ROI.

As discussed earlier, smart electric machines act as multipliers by optimizing the use of available energy. However, the true value lies in coordination — enabling the machines and the grid to communicate with each other — so they can get the most out of each other.

This is perhaps even more important in grids powered by renewable sources like wind and solar, which cannot be controlled or scheduled because we cannot control nature. As a result, the energy they produce will fluctuate, making effective power management and grid communication critical.

There are also local challenges, such as power generation issues, minimizing diesel use, weak connection to the utility, and storage needs to balance variability. Managing power is complex, but advanced load-side flexibility can greatly help. This again requires continuous information exchange through communication between the grid and the fleet.

On the other hand, as recent global turmoil shows, we might face a situation in which fossil fuels quickly become scarce, accelerating the shift to green energy.
This will cause a sharp rise in power demand, especially for renewable sources. Once again, flawless grid communication will be an absolute necessity.

Electrification is a big change – let's make it familiar

Electrification outclasses a continued dependence on fossil fuels. Its benefits are numerous, easy to measure, and all indicators point in the same direction.

However, there are risks and downsides if electrification doesn't include smart electric machines that communicate with the grid and understand it well. We also need to recognize that moving away from fossil fuels isn't just about the fuel itself.

There are other concerns or objections from companies, such as high capital costs for electrifying operations and cybersecurity issues. While these are important, we'll focus solely on the communication between the grid and the fleet.
A practical issue is that mines often have equipment from different manufacturers. It's one thing to have a single smart electric machine, but how do we get them all to work intelligently together? What if they can't talk to each other freely and fail to optimize the available grid capacity?

These hurdles can be quite high, but luckily, many mining companies already rely on a proven solution—SCADA (Supervisory Control and Data Acquisition) systems. These systems connect sensors, PLCs, and control systems, enabling operators to monitor and manage equipment and processes from a control room or remote site. We should build on that familiarity and trust. Using SCADA for grid communication helps companies enhance productivity, efficiency, cost savings, and reliability in electrified mining operations.

Here's a three-step breakdown of how that works:

1

Real-time management:
With a SCADA system, machines are connected to allow real-time monitoring of the grid. This helps when assessing the grid power management options and getting the most out of the fleet.

2

Seamless integration:
Mines can easily integrate their SCADA systems with other control systems, such as RCS or LinkOA from Epiroc. This helps reduce costs and improve the grid power.

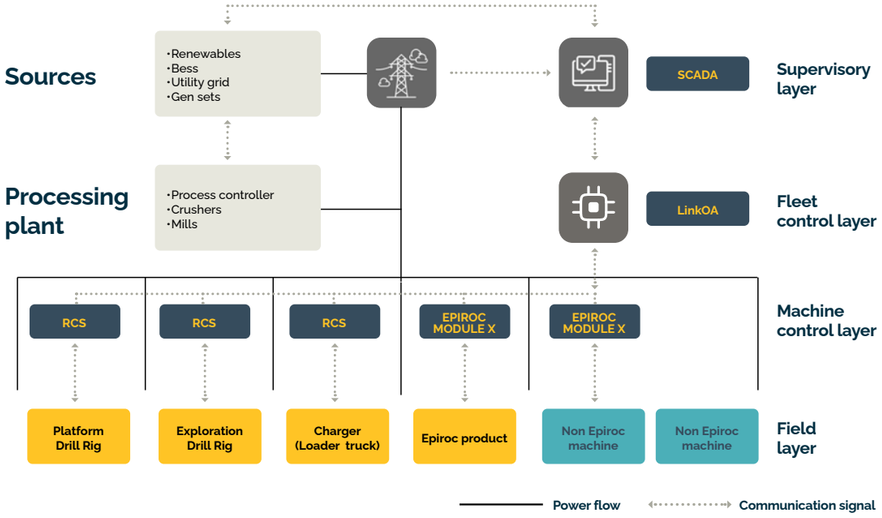
3

Better, more profitable operations:
With SCADA, companies make better power decisions, design smarter drill profile plans, and stay in control. This improves their operations, reduces costs, and increases profitability.

