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Haul Truck Electrification as a Pathway towards Carbon-Neutral Mining: A Comprehensive Emission Review and CO_2 Payback Analysis

TU Delft

Haul Truck Electrification as a Pathway towards Carbon-Neutral Mining: A Comprehensive Emission Review and CO_2 Payback Analysis

By

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in partial fulfilment of the requirements for the degree of

Master of Science
in Applied Earth Sciences

at the Delft University of Technology,
to be defended publicly on Wednesday October 25, 2023 at 09:00 AM.

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Abstract

This thesis investigates the impact of truck electrification systems on CO_2 emissions and financial aspects in mining. Through comprehensive simulations, the study analyses diesel-electric trucks with trolley assist as well as battery-electric variants with trolley assist and stationary charging. The research findings reveal a noteworthy decline in CO_2 emissions and an improvement in cost-effectiveness for the diesel-electric variant with trolley assist. Comparable CO_2 savings are observed in battery-electric scenarios, but with varying financial profiles. The transition to battery-electric trucks with trolley assist leads to improved efficiency and associated cost savings. On the other hand, stationary charging entails financial challenges owing to high equipment costs. The analysis of emissions was conducted by different scopes, allowing a differentiated analysis of direct emissions (Scope 1) and indirect emissions (Scopes 2 and 3). This research highlights the significance of adopting a comprehensive approach towards achieving a sustainable future in mining. It provides clear insights into the potential of electrification technologies, particularly highlighted by a 49% CO_2 reduction in battery-electric scenarios.

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List of abbreviations

AC	Alternating Current
AU$	Australian Dollar
BMS	Battery Management System
CAT	Caterpillar Inc.
CapEx	Capital Expenditures
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
Date	dd/mm/yyyy
DC	Direct Current
GHG	Greenhouse Gas
GR	Grade Resistance
Gt	Gigatonnes (metric)
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
IEA	International Energy Agency
IPCC	In Pit Crushing and Conveying
IPPs	Independent Power Producers
kt	Kilotonnes (metric)
LOM	Life of Mine
LTO	Lithium-titanium-oxide
LULUCF	Land Use, Land Use Change, and Forestry
Mt	Megatonnes (metric)
NEM	National Electricity Market
N_2O	Nitrous Oxide
NPV	Net Present Value
OEM	Original Equipment Manufacturer
OpEx	Operational Expenses
PFCs	Perfluorocarbons
PV	Photovoltaic
RF	Rimpull Force

ROM	Run of Mine
RR	Rolling Resistance
SA	South Australia
SF_6	Sulphur Hexafluoride
SWIS	South West Interconnected System
Tonnes	Metric Tonnes
TR	Total Resistance
TS Systems	Truck-Shovel Systems
UPL	Ultimate Pit Limit
V	Speed
WA	Western Australia
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

1 Introduction

Mining operations are necessary to sustain modern society; however, they are also responsible for 7% of global greenhouse gas emissions. The mining industry is under pressure to decrease its carbon footprint as the worldwide movement towards decarbonisation intensifies. In Australia, mining is a crucial area that contributes significantly to the country's economy but also releases a significant amount of carbon emissions, making up around 20% of Australia's total carbon dioxide equivalent (CO_2e) emissions. [1, 2]

An approach to reduce CO_2 emissions is to improve the transportation of ore and waste from open pit mines. As mines become deeper, the distances covered by haul trucks also increase, leading to higher fuel consumption and operational costs. In particular, the cost of transporting ore and waste from mines to processing plants can account for up to 50% of total operating costs. The electrification of haulage trucks is emerging as a promising way for the mining sector to reduce its carbon footprint while lowering operating costs. Current research suggests that this switch can produce significant advantages, such as a 44% increase in upgrade speed, a 16% reduction in travel duration, and fuel savings of over 80% per up-down cycle. These empirical outcomes provide a promising route towards achieving carbon-neutral mining procedures. [3, 4]

Currently, truck-shovel (TS) systems prevail as the most common mining system used in large surface mines. However, battery and energy recovery technology advancements are driving the evolution of electrified systems away from diesel-electric truck-based patterns towards purely battery-electric ones.

To evaluate the potential of electrically powered haul trucks in minimising emissions in open pit mines, it is important to consider the different scopes of emissions. It allows for a comprehensive assessment of the environmental impact of electric haul trucks, covering not only direct emissions (Scope 1), but also indirect emissions (Scopes 2 and 3) associated with their energy sources and supply chains. This method permits a more precise assessment of the environmental advantages and difficulties associated with the electrification of haul trucks.

The Australian government has established challenging goals to lower emissions, with a target of a 26-28% decrease from 2005 levels by 2030 and achieving net zero emissions by 2050. It is imperative that the mining sector contributes to achieving these goals, and the electrification of haul trucks presents a promising opportunity for the industry to make substantial progress towards achieving carbon neutrality. [5]

However, there is a substantial research gap in comprehensively understanding the emissions and CO_2 payback analysis associated with haul truck electrification in open-pit mining operations. This thesis seeks to fill the research gap by examining haul truck electrification as a potential pathway towards carbon-neutral mining in the Australian market, utilizing a comprehensive emission review and CO_2 payback analysis across all three scopes of emissions. By doing so, this thesis aims to provide valuable insights into the potential of electrification to decrease emissions and advance the Australian mining industry towards a more sustainable future.

This thesis aims to comprehensively evaluate both the environmental and financial impacts of different electrification systems in open pit mining, with a particular focus on truck emissions, over the entire life of the mine. The study aims to address the core research question: 'What impact do various electrification options, including diesel-electric on trolley line, battery-electric on trolley line and battery-electric with stationary charging, have on Scope 1, 2 and 3 emissions from mining trucks and the financial aspects over the whole life of mine (LOM), compared to a conventional diesel operation?

To achieve these objectives, the thesis will employ diverse research methods, such as data analysis, modelling, and simulations using the two software packages DESWIK.CAD and DESWIK.LHS. The study will draw on data from prior research on trolley electrification systems, in addition to data from the mining sector and other pertinent sources. In essence, the thesis aims to provide a comprehensive analysis of the potential of trolley electrification systems to reduce emissions and move the mining industry towards a more sustainable future.

The *Theoretical Foundations* chapter presents essential principles for the understanding of haul truck electrification in open pit mining. It details significant elements, like the Truck and Shovel system, Trolley Assist system, battery-electric haul trucks, CO_2 emissions, and the Australian electricity grid. The *Materials and Methods* section offers an in-depth depiction of materials and methodologies, encompassing scenario particulars, energy and CO_2 emissions calculations, and financial analysis. In the *Case Study* chapter, results of the base case and three electrification cases are presented and compared in the *Results* section. The *Discussion* presents an in-depth analysis of the outcomes, including CO_2 emissions, economic feasibility, potential future research areas, and recommendations. The Conclusion outlines critical findings, emphasising the paramount importance of electrifying mining trucks for CO_2 reduction and financial sustainability.

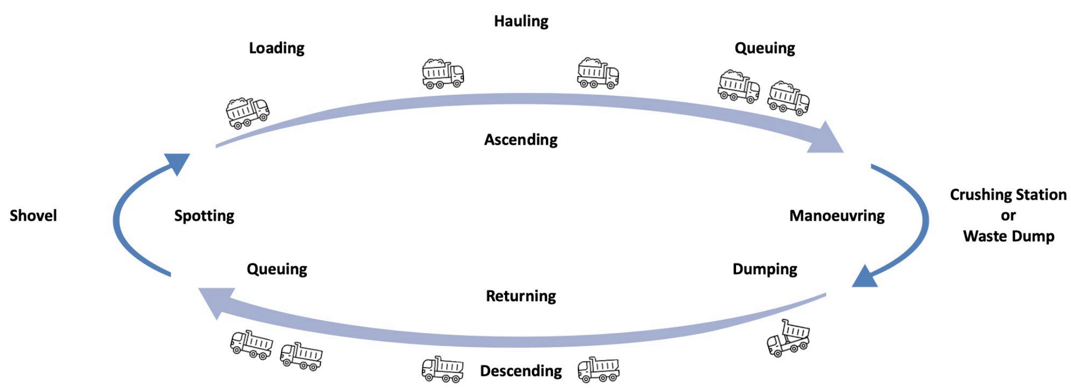
2 Theoretical Foundations

This chapter provides an overview of the theoretical underpinnings of the study of haul truck electrification as a pathway to carbon-neutral mining. It provides a detailed introduction to the conventional truck and shovel system widely used in mining operations. This includes an overview of its components, fuel consumption, and associated carbon emissions. The integration of trolley assist systems is examined, discussing how such systems enable trucks to shift between diesel and electric power. The chapter analyses CO_2 emissions by Scope 1, Scope 2, and Scope 3 methodologies. It accounts for emissions related to the operation of the standard truck and shovel system. Additionally, it examines the broader context of the Australian power grid and its implications for implementing electrification in mining operations. This thorough examination establishes the foundation for assessing the efficacy of trolley assist systems in attaining carbon neutrality in mining.

2.1 Conventional Truck and Shovel System

The conventional truck and shovel system represents the predominant mining and haulage method employed in surface mine operations (compare Figure 2-1). This method typically involves the collaboration of an excavator and a variable fleet of trucks working in conjunction. The excavators are responsible for the excavation of loose or pre-blasted material, which is subsequently loaded onto the trucks. Once loaded, the trucks transport the material to its designated destination, which may include the waste dump, crusher, or Run of Mine (ROM) stockpile, depending on the nature of the material. After unloading the material, the trucks return to the excavator to initiate the next cycle.

Figure 2-1 Conventional TS systems operating process



Note. Adapted from [3]

The distances covered in a single cycle vary significantly and depend on various factors, including mine design, increasing mine depth, and mine infrastructure. To mitigate the growing distances resulting from mine progression, large and long-lasting mines have adopted in-pit crushing and conveying (IPCC) systems. This solution considerably reduces haulage distances within the mine, as the trucks are no longer required to transport the ore out of the mine [3]. Despite the availability of IPCC systems, the truck and shovel system remain the preferred choice due to its notable advantages. The primary advantage lies in its ease of implementation. During the initial phase of a new mine, a small number of trucks and shovels can be procured, with the capacity for expansion through the addition of new equipment in the future, thereby keeping the initial investment modest. This method also offers great versatility as it can be readily scaled up to meet increasing demands as the mine advances. Furthermore, implementation merely necessitates the construction of a road network for the trucks.

Moreover, the Truck and Shovel system provides maximum flexibility. Through the fleet management system, trucks can be assigned new tasks in real-time within the mine, optimizing production processes. Additionally, individual breakdowns can be appropriately accommodated. Furthermore, trucks are capable of transporting various types of materials and can seamlessly switch between transporting waste and ore as required. [3]

In addition to the aforementioned advantages, the TS system presents certain disadvantages and challenges. Minimizing these factors is crucial to enhance the overall economic and operational efficiency of the TS system. A significant cost driver is the operating expenses associated with the TS system. Material handling and transport can collectively account for approximately 50% of the total operating costs in a mining operation [6]. As the mine depth increases, the haulage distance also expands, leading to a significant rise in diesel consumption and a subsequent decrease in productivity. To ensure that the excavator operates at its full capacity, an increased number of trucks is necessary to cover the extended distances. Consequently, this results in higher operating costs and greater diesel demand. Moreover, the growing demand for trucks corresponds to an increase in labour costs required to operate them. Around seven people are typically required to operate a single truck, including shift operators and maintenance staff [7].

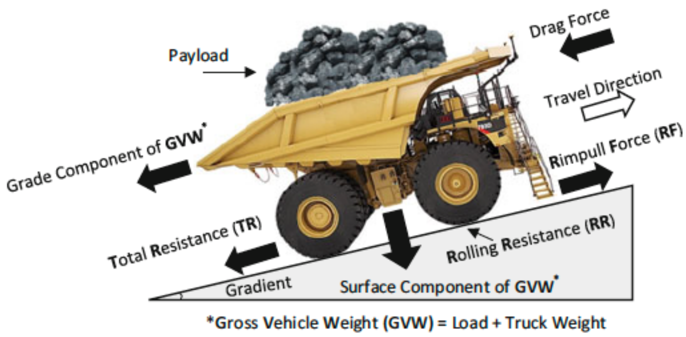
Diesel trucks play a significant role in contributing to the CO_2 emissions of an open pit mine. Roughly 40% of the energy consumed in such mines can be attributed to diesel consumption for material handling purposes [8]. In Australia, the mining sector's energy consumption in 2020-21 amounted to 850.4 PJ [9]. This corresponds to an estimated annual diesel consumption of nearly 10 billion liters, resulting in a direct emission of approximately 26.4 Mt CO_2.

