Mining Forward

ExxonMobil

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Digging into the potential for lower emission mining operations

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Mining Forward

How to use this White Paper

There's growing pressure for emission reductions, especially lifecycle greenhouse gas (GHG) emissions, from mining sector operations. This is coming from policy makers, shareholders and customers. Operators are therefore evaluating their options and preparing for a lower emissions future. But it's complicated and any missteps could be expensive to rectify. That's why ExxonMobil has created this document. It's a resource that can assist operators thinking through options to reduce their emissions while optimizing productivity, efficiency and working to meet societal expectations.

Section One sets up the defining **CHARACTERISTICS** and dynamics of the mining sector since they shape the challenges it faces and the solutions it is exploring. It reflects on why the sector exists, its scale, diversity, energy intensity and how that energy is consumed across its operations.

Section Two identifies inter-linked mining sector **CHALLENGES** including operator goals to reduce their emissions, while tackling the growing need for depleting resources, reskilling operational teams, and while advancing societal ambitions to reduce GHG emissions.

Section Three navigates the portfolio of **CHOICES** available to the sector in assembling their emission reduction plans over different time horizons. It summarizes potential options, the status of current readiness/deployment, their potential benefits and some of the associated challenges. The technologies discussed vary in their maturity, with some in their infancy, while others have a wider level of adoption.

Section Four summarizes the key steps that mining operators might take to make **CHANGES** happen, from data-driven choices to effective implementation.

The index will help guide you to the sections that best meet your needs, with links and references for users who want to take a deeper dive into the topics covered in this paper.

With its primary focus on practical options to reduce emissions, including both GHG emissions and criteria emissions, from day-to-day mining site operations, this paper is complementary to our white paper, **Moving Forward: Planning the Journey to Lower Emission Commercial Diesel Fleets**, which focuses on steps to reduce emissions from commercial land transport operations.

As part of our preparation of this white paper, we commissioned Frost & Sullivan to conduct extensive research of mining operators across six diverse markets (US and Canada in North America, China, Indonesia and Australia in Asia Pacific, and South Africa). The 91 mining operators, which Frost & Sullivan engaged in 1Q25, spanned a mix of above ground and below ground operations, across multiple mining categories from coal to gold, and had an almost equal balance of national and multi-national operators.[1] We have complemented these research insights with our own commentary and analysis based in part on reference to public domain sources. We also spoke to stakeholders across the mining sector in November 2024[2] and we have included a number of quotations based on their feedback throughout the white paper, which have been edited for length and clarity. These quotations represent the opinions of the individual contributors and do not necessarily represent ExxonMobil's views, positions, or terminology.

We hope this document will be of use to a variety of mining sector participants, including mining operators, the customers they serve, and fuel supply chain participants.

ExxonMobil: A history of innovation

ExxonMobil has been providing product solutions of different kinds to multiple diverse commercial sectors, from road transport to mining, for over one hundred years.

ExxonMobil offers product solutions for both resource extraction operations and enabling onwards transportation of the sector's production through its value chain. Our Mobil, Esso and Exxon branded products serve customers in countries all over the world, whether supplied to mining operators directly by ExxonMobil, or indirectly via our channel partners.

ExxonMobil also has significant operational experience in the sector, including through its majority-owned affiliate Imperial Oil's Kearl Oil Sands Project in Alberta, Canada.

We are proud of our technology leadership, employing thousands of scientists and engineers in developing capabilities, technologies and product solutions for transport and other sectors.

The mining sector ecosystem is complex with many different players serving the sector's need to supply the raw materials used in producing the things which make society work, while operating ever more productively, efficiently, and sustainably. 'Sustainability', as that term is generally used by society, may span multiple sustainable development goals and impact categories. Sustainability priorities vary from company to company, and country to country, but reducing GHG emissions is often an ambition identified by many industries and sectors. ExxonMobil has strategic collaborations with players across the ecosystem, from OEMs to mining operators.

ExxonMobil intends to play a leading role in the energy transition. We understand that the mining sector is changing as it strives to reduce GHG emissions, while maintaining the levels of productivity and efficiency required to meet customer demand affordably, reliably, AND delivering financial returns.

We are working with governments at various levels to advance policies that will help enable a resilient and reliable energy future while energy-intensive sectors advance towards meeting societal ambitions to reduce GHG emissions.

> The journey of reducing emissions to support a net-zero future for the mining sector will require a portfolio of approaches. At ExxonMobil, we have demonstrated capabilities in large-scale solutions, proven technology expertise, and experience working with key industry stakeholders to create meaningful energy product solutions.

Patrick Rutherford,
Global Product Development & Marketing Manager, ExxonMobil

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Section One

Characteristics defining the mining sector

1.1
Mining is essential to modern life and demand is expected to grow

People have been mining for thousands of years. The mining sector underpins much of our daily life and future advancements, making it a cornerstone of modern civilization. It helps us make the things that make society work. It provides the raw materials we rely on for everyday products and infrastructure — minerals and metals for construction, electronics, vehicles, and even certain renewable energy technologies.

Examples:

- Solar Panels (copper, iron, titanium, silver, gallium, indium).
- Batteries (nickel, cadmium, lithium, cobalt, manganese, iron, phosphorus).
- Circuitry (gold, copper, aluminum, steel, lithium, titanium, silver, cobalt, lead, zinc).
- Smartphones (silicon, boron, lead, barium, strontium, phosphorus, indium).
- Electric vehicles (copper, lithium, aluminum, nickel, cadmium, cobalt, manganese, iron, phosphorus, zinc).
- Wind turbines (metallurgical coal, iron, copper, nickel).

The mining industry significantly contributes to economic growth, creating jobs and supporting local economies, including participating in healthcare and infrastructure developments. It plays a vital role in both developed and developing countries – in the US alone, mining directly employs just under 200K people.[3]

Mining is crucial for extracting fuels that power our society today, including coal and oil. And many modern technologies that support the energy transition depend on minerals extracted through mining, making it integral to innovation and development in various sectors. Significant scaling of battery metals is required to power the electrification elements of the energy transition, so the mining sector as a whole has both its own energy transition to consider and is potentially an enabler for the energy transition in other sectors. The International Energy Agency (IEA) estimates that the demand for minerals (like copper, nickel, graphite and lithium) used in 'clean energy' technologies will almost double from 2023 to 2030 in the IEA World Energy Outlook 2023 STEPS scenario.[4]

As the world's population continues to grow, and countries develop their economies, the mining sector is expected to grow to keep pace. Total mining production has approximately doubled in less than 40 years, from ~9M tonnes in 1984 to ~18M tonnes in 2022.[5] Between 2024 and 2029 the value of the mining sector is expected to grow from 2.3 to 3.0 trillion USD.[6]

Figure 1
Mining Sector is Growing, and That Growth is Expected to Continue

Source: Mining Global Market Report 2024.

Existing resources will become depleted, and new resources will be needed to keep pace. The global population is expected to rise from ~8 billion in 2023 to ~10 billion by 2050, and this will be accompanied by an expected doubling of GDP.[7] This will further drive demand in commodities and pressure to increase mining sector activity.

1.2
Mining operates over long timelines, requiring significant capital investment

Growth in demand for mining commodities will require development of new mines and these can involve lengthy prospecting, planning, permitting and financing cycles and require close cooperation with authorities and communities.

Capital investments can be higher than 10 billion USD for a large mining project.[8]

The lifecycle of mines varies but 25 years or longer is typical. Productivity of mines and ore grades often fall over time as mining planners will seek out the most accessible and higher-grade metal and mineral deposits first. Pits and mines get deeper over time. And the ratio of overburden to ore production typically becomes more challenging over time. This places greater pressure on the energy intensity and economics of operations.

The high level of investment means the mining sector is often conservative and cautious in the face of change, with a high burden for demonstrating the benefit of potential improvements. The remaining lifecycle of a mine also influences the attractiveness of investments.

> Just because that's the way we've done it for hundreds of years doesn't mean that that's how we have to do it forever. And if we insert something into the mix that says, 'If you change the way you're doing things, or just think about the way you're doing them, maybe this will benefit you', that's possible.
>
> **Mining Operations Lead[2]**

Mining operations are developed based on a mining plan. Operations feature a series of key steps as shown in **Figure 2**.

1.3
Mining is operationally very diverse

Mining is a very diverse sector and there is not a one size fits all when it comes to operations. There are significant differences in practices between strip, open pit and below ground operations. Mining operates across significant geographic diversity, often conducted in remote locations and challenging conditions – extreme heat or extreme cold. Below ground operations can be as much as 4km underground.[9] Mobile equipment is typically subject to significant vibration over rough terrain. Operating safely and responsibly are critical in maintaining license to operate.

The scale of mining operations also varies significantly from mine to mine, and from commodity to commodity. Iron ore and coal mines typically tend to be bigger than average.[10]

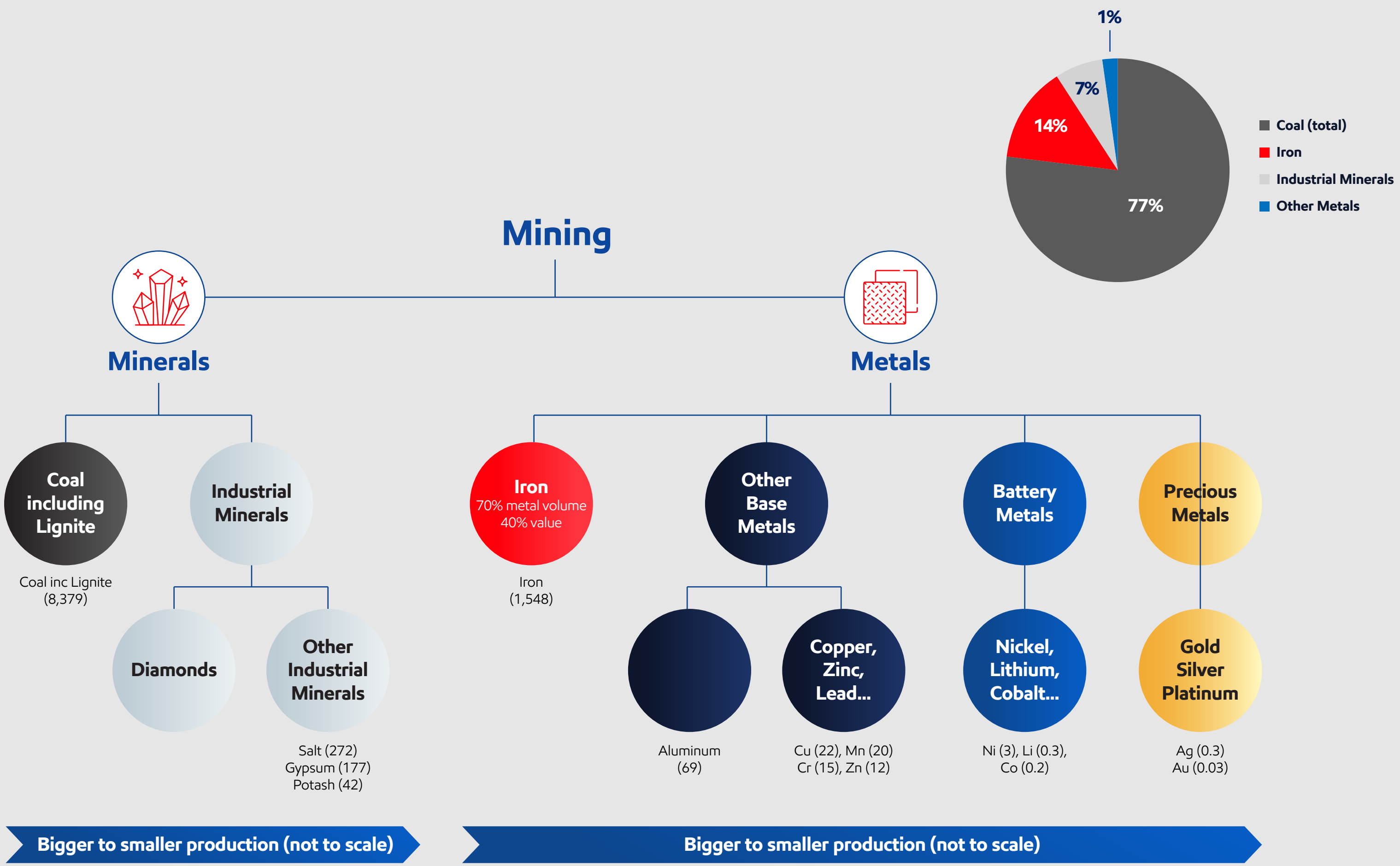
Geopolitics also plays an important role in mining. Just under two-thirds of mining production[3] takes place in developing countries, and reserves of some sought after resources are highly concentrated in individual territories.

Mining covers a wide range of commodities, which are typically split into metals and minerals as shown in **Figure 3**.[11]

The metals category can be split into iron production (~70% of metals volume comes from iron ore mining), other base metals (aluminum production the largest, followed by copper), battery metals (including nickel, lithium & cobalt) and precious metals (including silver & gold). The minerals category can be divided into the mineral fuels (primarily coal) and the smaller subset category of industrial minerals (including salt, gypsum & potash).

Figure 2
Key Steps in Mining (simplified)

Figure 3
Mining Commodity Categories & Relative Scale



Source: 2022 Annual Global Production, Million Tonnes — World Mining Data 2024.

These categories all have their own characteristics with higher/lower energy intensities and significant differences in scale. Some mines/sector categories conduct high amounts of on-site processing. Some ship ore overseas for processing. This significantly impacts the energy intensity and mix of mining operations.

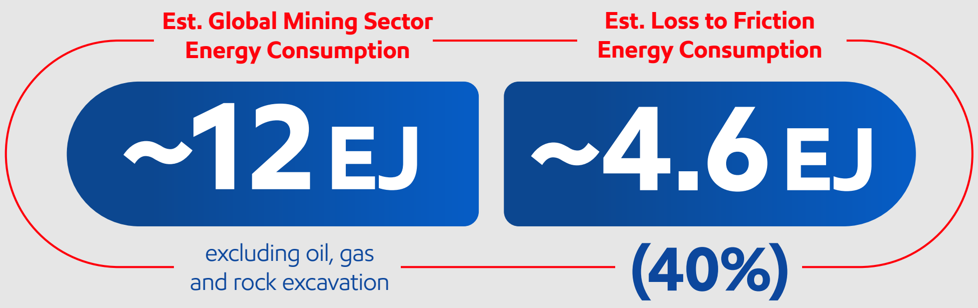
Growth trajectories are also expected to differ widely with coal production expected to fall with a shift towards gas and renewables (e.g., wind and solar) in power generation, and battery metal demand running well above the sector trend line with the shift towards electrification in transport and battery energy storage systems.

Mining operations distant from population centers are often off-grid, generating their own electricity on site, often relying on diesel generators. But more mature, larger scale mining regions, like the Pilbara in Western Australia, have established infrastructure over time with rail connections to ports and connection to private gas-powered electricity generation. Geography also impacts the future availability and mix of renewable electricity options, which is expected to play a key role in reducing mining carbon intensity.

1.4
Mining is extremely energy intensive

Moving large amounts of earth is hard work and takes A LOT of energy. Globally, it has been estimated that mining consumes ~12 exajoules (EJ) of energy (1 EJ = 1,000 PJ ~ 278 TWh or ~24M tonnes of oil equivalent Mtoe). Forty percent of that has been estimated to be lost to friction — see **Figure 4**.[9]

Figure 4
Energy Consumption in the Mining Sector



Source: Global energy consumption due to friction and wear in the mining industry Holmberg et al 2017.

