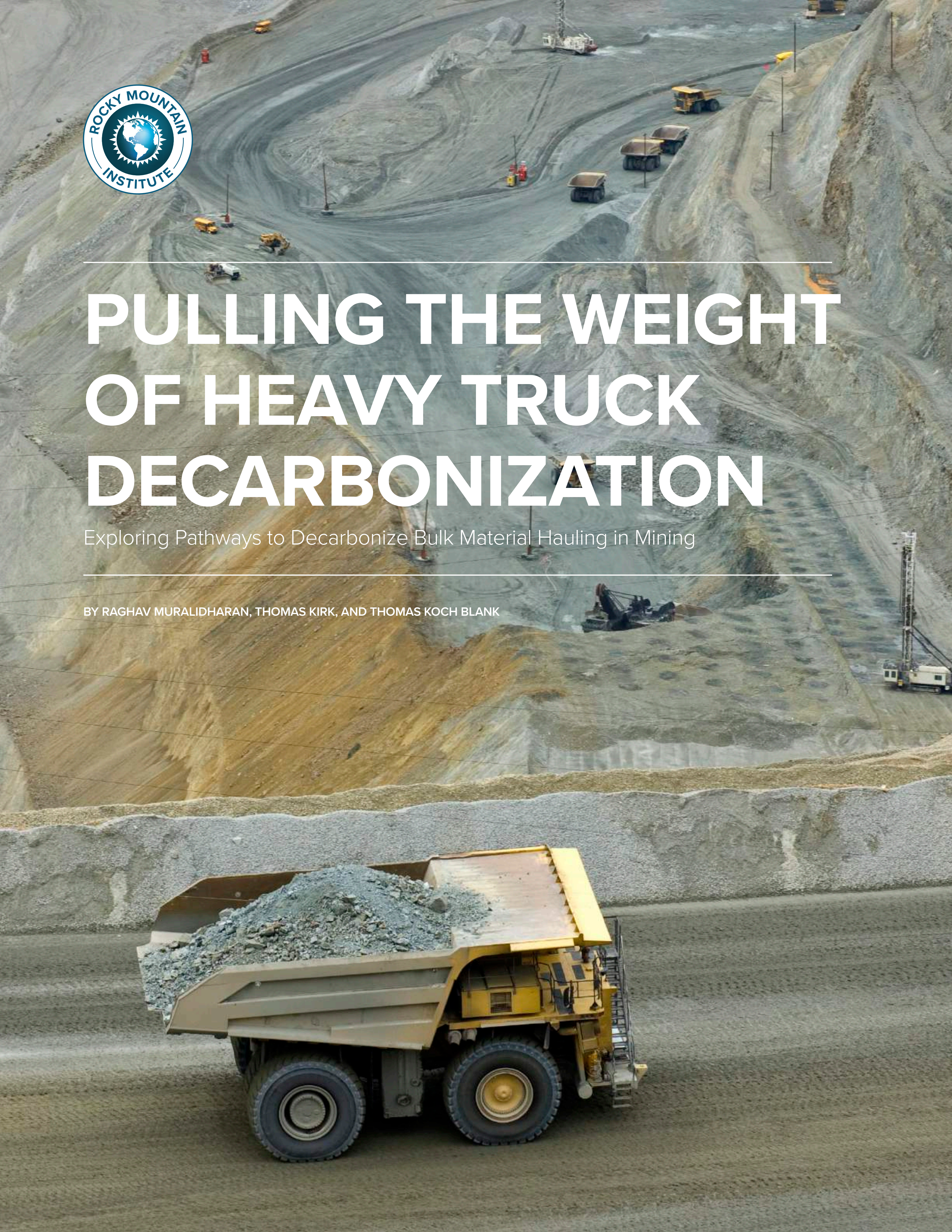

ROCKY MOUNTAIN INSTITUTE

PULLING THE WEIGHT OF HEAVY TRUCK DECARBONIZATION

Exploring Pathways to Decarbonize Bulk Material Hauling in Mining

BY RAGHAV MURALIDHARAN, THOMAS KIRK, AND THOMAS KOCH BLANK

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Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; the San Francisco Bay Area; Washington, D.C.; and Beijing.

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EXECUTIVE SUMMARY

Globally, there are around 28,000 large mine hauling trucks in service today. Almost across the board, these haulers are diesel-powered. Each of these trucks will consume roughly 900,000 liters of diesel per year and make up 30%–50% of their mines' total energy use. Together, these mining trucks emit 68 million tons of CO_2 ($MtCO_2$) per year, equivalent to the total greenhouse gas footprint of Finland or New Zealand. Diesel haulers are standard equipment because they offer a low-capex, flexible, well-understood solution with a highly developed supply chain. However, those benefits may hide their long-term risks. In addition to carbon, diesel trucks emit a number of other pollutants, and are subject to diesel fuel price volatility.

Mining companies that want to get serious about combating their carbon emissions and lowering operational expenditures will need to find a way to replace or upgrade their diesel fleets. A number of emerging solutions offer both environmental benefits and potentially lower cost. These solutions include diesel replacement fuels, electrification, and non-trucking methods to move materials. But, in most cases, it boils down to two strategies: (1) pursue early, marginal emissions reductions with currently available technologies, or (2) wait for more disruptive technologies to become available and transition hauling fleets only once to avoid stranded investments.