Globally, there were about 52,200 operational trucks with a payload capacity exceeding 90 tonnes in 2022 [10]. This emphasizes the pivotal role that haulage trucks will play in the future of achieving carbon-neutral mining practices.

The most important factors that (shown in Figure 2-2) influence the diesel consumption of haulage trucks therefore are:

- Gross vehicle weight (GVW);
- The speed at which the vehicle is driven (V);
- Total resistance (TR), which is the sum of rolling resistance (RR) and grade resistance (GR), the latter of which can be negative; and
- The rimpull force (RF), is described as the force exerted at the point where the vehicle contacts the road surface. [8]

Figure 2-2 Effective parameters for the fuel consumption of a truck



Note. Adapted from [8]

2.2 Trolley Assist System

This chapter provides an introductory overview of the Troll Line system, including its advantages and challenges. Subsequently, the required infrastructure and the interaction between the truck and the Trolley Line are described.

The Trolley Assist System is a technology that utilizes overhead wires positioned above the roadway to provide trucks with direct current (DC) power through a pantograph. The truck's drive motors are subsequently directly powered from the mine's electrical supply. This system was initially introduced by Werner von Siemens at the "International Exposition of Electricity" in Paris in 1881. It was initially implemented for trams and trains starting from 1883. Over time, the technology has evolved and continues to be the cutting-edge solution for powering trains, trams, and buses in modern transportation systems. [11]

The initial interest in implementing the trolley assist system in the mining industry emerged following the oil crisis in 1973, during which the oil embargo caused a fourfold increase in oil prices, escalating from US$2.59 to US$11.65 per barrel [12]. Prompted by the surge in fuel prices, numerous surface mines began considering the adoption of this fuel-saving technology as a means to reduce operating costs. However, the limited availability of diesel-electric heavy haul trucks suitable for trolley line operation has hindered the widespread adoption of the system in the mining sector. Renewed interest in the trolley line system arose when Caterpillar introduced a new ultra-class diesel-electric truck with a payload capacity of 345 tonnes. This development sparked enthusiasm for the trolley assist system as the new truck model demonstrated the potential for effective integration with the technology, paving the way for its further exploration and implementation in the mining industry. [13]

The objective of the Trolley Line system, as previously outlined, is to substitute diesel engines with electric power, offering several notable advantages. [3, 13-16]

1. Reduction of diesel consumption: The transition from a diesel engine to an electric drive system result in significant fuel savings, potentially reaching up to 90%. This substantial reduction is achieved by operating the engine solely at idle during Trolley Line operation. Idle operation is utilized to power auxiliary systems, accounting for approximately 10% of the total engine power. The electric drive motor, which draws energy from the Trolley Line, exclusively provides the power required for the truck's movement. The most substantial fuel savings are observed during uphill ascents, where the diesel engine typically operates at maximum load.
2. Energy efficiency: Electric drives exhibit a higher level of efficiency compared to combustion engines. Typically, diesel engines operate at an efficiency of approximately 40%, whereas electric motors achieve an efficiency of around 80%. This discrepancy can result in a reduction in overall energy consumption.
3. Productivity enhancement: Electric motors not only exhibit higher efficiency but also provide greater torque at lower speeds in comparison to combustion engines. With the trolley line system capable of supplying more energy to the electric drive than a diesel engine, accelerated acceleration and increased speed can be attained. On inclines, the final speed can be augmented by a factor up to 2.0, contingent upon the truck class. Consequently, this can lead to a noteworthy reduction in cycle time.
4. Emission Reduction: Diesel engines represent the primary source of Scope 1 carbon emissions in open pit mining operations. Through the substitution of diesel fuel with

electricity, the direct emissions of CO_2 are significantly reduced, leading to improved Scope 1 emissions and enhanced air quality.

5. Cost Savings: Enhanced truck efficiency translates into a reduced requirement for trucks throughout the LOM, leading to diminished capital expenditures and ongoing maintenance costs. Notably, the primary expense associated with material handling in mining operations is attributed to diesel consumption. However, the Trolley Line system replaces diesel with electricity, which generally entails lower costs in Australia and many countries worldwide. Switching to electricity also creates independence from fluctuations in the global price of diesel.
6. Dynamic Charging (Battery-electric Trucks): The Trolley Line system provides the potential for dynamic charging when utilizing battery electric haul trucks. Unlike a stationary charging system, dynamic charging enables continuous charging without the truck coming to a complete stop, thereby minimizing disruptions to the truck's productivity. Additionally, in Trolley Line mode, the available power is divided into two parts: one portion directly powers the electric drive for propulsion, while the second portion charges the onboard battery. This approach offers the advantage of not relying entirely on the battery to supply the power required for a cycle, as would be the case with stationary charging. As a result, the battery is protected, leading to an extended service life.
7. Noise Reduction: Diesel engines can contribute significantly to noise pollution. However, by utilizing the Trolley Line and Electric drive system, the diesel engine operates at idle, resulting in a reduction in noise levels.

In addition to the advantages provided by trolley line systems, it is crucial to acknowledge and address the associated disadvantages and challenges in order to fully leverage the benefits. [3, 13, 17]

1. Infrastructure Investment: The implementation of trolley lines necessitates substantial capital investment. This encompasses the installation of the catenary system, modifications to the ramps, and the establishment of an electrical infrastructure, including transformers and substations.
2. Restricted Mine Planning Flexibility: The operation of the Trolley Line system introduces a fixed catenary infrastructure, which imposes limitations on one of the key advantages of the Truck and Shovel system, namely, its mobility and flexibility. Once the overhead lines are installed at specific locations, mine planning must be tailored to fully utilize their capacity and maintain them in the same positions for as long as

feasible. Although it is possible to relocate the overhead lines within the mine, this process necessitates meticulous planning, a proficient team, and time, all of which can result in downtime and associated costs. Hence, it is preferable to plan for the extended deployment of the overhead lines and minimize the need for relocations.

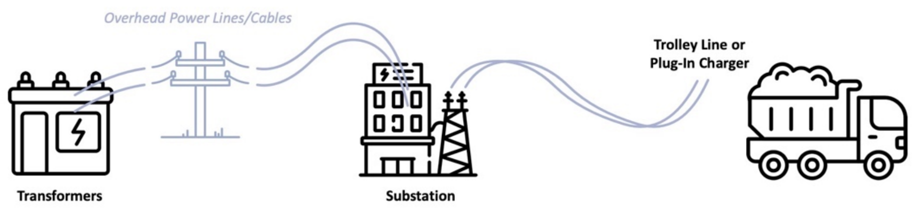
3. Power Supply and Grid Stability: Trolley line systems represent a critical component within the haulage system, and any interruptions or failures in power supply, as well as other technical malfunctions, can significantly disrupt mining operations. Thus, ensuring an adequate and stable power supply poses a fundamental challenge, particularly for remote mines. It is crucial to consider the source of electricity generation as it directly impacts environmental considerations. Depending on the electricity mix, power generation may result in higher CO_2 emissions compared to the combustion of diesel fuel. Therefore, the ideal approach entails the utilization of renewable energy sources to achieve the most substantial reduction in carbon emissions.
4. Operational maintenance: In order to ensure the consistent reliability and functionality of trolley lines, regular inspections and maintenance procedures are necessary, resulting in additional maintenance expenses. The road infrastructure requirements for the overhead line sections are particularly stringent. The permissible tolerance for the distance between the road surface and the trolley line is extremely small, to guarantee uninterrupted contact between the pantograph and the overhead line. Consequently, the maintenance work associated with these road sections is considerably more intensive in comparison to conventional truck and shovel operations.

2.2.1 Trolley Line Infrastructure

The power supply infrastructure assumes a critical role in the implementation of trolley lines, as depicted in Figure 2-3. Mines establish a connection to an external power grid through an alternating current (AC) substation, which serves as the interface between the external power supply and internal power distribution. The alternating current voltage from the transmission line is transformed to a voltage suitable for mine operations. Subsequently, the power is distributed via cables from the AC substation to designated locations within the mine. [1, 14, 16]

To facilitate the supply and control of power for the trolley lines, rectifier substations are connected ahead of the trolley lines. Within the rectifier substation, rectifier transformers capture the AC voltage and adjust it to values compatible with the rectifiers. The rectifiers then convert the electrical current from alternating current to direct current, ensuring compatibility with the electrical systems of the trucks. The rectifiers subsequently distribute the requisite power to the catenary system through the employment of DC switchgear. The catenary system, in turn, supplies the necessary voltage and current to the trucks. Depending on the length of the catenary and the power demands of the trucks, a rectifier substation can cater to approximately two trucks simultaneously on the trolley line. [1, 14]

Figure 2-3 Power supply on mine site



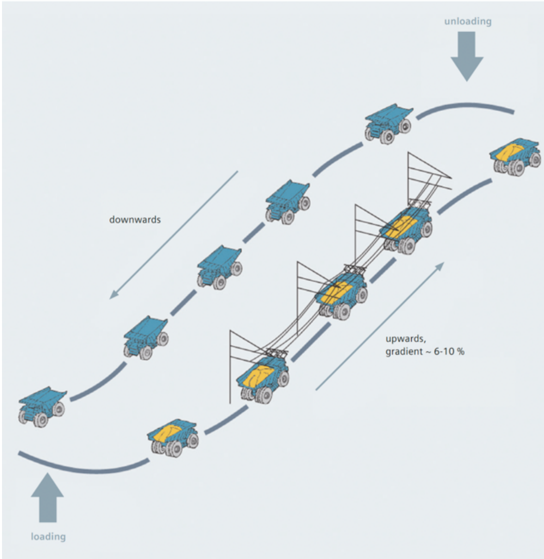
Note. Adapted from [16]

Overhead lines, known as elevated transmission lines, are supported by poles spaced at intervals of 30-40 meters. These lines traverse directly above the track within the trolley assist segment. Consisting of two copper DC conductors, the overhead lines establish direct contact with the carbon brushes of the truck's pantograph during the trolley line section, thereby supplying power to the truck. [1, 14]

2.2.2 Truck-Trolley Line Interaction

In accordance with Figure 2-4, following the loading process, the mining haulage truck proceeds towards the ramp while operating in diesel/battery mode. Trolley lines are predominantly installed along ramps as the diesel engine operates at maximum load during this phase, allowing the trolley line to provide the greatest fuel-saving benefits and take advantage of increased speed. Upon reaching an adjusted speed of 10-15 km/h, the operator deploys the pantograph as soon as it aligns with the trolley line. When contact is established with the trolley line, the trolley control box depicted in Figure 2-5 transitions into trolley mode. In this mode, the truck no longer draws current from the generator, which is driven by the diesel engine, but rather from the trolley line itself. Two conductors are necessary to convey the direct current. One conductor supplies the positive traction current while the other serves as the return path, carrying the current back from the truck to the substation. While operating in trolley mode, the diesel engine idles, supplying power to auxiliary equipment. Downstream of the trolley control box, an inverter is connected, which converts the DC current sourced from the trolley line into AC current and subsequently propels the electric drive motors on the rear axle of the truck. Upon reaching the termination point of the trolley line, the operator retracts the pantograph, causing the trolley control box to switch back to either generator or battery power, depending on the configuration. [3, 17]

Figure 2-4 Truck Cycle on Trolley Line

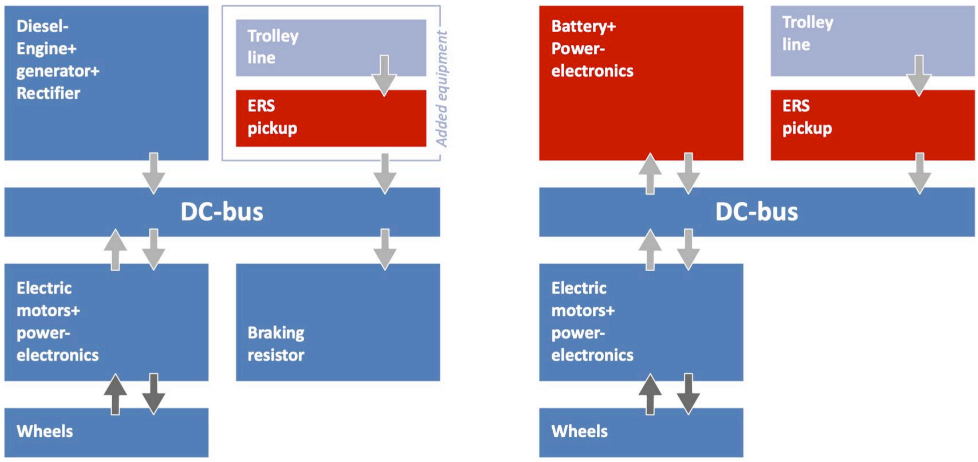


Note. Source [18]

The diesel-electric setup of the haulage trucks makes it possible to provide existing trucks with a pantograph and the necessary control elements. This is an important advantage, as no new trucks have to be purchased for the installation of a trolley line and the truck fleet only has to be converted.