To put this in context, this is more than double the UK's entire 2023 energy consumption estimated at 125Mtoe (~5 EJ).[12] Australia's mining sector (excluding oil & gas), for example, alone consumed 0.4 EJ (~10 Mtoe) energy in 2022/23, representing ~7% of Australia's total energy demand.[13]

Access to grid electricity and natural gas can influence the mining sector's energy mix significantly. It has been estimated that ~70% of Australia's mining energy comes from diesel consumption (~7.6 BL) compared with ~27% from electricity.[12] This is in comparison to Canada of which 22% is diesel, 45% is natural gas and 29% is electricity-powered.[13]

1.5
Mining consumes energy across its operations, powering highly-specialized mobile & stationary mining equipment

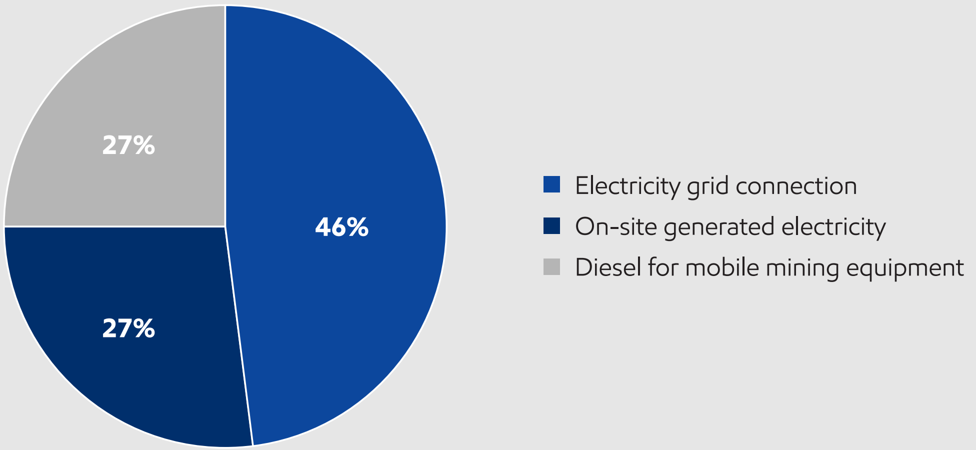
Mining requires highly specialized and, often, very large equipment which in many cases stays at the mine throughout its life: drilling rigs, excavators, haul trucks, dozers, graders, conveyors, separators, and ball mills being common examples.

This equipment is supplied by original equipment manufacturers (OEMs) such as Caterpillar, Komatsu, Liebherr, Hitachi & Sandvik, which specialize in the mining sector and in many cases also with product offerings in one or more of the agriculture, construction (more for mobile equipment) and industrial application sectors (more for stationary equipment), due to similarities in application and expertise, if not always in scale.

There is a significant difference in the energy sources used to supply stationary and mobile equipment, with stationary equipment primarily electric powered and mobile equipment primarily diesel powered. In off-grid mines, diesel often plays a significant role in on-site electricity generation. Energy consumption mix varies between operations, even within a country, with the amount of on-site processing required strongly influencing the mix between mobile and stationary equipment as shown by way of example in **Figure 5**.[1]

Figure 5
Mining Operation Energy Mix 2025

Q1. What is the current energy mix used in your mining operation? – % Total Energy Consumption



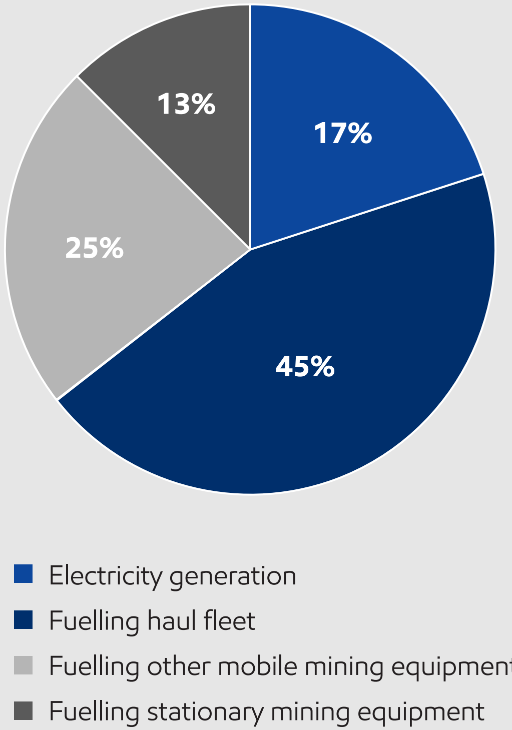
Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

a) Mobile mining equipment:

Mobile mining equipment is predominantly diesel powered, although some less-mobile electric equipment can be connected to a power supply by cables. Overall, mobile mining equipment often consumes more than half of a mining operation's diesel consumption, with haul trucks making up the majority — see **Figure 6**.[1]

Figure 6
Mine's Annual Diesel Consumption

Q20. Taking the overall Diesel consumption at the site, please allocate the approximate consumption split.



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

i) Haul trucks

Haul trucks are almost exclusively diesel powered due to mobility, high utilization rate and the energy density required. Some manufacturers have shifted to electric drives, with the diesel engines operating in electricity generation mode.

There are significant differences in design between underground and above ground equipment. While both are usually much bigger and designed to carry far heavier loads than on-road vehicles, above ground haul trucks are usually much bigger than underground equivalents — they can be up to 8m high, 10m wide x 16m in length, accessed by ladders.

The biggest surface mining haul trucks have a gross operating weight of over 600 metric tonnes, 14x more than a typical fully loaded class 8 on-highway truck. Engines can be 6x bigger with 7x the power, with diesel tanks holding over 5,000 liters.[14]

A haul truck in a mining operation can last 20 years, requiring a major rebuild at 60K hours, which is around 10 years of use, and can last up to 120K to 150K hours. The lifespan depends on operating conditions, with rough roads causing more wear and tear. Some sites replace frames to extend truck life further. There is a limited secondary market for haul trucks.[2] This is very different from how class 8 truck operators typically use their workhorses, with many of the bigger transport companies transitioning their fleets every 3–5 years with a secondary market that offers resell value.

Mining haul trucks also have a very different duty cycle from a class 8 truck, operating not just with higher loads but typically lower speed. In open pit mines they often operate a cycle between uphill full and downhill empty. An ultra class haul truck can consume nearly 900K liters of diesel annually,[15] refilling every 1–2 days, operating 18 hours a day, typically across 2 shifts with 80%+ utilization rates targeted. Autonomous haul trucks have even higher utilization rates. As haul trucks do a lot of the mine's heavy lifting and shifting, moving ore and waste materials, they can represent 30–50% of a mine's energy demand.[15]

A typical mine might have around 35 haul trucks. The largest mines might operate fleets of nearly 100 vehicles. Haul trucks are usually fueled when they return to base with routine daily and weekly maintenance checks.[13]

Major global mining companies in the world, like BHP, have haul truck fleets in the range of 800 vehicles[16] compared to the likes of large US hauler, JB Hunt, who operates with over 10K trucks.[17] However, a typical diesel class 8 truck might consume around 50KL/year diesel, significantly less than their mining equivalent.[18]

Below ground, haul trucks are smaller but are still often bigger than their on-road counterparts with payloads up to 63 Tonnes.[14]

ii) Loaders & excavators

Haul trucks work in tandem with loaders and excavators. Choosing the right size of equipment and optimizing the ratios are key to operational productivity and efficiency, depending on many factors, especially mine layouts and contours. Ratios of five haul trucks to one loader/excavator are not uncommon.[14]

Bucket excavators in mining can be huge, like the Caterpillar 6090 FS with bucket sizes as much as 60m^3, powered by two 60 liter 16-cylinder diesel engines.[14]

Diesel-powered loaders and excavators are primarily refueled by mobile fueling trucks that transfer diesel from the diesel storage facility to the mobile equipment.

Huge drag line excavators offer the largest excavation capacities and are often used in mass over-burden clearing operations. They are often electric powered. The CAT 8750, for instance, has a bucket capacity of up to 116m^3.[14]

iii) Earthmovers, loaders & graders

Dozers, skid (wheeled) and track loaders support earth moving and loading. Their operating modes vary with some repetitive applications which may be easier to automate. Graders, like dozers, are also larger earth-moving machines and used to smooth the surface for haul roads. These categories of mobile mining equipment are typically diesel powered today.

iv) Other mobile equipment

Mines can be significant in footprint so they often include other mobile equipment including buses to move personnel around and other mobile equipment such as refueling vehicles. By and large these are diesel operated today but may be suitable for electrification.

b) Stationary mining equipment

Stationary equipment is usually electrified, and often electricity is generated on site with large diesel- or gas-powered generators.

Conveyers are often used as an efficient way to move raw and finished ore in parts of the mining operation, working repeatedly and consistently over the mine's life.

Electric-powered equipment associated with comminution (grinding and sorting) is very energy intensive and a critical and expensive mining investment. Comminution typically consumes around a quarter of the energy in a mining operation although this varies depending on the commodity and operation.[16,19]

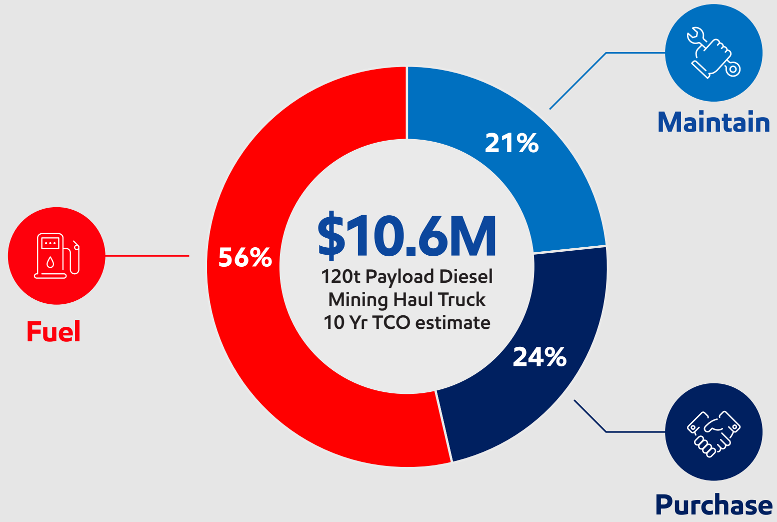
1.6

Productivity, efficiency & total cost of ownership are critical for securing mining returns

The energy intensive nature of mining, together with a largely commodity pricing model for their output, means mining operators seek to optimize productivity (reliability, equipment uptime, utilization rates and consequently daily production) while operating as efficiently as possible per tonne of ore produced (seeking to minimize the cost of the energy consumed), all while maintaining a focus on safety and the local environment.

Consequently, mines typically work 24 hours a day, 7 days a week, 365 days a year with very high equipment utilization rates. A key measure of productivity and efficiency is Total Cost of Ownership, commonly abbreviated to TCO. Mining equipment is expensive to own and operate. Estimates of TCO for a smaller 150t payload diesel haul truck indicate a 10-year TCO of 10.6M USD, of which the energy cost was 56% — see **Figure 7**.[20]

Figure 7
The Total Cost of Ownership (TCO) of a Mining Haul Truck TCO



Simplified analysis – excluding, for instance, driver cost.

Source: TCO equation 150-t payload – SRK Report Oct 2024 – International Mining.

When miners explore changes to their operations, they typically do so cautiously and in a data-driven way, with close attention to the impact on productivity and TCO. This has a significant bearing on the solutions the sector is choosing from, in relation to the energy transition (see **Sections 2.3 and 3**).

Section Two

Challenges the mining sector is embracing

In an ExxonMobil commissioned research of the mining sector, Frost & Sullivan interviewed leaders in mining operations across different geographies and a mix of mining operations (different commodities, surface mining and underground).[1] **Figure 8**, on the right, highlights how these operators see the top challenges facing the sector. Delivering on the fundamentals of operational efficiency and cost management, while operating safely, responsibly, sustainably and with lower lifecycle GHG emissions, represents a continuing challenge for the mining sector over the next decade, especially while managing depleting resources. Automation, digitization and electrification are all key enabling capabilities that the sector is acquiring. All the above will require tackling the talent pipeline and development of the existing workforce.

Figure 8

Top Challenges Facing the Mining Sector in the Next 10 Years

Q3. Of the following challenges, please select the five that you believe will represent the biggest challenge for the mining sector in the next 10 years.

Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

We have highlighted a few of these emerging challenges on the next pages.

> "I think the first challenge is rising costs and productivity pressures. Energy is expensive and the supply of energy they need goes up and the operating cost or the capital cost is going to rise. To balance that, they look for inefficiencies, how to reduce downtime, electricity and energy consumption. And there's a current competition for resources, labor and materials. So, that's another problem. Environmental sustainability ... is not just the decarbonization space. Energy consumption is one thing, but there's also water usage, dust, noise, and tailings management. They have to find solutions for all this and they're all expensive. And while they're doing all this, some of their mines are coming to end of their life, increasing operating costs further."
>
> **Leading Mining Consultant[2]**

2.1
Replacing depleting resources

With the projected growth in demand, mining companies need to plan ahead. Existing reserves will deplete over time and managing this depletion is among the top emerging challenges. There are three key implications of resource depletion.

Firstly, without action, this will tend to reduce productivity at existing operations, raise energy intensity and increase costs as less productive seams of ore must be reached. This represents an important challenge associated with reducing sector emissions, particularly GHG emissions, as highlighted in **Section 2.3** below.

Secondly, in parallel, new resources will need to be found, and securing permits is challenging, before the capital-intensive development cycle can commence. These new developments may beneficially present an opportunity to set up lower emission operations from day one, at the beginning of the capital investment cycle, rather than part way through when returns on investment from capitally intensive actions tend to be more challenged.

Thirdly, a highly-skilled and motivated workforce will be required to tackle the challenges of maximizing the effective use of existing operational assets while replenishing the resource pipeline and establishing new state of the art mining operations.

> Resources are depleting so [mining operators] have to go deeper. It's brownfield projects, so expensive to expand what they have. And they have to manage… water consumption, electricity consumption, tailings, a number of fronts. It's all about capital allocation, prioritizing where they're going to invest, allocating for future-facing priorities versus the cash cow and how they're going to manage that. Sustainability goes across everything when they make decisions like that. And then inorganic growth comes into the picture.
>
> **Leading Mining Consultant[2]**

2.2
Retaining, recruiting & reskilling the workforce

Mining has historically been very labor intensive. While modern, best in class mining operations bear little resemblance to most people's "pick and shovel" perception, even with a high degree of automation, a world scale operation can require over 2,000 employees.[21]

Mining is hard work in often remote, harsh conditions, typically requiring fly-in/fly-out work patterns. Many mining operators also highlight the ageing profile of their workforce and challenges in retaining experienced personnel in a cyclical industry which also struggles to engage a younger, newly emerging workforce in its mission.[22]

In their summary of the World Economic Forum's The Future of Jobs Report 2020, the International Council on Mining and Metals (ICMM) highlighted significant skills gaps and the need to reskill/upskill nearly half the sector's employee base.[23]

These skills reflect an industry going through significant change as we will see by the choices it is navigating in **Section 3** of this white paper, namely automation (number 2 in the list of challenges in **Figure 8**), digitization (number 6 on the challenges list), electrification (number 9 on the challenges list) and a shift towards renewable electricity (e.g., wind and solar), which as we will see later is a key focus area for GHG emission reduction.

> The first challenge is the social contract, the right to mine — there's a whole social element of challenge. Then there's the technical challenges of supporting the equipment and the pressures to decarbonize, electrify, to automate. Thirdly, the workforce is another challenge. The easy deposits have been mined, the mines are getting more and more remote, equipment is getting more sophisticated, and the people that have been doing this work for 20, 30, 40 years are retiring. The younger generation doesn't want to do it. It's hard work. It's remote. This is driving a lot of the desire for automation and control equipment remotely from somewhere where they can attract people.
>
> **Mining OEM[2]**

2.3
Operating more sustainably with a focus on reducing emissions

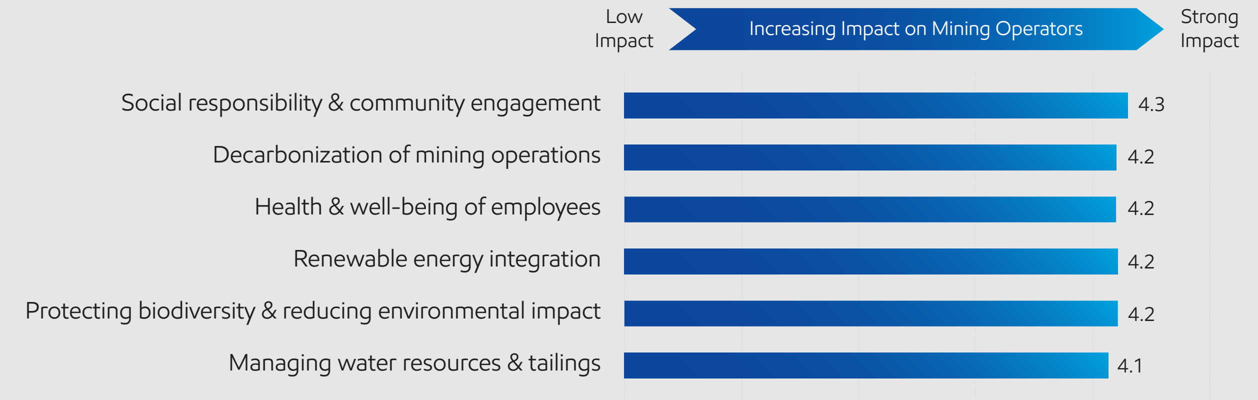
With a workforce to engage, local community relationships to maintain, and new sites to develop, defending the license to operate and managing associated reputational risks is the number one priority for responsible mining operators.