Interestingly, for open-pit mines, early, marginal changes will only lead to a two- to five-year deferral of when major investments will be required, suggesting the need for a more comprehensive strategy to stay on track to reach the decarbonization targets for 2050. Such a strategy would include the following:

1. **Expand the problem**—incorporate hauling in the broader portfolio of decarbonization efforts

2. **Selectively overdeliver**—differentiate the strategy to front-load decarbonization at assets where existing technology has most impact

3. **Accelerate technology readiness**—engage in R&D and policy influencing to ensure that new technology is available and cost-effective sooner

SIZING THE CHALLENGE

According to the industry carbon budget laid out by the International Energy Agency (IEA) in 2014,[i] mining companies—like companies in any industry—should reduce their emissions by 58% by 2050 compared to 2010. Meeting this absolute emissions reduction target is made more difficult by the fact that demand for minerals is expected to increase while, at the same time, mining is getting harder. Demand is being driven by a growing global population, rising average wealth, and a shift toward low-carbon technologies such as wind turbines, electric vehicles (EVs), and solar panels. On top of that, easier to mine and higher-grade ores are typically mined first, leading to decreasing head grades and yields, which means a larger total tonnage that needs to be moved longer distances.

In the case of copper, some research suggests as much as a two- to sevenfold increase in energy consumption by 2050,[1] including both for extraction (drilling, blasting, and trucking) and for on-site beneficiation (crushing, milling, concentration, and electrolysis). For the trucking component of this energy footprint, Exhibit 1 illustrates a scenario for this outlook, with three main drivers:

1. **Commodity demand**
   Depending on what source is consulted and what forecast of recycling rates for copper one relies on, demand for virgin raw material is anticipated to grow by 50%–100% between 2010 and 2050.

2. **Ore quality**
   The head grade of copper (the percentage of copper content in mined ore) has been declining fast, and while the trend is likely to stabilize over time, the deterioration of asset quality adds another 50%–120% of required run-of-mine (ore extracted from the pit) to meet the same final virgin commodity demand.

3. **Trucking need**
   As mining operations mature, their stripping ratio (the amount of waste rock that needs to be removed for each ton of extracted run-of-mine ore) generally declines because operations early in a mine's life need to expand horizontally proportionally more than operations later in a mine's life. However, to meet the required run-of-mine driven by (1) and (2), there will be portfolio effects with new mines countering that decline. Additionally, for the mature mines in a portfolio, hauling distances and pit depth are both increasing, leading to a higher total amount ton-km of ore hauled to deliver the same run-of-mine to processing plants.

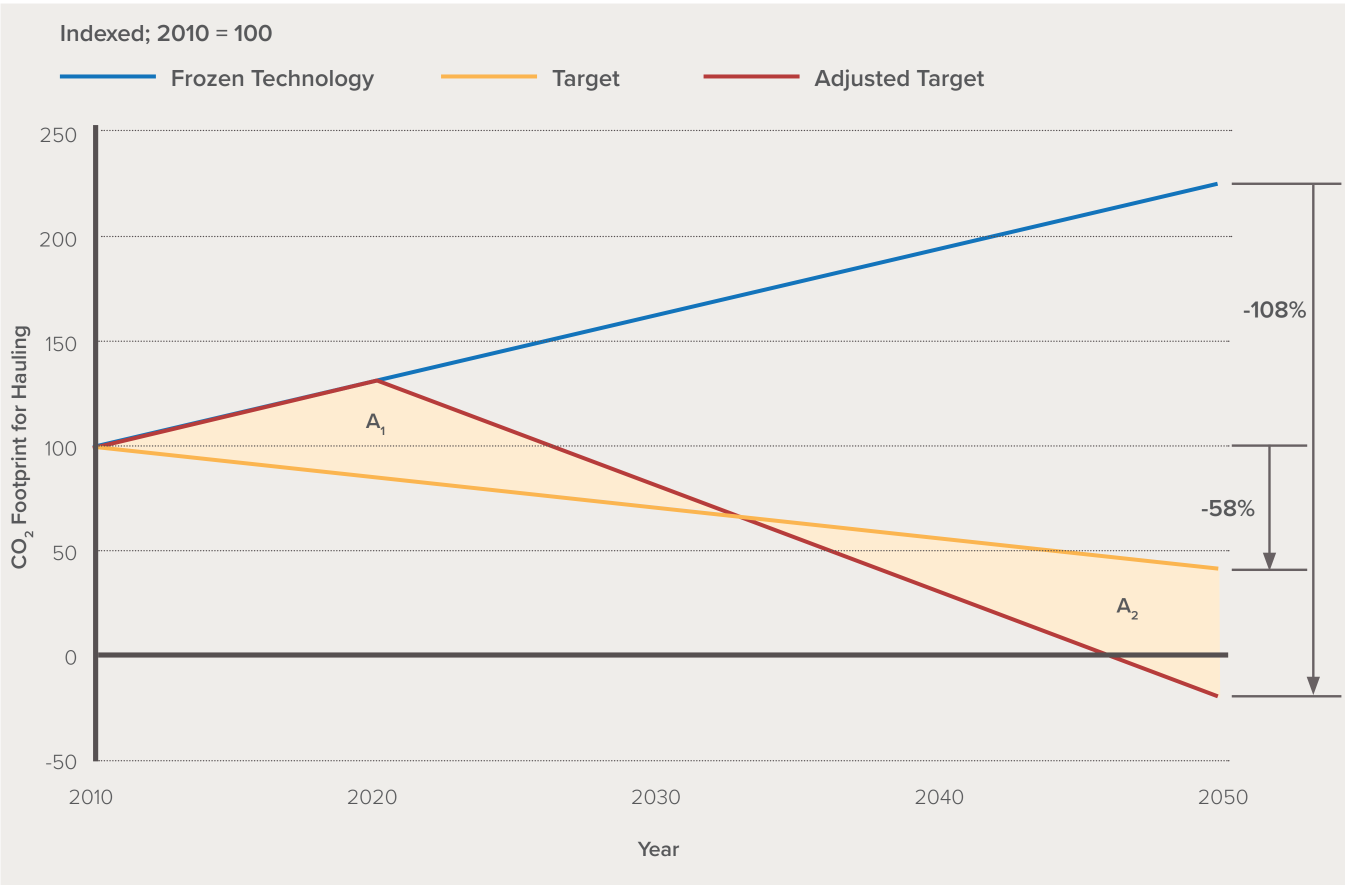
Even with conservative assumptions of a 50% demand increase, a 50% impact from quality deterioration, and a flat ton-km amount per extracted run-of-mine, these drivers compound into a total growth in trucking demand of 125%. We refer to this baseline outlook as the "frozen technology" scenario.