A notable challenge encountered during the interaction between a mining haulage truck and a trolley line system lies in the demands placed on the truck operator. The utilization of the trolley line necessitates trained operators who possess a high level of concentration and skill, primarily due to the increased speed and the narrow horizontal tolerance range involved. Human error represents the most common issue arising during the interaction between the truck and the trolley line. Insufficient concentration or lack of experience can lead to premature or delayed extension of the pantographs, resulting in system damage or underutilization and subsequent costs. Moreover, diminished focus can cause trucks to deviate from the prescribed low horizontal tolerance of the pantographs. Loss of contact triggers a protective mechanism wherein the pantographs retract, and the truck transitions to diesel/battery mode. A lack of concentration may also result in contact or collisions between the truck and the support posts of the trolley line, potentially causing damage or system breakdown.

Figure 2-5 Haulage trucks main powertrain components and power flows



Note. Adopted from [10]

2.3 Battery-Electric Trucks

One of the most promising solutions for mitigating CO_2 emissions in open-pit mines is the utilization of battery-electric trucks, which may become a viable alternative to diesel-electric trucks. The concept of replacing internal combustion engines with batteries to reduce CO_2 emissions is not a novel idea and is already widely adopted in the automotive industry [19]. However, unlike the automotive sector, there are currently no commercially available mining haulage trucks ready for purchase in the market.

The original equipment manufacturer (OEM) Caterpillar Inc. (CAT) showcased and demonstrated the inaugural battery-electric prototype in November 2022 at a designated testing site in Arizona, in the presence of mining industry representatives and delegates. The prototype in question was an electrified 793 large haulage truck. According to CAT [20], the truck successfully traversed a seven-kilometre test route while carrying its rated payload of 230 tonnes. Throughout the test, the truck attained a maximum speed of 60 km/h and ascended a one-kilometre ramp with a 10% incline at a speed of 12 km/h. Furthermore, the truck exhibited the capability to ascend a one-kilometre ramp, and on a downhill ramp with a 10% gradient spanning one-kilometre, it harnessed energy regeneration to replenish the battery. According to Caterpillar, the truck retained sufficient battery energy even after completing the test course to facilitate further complete cycles. More detailed information regarding the battery specifications and performance was not provided in the available information. [20]

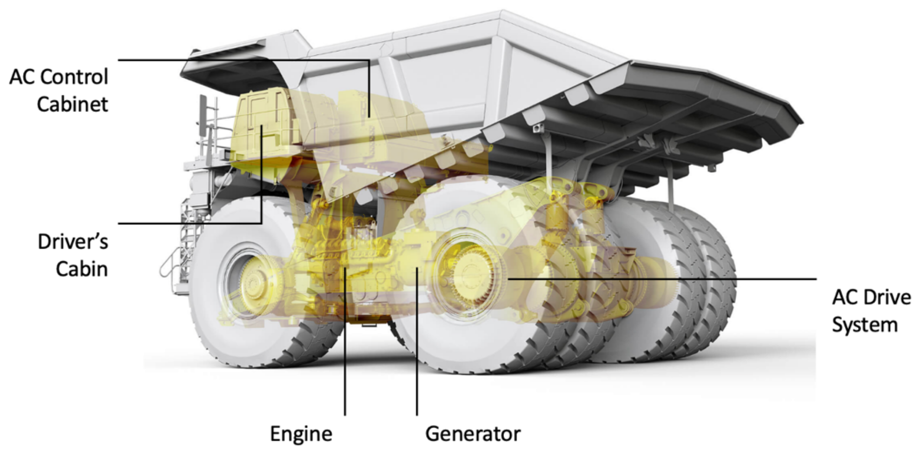
In January 2023, Fortescue Future Industries unveiled the initial prototype battery, designed for integration into the collaborative truck project with Liebherr. The prototype encompasses a 1.4MWh power system developed by WAE Technologies. As per Liebherr's statement, diverse battery types are presently undergoing testing, and their capacities will be contingent on the sizes of the machines involved. This phase primarily focuses on the testing of various battery types and determining their compatibility with the truck system. The power system developed by WAE Technologies will be incorporated into a T264 truck, specially modified by Liebherr, featuring a payload capacity of 240 tonnes. [21]

In March 2023, the OEM Hitachi Construction Machinery and the mining company First Quantum Minerals announced a collaborative effort to conduct a proof of concept for Hitachi's inaugural battery-electric trucks. This collaboration builds upon their prior partnership, as the Kansanshi copper-gold mine operation already possesses 41 diesel-electric Hitachi trucks of the 180-tonne payload class. These trucks currently operate on a trolley line system developed in conjunction with the energy and automation technology group ABB. Given the existing infrastructure, the mine provides an ideal testing environment for the battery-electric trucks. It is planned that in March/April 2024, a battery-electric EH4000AC-3 truck with a payload capacity of 220 tonnes will be deployed. Hitachi is utilizing an ABB lithium-titanium-oxide (LTO) battery system, achieving an approximate capacity of 500kWh. [22]

2.3.1 Construction and Design

The construction process typically involves utilizing the pre-existing design of a diesel-electric truck. As illustrated in Figure 2-6, the conventional components such as the diesel engine, generator, and rectifier, which are located in the lower front part of the vehicle, get replaced by a battery, inverter, and battery temperature control system.

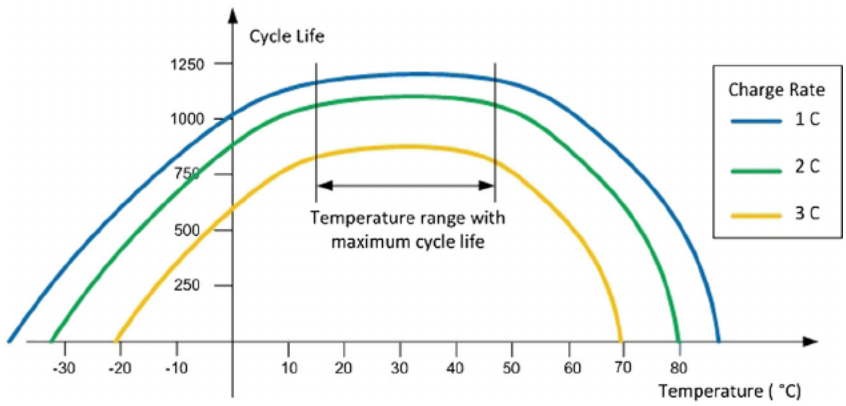
Figure 2-6 Positions of the main components of a truck



Note. Adopted from [23]

The battery temperature control system takes a vital role in preserving the battery's lifespan. As shown in Figure 2-7, the lifetime of a battery is considerably influenced by external temperatures. The diagram describes the dependence of temperature and charge rate on the number of life cycles of a lithium-ion battery. The x-axis describes the temperature on a scale from -30° to 80° Celsius. The y-axis describes the life cycles to be achieved in relation to the charge rate, which is indicated by the different colours blue, green and yellow. For a lithium-ion battery, the optimal temperature range lies between 15° - 45° Celsius; temperatures outside this range noticeably impact the battery's service life in a negative manner.

Figure 2-7 Lithium-ion battery life vs. temperature and charging rate



Note. Adopted from [24]

The selection of appropriate battery chemistry for a haulage truck is significantly influenced by the limited volume of space available for accommodating the engine and generator. The development of batteries and related technologies is subject to continuous optimization and rapid progress. Nonetheless, certain key aspects hold significance in determining the battery choice:

- *Energy density:* The energy density of a battery describes the amount of energy in relation to its mass. The higher the energy density of a battery, the more compact it can be designed.
- *Capacity:* The capacity of a battery is the amount of energy that a battery can store. The capacity should be adapted to the needs of a mine. The charging infrastructure and cycle length play an essential role in determining the required capacity.
- *Weight:* The weight of a battery goes hand in hand with the energy density and selected capacity of a battery. If possible, the weight should be as low as possible to increase the efficiency and payload capacity of the truck.

- *Lifetime:* Lifetime describes the number of complete charge and discharge cycles a battery can go through before its capacity decreases significantly. The end of a battery's life is usually defined as a remaining capacity of 70% - 80%, but varies depending on the purpose, application, and specific performance requirements. Haulage trucks usually operate in three-shift operation around the clock. Due to the continuous utilisation of the trucks, there are a high number of charging cycles per day, which means that the end of life in charging cycles is reached quickly. A battery type with the longest possible service life should therefore be selected in order to keep the battery replacement rate and thus costs as low as possible.
- *Chargeability:* Different battery types have different chemical compositions and structures, which affects their ability to tolerate high C-rates. The C-rate is defined as the charge/discharge current divided by the nominal battery capacity. As shown in Figure 2-7, higher C-rates cause an increased rate of battery degradation, thus shortening battery life. Choosing a battery that can tolerate a high C-rate is therefore important so that the truck's batteries can take up as much energy as possible during the short periods in which they are charged.
- *Safety:* Especially in industries such as mining, safety is of utmost importance. The previously mentioned aspects are crucial parameters for the performance and efficiency of a truck but should not be designed at the expense of safety.

In addition to the battery, the truck requires a complementary Battery Management System (BMS). The implementation of a BMS is crucial for monitoring and controlling various essential parameters of the battery. These parameters include State-of-Charge, State-of-Health, Temperature, Cell Balancing, Charge, and Discharge Control. Through diligent monitoring and control of these parameters, the battery's performance can be optimized, thereby achieving the longest possible battery life expectancy. Additionally, early detection of potential risks becomes feasible, facilitating proactive measures and enhancing the ease of planning for maintenance and battery replacement activities. [25, 26]

Utilizing a battery enables the recovery of the truck's braking energy, which can subsequently be stored in the battery. In contrast, conventional diesel-electric trucks employ a friction-based braking system, leading to the dissipation of energy in the form of heat, resulting in energy loss. With the implementation of battery electric trucks, regenerative braking technology comes into play, wherein the electric motor functions as a generator. The mechanical energy is converted into electrical energy, which is then fed back into the battery for reuse. This regenerative braking technology proves particularly impactful in deep mines or situations where the mining site is situated at a higher elevation than the dump site. In such scenarios, fully loaded trucks can travel downhill, allowing for the recuperation of significant amounts of energy during braking, while empty trucks can ascend uphill with the assistance of the stored energy in the battery. This optimized utilization of energy not only enhances operational efficiency but also contributes to minimizing overall energy consumption and environmental impact. [27]

Another crucial aspect to consider is the charging system employed for battery electric trucks. There are two distinct approaches to charging battery-electric haulage trucks. The first approach involves a plug-in charging system, where the truck is connected to a circuit through an interface at a stationary location. Modern solutions available in the market now offer fully automated fast charging systems with a charging capacity of up to 3 MW. It is noteworthy that the development of charging systems is progressing at a similar pace to that of batteries, with multi-megawatt charging systems becoming the next target. In this system, the electricity from the connected source is dedicated solely to the charging of the battery. [28, 29]