Mines require permits for operation. Securing mineral and water rights, and, where feasible, access to the energy grid is crucial. Establishing credibility and a thoughtful, responsible, safe mining plan is a mission-critical first base. Mining operators also depend on their relationships with the local community and local, regional and national authorities.

Consequently, when considering different sustainability-related themes it is not surprising to see mining operators placing employee safety, community development, local employment and infrastructure, careful use of water resources and managing local biodiversity as themes of high impact — see **Figure 9**.[1]

Figure 9
Impact of Sustainability Themes on Mining Operators

Q4. How do the following sustainability themes impact your company?
5-point scale with 5 meaning "Strong impact" and 1 meaning "Low impact"



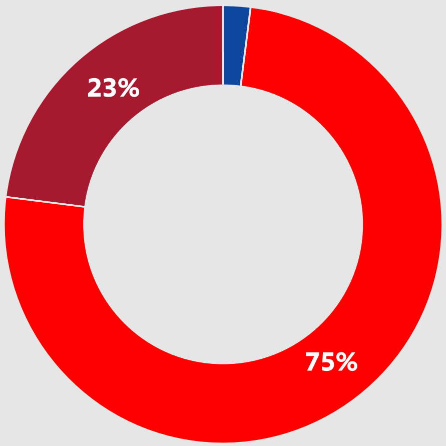
Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

The high energy intensity of mining means decarbonization, in the sense of needing to reduce GHG emissions, is also front of mind for major mining operators and the companies which serve them as is highlighted in **Figure 10**.[1]

Figure 10

Importance of Decarbonization For Mining Operations

Q6. How important is decarbonization for your mining operations?



- It is not a part of consideration at all (0%)
- It is one of our focus areas (2%)
- It is an important part of our strategy (75%)
- It is a cornerstone of our strategy (23%)
- Do not know (0%)

Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

> Making sure we maintain our community acceptance and are a positive economic driver in the communities is probably number one. And number two would be water, making sure that we are not impacting water for the local communities. I would say greenhouse gases might be next although every one of our sites has plans around managing biodiversity, not just minimizing impact, but trying to improve the biodiversity around the sites. And then the last one I would say is mine closure, making sure that we have good plans in place so that we can close the mine responsibly with minimizing the amount of environmental impact.

VP of Mining Technical Service[2]

> In addition to emissions reduction, sustainability areas include social license to operate, working with the local community leaders, providing jobs and training are very important. Giving back to the local communities is important as well, being sure to pay royalties, pay your people well, and making sure everyone goes home safely.

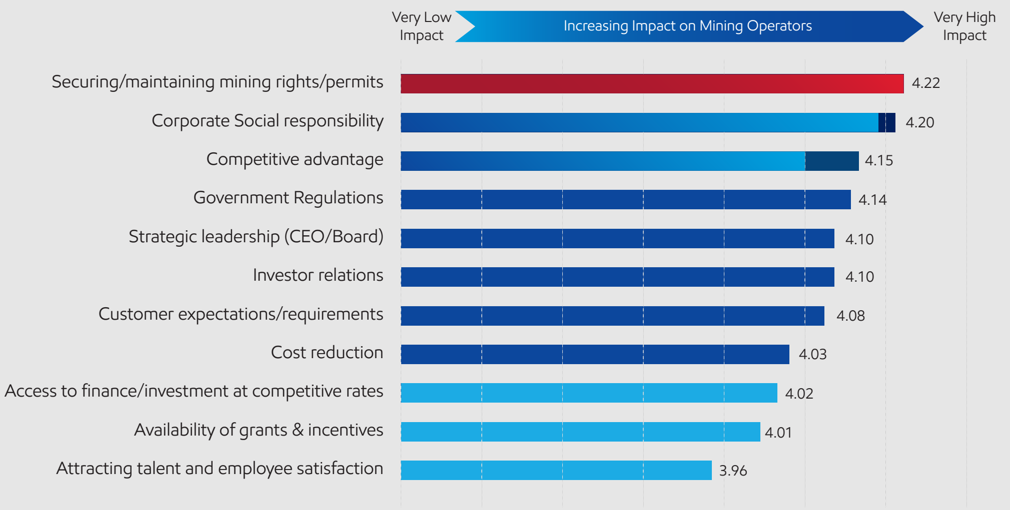
Principal Mining Engineer[2]

Mining operators highlight permitting and corporate social responsibility amongst the many drivers of their ambitions to reduce GHG emissions as shown in **Figure 11**.[1]

There are multiple perceived barriers to achieving lower GHG emission goals with upfront capital costs, availability of lower GHG emission diesel fuels and access to renewable electricity rising to the top. The skills base in the workforce is also highlighted[1] as a barrier for some operators as shown in **Figure 12**.[1]

Figure 11
Drivers of Decarbonization (Mean Impact Score)

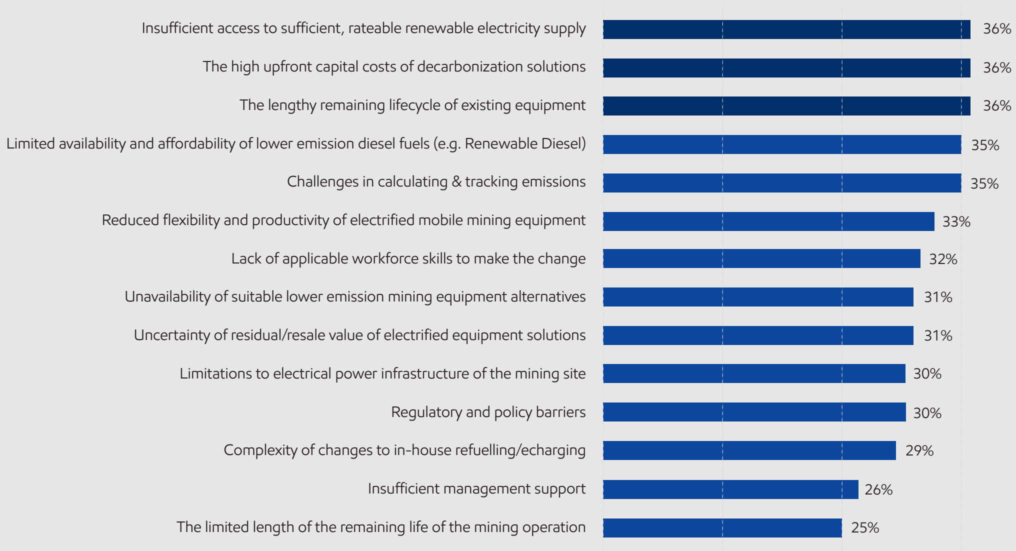
Q7. What is driving decarbonization in your company?
5-point scale with 5 meaning "Very High impact" and 1 meaning "Very Low impact"



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

Figure 12
Key Barriers to Decarbonization Efforts

Q8. What do you see as the barriers to your company's decarbonization efforts?
(Mean Barrier Assessment 1=no barrier to 5 = strong barrier) % respondents scoring 4 or 5



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

> Customers are under pressure to reduce their own carbon footprints. And that pushes them to push the companies they purchase the raw material from to lower their carbon emissions because it impacts their targets. Everything is connected in that manner.
>
> **Leading Mining Consultant**[2]

When it comes to emissions, many mining operators now report Scope 1 and 2 GHG emissions from their own operations. Some also report Scope 3 GHG emissions associated with the end use and 3rd party processing of their production.

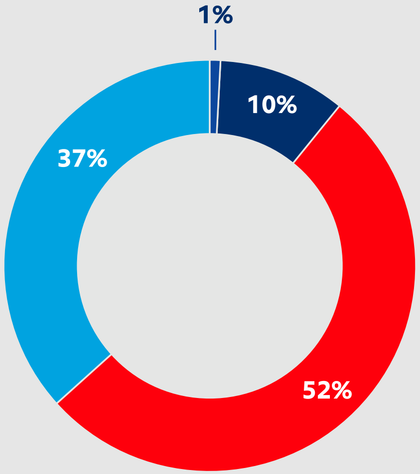
In 2021, the ICMM company members, featuring a third of global miners, including major players like Glencore, BHP, Rio Tinto, Anglo American, Teck Resources, Vale, and Newmont, committed to take individual action by the end of 2023 to build clear pathways to meet net zero Scope 1 and 2 GHG emissions by 2050 or earlier and work to accelerate Scope 3 GHG emission reductions also.[24] When introducing this collective ambition, ICMM acknowledged in 2021 that the rate and nature of the ultimate decline in GHG emissions will vary across the different commodities and geographies represented by their diverse membership.[25] Accordingly, many major mining companies have established GHG emission reduction targets and roadmaps as part of their wider sustainability objectives.

Almost all (**99%**) of the mining operators Frost & Sullivan interviewed, across a range of countries, confirmed they are working towards some kind of emissions reduction goal. In addition to quantitative emissions reduction goals, many mining operators have established key focus areas related to elements of their emission reduction roadmap, including electrification of their mobile mining fleet and a transition to renewable electricity — see **Figure 13**.[1]

Figure 13

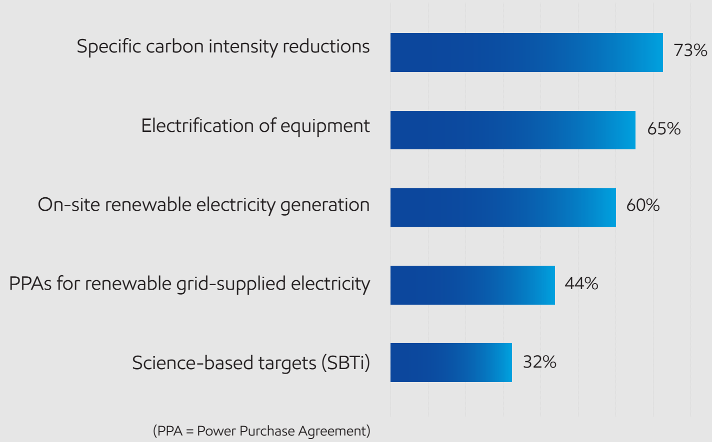
Scope 1 and 2 Emissions Reduction Goals in Mining Operations

Q10. What most closely describes your operational (Scope 1 and 2) emission reduction targets by 2030?



Key Current Focus Areas for Reducing Emissions

Q11. What are the key elements of your emission reduction targets by 2030?



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

> Mining customers are getting pressure to reduce their carbon footprint at the CEO level. And then those CEOs then are driving pressure to OEMs to do the same and actually help them achieve it. So, for mining OEMs, decarbonization and electrification is really at the executive level pushed by their customers. That's why R&D investment is so strong in electrification, decarbonization and automation. It's being driven by the customers.
>
> **Mining OEM[2]**

Regulatory frameworks and policy will have a role in shaping the journey mining operators take to lower GHG emissions. From a total value chain perspective, overall GHG emissions for mining commodities will depend on domestic, regional and international policy frameworks affecting a variety of adjacent sectors including energy producers, mining equipment manufacturers, and transportation companies. The level of value chain integration, and the specifics of end customer needs, will influence the impact of policy and regulation, as well as the roadmap priorities, choices, projects and collaborations which mining operators pursue in both reducing their own GHG emissions and helping others achieve their goals.

Equipment OEMs, like Caterpillar, are also adapting to meet the needs of the sector and some have established GHG emissions reduction goals of their own. Caterpillar has established a Scope 1 and 2 emissions reduction goal of 30% from its operations for 2030 vs a 2018 baseline. Caterpillar also established a "Product Emissions & Energy Efficiency" goal to make all new products through 2030 *"more sustainable than the previous generation through collaborating with customers, reduced waste, improved design for rebuild/remanufacturing, lower emissions or improved efficiency."*[26]

For ExxonMobil's perspective on rational and constructive policy, please see our **Advancing Climate Solutions Report**.[78]

Section Three

Choices the mining sector is navigating to reduce emissions

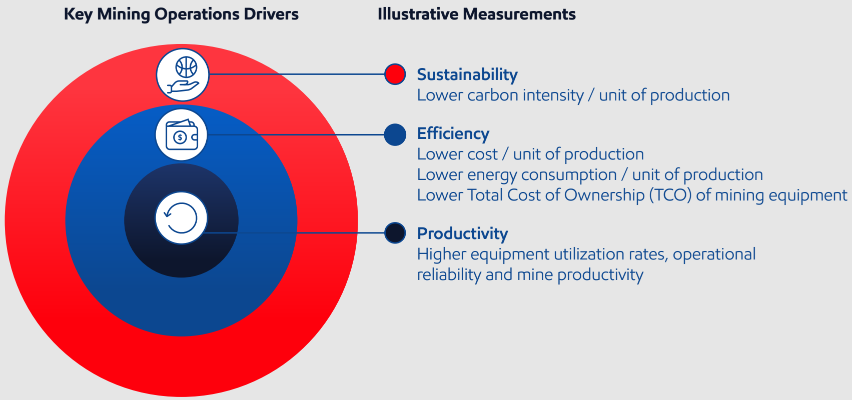
3.1 The factors shaping choice selection

In this section we will primarily focus on the choices up for consideration by mining operators with a focus on Scope 1 and 2 GHG emissions. Onwards transportation by rail, road and/or shipping is an important focus of some mining companies, but is a subject all by itself, as are Scope 3 GHG emissions associated with the end use of mining production.

Given the broad array of operations in the mining sector, a portfolio of solutions will be required to help the sector achieve its Scope 1 and 2 GHG emission reduction goals affordably, without compromising operations. Hence multiple participants in the mining sector's wider ecosystem, from OEMs to energy providers, are working to open up a portfolio of solutions from which mining operators can choose. Some offer greater potential to scale today and may be transitional or foundational for other choices which may offer longer term scalability potential. All require focus, dedication and a willingness to embrace change, test, learn and scale.

These choices are guided by sustainability objectives including an emphasis on lifecycle GHG emission reduction goals. They are also influenced by the pragmatic requirement for "economically sustainable" operations, as highlighted in **Figure 14**. This means mining operators make choices around sustainability, and especially GHG emission reductions, through a lens of productivity (maximizing reliability and productivity of operations), and efficiency (optimizing energy consumption and other costs of operations per unit of production and guided by key measures like Total Cost of Ownership (TCO) of equipment as highlighted in Section 1.6). The preferred options for an early GHG emission reduction roadmap will be those which least compromise (or better still enhance) productivity and efficiency and with favorable TCO outcomes.

Figure 14
Operational Drivers Influencing Choice Selection



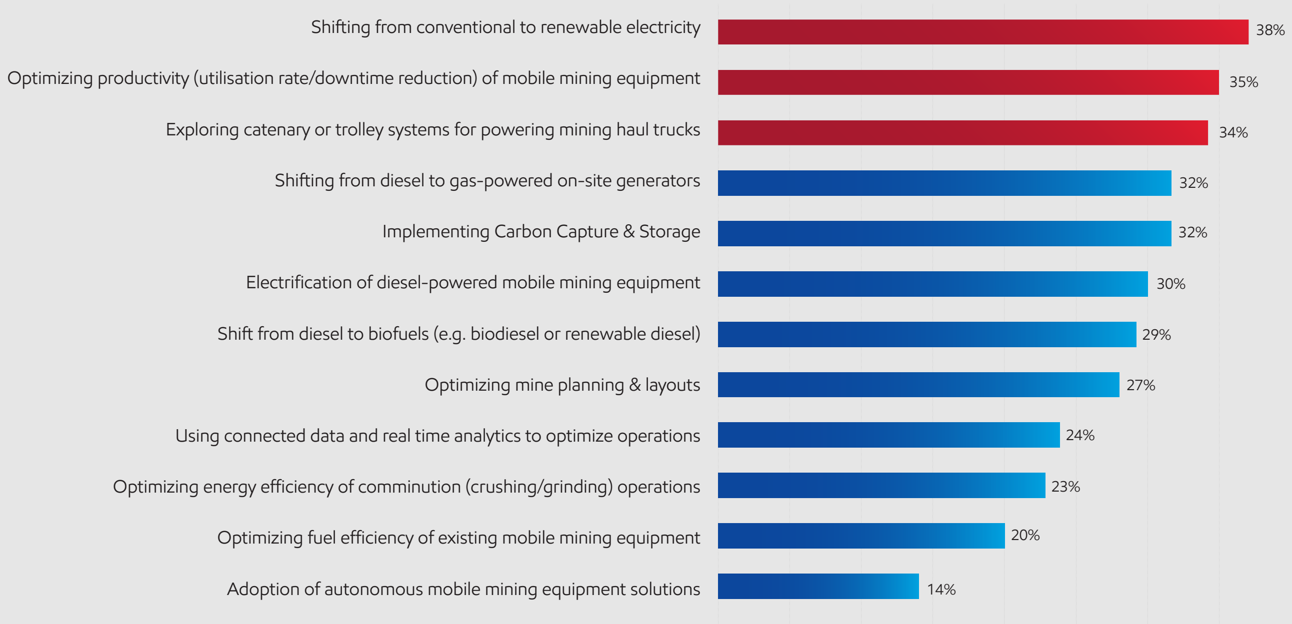
Source: ExxonMobil.