While there are some progressive examples of new technologies being deployed, very little has happened on a global portfolio level in rock hauling between 2010 and today, with the overwhelming majority of open-pit operations running large diesel trucks for waste removal and ore extraction. This means that the industry is still largely on this frozen technology trajectory and that a new target needs to be set in order to achieve the same impact that was intended

[i] There is a lot of continuing research into carbon budgets and the exact figures depend on the research organization (Intergovernmental Panel on Climate Change, IEA, CarbonTracker, etc.) as well as the desired goal in terms of degrees of warming and certainty. In addition, within the carbon budget, conversations about how much each industry should be allocated are ongoing.

EXHIBIT 1

CO_2 Target Adjustment



when the original 58% reduction target was set. As illustrated in Exhibit 1, this new target trajectory is defined as a line from 2020 for which the areas A_1 and A_2 are equal.

There are two main challenges to highlight from this example:

1. In reality, trucking needs to be 108% more efficient by 2050, not 58% as indicated by the IEA.
2. Every year the frozen technology trajectory is followed, a deeper "carbon debt" with regards to the 2050 target is accumulated, which will need to be compensated for with even steeper decarbonization.

The resulting carbon-reduction target of more than 100% is particularly intriguing, given that trucking in general is not an activity that is well-suited for some of the "negative emissions" technologies that are being explored for other sectors, using combinations of biofuels and carbon capture and storage. The remaining alternatives are either to work with offsets from other sectors to achieve an impact beyond 100%, or to front-load emissions reduction into a nonlinear pathway.

DECARBONIZATION OPTIONS

Understanding what viable pathways to decarbonize heavy hauling could look like requires a slightly more granular look at the available and emerging technologies. There is an inspiring amount of technology innovation and applied research going on in this area, and some technologies are commercially available at scale. Rating the options based on their abatement potentials on one hand and their technology readiness levels (TRLs) on the other allows a categorization into three groups of potential solutions,[2] as shown in Exhibit 2:

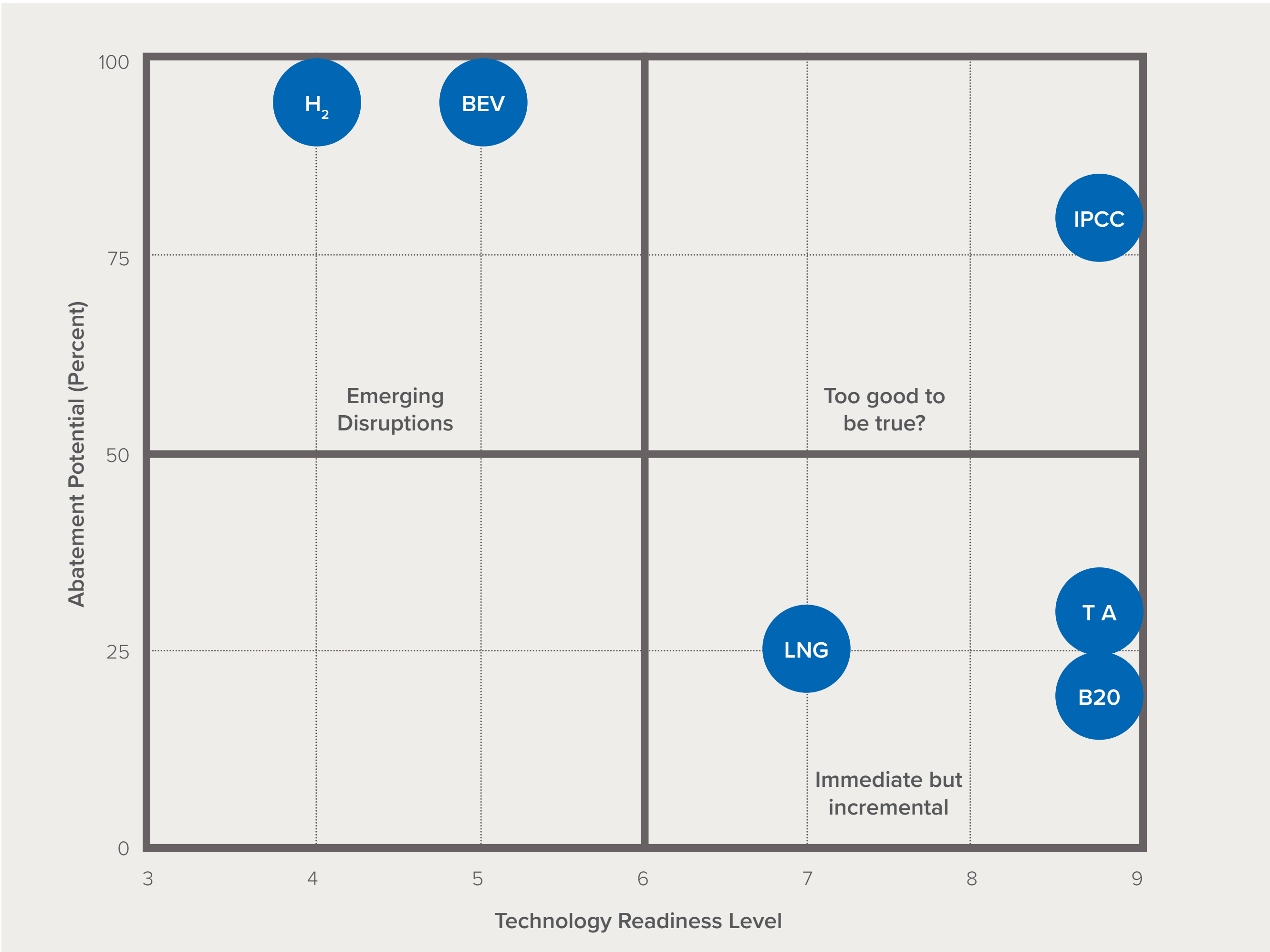
- **Immediate but incremental**
  Many of the technologies that are commercially available, such as liquefied natural gas (LNG), biofuels blending (B20), or trolley assist (TA), could provide immediate abatement impact with marginal change to existing truck fleets and infrastructures. However, their impact is limited to the 15%–30% range, which is unlikely to fully meet the high reduction targets for the sector.