The second battery charging system, as discussed in Chapter 2.2, is known as the Trolley Assist System. To utilize this charging mechanism, the battery-electric truck is equipped with a pantograph, which is affixed to the front of the haulage truck using a steel construction, allowing for its adjustable elevation. The pantograph itself has a weight of approximately seven tonnes. When the truck is connected to the grid, a portion of the DC current from the trolley line is directed through the AC control cabinet to charge the battery. Simultaneously, another portion of the current is routed through the AC control cabinet to power the AC drive system. As this constitutes a dynamic system, it permits bypassing the battery during charging, thereby reducing battery degradation. Charging power of the Trolley Line fluctuates based on the demand of the AC Drive System. The steeper the ramp and the higher the truck's speed, the less power from the Trolley Line remains available for battery charging. This variable charging capacity must be taken into consideration during operational planning and optimization of the Trolley Assist System to ensure efficient utilization of available power resources. [3, 10, 16]

2.3.2 Charging Infrastructure

For the effective integration of battery electric haulage trucks within a mining operation, a systematic and comprehensive approach to planning and establishing the charging infrastructure is of paramount importance. The successful implementation necessitates meticulous consideration of various factors, which are inherently site-specific and unique to each mine. Additionally, it is essential to differentiate the planning for each aspect based on its relevance to either a stationary plug-in system or a trolley-assisted charging system, as certain considerations may be more specific to one system over the other. The critical aspects to be addressed are:

- Power Supply and Capacity: In this phase, a thorough examination of the current power supply infrastructure is required to ascertain its capability to accommodate the additional energy demand. If the existing infrastructure falls short of meeting the required load, appropriate modifications and adjustments must be undertaken to rectify the situation.
- Charging locations: The strategic planning of charging locations is imperative for both the trolley line and plug-in variants. To minimize travel distances for charging, plug-in systems should be seamlessly integrated in close proximity to the haulage roads. Furthermore, positioning these charging stations after the ramp is crucial, as this is where batteries require the most frequent recharging. Depending on the length of the ramp and the battery capacity, an assessment is necessary to determine the specific locations where charging points along the ramp are required. In the design of charging points, utmost consideration should be given to ensuring easy accessibility for the trucks. Efficient entry and exit procedures should be implemented, eliminating the need for truck manoeuvring and interactions between vehicles.

  As for the trolley lines, their installation on the ramp should adhere to the aforementioned specifications. The passages for the trolley line must be straight, and the width of the roads should be sufficient or expandable to accommodate the trolley line posts.
- Charging Rate and Time: The adaptation of the charging rate for both the Plug-in Charger and the Trolley Line should be carefully aligned with the specifications of the truck batteries. The C-rate employed during battery charging must be tailored to the specific battery type to prevent accelerated battery degeneration. Notably, higher charging rates can be utilized with the same C-rate when larger batteries are installed. Regarding the plug-in system, prudent planning of the charging time is imperative to achieve optimal efficiency. Conversely, for the trolley line, the charging time is determined by the truck's speed, thus presenting an opportunity for strategic incorporation during the planning process.
- Compatibility and standardization are critical aspects for mining operations involving trucks from various manufacturers and/or different truck classes. To achieve compatibility in the context of the Plug-In System, the adoption of a uniform charging interface becomes imperative. As for the Trolley Line Assist System, it necessitates

equipping all trucks with suitable pantographs, while ensuring that the voltage and current on the trolley line are adeptly managed for each truck. In both instances, the battery charging rate is automatically regulated by the BMS integrated within each truck.

- Scalability: As the mine expands in size and depth over time, the driving cycles progressively extend, necessitating an increased number of trucks. Ensuring the adaptability of the charging infrastructure to accommodate these growing demands becomes imperative. The escalating energy requirements must be met by expanding the charging infrastructure within the mine. This entails constructing additional charging areas in newly developed regions and potentially enlarging existing ones. In the case of the trolley line system, the establishment of trolley line passages is necessary on newly constructed ramps. Moreover, existing trolley lines can be equipped with additional substations as deemed necessary.
- Monitoring and Control: The charging infrastructure constitutes a crucial system within the mining operation, and any failures in this system can lead to far-reaching consequences, potentially resulting in production shutdowns. Thus, it is imperative that the charging infrastructure is equipped with a comprehensive monitoring and control system. This system facilitates the tracking of charging activities, energy consumption, and potential issues. Additionally, integration of data from the trucks' BMSs into this monitoring and control system enables the dispatch team to collect and analyze real-time data pertaining to machine and charging system performance. This integration ensures a comprehensive and proactive approach to managing the charging process and related operational aspects.
- Planned maintenance should be meticulously designed for the charging infrastructures, following precisely defined guidelines. The regular implementation of maintenance procedures aims to minimize instances of unplanned downtime and effectively economize expenses. Qualified personnel, equipped with sufficient critical spare parts, must conduct the maintenance work. The real-time monitoring system facilitates the early detection of potential issues that may arise beyond the scope of scheduled maintenance work, necessitating prompt resolution.
- To ensure the safety of the plug-in chargers and trolley lines, a hazard analysis of the installations and operation of the charging infrastructure must be conducted. The identified hazards are subsequently quantified through a risk assessment. Probability

and potential consequences are defined, and strategies for direct risk reduction and risk elimination are then formulated.

The success of integrating battery electric trucks in open pit mines to mitigate carbon emissions is contingent upon the careful examination of crucial considerations and charging infrastructure requirements. The assessment of power demands, strategic positioning both within and outside the mine, as well as the monitoring of the system, plays a pivotal role in ensuring efficient operations. Additionally, the implementation of safety measures and the capacity for scalability, along with compatibility with future expansion plans, are imperative for achieving long-term sustainability. Furthermore, to effectively enhance the objective of carbon emission reduction, a thorough investigation into the integration of renewable energy sources becomes indispensable.

2.4 CO_2 Emissions Analysis and Scope Considerations

Greenhouse gas emissions stand as the primary instigator of climate change and global warming. These emissions encompass specific gases discharged into the atmosphere, augmenting the Earth's natural greenhouse effect [30]. As these gases accumulate in the atmosphere, they absorb heat from the sun, giving rise to escalating temperatures in the atmosphere. Subsequently, this phenomenon leads to the melting of ice caps and glaciers, heightened occurrences of extreme weather events, rising sea levels, and disturbances to ecosystems [31-34]. It is noteworthy that human activities have substantially amplified the concentrations of these gases in the atmosphere, thereby attributing the phenomenon to human-made climate change [35].

The most important greenhouse gases include [36, 37]:

1. Carbon dioxide (CO_2): Primarily generated through the combustion of fossil fuels (coal, oil, and natural gas) and deforestation.
2. Methane (CH_4): Emitted from agricultural activities (e.g., livestock), landfills, and natural gas production. (GWP_{100}: 28) [38]
3. Nitrous oxide (N_2O): Released during agricultural processes and fossil fuel combustion. (GWP_{100}: 265) [38]
4. Fluorinated gases: This category includes hydrofluorocarbons (HFCs) (GWP_{100}: 92 - 14,800), perfluorocarbons (PFCs) (GWP_{100}: 7,390 - 17,340), and sulphur hexafluoride (SF_6) (GWP_{100}: 23,500). They find application in refrigeration, air conditioning, and various industrial processes. [38, 39]

The Global Warming Potential (GWP) serves as a comparative metric for assessing the greenhouse gas effect of diverse gases. It quantifies, in relative terms, the amount of thermal radiation that a given gas would absorb within a specified timeframe (indicated in subscripts) compared to an equivalent mass of CO_2. Commonly used time horizons are 20, 100 and 500 years. [40]

This thesis primarily centers on the carbon dioxide emissions stemming from haulage trucks and explores potential strategies for their mitigation through the incorporation of electrification. The imperative to reduce GHG emissions is crucial in mitigating the adverse impacts of climate change. Numerous nations have pledged to curtail their CO_2 emissions, as reflected in various international agreements, including the Paris Climate Agreement and the Kyoto Protocol [41].

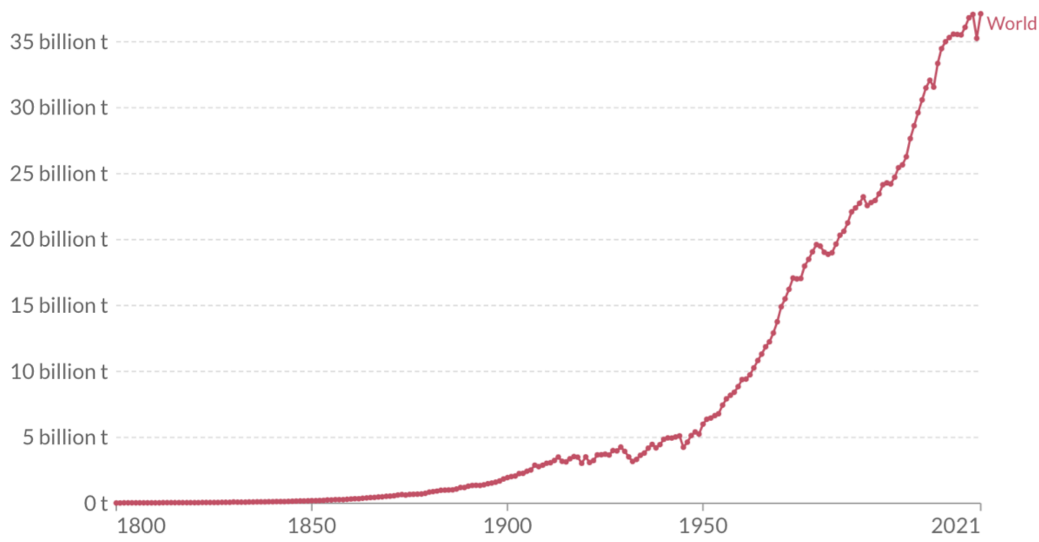
2.4.1 CO_2 Reduction Targets and Commitments

The Paris Agreement constitutes a legally binding international accord that was adopted by 169 countries during the 21st UN Climate Change Conference in Paris on 12 December 2015. The fundamental objective of this agreement is to restrict the global temperature increase to a maximum of 1.5 degrees Celsius compared to the pre-industrial era, or to maintain it well below two degrees Celsius. In order to accomplish this, a reduction of 45% in emissions must be achieved by 2030, ultimately reaching net-zero emissions by 2050. [42, 43]

Figure 2-8 illustrates the global annual CO_2 emissions, with the x-axis denoting the timeline from 1800 to 2021 and the y-axis representing CO_2 emissions in trillions of tonnes. In the context of the Paris Agreement, there is frequent discussion regarding the necessity of reducing greenhouse gas emissions to pre-industrial levels, which pertains to the period preceding the Industrial Revolution that commenced in the late 18th century. During this era, the concentration of CO_2 was approximately 280 ppm, in stark contrast to the global average of 407.8 ppm recorded by the beginning of the 21st century [44, 45].