Since the secondary market for mining equipment is relatively limited, the stage in the replacement lifecycle of existing mining equipment, and the remaining life of the mines in which they currently operate, will also influence choice set. Given every mine has its own operational dynamics, these will also play a shaping role, together with the location in which the mine operates.

Figure 15 highlights where mining operators are currently strongly focusing their efforts to reduce emissions and we will explore many of these focus areas further in the rest of **Section 3**.

Figure 15
Key Current Focus Areas for Reducing Emissions

*Q12. In your organization what are the current key focus areas for reducing emissions? (% with Strong Focus — 5 out of 5)**



*Respondents were asked to score each of the above potential focus areas from 1 (no focus) to 5 (strong focus). Percentages represent % of respondents who ranked focus in that area as strong.

Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

3.2
Shifting to renewable electricity via renewable power agreements & on-site generation

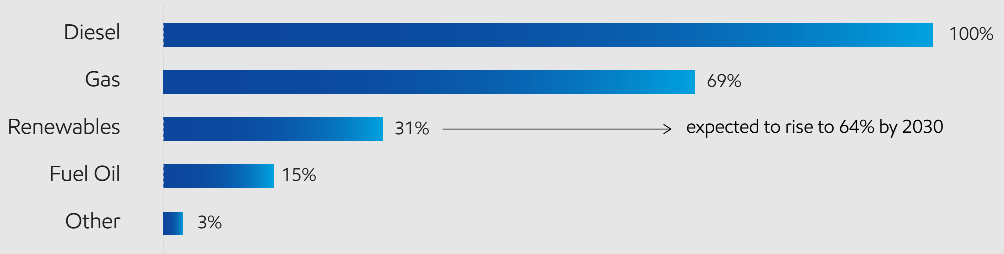
Per **Figure 15**, transitioning to renewable electricity is a strong focus area of mining operators.

Mines are already electrified to a degree, but not all are directly grid connected. Given the high utilization of electrical power in mining operations, transitioning, where practical, to renewable electricity is a key consideration of the lifecycle GHG emissions reduction plans of mining operators, especially for existing electric-powered stationary mining equipment.

Many mines are not grid connected and generate electricity on site, with diesel and gas-powered generators being most common as highlighted below in **Figure 16**.[1]

Less than a third of mines are using some element of renewables (for instance solar and wind) in their on-site electric generation but many operators plan to do so in the period up to 2030 as shown in **Figure 16**.[1]

Figure 16
On-Site Electricity Generation — Energy Source
Q2. Which of the following technologies do you currently use for your on-site electricity generation?



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

> Some [operators] are building their own solar wind farms and battery energy storage systems for capacity and grid stabilization. Most are purchasing via power purchase agreements, rather than building themselves because it's heavy capital intensive.
>
> **Leading Mining Consultant**[2]

> The first thing is trying to figure out how you get renewable electricity. In our mine in Portugal as an example, we partnered with the EU and we're going to build a solar farm that's going to sit right next to the mine that will supply the renewable energy. So, from that point going forward [in the mine concerned] something like 80% of the electricity we use will be renewable.
>
> **VP of Mining Technical Service**[2]

> In large open pits you can switch your shovels and a few other things to electric, but they're relatively small [diesel] consumers compared with trucks. So the easiest place [to start] is to get the current equipment that uses electricity onto renewable electricity.
>
> **VP of Mining Technical Service**[2]

> One of the reasons I was interested in connecting to the grid is that there was a project for a large solar array. I wanted to position ourselves as a cornerstone customer for the low carbon electrons from the grid. The challenge with solar and wind is it's not particularly firm power. We installed a battery as a smoothing technology.

Mining Operation CEO[2]

> We looked at solar arrays that would effectively fold up. You could transfer them from one bore field to the next as the mine progressed, fold them up to protect them from the blast and then open them up. The entire system was designed and constructed so that you would have solar, a battery pack, and a diesel generator. Within a few hours of the day, the early part of the day, you would replenish your batteries completely. We would run the bore water pumps off solar for the majority of the day. You would have battery then for maybe half the night before switching to diesel to keep you going through the night. The sun would come up in the morning and the cycle would start again.

Mining Operation CEO[2]

A transition to renewable electricity also positions mining operators to optimize the combined Scope 1 and 2 GHG emission benefits of electrifying mobile mining equipment.

Electrifying mobile mining equipment (see **Section 3.9**) additionally requires significant change to the mobile fleet, especially haul trucks, a significant expansion of electricity generation supply or capacity, and energy balancing systems. This will require a roadmap all by itself, progression of technology, many challenging projects, the sector reshaping its skills base, a highly collaborative approach, significant capital investment and it will take time.

Electrifying the haul truck fleet in the global copper mining industry alone was estimated by Wood Mackenzie in 2023 to require nearly 34 TWh electricity, the equivalent of Denmark's entire electricity consumption.[27]

Electrifying a typical Australia iron ore operation was estimated by McKinsey to more than double the mine's electricity consumption, requiring an incremental electricity consumption of 200-300 GWh per year.[28] This is similar to the anticipated electricity output of the Merredin Solar Array, the largest solar farm in Western Australia. From 462 hectares of land, this project is expected to generate 281GWh of electricity annually, enough to power approximately 42,000 Western Australian homes.[29]

The pressure on the grid would be significant and hence mining electrification requires long term investment and planning with the relevant authorities. For those mines not connected to the grid itself, it requires renewable electricity generation closer to the mine and in some cases, at the mine site itself, potentially starting small and expanding over time where space and conditions allow.

Renewable electricity generation is generally not ratable whereas mines operate pretty much continuously through the day and year. A shift to electrification requires, therefore, significant investment also in stationary energy storage and balancing systems.

Mining companies, like BHP, are actively engaging in renewable electricity collaborative projects. As an example, in 2019 BHP announced it had signed Power Purchase Agreements (PPAs), securing solar, wind and hydropower electricity for its Escondida and Spence copper operations in Chile with Chilean power generators, Enel Generación Chile and Colbun SA, under long term agreements of 6 TWh in total.[30]

In addition to renewable energy projects, longer term, small modular reactors (SMRs) may also play a role in electrifying and reducing GHG emissions from the mining sector, especially for remote, off-grid mine sites.[31]

3.3

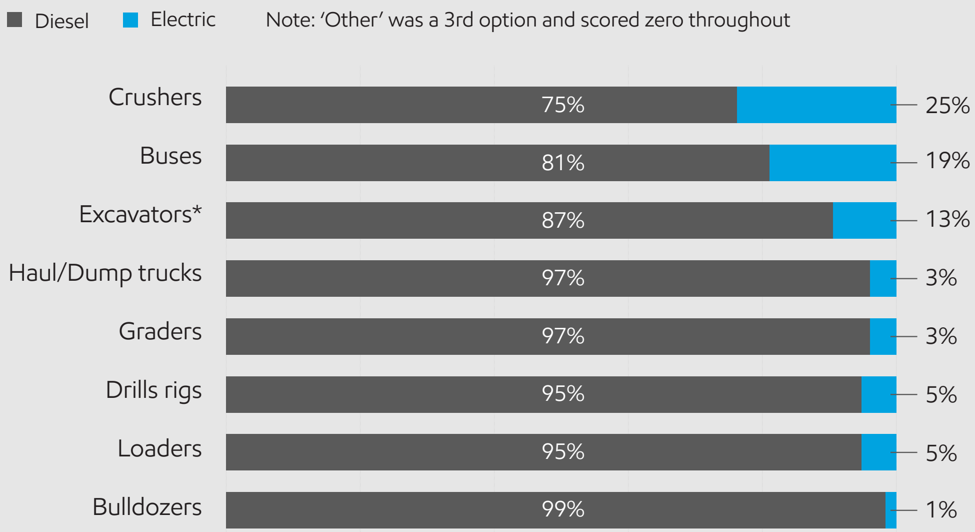
Securing incremental productivity & efficiency gains with a focus on mobile mining equipment

Per **Figure 15**, an early area of focus from operators is to squeeze out incremental operational productivity gains from mobile mining equipment. Each piece of equipment in the mine has its own potential optimization pathway and we will focus primarily on mobile mining equipment in this paper given its significant contribution to energy consumption (**Figure 5**) and reliance on diesel today — see **Figure 17**.

Figure 17

Average Energy Mix for Different Mining Equipment, 2025

Q18. What is the current approximate energy split for...



*including drag line, rope shovels, hydraulic shovels

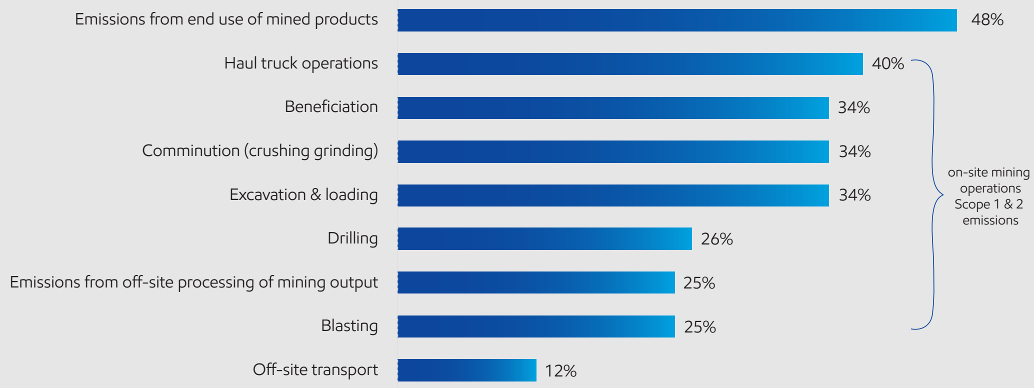
Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

In terms of mobile mining equipment, haul truck operations, followed by excavating & loading equipment, tend to receive the highest focus in plans to reduce emissions — see **Figure 18**. This is driven by the level of energy consumed moving ore and overburden around a mining site. Comminution and beneficiation activities also receive a level of focus.[1]

Figure 18

Operational Focus of Emissions Reduction Plans

Q22. In which element(s) of operations are you currently most focused in your emission reduction plans?



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

When planning a mining operation from scratch, maximizing productivity and efficiency is a key consideration, and will influence the right blend of hardware given the geology, seam characteristics and local conditions.

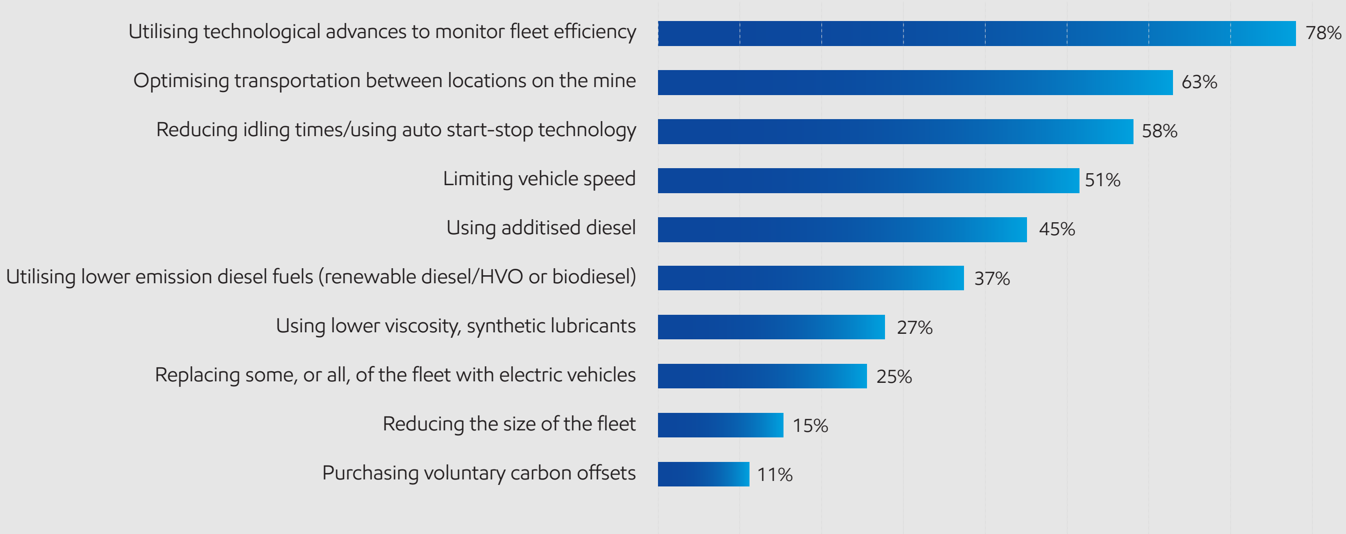
Given conveyers are easier to electrify, mining planners may consider rebalancing their use versus mobile hauling equipment. However, they represent significant capital outlays, and once installed are more difficult to move, whereas mobile equipment offers flexibility as the mine develops.

Hence, much of the focus is on reducing emissions from the existing fleet while exploring mid-to-long term options for electrification of the mobile fleet (see **Section 3.8**) with a particular focus on using technology to monitor fleet efficiency, optimize routings and reducing idle times — see **Figure 19**.

Figure 19

Measures Deployed to Manage Haul Track Fleet to Lower Carbon Emissions

Q23. What measures or tools do you plan to deploy in your organization to manage your haul truck fleet towards lower carbon emissions? (Top 3)



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

When looking to improve productivity and efficiency of existing mobile mining equipment, the first place to look tends to be enhancing the use of data to optimize human behaviors. Benefits from connected data systems and platforms can be taken a level further in automation solutions and, where possible, autonomous operations.

Areas of optimization include:

- Break and shift change processes.
- Off-haul travel.
- Maintenance schedules and real time monitoring to minimize downtime.
- Dispatch of hauling vehicles to loading units and their subsequent routing to dump sites or processing plant.
- Matching fleet number and vehicle size to evolving site configuration to fine tune the combined excavator-haul truck flow.

Other practices include maintaining optimum truck speed, good haul road conditions and leveraging double sided loading where operationally practical.

"Productivity and efficiency are top of the list. Are you using your trucks? Are they moving, and are they being operated at the optimal level? What is the utilization rate? Is the truck full? Are you mining properly so you don't have waste in there instead of ore? Are the trucks idling? Are people taking breaks and leaving the truck running? This is very important day to day."

VP of Mining Technical Service[2]

"Efficiency is the first place to look for emissions reduction goals... If you look at what's happening in a mine site, and what the mine manager thinks is happening, they're two totally different things. If you go in and dissect your operation, really report, really fine tune what you're doing, you're going to cut your waste. And automation is the first place I would look. Because computers do things more efficient than humans and you just can't change that, right? I would look at my current operation and make sure that it's as streamlined and as efficient as possible."

Mining Operations Lead[2]

"One of the things that we're focusing a lot on is the haul road conditions. There's no way that you'll have a tarmac road in a mine, but you can decrease the rolling resistance so rather than having 3% rolling resistance you might be able to cut that down to 1.5%, which will save 1.5% of your energy burn. With more focus on it, if the mining manager starts to take great interest in their roads, the grader operators and water truck operators are measured against it, what's measured is maintained. You can put some sort of poly-coating or polyurethane mix into your water carts and apply it on top to give a better caking effect and make it harder. Then you have good high quality main haul roads that have got much less rutting, much less wear, and you get better tire life as well. It benefits autonomous systems as well. Whether diesel or electric, these autonomous trucks run within a plus or minus of around 150 millimeters. They're on effectively tram lines, on rails, and you can see them."

Principal Mining Engineer[2]

3.4
Maximizing the benefits of data integration & fleet management systems

As the saying goes, *"What gets measured gets done"* — the establishment of emissions reduction goals places an ever-greater emphasis on integrated data capture as part of a real time improvement culture.

To augment their overall TCO improvement package, OEMs have acquired companies specializing in data-driven fleet management systems, an example being Komatsu's acquisition and integration of IVolve.[32]

Many mining operators, however, might wish to retain optionality in procurement strategies and may choose to deploy agnostic data management platforms. MaxMine is an example of one such platform. MaxMine is a Software as a Service (SaaS) business model, offering a platform which manages and optimizes haul fleet operations.