- **Too good to be true?**
  A technology that is both readily available and has a significant abatement potential sounds too good to be true, as though it were the silver bullet that could effectively decarbonize rock hauling—assuming that the necessary electricity supply were drawn from renewable sources. In-pit crushing and conveying (IPCC) is such a technology. And indeed, it is not the silver bullet it seems. While examples indicate a life-cycle cost comparable to that of trucks, IPCC is only employable at ore bodies that allow for development with a fixed ramp out of the pit, significantly limiting applicability.

- **Emerging disruptions**
  A set of technologies are under development that can provide low-carbon trucking, effectively allowing mines to maintain the flexibility of current operations with close to 100% reduction in CO_2 emissions. The most prominent options are battery electric vehicles (BEV) and hydrogen-based trucks (H_2).

EXHIBIT 2

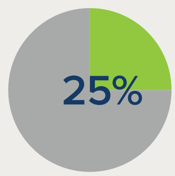
Decarbonization Options Characterization



Which technology is best-suited for a specific asset is highly contingent on local context and cost drivers, including the type of ore mined and the shape of the ore body, but for the purpose of exploring pathways, we have chosen to simplify even further. Putting aside IPCC for the moment, given its current limited applicability, the choice of pathways really boils down to whether to pursue a near-term opportunity that reduces emissions by ~25% and/or to invest in one of the emerging, more disruptive technologies that allow up to 100% decarbonization. Here we consider each of the decarbonization options in depth.

NATURAL GAS

Abatement Potential



Technology Readiness Level **7**

Currently, there are several fuel alternatives that can be used in place of diesel. For example, diesel trucks can be retrofitted to use natural gas. While both compressed natural gas (CNG) and LNG are suitable for transportation applications, LNG tends to be better-suited to medium- and heavy-duty vehicles due to its higher volumetric energy density. Currently, commercially available technology for natural gas vehicles includes both dual fuel (aka DGB-dual gas blend), which substitutes 50%–70% of diesel with natural gas, and high-pressure direct injection (HPDI), which can enable a truck to substitute about 95% of diesel with natural gas, using only a small amount of diesel as an ignition source.

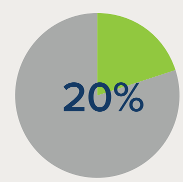
While natural gas is a fossil fuel, it can reduce CO_2 emissions by around 20%–25% compared to diesel, depending on how efficient the upstream supply chain is. Trucks using LNG could lower local pollutant and soot emissions, reducing concerns about mine-area air quality and effects on local communities. Furthermore, mining companies could retain their existing truck fleets, with only a few components needed to retrofit each truck to HPDI technology.

While LNG fuel is commercially available today, few companies offer the necessary modifications for heavy-duty vehicles such as mine haulers to run on LNG. There are costs associated both with retrofitting trucks and installing new fueling infrastructure.

Switching to LNG would require investments in cryogenic storage tanks, which have a higher capex than diesel fuel storage infrastructure. There are operational challenges as well; the driving range of natural gas-powered vehicles is generally shorter than that of comparable diesel vehicles, meaning trucks would require more frequent fueling or extra storage tanks. It is possible that the cost to retrofit diesel trucks will decrease, making LNG more appealing as a transitional fuel, but it is not a sufficiently effective long-term strategy or a path toward deep decarbonization given the limited potential for emissions reduction and the options for other, cleaner technologies.