Before the commencement of the industrial revolution in 1760, annual CO_2 emissions were approximately 10 Mt. Over the course of the following 200 years, by 1950, these emissions escalated significantly to reach an annual emission level of 6 Gt of CO_2. Subsequently, the rapid economic growth witnessed after the Second World War contributed to a sixfold increase in annual CO_2 emissions over the last 70 years. As of 2021, the global annual CO_2 emissions surpassed 37 Gt. Looking ahead to the year 2030, there is a pressing need to curtail emissions to a target level of around 20 Gt annually. Achieving this objective is vital to address the challenges posed by climate change and ensure a sustainable trajectory for our planet. [45]

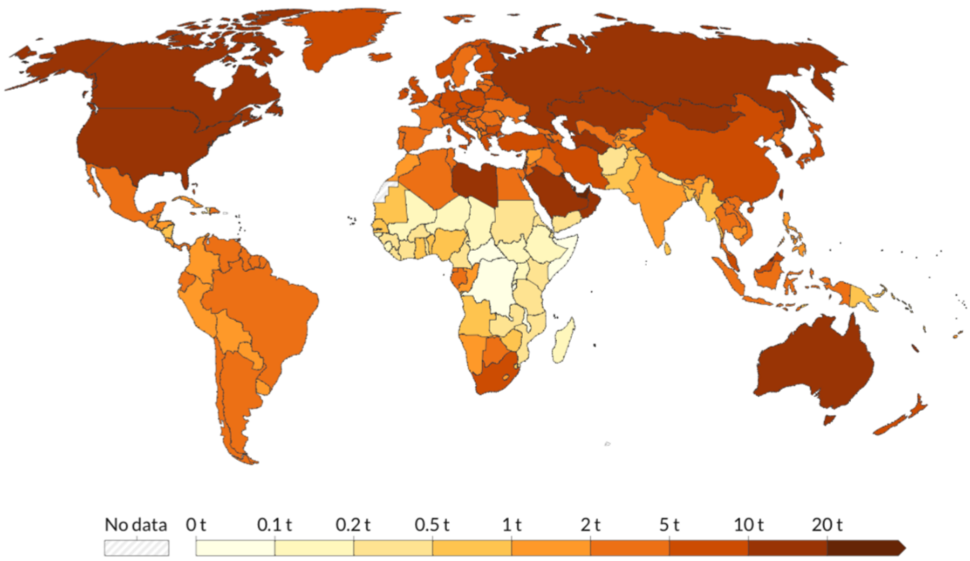
Figure 2-8 Global annual CO_2 emissions



Note. Data from [45, 46]

In 2021, Australia's CO_2 emissions amounted to 390 Mt, constituting approximately 1.05% of the total global CO_2 emissions. However, concerning CO_2 emissions per capita, Australia ranks 10th, with a figure of 15.09 tonnes, trailing behind oil-producing nations in the Arab Gulf States, as depicted in Figure 2-9. Following Australia are the United States with 14.86 tonnes and Canada with 14.30 tonnes. The per capita emissions of these three countries are three times higher than the global average, which stands at approximately 4.8 tonnes. [45]

Figure 2-9 CO_2 emissions per capita



Note. Adopted from [45]

Being a signatory to the Paris Agreement, Australia has undertaken a commitment to undertake substantive measures aimed at the reduction of greenhouse gas emissions. The composition of Australia's emissions currently comprises the eight sectors delineated in Table 2-1. The emissions delineated in the table are presented in terms of CO_2e. Carbon dioxide equivalent serves as a standardized metric for quantifying quantities of greenhouse gases, established upon the concept of GWP. It constitutes a method for expressing the influence of distinct greenhouse gases in relation to the comparable quantities of CO_2, generating equivalent levels of warming impact over a designated temporal span [47].

The most substantial portion, amounting to 33.3%, is generated through electricity production, reaching 254.6 Mt of CO_2e in 2022. Following this, the stationary energy sector constitutes the second-largest segment, contributing to a total of 104 Mt, accounting for 22.4% of the overall emissions. The Energy-Transport sector encompasses emissions resulting from the direct combustion of fuels for transportation. This category encompasses automotive gasoline, diesel oil, liquified petroleum gas, and aviation turbine fuel. Collectively, when combined with emissions from the five additional sectors namely Agriculture, Fugitive Emissions, Industrial Processes and Product Use, Waste, and LULUCF (Land Use, Land Use Change, and Forestry), Australia's total annual emissions amounted to 463.9 Mt of CO_2e. A comparison with the preceding year reveals a reduction in emissions of -0.4%. [48]

Table 2-1 Annual CO_2e emissions per sector

Sector	Annual emissions year to December 2021 (Mt CO_2e)	Annual emissions year to December 2022 (Mt CO_2e)	Change (per cent)	Share of total emissions (per cent)
Energy - Electricity	160.10	154.60	-3.5	33.3
Energy – Stationary energy excluding electricity	105.60	104.00	1.5	22.4
Energy – Transport	89.20	93.60	4.9	20.2
Energy – Fugitive emissions	49.70	48.80	-1.7	17.4
Industrial processes and product use	32.90	32.40	-1.6	10.5
Agriculture	78.70	80.70	2.6	7.0
Waste	13.50	13.60	1.0	2.9
Land Use, Land Use Change and Forestry	-63.90	-63.90	0.0	-13.8
National Inventory Total	465.80	463.90	-0.4	100.0

Note. Source [48]

In pursuit of emissions reduction, the Australian government has undertaken a commitment to decrease emissions by 26-28% by 2023 in comparison to the baseline year of 2005. This strategy necessitates a reduction of 26% in the emissions of each of the eight designated sectors. The realization of this goal demands a notable reduction in emissions, particularly within the transport, stationary energy, and fugitive emissions sectors.

As outlined in [5], calculations indicate that achieving the aforementioned target necessitates annual reductions of 5.0%, 5.3%, and 5.5% within the transport, stationary energy, and fugitive emissions sectors, respectively, during the period spanning from 2021 to 2030. However, an analysis of the percentage change within these sectors from 2021 to 2022, as presented in Table 2-1, reveals that, barring fugitive emissions, no discernible negative trend can be ascertained. Notably, the transport sector exhibits an increment of 4.9% in emissions, contrary to the requisite reduction of 5%. [5]

As an integral component of Australia's primary sector, the mining industry holds the distinction of being the nation's most substantial direct emitter of greenhouse gases, alongside the electricity, gas, and water sectors. In the year 2020, the mining sector's emissions amounted to a quantification of 102 Mt of CO_2e within the context of Australian emissions. This figure constituted 20% of the overall aggregate of Australian emissions and a substantial 68% of the cumulative emissions attributed to the primary industrial sector. It is essential to elucidate that these emissions fall under the purview of the Scope 1 classification, encompassing solely those emissions emanating directly from the mining enterprise itself through its infrastructural facilities and vehicular assets, which encompass excavation equipment, haulage trucks, auxiliary machinery, and cars. [2]

A substantial proportion of these emissions emanate from diesel haulage trucks, which operate at notably elevated utilization rates. The potential for considerable reduction in carbon dioxide emissions is presented through the electrification of materials transport within the mining sector, as delineated in Australia’s Long-Term Emissions Reduction Plan of the Australian Government. The integration of emerging low-emission technologies holds the promise of reducing emissions in the mining sector by over fifty percent from 2019 to 2050. This projected reduction constitutes a substantial advancement towards aligning with the carbon budget stipulated by the International Energy Agency (IEA) for the year 2050. As per the IEA's requirements, mining enterprises are compelled to curtail their emissions by 58% from the benchmark of 2010 levels by 2050. The electrification of haul trucks stands out as a crucial and pivotal measure in realizing these ambitious emission reduction objectives. [15, 49]

2.4.2 Greenhous Gas Emission Scopes

The Greenhouse Gas (GHG) Protocol constitutes a widely acknowledged and universally accepted framework designed to account for and report greenhouse gas emissions. Conceived as a result of collaboration between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), this framework serves the purpose of furnishing organizations with a consistent and lucid set of guidelines for the documentation and administration of their greenhouse gas emissions. The GHG Protocol is formulated with the intention of assisting governments, enterprises, and other entities in comprehending, quantifying, and, in the long run, diminishing their impact on climate change. [50, 51]

The division of emissions into three distinct scopes as shown in Figure 2-10 and outlined by the GHG Protocol, encompasses a range of both direct and indirect sources of emission. These delineated scopes serve to facilitate a comprehensive evaluation of an organization's carbon footprint and to discern domains where strategies for emission reduction may be effectuated. [50]

Scope 1: Direct emissions

> Scope 1 emissions encompass direct greenhouse gas emissions arising from sources owned or managed by the reporting entity. These encompass emissions stemming from activities including the incineration of fuel in company-owned vehicles and equipment, as well as the combustion of fossil fuels for both on-site heating and industrial processes. [50]

Scope 2: Indirect emissions

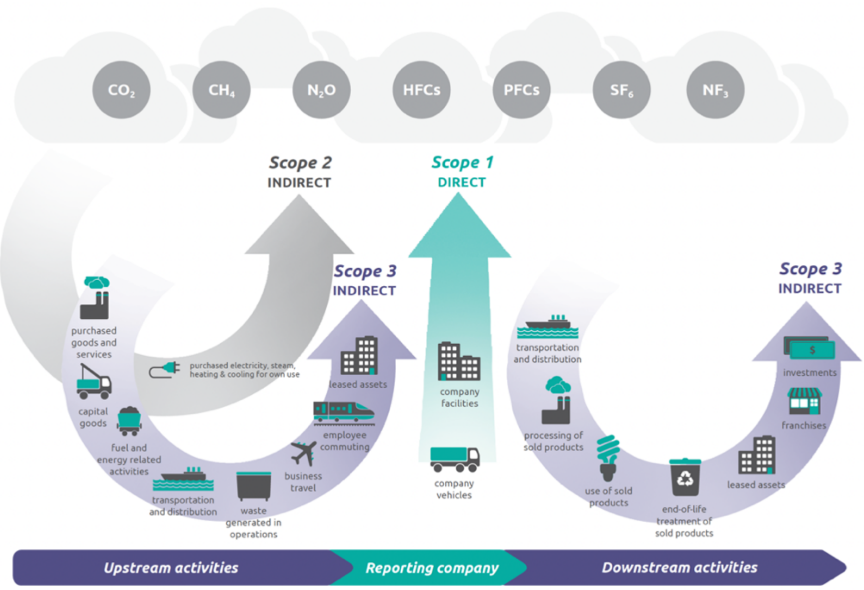
> Scope 2 emissions encompass indirect emissions associated with the production of purchased electricity, as well as the utilization of heating, cooling, and steam within the reporting entity. This scope acknowledges that although these emissions originate off-site, they are a consequence of the organization's operational activities. For example, in the context of integrating trolley lines, the emissions resulting from the electricity generation powering the trolley line operation are categorized as Scope 2 emissions. The mitigation of Scope 2 emissions can be substantially achieved through the procurement or generation of renewable energy. [50]

Scope 3: Other indirect emissions

Scope 3 emissions encompass a broader spectrum of indirect emissions stemming from activities situated upstream or downstream of the operational scope of the reporting entity. Despite their linkage to the entity's operations, these emissions pertain to ancillary activities. This category involves emissions originating from the entire lifecycle of products employed by the entity, as well as those arising from transportation, distribution, employee commuting, business-related travel, waste disposal, and numerous other sources. The division between upstream and downstream activities is illustrated in Figure 2-10. The assessment and management of Scope 3 emissions entail substantial constraints and challenges. The extent of these limitations varies depending on the operational context, at times necessitating extensive assessments that may compromise the precision of the results. Such processes demand considerable resource allocation due to their comprehensive nature. Compounded by data scarcity issues, assumptions often become imperative in instances where data availability is restricted. [50, 52]

Differentiating these three scopes assists organizations in comprehending the entirety of their emissions effects. Often, Scope 3 emissions, which are beyond the direct control of an organization, can be substantial and reveal opportunities for cutting emissions across the value chain. By considering all three scopes, organizations can create more comprehensive strategies to reduce emissions and make well-informed choices to achieve their environmental goals.

Figure 2-10 Overview of GHG Protocol scopes and emissions across the value chain



Note. Source [53]

2.5 Australian Power Grid and Electrification Considerations

Australia is characterized by the presence of three distinct electricity systems, namely the National Electricity Market (NEM), the South West Interconnected System (SWIS), and the Northern Territory System. The NEM, encompassing the six eastern and southern states of the country, stands as the world's most extensive interconnected electricity grid. It holds the significant responsibility of catering to approximately 80% of the nation's aggregate electricity consumption [54, 55]. Conversely, the SWIS system represents Western Australia's principal electricity network, spanning across the south-western region. Its geographical coverage extends northward to Geraldton and eastward to Kalgoorlie, effectively serving the coastal urban centres of Albany, Bunbury, and Perth [56]. The Northern Territory System constitutes a comparatively compact network dedicated to supplying electricity to 72 remote towns dispersed throughout the state. Primarily reliant on diesel power plants for its energy provisioning [57].