Speaking on the Digging Deeper Podcast series, Tom Cawley of MaxMine highlighted the "significant waste in the mining sector" and highlighted it as *"one of the least digitized, largest industries in the world with less than 3% of mining haul trucks automated."*[33] MaxMine claim[34] potential gains across the board, from payload to haul speed to fuel burn, by optimizing operations using data, including the benefits from reduced off-circuit travel and better haul truck queue management.

McKinsey quotes a Scopes 1 and 2 GHG emissions improvement potential of 5–20% from data-driven operational efficiency improvements alone, with a case study indicating 5–10% fuel reduction from leveraging a machine-learning based platform and focusing on a few key areas of mining operations.[35,36]

Whatever the platform, improvements require:

- High fidelity measurement and integration of data from sensors across each mining truck and the fleet as a whole.
- Real time data analytics.
- A cultural buy-in at all levels, a dedication to business improvement and integration of granular insights into daily operations.

With this combination there appears real potential for near term improvements and contribution to emission reduction goals, without major capital investment, using available capabilities with the existing fleet.

Figure 20 highlights the key themes around mining operator plans and the use of real-time connected data in mining operations.[1]

Figure 20
Using Real-Time Connected Data in Mining Operations

Enhancing Operational Efficiency with Internet of Things (IoT) and Real Time Analytics

Real-time data and IoT technologies is being used to **optimize equipment performance, monitor operations, and improve safety**.

Organizations plan to digitize operations and expand the use of **IoT sensors, predictive analytics, and data-driven decision-making**.

Predictive Maintenance and Downtime Reduction

Predictive maintenance strategies using connected data help forecast equipment failures and minimize downtime.

Advanced analytics and machine learning are driving **better asset management and equipment utilization**.

Improving Safety and Environmental Monitoring

Wearable devices are tracking **worker health and location** to ensure safety.

Real-time data is being used to **monitor air quality, emissions, and ventilation** in mining operations.

Data-Driven Strategic Decision-Making

Connected data enables organizations to **anticipate future demands** and make **proactive, data-driven decisions**.

Companies **plan to enhance their ability** to forecast operational needs and align with sustainability goals.

Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=50.
Question: Could you please briefly summarize your main efforts and future plans using real time connected data?

> There are lots of systems. They try to monitor things. There's actually lots of data in these organizations... but for you to be able to use that, you need to have sanitized data, which is meaningful data. You need to have one platform, so you can bring all the meaningful data together before adding on algorithms and analysis. That's where they fall short.
>
> **Leading Mining Consultant**[2]

3.5
Layering in additional benefits from autonomous operation

Autonomous operation takes data-driven operations to the next level. Operators view automation as one of the key challenges facing the sector (**Figure 8**)[1] but one the sector is starting to embrace. In this respect the mining sector stands out as being ahead of the curve vs its on-road fleet counterparts. This is driven by the scale of potential per truck benefits and the level of control of the driving environment compared with the complexities of on-road driving conditions.

> That is the direction I would expect in the next 15 years. Virtually all open pit mines will be autonomous and substantive amounts of underground mines will become autonomous. It improves efficiency because the machines run at the optimal level. The other is that driving large pieces of equipment for 12 hour shifts is one of the largest ongoing safety concerns you have at a mine site. People stop paying attention. And when you're driving those pieces of equipment, they can be extremely dangerous. That safety factor is another reason that lots of mines are working towards autonomous haulage.

Mining Technical Services VP[2]

> Large Western Australia mines have remote operating centers where you've got to have some individual sitting behind a computer and monitoring those automated systems in Perth. That way they don't have to fly people to site, reducing overhead cost to run camps and flights. There's a lot of upside with automation beyond the efficiency and the cost side of things.

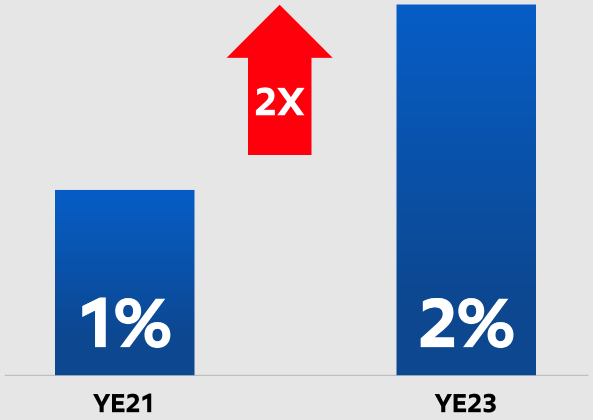
Principal Mining Engineer[2]

> We've primarily automated surface drilling and truck fleets. Automation works best for something that's repeatable and on a very set path. It brings a higher amount of productive hours and reduces total operating cost. When you pay for truck operators it adds up pretty quick but the repeatability of autonomous is also key. You're not going to send material to the wrong dump. It's going to be from this geotagged block. You know roughly what the material is from your grade control. You can GPS track the ore tons from digging to dumping location, so you're not going to have ore go over a waste dump like you would if someone just made a mistake and turned left. Repeatability, cost efficiencies, and greater productive hours, that's the rationale behind it.

Principal Mining Engineer[2]

GlobalData estimate there are approaching 100K mining haul trucks globally, of which, as of mid-2024, nearly 2,100 were operating autonomously, representing a doubling in nearly 2 years.[37] Based on these estimates, over 2% of all mining haul trucks are being operated autonomously today — see **Figure 21**.[37]

Figure 21
Rise in Autonomous Haul Truck Operations



Source: ExxonMobil analysis of haul truck populations, reported by GlobalData.

Geographically, Australia was the early adopter of autonomous operations in mining. By Nov 2023, they hosted over half the total number of autonomous haul trucks, followed by China and Canada in 2nd and 3rd place respectively. Mining operator BHP has transitioned more than 300 of their mining haul trucks to autonomous operation, with Rio Tinto and Fortescue also early adopters of the technology.[37]

In autonomous operations, a single operator can manage multiple vehicles, often from a remote operation center. Many of Australia's autonomous mining haul trucks are controlled from Perth, for instance, reducing the need for fly-in/fly-out operators.

In addition to this positive for operators, autonomous operations in mining get to the wider fundamentals of safety, productivity and efficiency, and tick a number of critical boxes:[38]

Some of these benefits may overlap with the benefits highlighted for data and fleet management systems.

Implementing autonomous operation is a major project, requiring a collaborative approach with equipment suppliers, service providers, mining operators and their teams. It also requires some change to operations to unlock benefits. For instance, autonomous operations benefit from more active haul route surface management.

Beyond haul trucks, other mobile mining equipment also benefits from autonomous operations, for example drill rigs and dozers operating more repetitive tasks. And in underground operations, adoption of autonomous drilling rigs, haul trucks, and loaders is growing. Indeed, the benefits of a shift to underground autonomous operations may be even greater, given the significant inhospitable nature and additional safety risks in underground mining (gas build up and cave ins).[39]

Figure 22 highlights the key themes around mining operator plans for autonomous mining operations.[1]

- **Productivity:** step change in productivity of fleets with increased time in-service from elimination of shift changes with improvements of 15-20% quoted in various sources. Autonomous trucks can also go faster when there is less staff-operated equipment on the scene.
- **Route optimization & better fuel efficiency:** with artificial intelligence (AI) and machine learning, operators can optimize routes, reducing the time it takes to transport materials from the mining site to the processing area, contributing to shorter cycle times, higher throughput and reduced fuel consumption per tonne of production.
- **Better resource management:** autonomous mining vehicles help companies manage resources more efficiently. These vehicles can reduce material waste by precisely controlling loading and unloading processes, optimizing ore extraction, and reducing overburden movement.
- **Lower maintenance costs:** more repeatable, smoother driving should lead to less wear and tear. Komatsu claims 40% better tire life and 13% reduction in overall maintenance costs.[39]
- **Reduced operating costs:** through reduced labor costs, fewer accidents, less equipment downtime, and optimized fuel consumption.
- **Safety:** fewer people, reduced fatigue and more consistent repeatable behavior.
- **Reduced recruitment challenge:** reduced staffing costs and recruitment need for remote fly-in/fly-out locations.

Figure 22 Operator Plans for Automation in Their Mining Operations

Autonomous Equipment Implementation

Companies are progressing with autonomous haul trucks, drills, and loaders to enhance safety, efficiency, and reduce operational costs.

Expansion plans by 2030 include broader deployment of autonomous systems across mining operations.

Increased Safety and Risk Mitigation

Remote operation centers and collision-avoidance systems ensure a safer work environment by minimizing human exposure to hazardous tasks.

AI-driven monitoring systems and wearable devices are improving real-time safety and compliance.

AI and Data-Driven Optimization

AI and machine learning are being used for fleet management, predictive maintenance, and performance optimization.

Real-time connected data and IoT sensors are enhancing decision-making and operational efficiency.

Energy Efficiency and Emissions Reduction Goals

Companies are exploring autonomous electric vehicles to reduce their emissions.

AI-driven route optimization and battery-powered autonomous equipment improve fuel efficiency.

Future Expansion and Scalability

Plans to integrate autonomous technologies in underground mining operations and scale automation across multiple processes.

Enhanced cybersecurity protocols safeguard autonomous systems as they evolve.

Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=50.
Question: Could you please briefly summarize your progress and areas of autonomous operations?

Imperial Oil's Autonomous Operation Case Study[40]

In November 2023, ExxonMobil's Canadian majority owned affiliate, Imperial Oil, announced they had successfully transitioned their entire Kearl Mining 81-strong haul truck fleet (CAT 797F 363t trucks) in their Alberta Oil Sands operation over to autonomous operation.

Imperial now operates the largest autonomous fleet in the Canadian mining industry and one of the largest autonomous mining fleets in the world. The application comes with the challenges of a remote north Canada location with unpredictable weather and ground conditions. Imperial is looking to improve truck productivity, safety, and reduce operating costs.

Imperial, Finning & Caterpillar collaborated on the shift to autonomous operation using a combination of the CAT™ MineStar™ Solutions suite of software including Fleet (dispatch system), Terrain (loading & grading system) and Command (autonomous haul).

3.6
Taking advantage of diesel engine technology developments to reduce criteria emissions

In commercial on-road land transport, regulators have enacted a series of ever-greater reduction targets for criteria emissions (for instance NOx and particulate matter). Regulations for off-road fleets are not as stringent as for on-road fleets, and the penetration of mobile equipment meeting even the latest standards — Class V in Europe and so-called EPA Tier 4 in North America[41] — lags on-road fleet equivalents, where truck tractor retention length tends to be shorter for the biggest fleets with the greatest ton mileage.

EPA Tier 4 emission standards, introduced in 2004 and phased-in from 2008-2015, required a further PM and NOx emissions reduction of about 90% over prior standards, which have largely been achieved by leveraging advanced exhaust gas aftertreatment technologies. Most manufacturers use urea-Selective Catalytic Reduction (SCR) catalysts for NOx control. Some, but not all, also utilize a Diesel Particulate Filer (DPF). While the California Air Resources Board (CARB) has explored the development and introduction of Tier 5 off-road standards, corresponding regulations have not yet been adopted by the US EPA.

European standards for non-road diesel engines harmonize with the US EPA standards, and increasingly stringent Stage I–V standards. Stage I-III standards were sequentially introduced between 1999 and 2013. Stage IV standards were enforced from 2014 with Stage V standards phased in from 2019 to 2021.

Given the lifecycle of much mining equipment, many items go through major refurbishments during their operational life. As part of this process, with criteria emissions reduction goals to achieve, some miners may adapt their operating practices either to shorten their target replacement cycle and/or to retrofit more modern, efficient engines and emissions systems during major refurbishments.

3.7
Optimizing fuel, lubricant & tire selection

While not as eye-catching as many other initiatives, managing the basics well regarding fuel, lubricant and tires is an important foundation for optimizing productivity, efficiency and consequently emissions per ton mile hauled by the mining haul truck fleet.

a) Fuels technology which optimizes engine performance

High pressure, precision diesel injection systems are designed to optimize fuel combustion characteristics. This elevates the importance of diesel detergency in sustaining the injection system performance over a vehicle's lifetime.

Injector cleanliness is critical for the performance of lower emission diesel engine technology. Fuels designed to help keep precision fuel injection systems clean can also contribute to reduced fuel consumption.

Diesel Efficient™ fuel, marketed under Esso, Mobil and Exxon brands, and available in many markets globally, incorporates additive technology that can help clean up fuel injectors and mining operators are already benefiting from its fully formulated performance benefits.

A shift towards additized diesel is expected by 2030 with nearly half of mining operators expecting it to form part of the plan in the next five years.[1]

b) Lubricants which help reduce friction & extend drain intervals

Similarly, greater use of lower viscosity, synthetic lubricants is also anticipated on a similar time horizon.[1]

Lubrication is crucial in maintaining mining equipment in operation. It brings protection against friction and wear enhancing durability and longevity of the moving parts. An effective lubrication strategy and the right product selection also help provide operational benefits such as longer oil drain intervals and fuel efficiency. This applies to most lubricated applications, including engines, hydraulic systems, transmissions and drivelines.[42]

Lubricants and hardware technologies are evolving and specifications to use lower viscosity synthetic lubricants, as they become more accepted in the industry, may help reduce fuel consumption, mainly for engine oils where most specifications still require SAE xW-40 grades. Several opportunities to work more fuel efficiently exist across haul trucks and other mining equipment – see, for example, our case study on **page 32**.

Advanced synthetic lubricants are formulated to optimize the tradeoffs between friction and protection across the range of operating regimes from cold start to full load, full speed operation. They offer the potential to unlock benefits across the mining equipment portfolio. Allied with condition monitoring and wear detection programs, and expert support models, advanced lubricant solutions can enhance protection of critical equipment, boost efficiency, and improve productivity by reducing unplanned downtime.[43]

Synthetic lubricants can also extend drain intervals* which reduces lubricant consumption and disposal considerations.[43]

c) Tire solutions which optimize efficiency and maximize uptime

Given the rough terrain, the contours of the operating cycle and the heavy loads carried, the tires and treads in mobile mining equipment are often very large (for example the CAT 797F tires are more than 4m in diameter, and each weigh around 5 tonnes), expensive to replace (the tires alone can cost more than $40K, with the added cost of personnel to replace them) and take a lot of abuse.[45]

Optimizing inflation pressure plays an important role in optimizing efficiency and reducing downtime risk. Real time tire pressure monitoring, for example Michelin MEMS Lite, and indeed on-board automatic tire inflation systems, can play an important role in managing cost, as well as safety and productivity risks from tire failures in operation.[46] As highlighted earlier, autonomous operation, with smoother more repeatable operations, has potential to reduce tire wear significantly, an important add on to the benefit case for automation.

Reducing fuel consumption of generators for power supply in remote mining operations*

Situation:

A remote northern Canadian mine wanted to reduce fuel consumption of generators. The mine was using an ultra low sulfur (S15) non-detergent fuel in their power generators. The site is accessible overland via ice roads and experiences ambient temperatures ranging from -50˚C to +30˚C. As these generators were the primary source of the entire mine site, it was critically important that any solution not negatively impact the reliability of these units.

Methodology:

Esso Diesel Efficient™ fuel was used to evaluate its clean up benefits on the power generators' fuel systems and its impact on fuel economy. A thorough Esso Diesel Efficient™ test fuel program was conducted with seven generators operating on Esso Diesel Efficient™ fuel.

Generator data and historical fuel samples, along with maintenance records were examined. The information reviewed consisted of roughly three and a half years of hourly operating data across 30 parameters for all seven generators.

Esso Diesel Efficient™ fuel performance was compared with historical data for each generator regarding fuel consumption, generator exhaust heat recovery, as well as fuel filter life and fuel injector maintenance.

Results:

The field demonstration was conducted over three and a half months, accumulating approximately 10,000 operating hours across the seven power generators. The positive feedback while operating with Esso Diesel Efficient™ fuel included:

Fuel Economy Improvement: Some level of fuel economy improvement was observed in all seven generators. The generator operating the longest since last overhaul, (i.e. oldest fuel system) showed the greatest benefit.

Reliability: Exhaust heat recovery remained within historical ranges. No fuel system failures, including no fuel filter plugging events, were experienced with the use of Esso Diesel Efficient™ fuel.

*This proof of performance is based on the experience of a single customer. Fuel savings were calculated over three and a half month field demonstration and annualized to calculate estimated yearly fuel savings. Actual benefits and fuel economy will vary depending on factors such as vehicle/engine type, engine conditions and diesel fuel previously used.

Restoring maximum fuel flow rates in injectors in Canadian haul truck operations#

Situation:

Imperial Kearl oil sands' operation is considered one of Canada's highest-quality oil-sand deposits and is being developed with technology innovations.

Kearl identified fuel system issues as a key contributor to unplanned downtime and decreased productivity of their haul trucks. An Esso Diesel Efficient™ fuel pilot program demonstrated less downtime and improved fuel injector performance compared with conventional, non-detergent diesel use.