What SCADA does and how it benefits users

Action	Benefit for mining company
Real-time data monitoring	Identifying and acting on sudden peak demands in the grid
Energy consumption tracking	Opens for peak shaving, peak shifting and demand response operations
Data logging and reporting	Possible to plan peak power demands and schedule maintenance
Power quality monitoring	Operations can be designed to mitigate power quality issues
Enhanced cybersecurity	No unauthorized access to the mining machines through advanced encryption
Integration with renewables/microgrids	Rigs can be made to run on solar/battery to reduce fuel consumption and costs

SCADA Connectivity To Machines - Block Diagram



With LinkOA you can get complete synchronization because it will know drill plans and machine sequence, it will have visibility of all connected machines, and can dynamically control multiple machines. LinkOA can then modify these drill plans to meet productivity targets, forecast and predict power consumption patterns, and enable grid-adaptive machine functions when integrated with SCADA.

Commanding a mixed fleet calls for an OEM-agnostic leader

Many mines have machines and equipment from different manufacturers. These may not communicate effectively or seamlessly, which is suboptimal. It also hurts the credibility of electrification when expected productivity and efficiency levels can't be achieved because machines operate independently. In short, the numbers don't add up when the machines don't speak up. Epiroc has developed LinkOA to address this. It's OEM-agnostic and provides the seamless connectivity needed for effective mining operations. Also, it's easy to integrate, retrofittable, scalable, and future-proof. Once installed, LinkOA connects all machines in the mine—drills, trucks, loaders, and more—and enables real-time data, control, and coordination to support autonomous or semi-autonomous operations. Consequently, it becomes the central system across the entire site by creating a common language and control framework.

To better understand this, consider a simple story: without LinkOA, machines are isolated, leading to fragmented data and reduced efficiency. Yes, each machine is smart; however, that intelligence isn't shared but limited to one machine.

With LinkOA, you get complete synchronization because it knows drill plans and machine sequences, has visibility of all connected machines, and can dynamically control multiple machines. LinkOA aims to modify these drill plans to meet productivity targets, forecast and predict power consumption patterns, and enable grid-adaptive machine functions when integrated with SCADA.

And here's the real kicker. SCADA connectivity should not terminate directly at the machines, but feed into LinkOA as the orchestration layer. This allows for merging grid constraints with production, safety, and fleet-level optimization decisions within a single system. From a visionary standpoint, LinkOA can act as a natural load management module for electrified sites.

This will be especially beneficial in mixed-fleet scenarios, while RCS can continue to handle local machine-level control and protection.

This addresses the SRD automation narrative that supports software-defined operations at the fleet level. It's a natural progression from the belief that electrification can be made viable for production in a highly automated environment. To us, this is a three-layered approach:

1. **Grid control:** Taking into account how the grid may serve many fleets and equipment in various places.
2. **Fleet control:** The fleet controller (LinkOA) interacts with the grid controller to optimize the operations of each machine in a specific fleet. It combines the collective requirements/flexibility of all machines, communicates with the grid, and distributes the power/energy between the machines.
3. **Machine control:** The machine controller communicates with the fleet controller and oversees the machine's functions. Our vision is for it to ensure the machine performs its tasks and adjusts to the power/energy consumption pattern by complying with grid integration functions.

Since LinkOA is a robust, vendor-neutral choice, we can also avoid vendor lock-in concerns, which might be a major obstacle when customers consider a business proposition.

Putting it all together, LinkOA is a prime example of an architectural vision for grid integration, by:

- Strengthening software-defined operations at the fleet level.
- Meeting the short-, medium- and long-term customer demands.
- Offering a scalable architecture with a future-proof functionality.

The term scalable is important because it offers a gradual path for the customers. They can proceed step by step, perhaps starting with just SCADA connections, then moving on to having separate machine integration with SCADA and LinkOA before eventually integrating SCADA with LinkOA, and finally linking SCADA, LinkOA, and machines entirely.