The composition of Australia's electricity generation fuel mix is presented in Table 2-2. During the year 2020-21, the nation produced a total of 265,554 GWh of electricity. Notably, 73.2% of this energy was derived from fossil fuel sources, while renewables accounted for 26.7%. Fossil fuels encompassed 40% from black coal, 12.8% from brown coal, 18.7% from natural gas, and 1.8% from oil. Among the renewable sources, solar photovoltaic (PV) installations constituted the largest portion at 10.4%, followed by wind energy at 9.7%, hydroelectric power at 5.7%, and bioenergy at 1.3%. [9]

Upon reviewing the average growth pattern over the past decade, an adverse trend of -1.5% becomes evident. While the proportional utilization of black coal and lignite has progressively diminished over these years, the use of oil as a fuel source has exhibited a 4.2% increase over the same period. Conversely, a pronounced surge is discernible in the proportional expansion of renewable energy resources, marking a noteworthy increment of 10.3%. This growth is attributed to the establishment of new solar PV facilities, wind energy projects, and advancements in bioenergy technologies. [9]

Table 2-2 Composition of Australia's electricity generation fuel mix

	2020-21 (GWh)	2020-21 share (per cent)	2020-21 growth (per cent)	10 year average annual growth (per cent)
Fossil fuels	194,756	73.3	-5.1	-1.5
Black coal	106,251	40.0	5.0	-1.0
Brown coal	34,060	12.8	1.2	-4.7
Gas	49,783	18.7	-9.8	0.2
Oil	4,662	1.8	3.4	4.2
Renewables	70,798	26.7	18.1	10.3
Solar PV	27,717	10.4	31.8	33.6
Wind	24,535	9.2	20.3	15.0
Hydro	15,200	5.7	0.3	-1.0
Bioenergy	3,346	1.3	-0.2	4.8
Total	265,554	100.0	0.1	0.5

Note. Source [9]

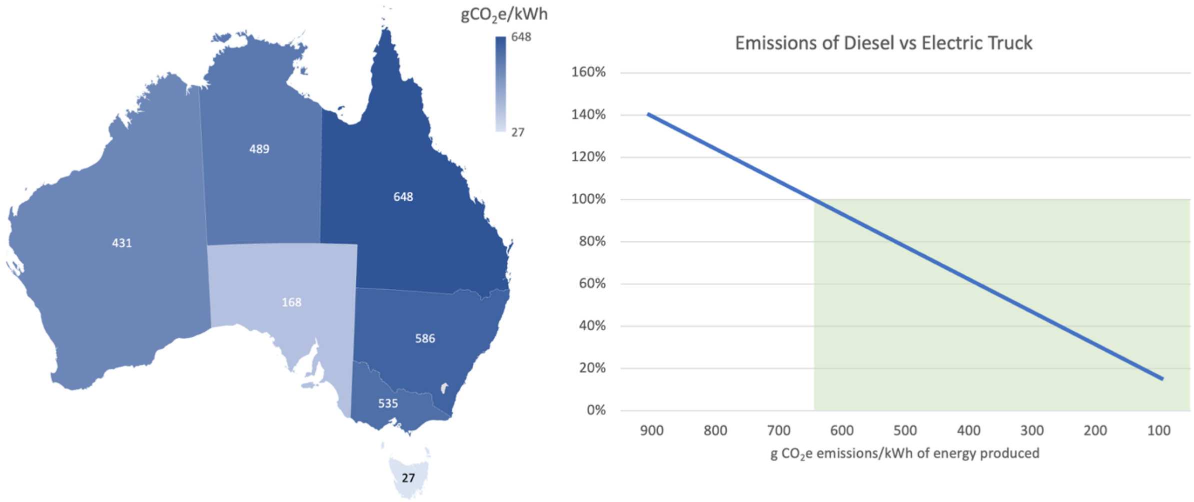
As indicated within Australia's comprehensive long-term emissions reduction strategy [49], the anticipated outcome of investing in low-emission technological solutions is the substantial reduction of emissions stemming from electricity generation, with a projected decrease of no less than 91% within the period from 2005 to 2020. This objective is being pursued through deliberate investments in the realm of renewable energy, with particular emphasis placed upon solar photovoltaic (PV) systems. Australia's unparalleled solar resource, characterized by an unprecedented solar radiation per square meter, surpassing that of any other continent, has substantiated the prominent focus on solar photovoltaics.

In 2018, Australia had over 400 operational mines, with around 65% sourcing their power demand from the NEM and SWIS. The NEM serves the majority of mines in the eastern states, and about half of the mines in South Australia (SA), while the SWIS caters to a third of the mining operations in Western Australia (WA). For those mines not linked to either grid, roughly 50% secure their power supply through local Independent Power Producers (IPPs). The remaining 50%, positioned in remote locales, fulfill their electricity demands via diesel generator systems. A shift towards hybrid renewable energy technologies assumes a pivotal role for these remote mines, serving as a strategic measure to curtail their respective emissions. [58, 59]

To meet the increasing demand for new technologies to reduce carbon emissions, the demand for raw materials is increasing accordingly. Considering that the mining sector currently contributes to 7% of global emissions, it is even more urgent to collectively mitigate the resulting emissions regardless of the increasing mining efforts. According to McKinsey [60], the process of electrification of mines is expected to increase their electricity demand by +115% to 175%. Given this emerging demand in an emissions-constrained context, the critical challenge is to balance the increased energy demand with the increased integration of renewable energy sources. This symbiotic integration aims to reduce emissions effectively and offset the increased electricity demand due to increased mining activities.

To ensure a reasonable and effective transition to electric alternatives in the mining sector, it is imperative that CO_2 emissions from electricity generation remain below a certain threshold. The diagram presented in Figure 2-11 on the left delineates the state specific CO_2e emissions, measured in grams per kilowatt-hour (gCO_2/kWh), which inherently vary based on distinct energy compositions. Correspondingly, the adjacent graph portrays the proportional emissions attributed to an electric truck across varying CO_2 emissions per kWh, compared against those of a conventional diesel haulage truck.

Figure 2-11 Emission threshold diesel vs. electric operation



Note. Left: Average gCO_2e/kWh per state and territory in 2022; Right: Emission comparison diesel vs. electric Truck; Source [61]

Assuming a 36% efficiency for diesel engines and 92% for electric motor, the analysis establishes a stipulation wherein the CO_2 emissions emanating from electricity generation should ideally fall below approximately 645 gCO_2/kWh. In instances adhering to these premises, the integration of electric trucks within Queensland, marked by the highest CO_2 emissions per kWh, would culminate in an increase of 0.5% in CO_2 emissions when contrasted with a diesel truck. Conversely, in Tasmania, characterized by electricity primarily sourced from 99% renewable energy origins, an electrified truck's operational emissions could feasibly experience a reduction of nearly 96%.

This data exemplifies the substantial potential inherent in the utilization of electrified trucks facilitated by renewable energy sources.

In instances wherein remote mining operations fulfil their power requirements via diesel generator systems, the electrification of haulage trucks necessitates an adjustment to the power provisioning. To effectively address the augmented electricity demands, an expansion and optimization of the power supply are imperative, ensuring that the vehicular electrification effectively translates into a reduction of CO_2 emissions. An exemplar approach involves the integration of hybrid systems, leveraging renewable energy sources such as solar photovoltaic (PV) systems in conjunction with diesel generators. Moreover, the integration of supplementary battery storage options is progressively gaining traction; however, these presently serve as supportive components within the systems and do not inherently offer a self-sufficient remedy to reliably counterbalance periods of reduced renewable energy availability. [62]

3 Materials and Methods

This chapter aims to clarify the methodology used in this thesis. It starts by outlining the conceptual framework adopted for this study, thus providing an understanding of the existing context and baseline conditions from which the electrification of trucks is being undertaken. This explanation covers important contextual factors, operational components, and essential parameters that play crucial roles during this transition. This exposition contextualizes the subsequent exploration of diverse case scenarios, following the electrification analysis. Subsequently, the simulation of the different cases is described, focusing on pit design, scheduling, equipment selection, energy consumption calculations and CO_2 emission calculations. The input data and the justification for the assumptions made will also be explained. The aim is to provide a clear understanding of how the different electrification scenarios have been simulated and evaluated. The calculations of investment and operating costs are presented hereafter. This section addresses the financial considerations and assumptions associated with each electrification scenario. It includes a breakdown of the capital and operating expenses that are impacted by the different truck electrification options. By providing insight into the cost components and explaining the assumptions made, the aim is to provide a transparent view of the financial implications of the different cases.

3.1 Scenario Description

A hypothetical mining scenario was devised to simulate various scenarios. The mine selected for this simulation is an open-pit iron ore mine situated in Australia. The analysis conducted in this study pertains to overarching trends, strategies, and challenges applicable to the entire country; hence, a specific geographic location was intentionally omitted. This mine was established in 2016 and possesses a projected LOM of approximately 35 years. Conventional truck and shovel operations are employed for ore extraction.

In alignment with the emission reduction goal set for 2030 and the long-term objective of achieving net-zero emissions, the process of electrifying the truck fleet is scheduled for completion by January 2024. This study will examine and quantify three distinct approaches to electrification. Subsequent to the quantification, the outcomes of the analyses pertaining to CO_2 emissions and associated costs will be compared with the Base Case scenario of diesel-powered truck and shovel operations. This comparison aims to determine the electrification strategy that offers maximal emissions reduction in the long run and to evaluate the financial implications of these measures against the project's objectives.

The initial scenario pertains to the incorporation of trolley line infrastructure intended for utilization by diesel-electric haulage trucks. The trucks that were procured before January 2024 will be retrofitted with pantographs and the necessary technical adaptations. During the electrification commencement, the installation of three trolley lines spanning a cumulative extent of 4.1 km will take place. This endeavour will culminate in the assimilation of eight trolley lines covering a combined length of around 8.8 km by the project's conclusion. The placement of these trolley lines is confined to inclines or ramps. Beyond stationary trolley lines, the installation of semi-stationary trolley lines is also anticipated. These semi-stationary lines will necessitate periodic relocation in alignment with the progression of mining activities. The comprehensive deployment of trolley lines across various ramps holds the capacity to curtail diesel consumption, thereby engendering substantial savings markedly. Furthermore, the incorporation of this infrastructure is poised to notably enhance haulage efficiency.

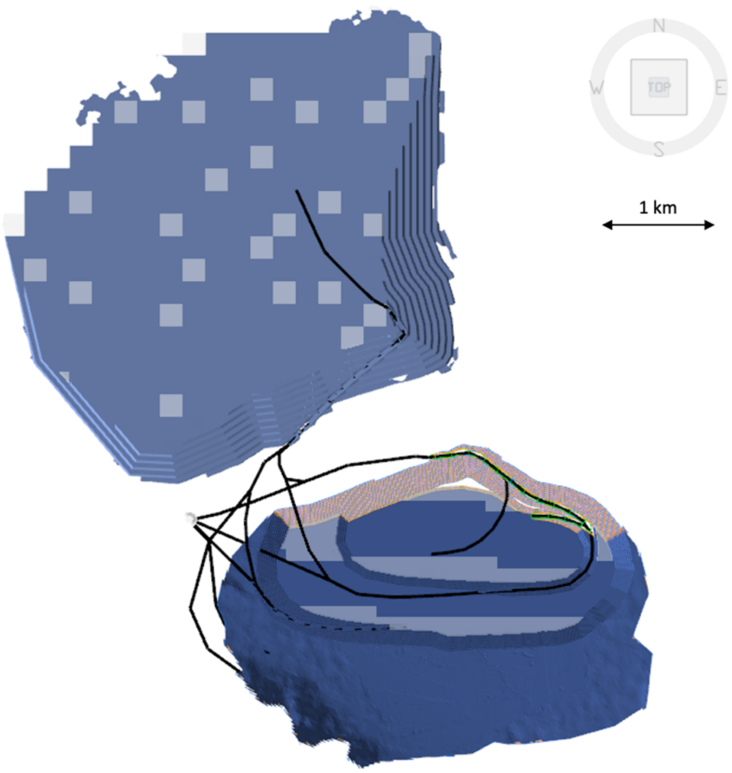
The second scenario involves combining trolley lines with a switch from diesel-electric trucks to battery-electric trucks. In this context, the pre-existing trucks will also undergo conversion procedures. This involves the replacement of the engine and fuel tank with battery units, as well as the incorporation of a pantograph mechanism to facilitate electricity absorption. Importantly, the configuration places higher demands on the trolley line infrastructure due to the trucks' reliance on their power supply owing to their relatively limited battery range when compared to diesel trucks. To meet the power requisites of the trucks in this context, in addition to the trolley lines already employed in the first scenario, supplementary trolley lines become necessary, specifically on level segments post the ramps. This additional infrastructure facilitates the recharging of the trucks' batteries. In this regard, a total of nine trolley lines, spanning a collective extent of 11 km, are installed as part of the LOM strategy.