Methodology:

A rigorous test program was developed to measure injector performance in Kearl's CAT 797F haul trucks, before and after the site's transition to Esso Diesel Efficient™.

Fifty-seven injectors across four haul trucks were evaluated, with injector performance testing conducted by an independent 3rd party research lab, Southwest Research Institute. Injectors were removed for performance analysis in the following phases:

- **Baseline:** Mid-life injectors (avg. 5,000 hours) fueled only with non-detergent diesel prior to transition.
- **Clean Up:** Late-life injectors fueled with non-detergent diesel followed by approx. 3 months (avg 2,200 hours) of Esso Diesel Efficient™ fuel.
- **Keep Clean:** New injectors installed and fueled mainly with Esso Diesel Efficient™ fuel for an average of 4,000 hours.

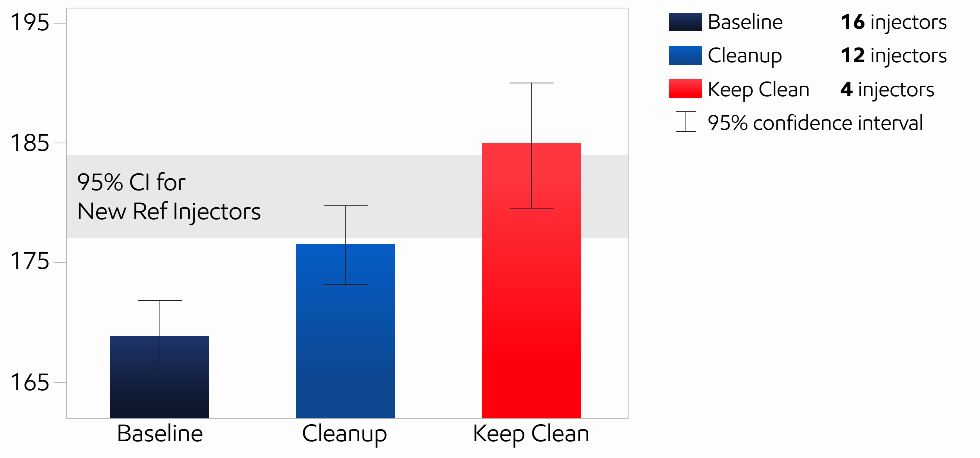
Results:

On average, maximum injector flow rates increased 5% in clean-up and 10% in keep-clean samples, versus baseline (see top left). The results supported Esso Diesel Efficient™ fuel's clean-up claim and showed evidence that Esso Diesel Efficient™ fuel helped to reduce injector nozzle deposits. Improvements include:

- **Smaller Droplets:** Injectors on Esso Diesel Efficient™ fuel showed smaller and more uniform fuel spray particle size distribution. Smaller fuel droplets and a more uniform spray pattern help to improve combustion, which may lead to better fuel economy.
- **Maximum Injector Flow Rate Increase:** Injectors on Esso Diesel Efficient™ fuel saw improvements in maximum flow rates compared with the baseline. Following the pilot, the mine decided to transition from non-detergent diesel to Esso Diesel Efficient™.

Average Injector Fuel Draw at Maximum Injector Open Signal

(mm³ @ 1.2ms Injector pulse width)



Injector Spray Pattern

(Illustration purposes only)

#All comparisons are based on Esso Diesel Efficient™ fuel compared with diesel fuel without detergent additive. Actual benefits will vary depending on factors such as vehicle/engine type, driving style and diesel fuel previously used.

Case Study: Mobil Serv℠ Technical team helps mining company improve haul truck availability and lower operating costs

CAT 793 C/D/F production haul trucks — mining company in Minnesota, United States

Mobil Serv

Situation:

A mining company in Minnesota operates 48 CAT 793 production haul trucks. The mine was interested in improving haul truck availability by 2% as well as lowering fuel and operating costs. The **Mobil Serv℠ Technical team program** was recommended by ExxonMobil engineers to the mining company to optimize its preventative maintenance strategy and conduct a fuel efficiency demonstration study.

Recommendation:

As part of ExxonMobil's **Planned Technical Services program**, the Mobil Serv℠ Technical team analyzed historical data from the past three years, current preventative maintenance strategies as well as oil and filter analysis data. The **Mobil Serv Technical** team then recommended a change in preventative maintenance strategies, filtration technology improvements and that the company switch to **Mobil Delvac™ 1 FDAO** synthetic gear oil. A fuel efficiency demonstration was also recommended to validate the fuel economy improvements.

Impact:

Since implementing the preventative maintenance strategy recommendations and upgrading to **Mobil Delvac 1 FDAO** synthetic gear oil in the drive train of its CAT haul trucks, the mining company confirms that haul truck availability improved by 2% and fuel economy by 2.4%. As a result of these benefits, the company reports reducing consumption by 30,000 liters and tripling its oil drain intervals.

Source: This Proof of Performance is based on the experience of a single customer. Actual results can vary depending upon the type of equipment used and its maintenance, operating conditions and environment, and any prior lubricant used. In this document, ExxonMobil means Exxon Mobil Corporation or one of its affiliates.

3.8
Transitioning from conventional fuels to biofuels

Beyond these measures to optimize productivity, efficiency and associated tailpipe/stack emissions of their mobile mining fleet, mining operators have the option to go an extra step with their existing internal combustion engine-based platforms and/or on-site generators by leveraging biofuels to further reduce lifecycle GHG emissions.

Biofuels are not all the same. There are many variables and associated choices, including:

- Bio-feedstock.
- Production pathway.
- Carbon intensity (which depends on several factors including the above).

There are two main biofuel solutions:

- Biodiesel, also known as Fatty Acid Methyl Ester (FAME).
- Renewable diesel, also known as hydrotreated vegetable oil (HVO) and HDRD (Hydrogenation Derived Renewable Diesel).

The GHG emissions reduction potential of biofuels is generally measured across the fuel lifecycle from growth of the bio-feed to end use. During the biofuel lifecycle, CO_2 released in the combustion phase of the product is at least partly abated by absorption in the growth phase, meaning biofuels often have a lower carbon intensity than conventional fuels.[47]

Biofuels can either be used neat and/or blended with conventional diesel. The benefits for use of biofuel and/or blends in a mining operator's roadmap to reduce operational fuel lifecycle GHG emissions, depend on a number of factors as highlighted above. The lower the biofuel blend percentage, the more modest the GHG emissions reduction potential.

More detail on Biodiesel and Renewable Diesel, including the impact on GHG lifecycle and tailpipe emissions, can be found in our white paper on commercial transport, Moving Forward: Planning the Journey to Lower Emission Commercial Diesel Fleets.

Regulatory frameworks in transportation will influence availability of biofuels solutions. Policy which is technology neutral and focused on well-to-wheels or cradle-to-grave lifecycle GHG emissions, rather than narrowly on tailpipe emissions standards, have the potential to contribute to greater availability of lower GHG emission diesel fuels like biodiesel and renewable diesel for the mining sector.

a) Biodiesel

Biodiesel is a cost-effective choice to help reduce the carbon intensity of fuel for compression-ignition engines.[47] Biodiesel, where it is used, is primarily supplied in blends with conventional diesel. This is done because biodiesel contains oxygen in its chemical structure, which amounts to a lower energy density vs. conventional diesel. OEMs tend to limit their approvals for use of biodiesel to blends of up to B20 (up to 20% by volume FAME content). Some OEMs recognize the value of biodiesel and have qualified their engines for B30 or even B100 usage. Operators should consult their owner's manual to understand the extent to which biodiesel can be used in their equipment.

While biodiesel has some usage constraints, it is a well-established biofuel for diesel applications. In practice, biodiesel has long been blended into conventional diesel in many markets around the world to comply with regulations mandating use of biofuels. In North America, biodiesel blending at up to 5% by volume (B5) and, in Europe, up to 7% by volume (B7) is common.

In Indonesia, a major mining market, diesel used in mining (amongst other sectors) is subject to a bio-mandate requiring blending of minimum quantities of biodiesel with conventional diesel. This minimum limit has been progressively raised from B20 in 2018 to B30 in 2020, to B35 in 2023 with a further rise to B40 in 2025.[48] This is in part driven by energy security concerns domestically. Managing the pace and magnitude of biodiesel use and considering carefully the whole pie of associated financial costs (including operator TCO impact and biofuels subsidies) in markets following similar pathways requires careful thought and a coordinated approach.

Biodiesel can have poorer low-temperature performance and storage stability than conventional diesel, and may contain impurities from the manufacturing process that can contribute to corrosion and filter blocking tendency, especially at elevated blend levels. Careful sourcing of biodiesel from a reputable supplier to ensure it meets a suitable quality standard is important in determining the operational experience. Operators should always check with their equipment supplier before first use and careful in yard biodiesel storage disciplines are critical.

With growing use of biodiesel, and a move to use of higher percentage blends, many OEMs see fostering support of this fuel as a strategic market advantage for themselves and end users.

Caterpillar states that biodiesel fuel is acceptable for use in their equipment, highlighting the importance of fuel quality in successfully using biodiesel. Caterpillar indicates that blends of 20% biodiesel with conventional diesel (B20), such as those meeting EN 16709 or ASTM D7467 specifications, are acceptable in most Cat engines, including Tier 4 engines. Caterpillar also indicates that neat biodiesel (B100), such as that meeting ASTM D6751 or EN 14214, is acceptable in many Cat engines including equipment powered with its 2023 Cat C13D platform.[49,50]

Cummins with a strategic collaboration with Komatsu, and generators featured in both Komatsu and Hitachi excavators, has approved use of B5 in all their engines. Cummins has also approved use of B20 in high horsepower engines built after January 1, 2008, except Tier 4, in a series of models (QSK78, QSK60, QSK50, K2000E, K50, QSK45, QSK38, K1500E, K38, QST30, QSK23, QSK19 and K19) when used with a variety of fuel systems (Pressure Timed, High-Pressure Injection, Modular Common Rail Fuel Injection System and BOSCH Pump-Line-Nozzle).[51]

Komatsu America indicated in 2008 that blends up to B20 can be used for all Komatsu engines but indicated a number of caveats in terms of quality requirements and storage and handling of the fuel.[52]

At FAME contents of B20 and above, particular care is required for storage and handling of the biodiesel blends as FAME attracts water. The presence of free water can encourage microbial growth.

In research commissioned by ExxonMobil, Indonesia-based mining operators have reported operational challenges at FAME contents of 20% and above, including filter blocking. The actual experience of fleet operators may depend on factors such as the FAME quality, application, and operating conditions.[53]

The performance additive technology used in ExxonMobil's Diesel Efficient™ fuel formulations can help to mitigate many of the usage issues typically associated with biodiesel. Collaboration with a key mining customer in Indonesia demonstrated significant benefits from using this performance additive technology in the higher biodiesel content blends.

Indonesia Mining Operator — Mobil Diesel Efficient™ B35 Case Study

Mobil Diesel Efficient™ B35

Mobil Diesel Efficient™ helps to improve:[1]

- Performance of engine and fuel efficiency
- Protection against vehicle fuel filter blocking
- Productivity of fleet with reduced downtime

Situation:

With the increasing palm oil blend mandated in biodiesel, a major mining operator in Indonesia highlighted its fleet of more than 150 vehicles was experiencing more incidents of low engine power, more frequent clogging of vehicle fuel filters, or at times vehicles completely stopped functioning.

Seeking solutions to help reduce downtime, save operating costs and improve productivity, the mining operator turned to Mobil.

Solution:

Introducing **Mobil Diesel Efficient™** fuel, an advanced fuel formulation developed by Mobil from decades of experience in fuel technology.

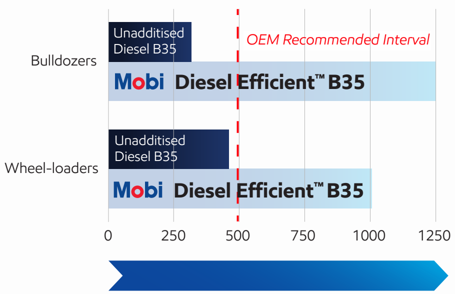
Proven effective in other markets globally, Mobil worked with the mining operator to explore how **Mobil Diesel Efficient** fuel could help improve the performance of its mining fleet.

Over a period of approximately 9 months, we studied the effects of using **Mobil Diesel Efficient** fuel B35 versus unadditised Mobil Diesel B35 in 3 bulldozers (Caterpillar D9 model) and 3 wheel-loaders (Caterpillar 980 model).

Observed benefits from the field trial:[2]

- Significantly cleaner fuel injectors for better engine performance and fuel efficiency.
- Extended vehicle fuel filter lifetime beyond OEM recommended 500 hours for preventative maintenance, increasing productivity.[3]
- Vehicle fuel filter savings ranging between 50% (wheel-loader) to 75% (bulldozer).

Average Fuel Filter Lifetime (hours)



1. Mobil Diesel Efficient™ fuel claims are based on internal and third-party vehicle engine testing, laboratory testing and/or industry or other scientific literature. Basis of comparison for all claims is versus unadditised Mobil Diesel B35 in Indonesia. Vehicle type, engine type, driving behavior and other factors may impact actual results. Mobil Diesel Efficient fuel may be used in other heavy equipment, but results may vary.
2. This Proof of Performance is based on the experience of a single customer who used Mobil Diesel Efficient B35 for approximately 2000 operating hours in wheel-loaders and approximately 3500 operating hours in bulldozers, after baseline monitoring of approximately 2000 operating hours using unadditised Mobil Diesel B35. Trial was performed in Indonesia, with a major mining operator across 6 mining vehicles. Actual results can vary depending on factors such as type of operation, vehicle, engine, driving conditions, driving behavior and fuel previously used.
3. Based on extrapolation of test data, reduced downtime for filter changes would correspond to an estimate of up to +24 hours/year per bulldozer.

b) Renewable diesel

Renewable diesel is increasingly gaining attention, offering a potential pathway to lower lifecycle GHG emissions with existing diesel infrastructure. Hence it is in the consideration set for mining operations, especially where remaining mine life is shorter and hence payback on capital projects is more challenged.

> I read two weeks ago about a mine that had switched entirely to renewable diesel. That seems like a no-brainer. Nobody's talking about it or doing it. They're looking at other alternatives. And the one that is most obvious to me is just change your fuel source.
>
> **Mining Operations Lead**[2]

> Right now, that's the real current reality. They could use renewable diesel, biodiesel. Alternatively, they need to completely replace them or retrofit them with electrified versions of them. When they do that... they have to increase the current electricity supply... because the energy consumption is going to skyrocket. So, that's why they look at alternatives, so they don't have to electrify the whole thing, because that's a massive energy consumption need, so they look at what renewable diesel and biodiesel options are available. They are showing really promising results.
>
> **Leading Mining Consultant**[2]

Per **Figure 19**, only a minority of mining operators have deployed renewable diesel to date but a directional shift towards renewable diesel is expected by 2030 with **49%** of operators expecting it to form part of the plan in next five years.[1]

Like biodiesel, renewable diesel (also known as hydrotreated vegetable oil, HVO) is made from bio-feedstocks, however, it is produced via a completely different transformation process to that involved in biodiesel production. Consequently, renewable diesel is chemically similar to conventional diesel, but without significant aromatic content. Critically, production largely eliminates the oxygenates that drive many of the challenges of biodiesel. So renewable diesel can be used as a drop-in fuel, even in neat form (HVO100/R100), in many vehicles.[54] It has high storage stability and, depending on the production pathway, can offer the potential for great low temperature performance.[55]

The carbon intensity of renewable diesel depends on several factors including the feedstock, its source, the transportation of feedstock, the production process, and the transportation of the finished product. Models, such as Argonne National Laboratory's GREET model, help guide calculation of estimated renewable diesel carbon intensity based on feedstock and pathway.[56]

Production from non-edible, waste-based feedstocks including used cooking oil, typically offer lower carbon intensities relative to production from other feedstocks. Calculations and estimates vary between models and across jurisdictions but, by way of illustration, EU's RED II (Renewable Energy Directive II) assigns to renewable diesel from used cooking oil a default carbon intensity reduction vs conventional diesel of 83% and a typical reduction of 87%.[47]

The carbon intensity of renewable diesel is dependent upon production pathways. Lower carbon intensities can be achieved when using lower GHG emission hydrogen (H_2) in hydrotreating, such as hydrogen produced in conjunction with carbon capture and storage (CCS).[57]

All these factors combine to make renewable diesel an attractive solution to mining operators when building their lifecycle GHG emissions reduction plans.