BIODIESEL

Abatement Potential



Technology Readiness Level **9**

Biodiesel is a clean-burning diesel replacement fuel, derived from natural sources such as soybean oil, jatropha, or animal fats. There are various blends, identified by the proportion of biodiesel to conventional fuel, the most common being B20, containing 20% biodiesel and 80% diesel.

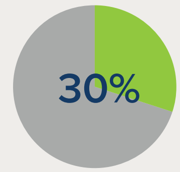
From an emissions standpoint, B20 releases ~20% less CO_2 per gallon than diesel fuel but is slightly less energy dense. Biodiesel is often spoken of as carbon-neutral because of the offset CO_2 absorbed by the crops grown to produce it. While some CO_2 is also released in the production and transportation of the fuel, the CO_2 offset is an important value-add that should be considered in evaluating fuel alternatives. Additionally, biodiesel reduces emissions of other non-CO_2 gases, such as CO and sulfate (SO_x), as well as particulates (i.e., soot). It increases nitrogen oxide (NO_x) emissions slightly, but the excess NO_x could be controlled by adding a cetane enhancer or blending biodiesel with kerosene or Fischer-Tropsch diesel.

Two of the significant advantages of biodiesel are that it is available globally today and that lower concentration blends such as B20 can be used in existing engines with no adjustments required. Mining companies interested in adopting biodiesel only need to secure the sourcing and transportation of the fuel, allowing for quicker adoption and near-term emissions reductions.

However, there are concerns about long-term use of higher-percentage biodiesel in unmodified engines. Rubber fuel-system components, such as hoses and pump seals, can degrade faster and might need to be replaced more often. Careful storage methods are also required for extended fuel storage in tanks or in engines that are only operated occasionally (such as standby power generators), as biodiesel can partially solidify over time. That said, use of a low-level biodiesel blend is a low-risk, low-capex alternative with environmental benefits. It is not a zero-emissions solution, but a good intermediary step that can be implemented quickly.

TROLLEY ASSIST

Abatement Potential



Technology Readiness Level 9

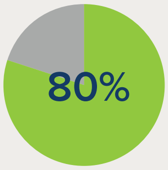
Trolley assists are overhead electric lines to which vehicles can connect during operation, similar to the electric lines that power trams on city streets and overhead electric trains. Mining vehicles equipped with electric motors could use overhead electric lines running the length of the ramp to provide power to haulers.

Trolley assist system's emissions reductions are directly dependent on the sources of their electricity as well as the trucking solutions they're paired with. Even without any changes to the trucking fleet or electricity source, TA systems often reduce greenhouse gas emissions simply by reducing diesel consumption. Existing TA systems in use with diesel haulers can independently reduce emissions by up to 30%. These trolley assist systems could be used with vehicles powered by any fuel, so further supply shift to renewable energy from the grid or from on-site generation can offset more CO_2 emissions. Theoretically, they are capable of charging a BEV during operation, which could mitigate the battery-size and charging-time issues mentioned in the BEV section.

Trolley assist systems are in place and available on the market today, but involve high capital expenses and have fixed locations. While they can be redeployed at the end of a mine's life, disassembling and transporting them is difficult. Current market and cost conditions suggest a best practice is to keep a trolley system in place for at least 10 years. For mines with a suitable topography and sufficiently long remaining lifetime of the operation, these systems are often an economic no-brainer.

IN-PIT CRUSHING AND CONVEYING

Abatement Potential



Technology Readiness Level 9

Trucks are often favored on mine sites because of the operational flexibility they provide, but a well-planned mine can avoid using trucks at all.

In-pit crushing and conveying is a well-established method for transporting bulk materials at a significantly lower cost. The actual form of the conveyors varies considerably from more traditional belts to rows of mine carts. The specific type of conveyor used will determine the maximum allowable angle of the pit as well as the required material size. The pit angle has implications for the need for overburden removal, or the operation's "strip ratio." Current drill and blast methods are optimized for trucking and create material that generally cannot be conveyed due to its large size. By adding a crusher in the pit, in combination with reoptimized blasting practices, the resulting rocks can be made small enough to be transported on a conveyor.

Conveying systems can run continuously with much lower energy and O&M costs and fewer workers. They are an electrification-focused solution and are only zero carbon if their energy is supplied from renewable sources, which means they offer the opportunity for operations to become less carbon-intensive as the local grid or on-site energy supply becomes cleaner. The impact on emissions is controlled by the mine design and the location of the IPCC system, as some hauling will be required to bring the ore to the crusher. Combined with a zero-carbon hauling solution, such as BEVs or hydrogen fuel-cell electric vehicles (FCEVs), the total emissions reduction could be up to 100%.

Conveying systems are available on the market today in stationary, adjustable, and relocatable designs, but are limited in placement and movement. They can typically only be used in pits that have ramp slopes less than 10°, with some high-angle systems allowing for slopes of up to 20°. Furthermore, for their relocation to be economical, they typically need to be planned for use in one location for 5 to 10 years. Conveyors are a potential single-point-of-failure system. If the system needs to be moved, or the belt tears or becomes misaligned, all production will stop. This contrasts with trucking, in which production can continue in the absence of any given truck needing maintenance. Proactive maintenance and mine planning can minimize halts in production from conveying systems, but the overall applicability restrictions make IPCC systems fall into the "too good to be true" category of strategies for large-scale decarbonization.