In the third and final scenario, the haulage process undergoes a transformation with the integration of battery-electric trucks, which receive their power from stationary plug-in rapid battery charging systems. Similar to the second case, the existing trucks undergo a conversion to battery-electric and are equipped with requisite battery units. In this context, an interface designed for connection to the rapid charging system is incorporated.

In the context of this electrification alternative, the establishment of charging stations becomes imperative. These stations need to be strategically positioned both within and beyond the pit to effectively address the electricity demands of the trucks. Similar to the concept of trolley lines, the expansion of the charging infrastructure becomes an ongoing necessity in conjunction with the mine's expansion and the augmentation of the fleet size. Thus, a continuous integration of new charging points throughout the LOM emerges as a requisite practice.

The initial scenario from which the electrification process is planned to start is illustrated in Figure 3-1. The mining operation follows a mining mode, progressing after reaching a certain depth with mining guidance that gradually expands towards the southern direction. The mine encompasses two ramps; the primary ramp is situated in the northern section of the mine, maintaining a consistent trajectory that extends throughout the mine's developmental stages, ultimately reaching the deepest point. Adjacent to the mine's southwestern region are the ramps associated with the individual stages, which exhibit significant variations across the distinct mining phases within the LOM. The waste dump is located in the northwest corner of the open pit, with a ramp leading south towards the mine. The ore crusher is located on the western perimeter level of the open pit. It is strategically positioned between the mine and the waste dump.

Figure 3-1 Status quo of the mine before electrification



Note. Waste dump in the north and pit in the south, the crusher is in the west between dump and pit

The fictional operation was initiated in 2016, commencing with a two-year ramp-up phase. During this phase, four Hitachi EX5600 excavators were employed in conjunction with 22 Hitachi EH5000AC-3 trucks, each with a payload capacity of 300 tonnes. This collaboration facilitated an annual material movement of approximately 90 Mt within this initial two-year span. Subsequently, by 2018, an additional acquisition of four Hitachi EX5600 excavators and 25 more Hitachi EH5000AC-3 trucks was effectuated. This expansion was aimed at achieving the targeted annual material movement of 180 Mt. Looking ahead to 2024, the expected year for the shift to electric haulage, a total of 65 diesel-electric trucks, each with a payload of 300 tonnes, have been purchased.

The projected mine's Ultimate Pit Limit (UPL) demonstrates a west-east extension measuring 3,850 meters and a north-south extension spanning 2,800 meters along the boundary of the open pit. The deepest point of the mine is at a depth of 645 metres. The calculated reserves of the mine are estimated at 538 Gt, featuring a stripping ratio of 12:1 and a specified cut-off grade set at 10%.

The technical feasibility of the scenario depends on reserves whose economic viability for the mining project had been established by independent analysis. This study will focus on the comprehensive scenarios and will investigate the potential reduction of CO_2 emissions, decrease in energy consumption, and evaluate economic implications associated with electrification of haulage trucks.

3.2 Description of the Simulation

This chapter covers the detailed simulation process, including the central elements that build our comparative analysis of haul truck electrification scenarios. A comprehensive breakdown highlights the stages of pit design, scheduling, energy calculations and CO_2 emission estimates.

Cutting-edge software tools played a pivotal role in facilitating precise simulations and data-driven comparisons to accurately model and analyse the various scenarios. Specifically, the realization of pit design was achieved through the utilization of Deswik.CAD, a robust software suite designed for mine planning and design. This platform enabled the creation of intricate layouts tailored to the unique requirements of each electrification scenario. Furthermore, Deswik.LHS emerged as an indispensable tool for simulating haulage operations. This software facilitated the dynamic assessment of haul truck movements, energy consumption, and subsequent environmental impacts. Through the utilization of Deswik.LHS, different electrification strategies were evaluated with a high degree of precision, yielding insights of paramount importance for the comparative analysis.

3.2.1 Pit Design

The input data used and created for the pit design are listed in Table 3-1. Table 3-2 contains the parameters and assumptions used to create the pit design.

Table 3-1 Input data for pit design

Data	Format	Source	Comments
Block Model	.gmdlb	Supplied by MEC	Implementation of a correction factor
Topography Surface	x, y, z data	Supplied by MEC	Modified for this work
Stage Designs	.dxf	Created	Breakdown into 5 Stages
Pit Stage Solids	Triangulation	Created	
Schedule Blocks	Triangulation	Created	Created for pit and dump

Note. Adopted and created data used in Deswik

Table 3-2 Input Parameter for pit design

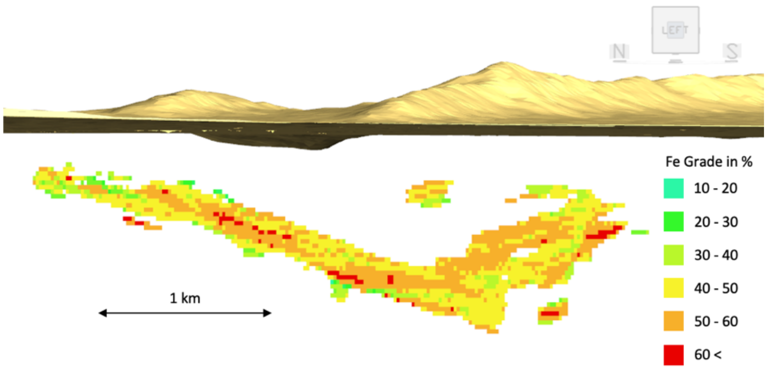
Design Parameters	Value	Unit
Pit		
Bench Height	15	m
Face Angle	60	deg
Berm Width	10	m
Ramp Gradient	10	%
Ramp Width	40	m
Overall Slope Angle	39	deg
Schedule Mining Block	100 x 100 x 15	m
Dump		
Bench Height	15	m
Face Angle	35	deg
Berm Width	40	m
Ramp Gradient	10	%
Ramp Width	40	m
Overall Slope Angle	13	deg
Schedule Dump Block	200 x 200 x 15	m
General		
Overall Haulroad Length	41,371	m
Speed Limit	50	km/h
Downhill Speed Limit (gradient < -3%)	30	km/h

Note. Parameters chosen for the design of the pit

The initiation of the pit design process involved the formulation of the UPL and the subsequent delineation of stages. The foundation for this process was established through the integration of the block model, illustrated in Figure 3-2, and the resultant pit optimization analysis output shells. These shells were formulated as a component of the comprehensive economic viability assessment conducted externally.

The nested pit shells derived from the external optimization served as an initial reference point, ensuring a certain degree of economic feasibility within the context of electrified scenarios. It should be noted, however, that the primary objective underlying the pit layout development was not exclusively governed by economic parameters. Rather, the primary focus has been to align the design with the operational, energy and environmental requirements inherent in electrification concepts.

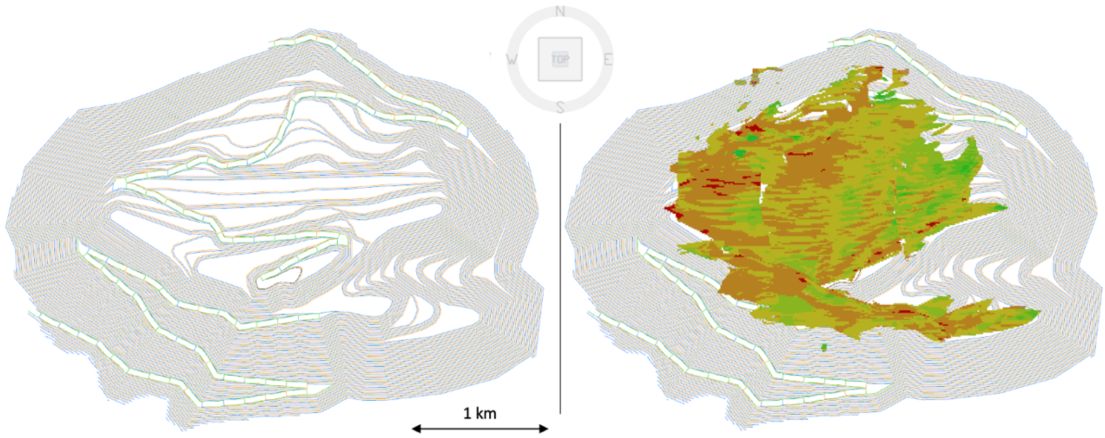
Figure 3-2 Block model with topography



Note. View from the west towards the east

The deposit displays a notably gentle angle of inclination extending from north to south. Consequently, the northern wall of the UPL was developed to align with the deposit's gradual dip angle. In devising the pit configuration, specific parameters were adopted: a bench height of 15 metres, a face angle of 60 degrees, and a berm width of 10 metres. These dimensions yield an overall slope angle of approximately 39 degrees. The choice of these parameters was determined by their widespread use in the Australian context. Additionally, it is worth noting that an overall slope angle of 40 degrees, as analysed by Abdellah et al. [63], is associated with a minimal probability of slope failure, while concurrently maintaining a reasonable stripping ratio.

Figure 3-3 Ultimate pit limit with block model

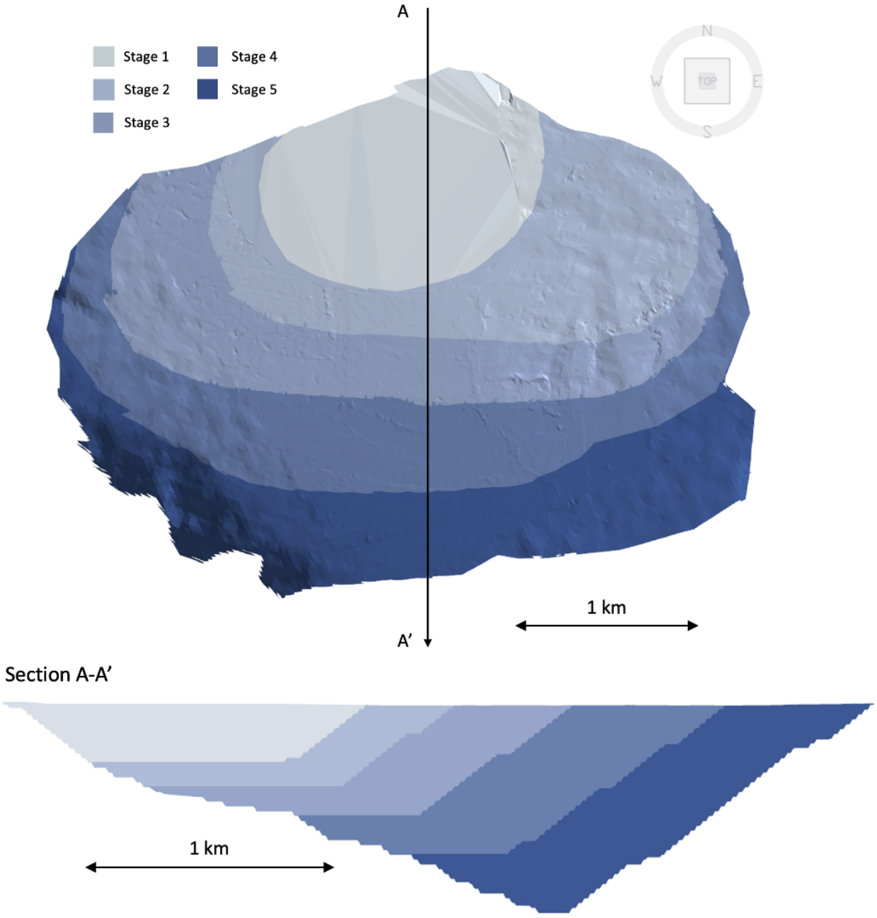


Note. View from above

Following the creation of the UPL (show in Figure 3-3), the mining progression stages illustrated in Figure 3-4 were established. The initial Stage 0 was initiated in the north of the mine, capitalizing on the ore's proximity to the surface. Subsequent stages were sequentially configured, progressing from the north to the south of the deposit. In the stage design process, a deliberate selection of a moderate number of stages was made to facilitate the attainment of adequate stage widths. This optimal width, along with the associated volume of material to be excavated, contributes to the prolonged durability of the ramps. This extended operational lifespan significantly simplifies the incorporation of trolley lines. Their operational duration is prolonged, allowing them to function for an extended period before necessitating relocation to other ramps due to the ongoing mining process.