Rio Tinto has successfully transitioned its whole Kennecott copper mining operation in Utah, US to renewable diesel. Following a successful trial in a smaller boron mining operation a year earlier, Rio Tinto's 97-strong haul truck fleet and all heavy machinery at Kennecott transitioned to renewable diesel in 2024, along with consumption from the concentrator, smelter, and refinery. This represents more than 10% of Rio Tinto's entire global diesel consumption.[58]

Cummins has approved the use of renewable diesel[59] in its high-horsepower engines which are used by operators like Hitachi and Komatsu in some of their mining mobile mining equipment. Komatsu recently announced a transition of the factory fill fuel of their equipment produced in Europe to HVO.[60]

Caterpillar also approved the use of HVO meeting EN 15940 or ASTM D975 in its latest equipment.[61] Likewise, Liebherr supports the use of HVO in a wide variety of applications.[62]

Global renewable diesel production capacity is growing steadily[44] and ExxonMobil now offers renewable diesel containing products up to and including 100% renewable diesel in a number of markets globally. ExxonMobil's majority-owned affiliate Imperial Oil's Strathcona renewable diesel production facility in Alberta is due to come on stream in 2025, producing renewable diesel with suitable low-temperature performance for Canada's cold winter climate.

Kearl Mining Renewable Diesel Case Study

Imperial collaborated with Finning, the world's largest Caterpillar dealer, on the potential for renewable diesel as a practical solution for helping the Canadian mining sector's productivity and lower lifecycle GHG emission ambitions.

They worked together to trial renewable diesel in CAT haul trucks at the Kearl oil sands mine in Alberta. The results confirmed that this equipment can operate on a fully renewable diesel fuel, with similar equipment power and performance.*

*All trial results and comparisons throughout are renewable diesel compared with conventional diesel fuel. Actual benefits will vary depending on factors such as vehicle/engine type, driving style and diesel fuel previously used. Consult the original equipment manufacturer (OEM) for guidance on compatibility with renewable diesel.

Source: Imperial Oil & Finning Trial.[63]

3.9
Adopting a stepwise approach to electrification

Building on plans to transition towards renewable electricity (e.g., wind and solar power) supply (**Section 3.2**), mining operators are at different stages of navigating the electrification of mobile mining equipment. There are different potential steps which are at different levels of adoption, maturity and with different operational implications.

a) Diesel-electric and diesel hybrid powertrains

Combining an electric drive and a diesel drive can act as a bridging technology towards fully electrified operation of mobile mining equipment. There are two main approaches: hybrid drivetrains and diesel-electric drivetrains. Both systems use electric motors to move the equipment and couple a combustion engine with a generator to convert mechanical energy to electricity. The main difference is that in hybrid drivetrains the generator is connected to an electrical energy store, typically a battery, whereas in diesel-electric drivetrains there is no battery.

Diesel-electrics: the main advantage of diesel-electric drivetrains is that the mechanical motion of the combustion engine does not have to be diverted and distributed to the respective drives in complex ways. The alternating current produced by the generator in a diesel-electric drivetrain can be adapted in frequency and amplitude allowing the electric motors to be operated with the appropriate speed for each situation. This makes them well suited to large applications such as mining haul trucks with varying load requirements. However, further efficiency gains are limited by their inability to capture braking energy due to the lack of a battery.

Diesel hybrids: the presence of a battery or other electrical energy store in a hybrid drivetrain adds cost compared with a diesel-electric drivetrain. However, it enables use of energy recovery systems, such as regenerative braking, to further improve efficiency. Hybrid drivetrains are well suited to applications with a greatly fluctuating load profile where they can benefit from frequent acceleration and braking events. For example, in mining operations this could be through braking of the swing motion of excavators which use ultra-capacitors to store recovered electrical energy.

Retrofits that convert existing diesel-electric mining equipment into hybrids through addition of a battery module integrated with power electronics are another potential solution. Given the long life of these vehicles, this can be a cost-effective entry point towards electrification of mining haul operations. For example, First Mode[65] (now operating through the Cummins Inc. Power Systems business unit) is offering a hybrid electric vehicle retrofit for existing diesel-electric haul trucks. This retrofit leaves the existing drivetrain fully intact and adds a battery pack, battery management system and AC/DC converter along with control system integration. When the truck is descending a hill, it uses its wheel motors as brakes. The electrical energy generated is stored in the battery and later used to help power the truck. First Mode claims this results in immediate fuel cost savings and a reduction in CO_2 emissions of up to 25% (depending on various factors such as haul route and operator driving style).

In both systems, the high efficiency of electric motors in partial-load operation (parallel hybrids) or the use of a combustion engine as a generator (series hybrid and diesel-electric) makes it possible to maximize the working time of a combustion engine at its most efficient operating point, which improves the efficiency of the entire system. However, the combination of two systems adds complexity, requiring specialized technology and hardware that adds cost compared with a diesel drivetrain.

> There is some real potential there because as the trucks climb up, they also then need to climb back down. So, you can use sort of a hybrid technology where you're charging the battery going back down. I just have yet to see one in operation. Mining companies broadly are pretty technology-averse because of the high capital requirements and the length of investment. So a mine truck will last you seven or eight years and cost a couple million dollars and if they don't work the way you expect, so even if you lose 2–3% efficiency for whatever reason, it has a major impact on your costs and it takes time to pay back, even if it does work out. You don't want to switch out trucks that are half used. So, if you have a fleet that would require you eight years to do the full switch, then it's going to require whatever testing time comes up front and then eight years to change the whole fleet.
>
> **VP of Mining Technical Service[2]**

> One mining operator built their legacy on refurbishing their haul trucks and have haul trucks that are 30, 40 years old, so if that's the business cycle, then swapping out for hybrid systems and things like that potentially is somewhat attractive, because if you're going to wait until you replace the whole unit, and you're serious about a decarbonization agenda, it's going to take years.
>
> **Mining Operations Lead[2]**

b) Cabled and trolley/catenary systems

Electrically driven equipment is already widely used in mines, even in some mobile applications. For example, electric drive excavators are commonplace with some of these relying upon on-board diesel generators, and others operating on cables, powered directly from the mine's power system. However, cabling has self-evident disadvantages in more mobile mining equipment, such as haul trucks, which move extensively during their daily operations.

While not a new concept, the push to achieve sector GHG emission reduction goals has renewed interest in catenary or trolley systems. In these systems, a network of overhead electric cables connected to the mine's power system is installed over the most common haul routes, and connects to a pantograph on the truck. These systems have the most impact when replacing diesel on the most demanding stages of the haul journey, for instance when climbing fully loaded out of an open pit. They can also provide additional productivity gains due to their potential for greater speed of ascent.

OEM Komatsu, for example, offers a trolley assist solution, claiming benefits in reduced diesel consumption and productivity gains compared to similar Komatsu haul trucks in the same class without the trolley assist system. Their implementation at a Canadian copper mine on a 900m uphill section of the mine showed several benefits when comparing the half of the haul fleet remaining on diesel with the trolley assist optimized trucks.[66]

The Kansanshi deep open pit copper and gold mine operation in Zambia, operated by Kansanshi Mining PLC , which is 80% owned by First Quantum Minerals Ltd., has a trolley assist system, currently operating over forty Hitachi Construction Machinery diesel electric trucks. First Quantum Minerals and Hitachi Construction Machinery announced in 2024 a technical feasibility study to leverage this trolley infrastructure to support full battery electric truck operations.[67]

Another example, with an investment estimated at 250M USD, is the planned Mining Truck Electrification System in Escondida Norte project, involving the installation of a haul truck trolley system. The planned project includes the construction of a new electrical substation and transmission lines both inside and around the Escondida Norte pit.[68] Facilities would electrically assist the movement of trucks inside the mine in the areas where they ascend fully loaded with ore.

These catenary systems have not yet achieved widespread adoption, requiring significant one-time capital investment, buy-in and a fresh mindset from the operations team to gain acceptance. While catenary systems are available in limited use cases for open-pit and can be attractive for underground mining, these systems can be inconvenient where routes are not well defined and where a mine is expanding or further developing. GlobalData estimate that there were over 200 trolley assist trucks operational by the end of 2023.[37]

> I have worked at a mine that had trolley assists in parts of the mine where the trucks were climbing up out of the pit, very much like a streetcar, with power lines overhead. But it wasn't as effective as we initially thought. The operator didn't like it, because it slowed them down, so they would skip it if they could and just run diesel.
>
> **VP of Mining Technical Service[2]**

> Trolley systems or pantographs are really useful in two situations. Firstly, where you have a very large bulk deposit that you can develop from one end and eat your way across it — coal mines are an example of that — where you set up infrastructure on one side and make way across the whole operation via a very predictable path, and not a lot of dynamic response is required. Secondly, where you have ultra-large copper deposits that tend to be essentially the shape of an ice cream cone with a wide top which is perfect for a pit. You can set up a ramp system very easily and have very deep operations. You go downhill on either battery or diesel power, drive to the shovel face and come back uphill on power for two reasons. You've got a diesel-electric truck there, you'll lift up your pantograph and you'll engage, you'll go up the hill faster because you can actually get more power through the electric system when you're [using] a panto than you can out of your diesel engine. And the second one is you've got better pricing power in a lot of those for power than you do for diesel. So it's faster and it costs you less. But where you need flexibility and don't have the deposits that allow you to have 10-15 years' worth of infrastructure set up and you need to move power lines and cables every year or 18 months, it gets expensive.
>
> **Principal Mining Engineer[2]**

c) Leveraging full battery electric powertrain technology (BEV)

Full electrification of mobile mining equipment also requires not just acquisition of BEV haul trucks and/or retrofit solutions, but also significant investment in MW fast charging infrastructure for haul trucks, and/or catenary systems, and cabling for excavators.

Fast charging will be critical given the high utilization rates of haul trucks. Autonomous haul truck fleets in mines, as highlighted earlier, are enabling enhanced utilization rates of haul trucks of upwards of two additional hours per day[69] due to elimination of shift changes and better queue management but this reduces time available for charging.

While battery technology is expected to improve over time, current batteries with the capacity to power haul trucks are also heavy. Fortescue's recent collaboration with Williams Engineering for instance resulted in delivery of battery technology for prototype retrofit of 240 Te haul trucks to BEV.[70] The 15 tonne power system measures 3.6m long, 1.6m wide, and 2.4m high. It is made up of eight sub-packs, each with 36 modules, all individually cooled and each with its own battery management system. At 1.4 MWh stated capacity and the capacity to regenerate power as it drives downhill, it will require charging during the course of the day. A fast-charge capability, stated to be 30 minutes, will be key to manage productivity impacts of the retrofitted solution.

Bringing all this together, electrifying the average mine is a significant, complex program requiring long term planning and collaboration. For existing mines, the remaining mine life will have a bearing on the economic viability of such a venture.

But learning by doing, and building experience is required to move technology forward. Australian mining company Fortescue is pursuing electrification given its plan to eliminate diesel and other fossil fuels from its Australian iron ore mining operations by 2030. Learnings from the implementation of its early projects will be valuable for Fortescue and the mining sector as a whole.[71]

Other leading mining companies like BHP & Rio Tinto are also starting their early forays into haul truck electrification via collaborations with Caterpillar and Komatsu in their Pilbara, West Australia, mining operations.[72] The sector has a long way to go before full electric haul trucks are widely adopted (GlobalData estimated ~100 battery electric haul trucks globally by the end of 2023).[42] The second half of this decade seems set to be an agile learning period and should add clarity to ambitions to electrify mining haul fleets at scale through the coming decades.

With typically smaller haul trucks, the prevalence of electric supply and cabling along underground routes, and the noise and ventilation benefits of fully electric operation, underground mining may see faster adoption of electrified solutions than open pit mines. Cabled electric drilling is already the norm in underground operations, for instance, whereas in open pit mines this is more of an exception.

Figure 23 highlights some of the key themes shaping mining operator plans for electrification of their operations.[1]

Figure 23
Electrification Strategies of Mining Operators

Strategic Electrification Goals

Majority of respondents plan to electrify a significant portion of their fleet by 2030, with a focus on haul trucks, loaders and drills.

Full electrification by 2040 is a long-term objective, with support from improved battery technology and necessary infrastructure.

Investment in Battery Technology and Infrastructure

Organizations are investing in battery technology and charging infrastructure to support the transition.

Fast-charging systems, AI-driven battery monitoring, and modular battery designs are being adopted to optimize performance and reduce downtime.

Pilot Projects and Testing in Progress

Many organizations are piloting electric and hybrid vehicles, focusing on both surface and underground mining operations.

Feasibility studies and pilot programs are evaluating the suitability of electric equipment in various mining conditions.

Emission Reduction Focus

Transitioning to electric fleets is driven by the need to lower GHG emissions, improve air quality in underground operations and enhance operational efficiency.

Some companies are exploring renewable energy sources (solar, wind) to supplement electricity needs and further reduce their carbon footprint.

Collaboration

Organizations are collaborating with technology providers, regulatory bodies, and government agencies to establish standards and accelerate adoption.

Strategic relationships with battery technology providers and suppliers to smooth the transition to electric fleets.

Exploration of Future Innovations

AI-powered battery monitoring, digital twin technology, and regenerative braking systems are being explored to optimize performance and minimize costs.

Secondary applications of waste mining batteries and lifecycle management are being investigated to enhance circularity.

Training and Workforce Readiness

Organizations are developing training programs to equip their workforce with the skills required to operate electric mining equipment.

Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=56.
Question: Could you please briefly summarize your main efforts & future plans regarding the electrification of your mobile mining equipment?

"It's not as simple as people would like it to be. If you stop a truck, it's no longer producing anything, so the economic model starts to fall down — that's a challenge for recharging. If it only takes you 30–40 minutes to refuel a truck, do its service, and swap it out, then that's what you've got to meet with a battery. And when you're automating trucks, you no longer need to swap a driver out, so you are stopping only to do an inspection and to refuel, which means that your use of availability goes up. And so that then works against you unless you have a very slick system for charging or swapping batteries out, that then tends to work against the electrification model. The technology piece is probably not solved just yet… and that's just the truck fleet."

Mining Operation CEO[2]

"There are no battery electric solutions today. There's some things that can help, trolley assist, for example, but we do not have a viable solution for large open pits. That is different underground, we do have some lines that can run battery trucks underground, but it's a balance that the industry is slowly working its way through."

VP of Mining Technical Service[2]

"[For electric haul truck operations], we're looking at a couple of options. You will have to have a slightly larger fleet, that's one of the solutions. Alternatively, you're going to need to have charging locations close to where trucks are stopped frequently. At crushers for example where trucks might be queuing, can we get a couple of charges there? If we've got an automated truck that's linked into the crusher control system and the crusher is going to be down or doesn't need to have a truck for 20 minutes, can we go to an automated charging point, get plugged in and get 20 minutes' worth of charging while we wait for that crusher anyway to go from say 25% to 50% charge in 20 minutes, making use of what would otherwise be idle or dead time."

Principal Mining Engineer[2]

"I don't think that battery swap out can be done simply for the scale of trucks in surface operations. An underground mining contractor in Australia has an underground battery truck that does exactly that. They go up on one battery pack, they get to the surface, they drop their load off, they swap a battery out, and they go back down and back up in one battery pack."

Principal Mining Engineer[2]

"Battery chemistry will evolve over time and battery density will start to pick up. But one of the reasons why we use diesel is it's incredibly, incredibly energy dense. The energy density of diesel is phenomenal. It's hard to beat. Battery generation one will come out, then generation two, three, four, and five will come out. Chemists, metallurgists, everyone is testing them and because of the way that the batteries age you're going to need to be able to recycle and refurbish the batteries every so often, so you can get more than one generation or more than two generations, potentially even three or four generations, out of one truck. So you're going to have a modular battery pack and you're just going to put different types of batteries in as the battery chemistry improves over time."

Principal Mining Engineer[2]

3.10
Exploring the potential for hydrogen

Hydrogen fuel cell EV (FCEV) and ICE (internal combustion engine) technology are being explored for mining haul truck operations with differing trade offs as assessed by ExxonMobil technical experts — see **Figure 24**.

Figure 24
Directional Comparison of Hydrogen Technologies for Mobile Mining Equipment

	Hydrogen Fuel Cell Electric Vehicle (H_2FCEV)	Hydrogen Internal Combustion Engine (H_2ICE)
Advantages	• Zero tailpipe emissions except water vapor. • Higher low load efficiency than H_2ICE & diesel ICE. • Full payload, better suited for long range. • Fast refueling time compared with EV charging time.	• Zero CO_2 tailpipe emissions. • Familiar technology to diesel ICE (mines will be able to leverage existing in-house maintenance knowledge for ICEVs). • Better heat rejection and better efficiency at high loads than fuel cells. • More tolerant of ambient air and hydrogen impurities vs. FCEV. • Ruggedness and durability better than FCEV and similar to ICEV. • Fuel flexibility possible with dual fuel engines (e.g. diesel/hydrogen compression ignition engines and natural gas/hydrogen spark ignition engines).
Challenges in mining applications	• Hydrogen storage system size and management. • High hydrogen cost. • Safety (especially in underground mines).	
	• Evolving technology & high current vehicle cost. • Fuel cell stack durability and sensitivity to vibration. • Higher hydrogen purity required compared with H_2ICE. • Higher cleanliness of intake air required (air purity challenging in dirty/dusty environments). • High cooling needs (affects space requirement & more challenging in low-speed applications due to low air velocity for cooling.	• Non-zero tailpipe criteria emissions (NO_x) requires exhaust after-treatment.