ELECTRIC TRUCKS

Abatement Potential	**100%**
Technology Readiness Level	**5**

Battery electric vehicle technology is reshaping the automotive world and has potential to reduce emissions as well as operation and maintenance costs for open-pit mine hauling applications. Electric vehicle technology is quickly moving from the light-duty vehicle market into the medium-duty vehicle and heavy-duty vehicle (HDV) segment. BEVs provide more value streams to underground mines than open-pit mines, and several underground vehicles are already commercially available, such as those produced by Epiroc AB and Artisan.

BEVs have a number of advantages: They have instant torque and can ascend ramps at higher speeds than conventional trucks, greatly improving the hauling tempo. Their operation and maintenance (O&M) needs are typically lower than those of internal combustion engine (ICE) vehicles. EVs incorporate regenerative braking technology, which enables the vehicle to capture energy from deceleration and store it in a battery, prolonging the run time between stops to charge. Lastly, they provide the opportunity to take advantage of falling renewable energy prices.

Assuming that the vehicles are receiving their energy solely from renewable sources, they will produce no additional operational emissions. Even if the power were from less than 100% renewable sources, EV technology would be less carbon-intensive than comparable ICE technology. For example, with US average emissions factors and electricity transmission losses of 3%, EVs operating on an electric grid that is supplied from about 25% renewable sources would be less carbon-intensive than diesel on a per-MWh energy basis, even if the remainder of the energy came from natural gas.[3] That estimate assumes negligible emissions from renewable energy production.

Currently there are no commercially available open-pit battery electric mine haulers. However, electric vehicles are beginning to enter the off-road ultra-heavy-duty market, and are currently being tested in the mining industry for large-scale applications. Two Swiss companies, Lithium Storage GmbH and Kuhn Schweiz AG, converted a Komatsu 605-7 dump truck from diesel to battery electric by retrofitting the vehicle with a 700 kWh battery pack and an 800 hp electric motor with up to 9,500 Nm of torque. Implementation of a BEV fleet requires investment in charging infrastructure and associated operational changes. The necessary technology and charging infrastructure at the HDV scale is projected to be economically feasible in the next 8 to 15 years.

Currently, barriers to BEV adoption are battery sizing for HDVs, investments in charging infrastructure, and operational changes necessitated by charging. Finding the scale at which battery electric hauling vehicles make sense is crucial. The challenge is that, as a vehicle becomes larger, a proportionally greater area of the vehicle needs to be dedicated to the battery, which in turn increases the overall weight and size, necessitating a larger battery. This is a problem similar to that faced by spaceships struggling to pack on enough fuel to reach orbit. Vehicles will need to charge periodically, as they will not be able to recuperate enough energy from regenerative braking for continuous operation, and electric charging takes longer than an equivalent ICE vehicle's fueling. Vehicle idling due to charging time could be a smaller barrier with the use of additional batteries and change-out stations. It is still unclear what the maximum practical size of battery electric vehicles can be. If moving to BEV technology requires utilizing vehicles with a smaller capacity, more vehicles would be required, but their higher haul speed could provide comparable productivity without congestion. Additionally, electric vehicle range can be significantly affected by extreme temperatures. In temperatures below freezing, battery performance can drop 25%–30%.[4] As battery technology improves, this could become less of an issue.

HYDROGEN FUEL

Abatement Potential	**100%**
Technology Readiness Level	**4**

Hydrogen fuel-cell electric vehicles (FCEVs) have existed since the mid 1960s, but recent developments, partly spurred by the promise of "green hydrogen"—hydrogen produced with energy from renewable sources—have increased hydrogen's viability as a HDV fuel source. Hydrogen can be produced through several methods, but most hydrogen today is produced using the steam-methane reformation process, in which high-temperature steam produces hydrogen from a methane source, such as natural gas. This process requires a high thermal input, often from fossil fuels, to heat the steam, as well as natural gas. The hydrogen industry is working to develop green hydrogen produced entirely from renewable energy. The most promising such pathway is through electrolysis, which uses electricity to separate the hydrogen out of water molecules.

The major benefit of H_2 fuel-based vehicles is that they generate no direct emissions from their use, and so, if combined with renewable energy-based hydrogen production, could abate 100% of their fuel emissions.[ii] The development of economic green hydrogen is dependent on large-scale, low-cost renewable energy used in producing it and the up-front cost of electrolyzers. With projected solar and wind energy costs decreasing, and with electrolyzer costs expected to drop 35% or more in the next 10 years through improved efficiency and technology innovation such as membrane-less devices, the transition to green hydrogen and large-scale availability of these technologies are likely to be accelerated.[5] In the nearer term, hydrogen fuel is also being explored as an additive to diesel engines, both through secondary storage and onboard electrolysis devices. Introducing hydrogen as a diesel additive can result in a better fuel-air ratio, and in cooler, more complete combustion that reduces soot and particulate emissions.

Presently, the main barrier to hydrogen fuel implementation is that the required infrastructure is in its infancy. As a result, establishing secure supply chains at the scale required for hauling operations is challenging. However, maturation of the industry and the technology will allow for secure supply chains or on-site hydrogen production.

[ii] There will still be emissions from the manufacture of the vehicles.

CONCLUSIONS FOR STRATEGIES TO MEET THE EMISSIONS TARGET

Mines must take significant action in order to stay within the carbon budget defined by the 2010–2050 target trajectory. For example, returning to the example of copper, while retrofitting a haul fleet to run on LNG could reduce emissions by approximately 20%, that is not sufficient to achieve the longer-term performance requirements needed by the target trajectory. This means that, apart from IPCC, the technologies that are available for immediate deployment will need to be complemented by future investments when more disruptive options are commercially available.