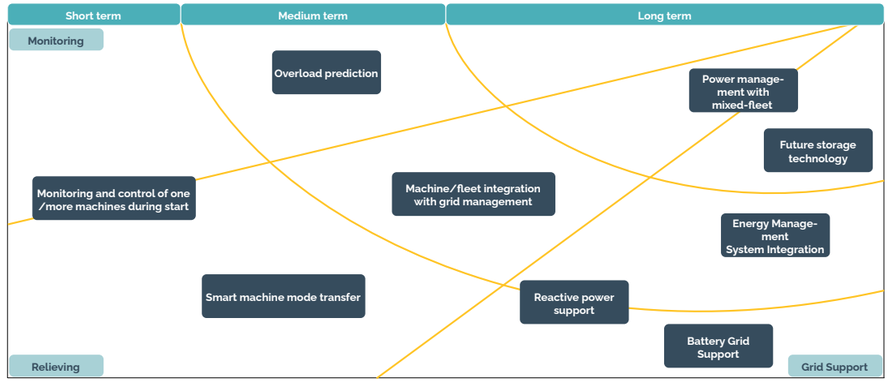
The architecture selection depends on the specific mine's infrastructure and grid conditions, as well as the customer's readiness and ability to commit to electrification.

Smarter machines thanks to power electronics, control, automation and software

If someone from yesteryear looked at today's smart electric machines, they would be in awe. And the smartness is staggering. Still, with more mines being electrified, the machines must become even more advanced.

Pictured here is how we foresee machines evolving and step-by-step becoming even better at adapting to the grid conditions and making the most of the available energy.

And LinkOA will follow suit. This roadmap shows how we foresee its evolution benefitting ever smarter machines and further improve electrified mining operations.



A real-life case with real numbers that prove our case

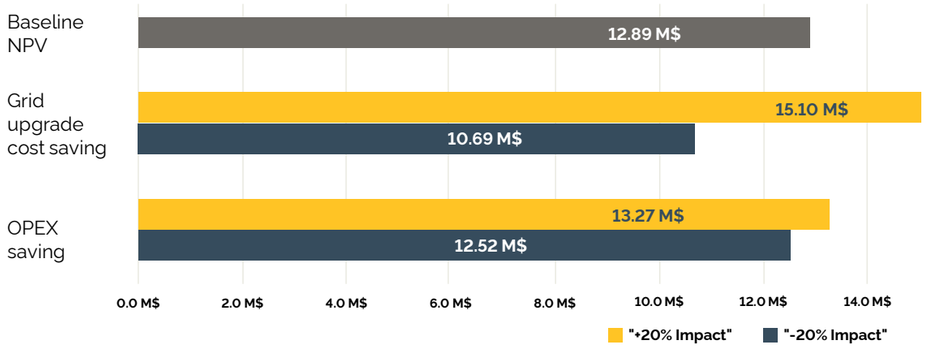
We need to withhold the name of the customer for competitive reasons, but here is a quick look at what a switch from conventional to smart electric machines from Epiroc meant to them.

Business Case
Conventional vs Epiroc Smart Machines

Case A:
A conventional grid upgrade approach. The total cost includes costs for grid upgrades and conventional machines.

Case B:
Optimized grid upgrade enabled by Epiroc smart electric machines. The total cost includes costs for grid upgrades, smart electric machines and upgrades.