Source: ExxonMobil analysis.

FCEV is at prototype stage in mining. First Mode, Anglo American and others retrofitted a Komatsu 930E 290 Te mining dump truck in 2022 in South Africa, completing one full year of operational trials.[73]

Cummins has been looking at hydrogen solutions, developing hydrogen ICE technology for heavy duty applications with a recent proof of concept in a US class 8 on-highway truck as part of a program with Southwest Research Institute (SWRI), partly sponsored by ExxonMobil.[74] This technology has potential for mining applications also, leveraging more proven and robust ICE technology platforms.

Whether considering fuel cell electric or hydrogen ICE technologies, improvements to hydrogen infrastructure and scaling are required to make hydrogen a more attractive solution for mining. Further considerations are the robustness of fuel cells in the challenging operating environment of mines, and safety concerns over hydrogen use in mining operations. Safety is a critical consideration for adoption of hydrogen as a fuel choice for the mining sector, particularly in underground applications – hydrogen leakage, storage and transportation, and high heat rejection (particularly for FCEV) are also important considerations.

Widespread use of hydrogen in mining currently looks some way away. Whether it will play a complementary role to electric and renewable diesel solutions remains to be seen.

> [The main problem with hydrogen] is infrastructure. Nobody has anything set up to move hydrogen into their site and transfer it from one vessel to another. That's going to take years to get through.
>
> **Mining Operations Lead[2]**

3.11
Considering the potential for renewable natural gas

Natural gas, where supply is an option, is being used by some mining operators for power generation as an alternative to diesel for off-grid mining operations or to complement and/or balance grid supply.

Some mining operators might consider transitioning to renewable natural gas, generated from sources like manure ponds and landfill operations, and supplied under renewable energy certificates and/or long-term offtake agreements.

Dependent on the prevailing regulatory model, renewable natural gas can have very low or even negative estimated lifecycle carbon intensity values, potentially making it an attractive pathway for mining operations to reduce GHG emissions from power generation.[75]

Some commercial road transport operators use compressed and/or liquified renewable natural gas (RNG) to reduce lifecycle GHG emissions from their trucking operations.[76] Switching of fleets from diesel to natural gas (RNG or otherwise) provides greater benefits when scaled up, given it often requires new truck powertrains, repurposing of in-yard facilities and training of maintenance teams. Mining operators will do well to factor this into consideration of alternative pathways including future electrification plans. Retrofit solutions have been explored including diesel/natural gas hybrids. Westport Innovation, for instance, has explored utilization of its High Pressure Direct Injection (HPDI) technology in Caterpillar's 793, 795 and 797 haul trucks.[77]

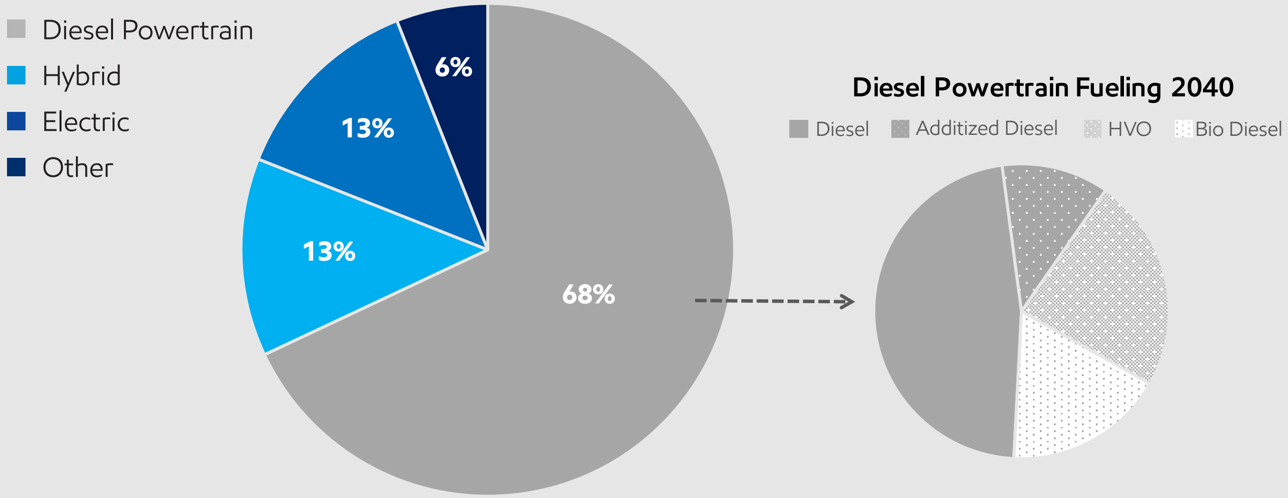
The lower energy density of renewable natural gas compared with diesel is an important consideration for use in larger, heavier haul equipment, meaning liquified storage is likely a better bet than compressed natural gas solutions. For mining operators with natural gas liquefaction/storage on site for power generation, transitioning some mobile mining equipment to natural gas operation might be in the consideration set.

However, natural gas has gained only limited traction in mobile mining equipment so far. It is not attractive for underground mining, primarily due to safety concerns. As well as the safety perspective, avoiding fugitive methane emissions is also critical from a lifecycle GHG emissions perspective. For open-pit mining, there is potential for cost savings compared with diesel, but price differences between diesel and gas can be volatile — to date, few mining operators have followed this route with other options available for consideration.

3.12
A portfolio of solutions by 2040

Overall, when it comes to haul truck operations, the largest consumer of diesel in today's mining operations, mining operators anticipate change but expect electrification to take time — see **Figure 25**.

Figure 25
Anticipated Haul Truck Fleet Energy Mix 2040
How will the mix of fuel types in your haul truck fleet change by 2040?



Source: Frost & Sullivan Research of Mining Operators in US, Canada, Australia, China, Indonesia & South Africa. 1Q25. N=91.

When asked about the anticipated mix of fuel types in their operation's haul fleet of 2040, the average electric share represented a modest 13% with an expectation that hybrids would rise to a similar share. Operators on average expect diesel powertrains would still make up the majority of their haul truck fleet with an average share of 68%, but with a significantly greater role for biofuels, like HVO, in the fueling choice for those vehicles. Hydrogen and natural gas are anticipated to make up the balance.

> Solutions will change from asset to asset, operation to operation, and by country context. Hydrogen technology is still not proven and it's more expensive than anything else so they will leave that behind. Automation of haulage is happening. The next thing they need to do is electrify it or use renewable diesel. If they electrify it, they have options — trolley assists or completely electrified trucks — that give them different diesel consumption reductions.

Leading Mining Consultant[2]

Making change happen in your mining operation

Choosing from an array of options

Recognizing this is a lot to digest, **Figure 26** summarizes the available options.

Figure 26 Summary of Choices

Directional

Opportunity	Section	Adoption	Overview
Renewable electricity via PPAs and/or on-site generation	3.2	Available and key focus area for 0-5yr adoption.	• A major focus area for operators. Where affordable and practical, can contribute to significant lifecycle GHG emission reductions. Enablers include grid connectivity, collaborations with expert solution providers and careful capacity planning. For on-site renewable electricity, reliable renewable resources (e.g. solar), space and storage systems are critical enablers.
Data integration and fleet management systems	3.3, 3.4	Widespread - room for more gains.	• Foundational enabler of improved efficiency and productivity, regardless of powertrain mix. Opportunities exist for many operators. Requires pairing right solution providers with capable, empowered in-house leadership and operational engagement.
Autonomous operation	3.5	Early adopters active with 100% haul fleets at key operations.	• Key enabling technology. Early adopters already demonstrating wins (productivity, efficiency, safety and costs). Builds off data integration/fleet management systems. Requires pairing effective solution providers with empowered in-house team and operational focus.
Upgrading diesel engine tech	3.6	Available but limited voluntary adoption.	• More criteria emissions focussed. Cost may be a factor and, for above-ground operations, lifecycle GHG emissions may be a greater focus area. Adoption is dependent on equipment lifecycle and major maintenance windows.
Fuels performance additive technology	3.7 (a)	Available and growing adoption.	• Product solutions like Esso and Mobil Diesel Efficient™ fuel are drop in fully-formulated solutions with the potential to clean up fuel injector deposits, improve haul fleet efficiency, and may offer filterability benefits for biodiesel blends.*
Lubricants technology	3.7 (b)	Available and growing adoption.	• Synthetic lubricants, like Mobil Delvac™ offer potential for reduced friction, better efficiency and extended drain intervals for productivity gains, and, dependent on the equipment guide, can be often be used with the existing mobile mining fleet.
Tire solutions to optimize efficiency and maximize uptime	3.7 (c)	Available and growing adoption.	• Real time tire pressure monitoring and on-board automatic tire inflation systems can play an important role in managing cost, safety and productivity risks from tire failures in operation.
Renewable Diesel	3.8	Availability and growing adoption where supported by policy.	• Can leverage existing infrastructure and vehicles. Dependent on factors such as feedstock and production pathway, lifecycle GHG emissions benefits can be material according to models like GREET. Availability and cost are key factors and policy dependent.
Diesel Electric Powertrains	3.9 (a)	Fairly common, OEM dependent.	• Productivity gains versus mechanical drive trucks. Potential to augment with energy recovery systems.
Diesel Electric Hybrids	3.9(b)	Limited – retrofit options available.	• Significant potential energy recovery potential/efficiency gain in mining operations, e.g. braking on descent into pit for re-use on climb out. Comes with incremental up front capital cost for mobile mining equipment.
Trolley/Catenary Systems	3.9 (c)	Long-standing technology — focus area for some operators.	• Area of focus of some mining operators and available technology. Best suited to mining applications with consistent routing. • Significant capital investment. GHG emissions reduction potential depends on source of electricity.
Battery electric powertrain technology (BEV)	3.9 (d)	Early adopters.	• Cost and maturity of existing solutions and haul truck productivity impacts are a potential barrier — fast charging infrastructure and sufficient electric capacity are key enablers and represent complex projects, requiring expert solution providers.
Hydrogen FCEV or ICE	3.10	Demos/pilots only.	• Safety, cost and infrastructure barriers to adoption. Hydrogen ICE technology may prove a more durable, lower cost option for mining.
Renewable Natural Gas	3.11	Power generation. Limited mme.	• Use of natural gas (renewable or otherwise) in mining operations is focused today on power generation. • Requires on-site infrastructure investment and adaption to hardware and operations. Access to gas grid is likely a key enabler.

*Vehicle type, engine type, driving behavior, and other factors also impact fuel and vehicle performance, emissions, and fuel economy. Find more information and product availability on your regional Exxon, Esso, or Mobil website.

Source: ExxonMobil analysis. See individual sections for more information and references.

Navigating a practical pathway

Ultimately, every mine is different with many variables including prevailing policy, operational set up, current energy mix, access or otherwise to sufficient renewable electricity resources (e.g., wind or solar), stage in the lifecycle of mine and/or equipment. Consequently, preferred pathways will vary in pacing, priorities and sequencing of choices. Resilience in the face of emerging challenges is essential, but the sector is used to breaking new ground!

A logical, practical pathway might look something like this:

1. Establishing an agile, learning mindset

Establishing and championing a common vision, adjusting the culture, mindset and priorities, and recruiting for or retraining to the new skills which are required will be an important ingredient of success. Larger corporations may be able to pilot at certain locations before implementing on a wider scale. An agile approach to test and learn is critical as pivots may be required based around experience, readiness and reliability of technology solutions. Smaller operations, with fewer resources, may need to approach things a little more selectively.

2. Defining practical goals

It starts with establishing an emission reduction goal based on operational/behavioral changes and market-available technologies (quantified and time based). For many mining operations which are part of larger corporate enterprises this will be established corporately, together with an overall approach.

Tracking and reporting progress is essential to focus efforts.

3. Building operational roadmaps

Ultimately each mining operation has a role to play in shaping its emission reduction roadmaps — understanding the context of each mine and its unique opportunities and challenges, leveraging local expertise, data and adapting to local opportunities. Our research of mining operations across a range of geographies highlighted some key focus areas across the 2025–2040 time horizon. While there are many current areas of focus for mining operators, a few opportunities stand out.

a) Reducing the carbon intensity of the mine's electricity consumption

The roadmap for almost all mines is likely to include an element of electrification. Forward planning and creating a clear short, medium, and longer term blueprint for future power supply and infrastructure needs is critical. Then mining operators can establish the right collaborations and/or start to build some level of local renewable electricity (e.g., wind or solar) capacity. In addition to growing renewable electricity sources, some are shifting from diesel to gas in their on-site electrical generation and, if it becomes more practical, some may consider leveraging CCS in conjunction with gas-powered generators.

b) Securing foundational productivity & efficiency gains

Productivity is another near-term focus area with a specific focus on haul truck operations. There is a win-win-win benefit from optimizing productivity and efficiency as it can help reduce fuel consumption vs the existing trendline for the operation, reduce costs and contribute to emissions reduction gains. Establishing integrated data and analytics capabilities can benefit the operation regardless of whatever energy solution is adopted for mobile mining equipment. Establishing the right platform, capabilities and collaborations is a fundamental step. In many operations it can also lay the groundwork for autonomous operations. The right diesel, lubricant and tire selection/support models can play a complementary role.

c) Leveraging renewable diesel

Where available and supported by policy, renewable diesel is an excellent and proven drop-in solution with potential to make a significant contribution to lifecycle GHG emission reduction goals for existing diesel-powered equipment leveraging existing fueling infrastructure. This has the potential to accelerate GHG emission reduction plans for off-grid mines and/or those with significant diesel-powered equipment.

d) Electrification of mobile mining equipment

If the economics are right and suitable applications are identified, consider starting with lower load, lower power mobile applications like support vehicles. This helps build experience with charging and may be easier to deploy with existing power resources. For higher diesel consumption, harder working, higher utilization specialist equipment, especially haul trucks, full BEV solutions are not yet proven. Identifying potential collaborators, planning, testing and learning with them looks to be a logical next step. Exploring an interim transition to diesel electric drives and hybrid solutions on planned refits may be a good steppingstone towards wider electrification via full battery electric and on catenary systems. Battery technology is anticipated to improve over time. This, together with learnings from early BEV trials, should shape the transition plans and pathways for mobile equipment.

A vision for the future

At ExxonMobil, we develop and deploy technology solutions that help meet society's evolving needs. Today, that means providing products that are needed for modern life, reducing our own greenhouse gas (GHG) emissions and developing technologies to advance a lower-GHG emissions future. For more details on our corporation's plans, we draw your attention to our Advancing Climate Solutions Report.[78]

We're pursuing up to 30 billion USD in lower-emission investments from 2025 through 2030, with about 65% directed toward reducing the emissions of other companies.[79] We're engaged with customers in the heavy industry, power generation, and commercial transportation sectors.

These sectors provide great economic value and generate significant emissions that aren't easy to cut. Together, these sectors account for about 80% of energy-related CO_2 emissions today.[78] Carbon capture and storage, hydrogen, biofuels, and lithium align with our capabilities and have the potential for application in these hard-to decarbonize sectors.

With advancements in technology and the clear and consistent government policies that support needed investments and the development of market-driven mechanisms, ExxonMobil aims to achieve net-zero Scope 1 and 2 greenhouse gas (GHG) emissions in our operated assets by 2050, backed by a comprehensive approach centered on developing detailed emission reduction roadmaps for major operated assets.[78]

Our land fuels business

Our Product Solutions land fuels business currently markets our Diesel Efficient™ fuel and lower emission fuels in multiple countries around the world such as the US and Canada in North America, to the UK and the Netherlands in EAME, to Singapore and Indonesia in Asia Pacific. We are excited about our plans, the transportation sector ecosystem collaborations that are enabling them and we look forward to continuing the productive conversations, to help enable lower lifecycle GHG emissions solutions in the mining sector. To learn more about our land fuels plans, we invite you to follow our ExxonMobil Global Land Fuels LinkedIn page so we can share ecosystem developments, input from those we work with and updates on product solutions we are bringing to market. We look forward to hearing from you.

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