Exhibit 3 shows two illustrative pathways that both meet the original carbon budget set out in 2010 (note that the graphs have been reindexed so that 2020 = 100). For both of the pathways, it's noteworthy that complete decarbonization needs to happen before 2035. More concerning, the near-term investment in partial decarbonization only has a three-year impact on the timing for when the more disruptive solutions are needed.

For a commodity with significant demand growth and ore-quality deterioration such as copper, a strategy of buying time for any larger technology intervention by investing in existing solutions with marginal impact is a recipe for failure. Counterintuitively, this is also true for commodities with lower growth trajectories.

Exhibit 4 shows the year when disruptive, zero-carbon hauling needs to be introduced in order to stay on track for the 2050 target as a function of the underlying anticipated growth in material movement. The two lines in the chart represent the two strategies that were used in the copper example, a strategy of implementing immediate, incremental levers (Pathway 1) and a strategy of waiting for disruptive technologies (Pathway 2). The horizontal bands indicate ranges of growth forecasts for the highest-volume commodities: coal, iron ore, and copper.

EXHIBIT 3

Potential Decarbonization Pathways

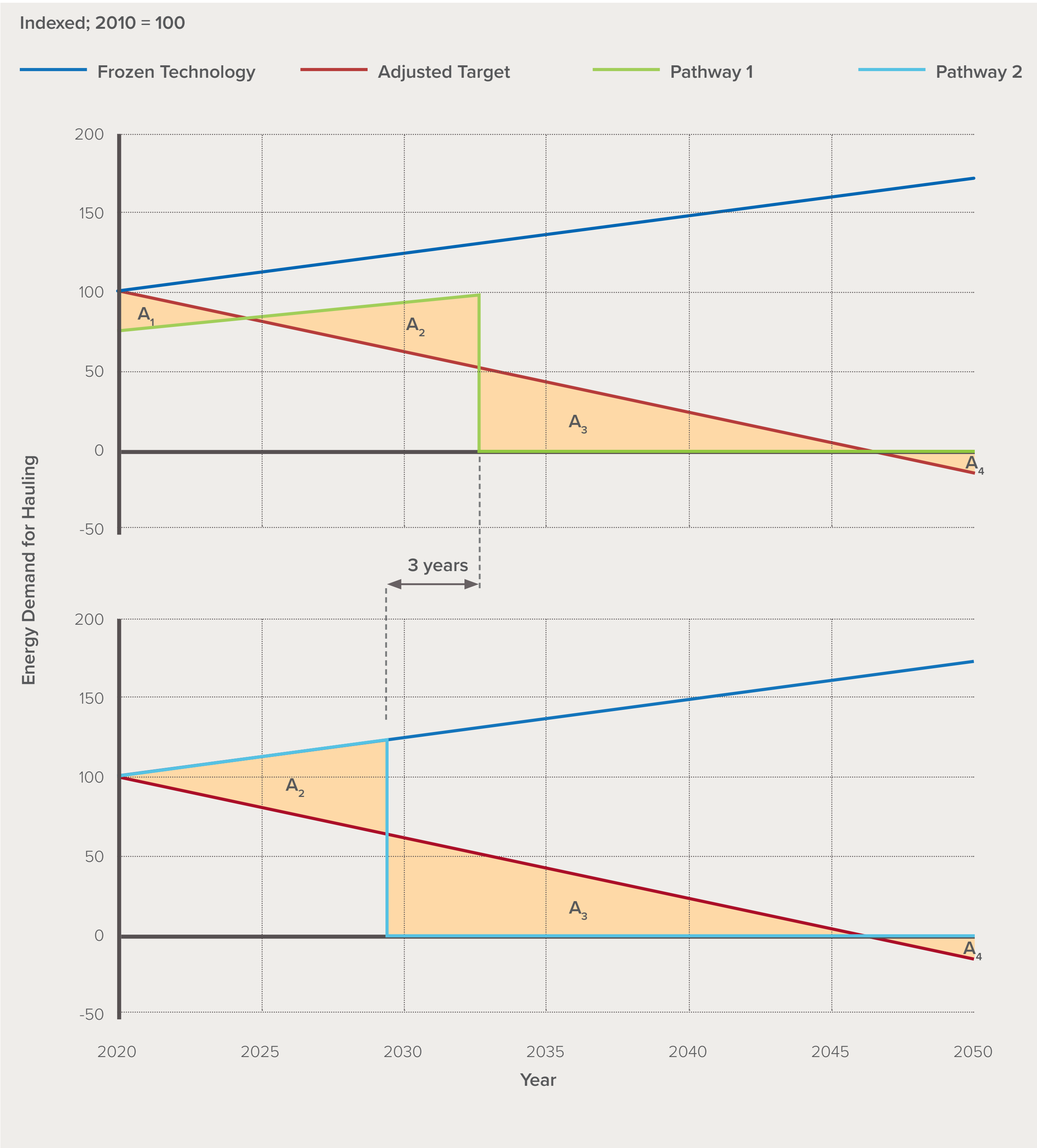
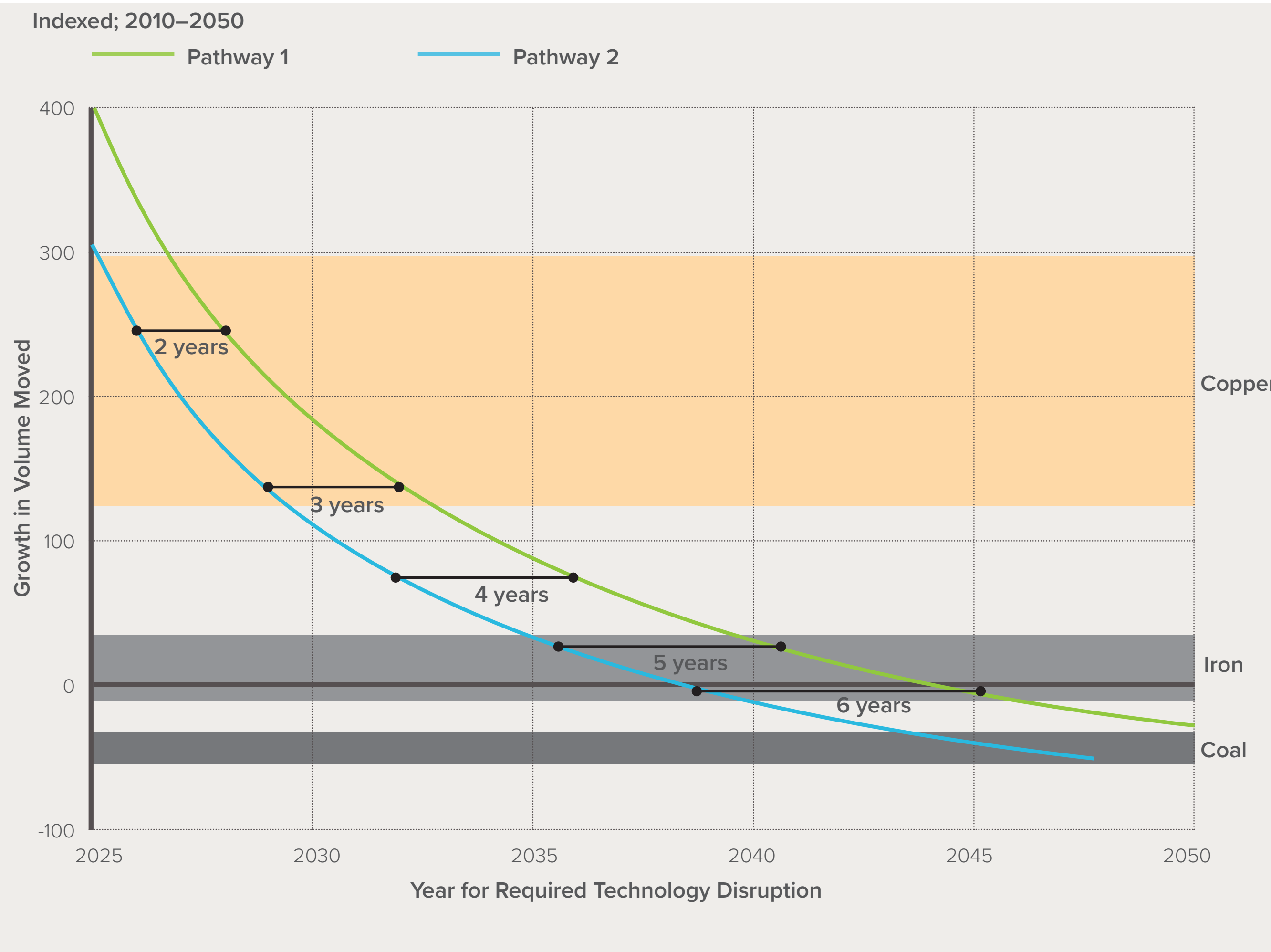