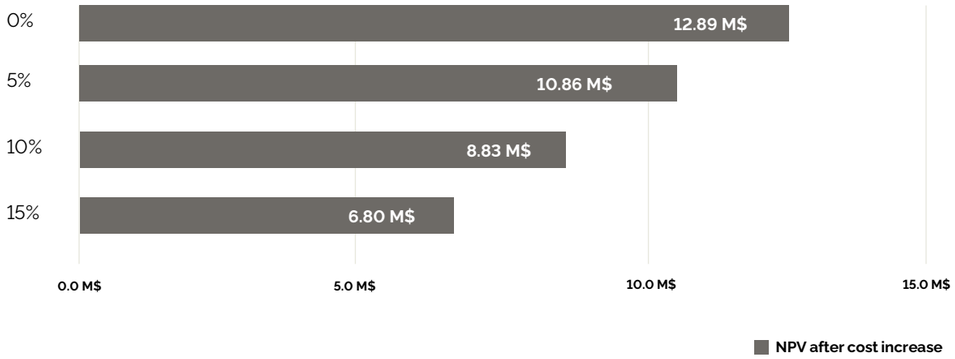
Australia NPV



Conclusion: Case B is the more viable investment option. Estimated baseline savings are 11.02 M$ in CAPEX and 190.66 k$ in OPEX, with a sensitivity range of ±20% considered. Based on this, the NPV is calculated at 12.89 M$.

Machine upgrade - NPV

Machine upgrade cost: Integrating smart electric machine functions in Epiroc conventional machines may increase machine cost up to 20%. However, the overall project still delivers a positive NPV, indicating strong economic viability.



Basis for the financial study* and NPV: 100 MW mining grid, 10 Epiroc machines of 1 MW each located at the same feeder.
*All financial study figures are in USD.

Electrification is unstoppable – if we power it, smartly

In conclusion, to sustain and accelerate the electrification transition, the mining industry needs more power, which requires global infrastructure investments. These investments will take time and are extremely costly. In the meantime, we must enable communication between machines and the grid to optimize the use of the current electrical grid capacity.
We must multiply the smartness of machines by ensuring flawless grid communication. This way, each machine can contribute to increased productivity by operating in the most beneficial way for the entire operation. This process must happen in real-time, with highly adaptable systems like SCADA integrated with fleet management software like LinkOA, to ensure the whole site is always on the same page.

With this integration, mining companies can benefit from smart grid management and enjoy the advantages of electrification, as it ensures the highest possible productivity levels based on the grid's status.

A truly electrifying example that reveals some truths
Let's consider what this means in practice by looking at an example.

	Pressure (bar)	Approx Drill Speed (m/min)	Power consumption from rig kW
Drilling (Full power)	30	1	365
Drilling (derated power)	18	0,6	260
Tram/pos	7	0	80
Trip recovery	18	0	260

	Drilling (%)	Tram/pos (%)	Shift Time (min)	No. Rigs
Utilization	65	35	480	2

Scenario	trips (minutes/rig)	trips recovery (minutes/rig)	Derate (minutes/rig)	Uninterrupted (minutes total)	Drilled meters total	Energy (kWh tot)	kWh/m	Productivity (%)
Uninterrupted	0	0	0	960	624	4244	6,8	100
1 trips à 20 min	20	5	0	910	592	4066	6,9	95
2 trips à 20 min	40	10	0	860	559	3889	7,0	90
Grid-adaptive rigs	0	0	15	930	612	4241	6,9	98

What we see is that:
- Trips mean a loss of 5–10% in productivity, whereas grid-adaptive rigs only lose 2%.
- When you have trips, you drill fewer meters but use more kWh/meter.
- With grid-adaptive rigs, you have 98% uptime, while trips reduce that to 90–95%.

Start talking – the rest will follow

While optimizing operations doesn't eliminate the need for global grid investments, it maximizes the integration between the grid and machines today.

That will create more success stories and make electrification more than just an exciting step for early adopters. Instead, it will become an obvious path for anyone aiming to stay competitive and meet future market demands and new regulations.

There are challenges, but if we all work toward the same goal, we will create a positive chain of events. By optimizing individual sites, we reduce pain points by introducing and scaling up electrification. As a result, mining companies become stronger, especially financially. They can then invest in site infrastructure and help cover part of the costs of expanding the electric grid. With more power available, they can run even more efficient and sustainable operations, lowering their TCO while increasing output.

Three key points to hammer home, one final time:
1. A system-level control is imperative
2. Fleet control is vital for optimizing machine behavior and SCADA integration
3. You can expect estimated upsides such as an approximate 20% reduction in infrastructure costs and around 10% improvement in production efficiency

Now, while some might argue that it's not as simple as just talking about it, the key to success is actually – get the machines and grid talking, and the rest will follow.

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