EXHIBIT 4

Technology Disruption Timelines



Even for commodities with less aggressive growth forecasts, the benefit of early adoption of marginal improvement technologies provide only a five- to six-year respite. At the same time, expecting disruptive technologies to be available at scale for full rollout by 2030 is a high-risk bet. We see three main strategies that could successfully put the mining industry on a pathway to decarbonize heavy hauling at the required pace:

1. **Expand the problem**
   Siloing the challenge of pursuing decarbonization pathways according to specific activities is likely to fail unless the pace of technological change is faster than expected. A more holistic strategy is likely to be more effective, for example, implementing pathways including the fixed assets on site, which are largely electrified already and can be decarbonized with a renewable power supply.

2. **Overdeliver on selected assets early**
   Within a portfolio of extractive assets, some will have operating circumstances wherein commercially available technologies can have significant impact, whether it be in an ore body that allows for fixed-ramp operations and IPCC, or where there is a local source of biofuels that allows for blending beyond 20%. These opportunities should be maximized, because each year of front-loading disruption in one asset allows for the mirrored deferral of disruption for a comparable but harder-to-decarbonize asset within the same portfolio.

3. **Accelerate technology readiness**
   Invest in research and policy support to accelerate the development and deployment of the truly disruptive technologies that enable (close to) full decarbonization.

In the near term, the mining industry also needs to establish what the specific target pathways look like for material movement in a way that is anchored in different commodities' growth outlooks for material movement, and that translates to efficiency metrics that allow stakeholders to track progress toward this goal without penalizing structural changes or market-share gains. While each actor in the market needs to own and account for its own performance and rate of improvement, there is a role to play for industry organizations or independent institutes like the International Council of Metals and Mining (ICMM), the World Bank, or the International Energy Agency to develop some of the basic research that will constitute the foundation for such a commodity pathway.

ENDNOTES

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