In the context of ramp design, a gradient of 10% was selected, a choice elucidated by Thompson [64] , given that mining trucks typically demonstrate optimal performance within the range of 8% to 10%. The dimensioning of the ramp width was established at 40 meters. The specific parameters employed for calculating the ramp width are itemized in Appendix 3.1. Concerning the switchbacks, a preference was made for flat switchbacks characterized by a length-to-width ratio of 1.0 and an inside radius of turn measuring 0.0. These values align with established best practices when utilizing the switchback function within Deswik.CAD. Notably, the switchback pads were designed to be of greater dimensions, thereby affording supplementary space for potential power infrastructure requirements.

Figure 3-4 Pit solids coloured by stages

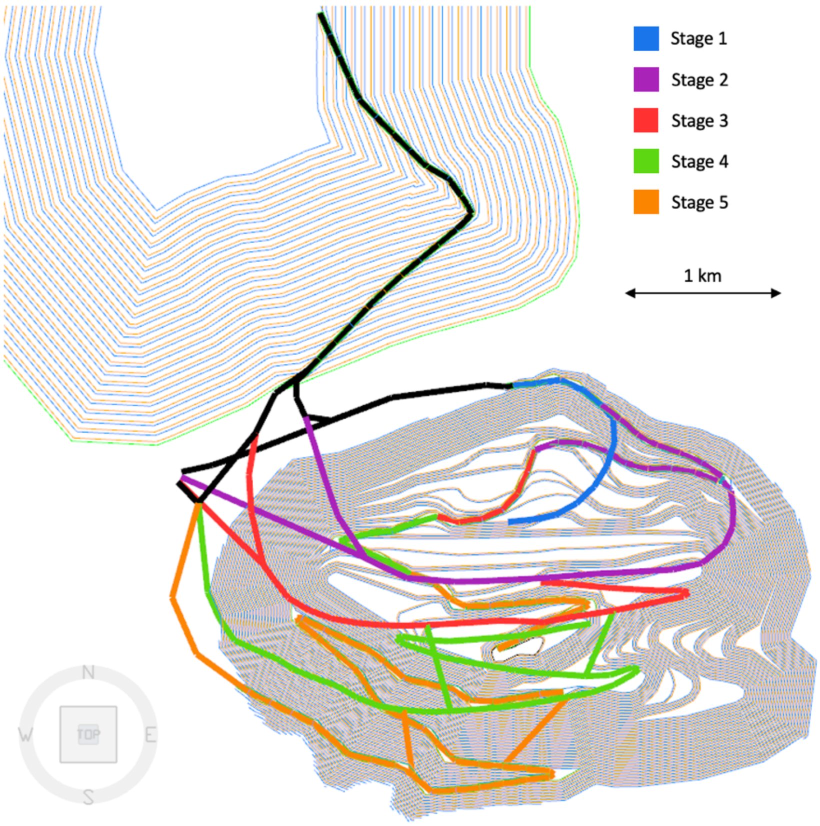


Note. Top: View from above; Bottom: Sectional view

A bench height of 15 meters was selected for the design of the waste dump. The dimensioning of the face angle was set at 35°, while the berm width was established at 40 meters. Similarly, the haulage road was configured within the pit, possessing a width of 40 meters and a gradient of 10%. As determined by the design, the solid constituents of the dump were segregated into blocks measuring 200 x 200 x 15 meters.

As shown in Figure 3-5, following the design and construction of the pit, dump areas and their respective ramps, an extensive mine haul road network has been established. This system enables the interconnection of the different ramps that cover various operational phases with both the crusher and the waste dump ramp, thereby determining the layout of the interconnecting roads. In addition, a speed limit of 50 km/h has been established for the haul roads on flat haul roads and 30 km/h on ramps with a gradient of less than -3% for safety reasons.

Figure 3-5 Haul road network by stages



Note. Haul roads shown in black are stage independent

3.2.2 Schedule

The objective of the schedule in this study is to delineate a comprehensive and impartial timetable for the activities entailed in mining operations. This schedule functions as a fundamental framework for appraising the feasibility and efficacy of various electrification scenarios, thereby facilitating a standardized evaluation that incorporates parameters including energy consumption, carbon emissions, and cost implications. It additionally functions as the underpinning for the haulage simulation within Deswik.LHS. The simulation operates based on the date and time generated during the scheduling process, which is subsequently allocated to the mine blocks defining the chronological sequence of mining activities.

It is worth noting that whilst the schedule aims to provide a realistic representation of the mining process under various electrification scenarios, it does not incorporate advanced optimisation techniques, specific market requirements or financial considerations such as Net Present Value (NPV). The schedule is primarily intended to provide a comprehensive understanding of the timing of mining operations in the context of electrification.

Table 3-3 presents the data employed for scheduling purposes, while Table 3-4 enumerates the parameters associated with the scheduling procedure. The scheduling process was formulated within Microsoft Excel, utilizing the exported attributes of the mining solids. The resulting parameters, namely Net Duration, Duration, Start Date and End Date, were then imported into Deswik.CAD as attributes. These attributes were then associated with the respective mining blocks by their specific mining block ID (ID_2.0). The ID is a combination of attributes including Stage, Bench, _I and _J, providing a unique identification for each individual block.

Table 3-3 Input data for mining schedule

Data	Format	Source	Comments
Schedule Attributes	Data Stored on Mining Blocks	Created	Created by 'Block Model Interriogation' Function
Scheduled Block Priority	Values	Created	Prioritisation: Stage > Bench > Direction

Table 3-4 Input parameters for mining schedule

Schedule Parameters	Value	Unit
EX5600 Shovel		
Dig Rate	3,825	t/h
Utilisation	68	%
Work Hours	5,800	h/y
Shovels per Stage	4	
Simultaneous Operation	2	Stages
Dates		
Operation Start Date	01.01.16	dd.mm.yy
Operation End Date	29.10.50	dd.mm.yy
Life of Mine	34.85	years
Attributes		
Stage	Block dependent	$\mathbb{R}$
Bench	Block dependent	$\mathbb{R}$
_I	Block dependent	$\mathbb{R}$
_J	Block dependent	$\mathbb{R}$
Ore Tonnes	Block dependent	t
Waste Tonnes	Block dependent	t
Net Duration	Block dependent	h
Duration	Block dependent	h
Start Date	Block dependent	dd.mm.yy hh:mm
End Date	Block dependent	dd.mm.yy hh:mm

To establish the mining sequence, the mining solids attributes, namely Stage, Bench, _I, and _J, were employed. Subsequently, a directional value was derived from the latter two parameters, following the formulation outlined in equation (3.1). This procedural phase imparts numerical designations to the blocks, effectively delineating the mining orientation from north to south.

$$\text{direction} = \text{J} + \frac{I}{1000} \tag{3.1}$$

For the prioritization of mining blocks, the stage attributes were arranged in ascending order, followed by the bench attributes in descending order, and ultimately the directional values were arranged in ascending order. After the establishment of prioritization, the mining duration was computed for each individual block. The EX5600 excavator has a dig rate of 3.825 t/h. Four excavators per stage were utilized, resulting in a net duration of 15.300 t/h. The net duration was also obtained for the total duration. Additionally, a utilisation rate of 68% for the excavator was included in the overall duration calculation. The start date was set as 01/01/2016 at midnight. From there, digging times were progressively added to establish precise starting and ending dates for each mining block, including their respective beginning and end times.

Following the initial phase, which included four excavators, the acquisition of four new excavators is planned for 01/01/2018. The new dredgers will be utilised for Stage 1, as specified in Table 3-5, while Stage 0 remains in operation. In this way, two stages with staggered start phases can run simultaneously.

Table 3-5 Mine schedule outcome

	Start Date	End Date	Shovel Group
Stage 0	01/01/2016 00:00	05/01/2020 22:59	A
Stage 1	01/01/2018 00:00	25/03/2026 23:30	B
Stage 2	05/01/2020 22:59	20/12/2031 04:43	A
Stage 3	25/03/2026 23:30	29/01/2044 00:54	B
Stage 4	20/12/2031 04:43	29/10/2050 11:41	A

Note. A Shovel group consists of four excavators

Following the completion of Stage 3 mining activities, the ramp-down phase is initiated. Within this phase, the production rate undergoes a gradual reduction, accompanied by a corresponding decrease in the number of operational excavators, which is ultimately stabilized at four units. The final outcome of the scheduling process is a LOM projection of 34.8 years for the mine.

3.2.3 Simulations

The simulation of diverse electrification cases was conducted using the *Scenarios* tool within the Deswik.LHS software. Deswik.LHS is expressly developed for the optimization of mine planning and haulage activities. The embedded *Scenarios* tool provides users with the capability to formulate and evaluate multiple operational scenarios pertinent to a mining operation. This tool facilitated the formulation of distinct cases for this investigation, the results of which constituted the foundational data for the subsequent emissions analysis.

Table 3-6 lists the input data that must be integrated into the Scenarios tool settings to model the different cases. The data comprise project elements formulated within Deswik.CAD and Deswik.LHS, coupled with direct modifications within the advanced scenario setting.

Table 3-6 Simulation input data

Input Data	Format	Source	Comments
Mining Blocks	Triangulation	Created	-
Dump Blocks	Triangulation	Created	-
Haul Roads	Polylines	Created	Categorised into different stages
Mining Slot Connectors	-	Created	Connects each Pit Block with a ramp, according to set constraints
Dumping Slot Connectors	-	Created	Connects each Dump Block with the ramp, according to set constraints
Schedule Sources	-	Created	Start date, End date
Dump Dependencies	.exf	Created	Vertical dependency, maximum 35° overall face angle
Haul Availability	-	Created	Closing and opening of specific lane sections
Trolleys	-	Created	Dependent on the case
Destination Mapping	-	Created	Crusher = Infinite Haul
Material Mappings	-	Created	-
Dumping Strategy	-	Created	Minimizing cycle time

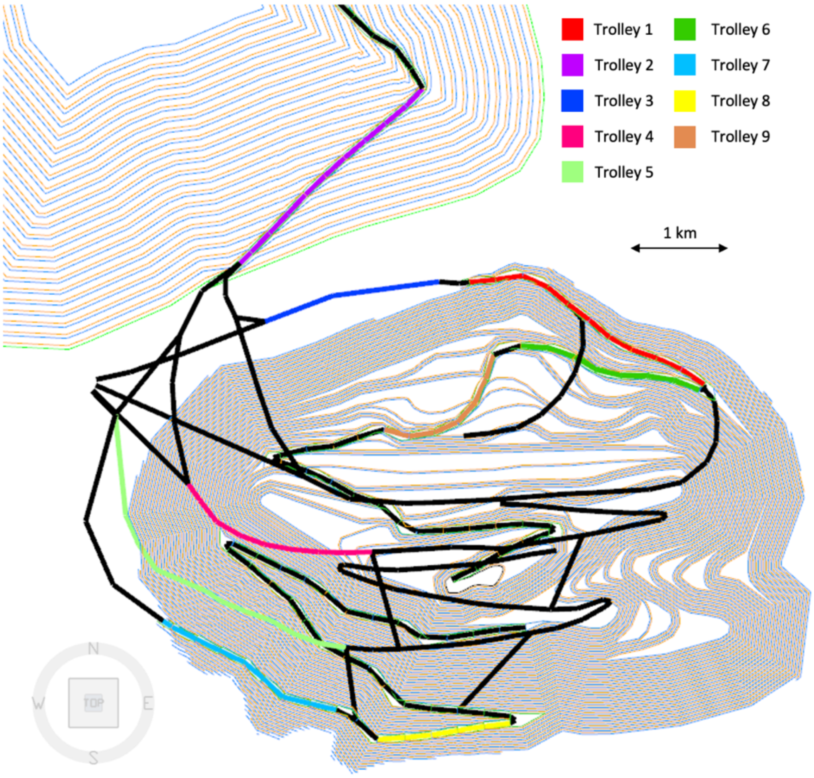
Note. All input data had to be created in previous steps

Through the development of Mining Slot Connectors, a linkage is established between the Mining Blocks within the pit and a Haul Road, subject to predefined constraints. The dump slot connector connects the dump blocks to the haul road. The blocks were interconnected through implementation of the *Nearest within Vertical Tolerance* connection method, with tolerance thresholds adjusted based on the respective stages. To accommodate potential future curves in the haulage road between the block and the ramp, a supplementary distance of 50 metres was incorporated. The regulations and limitations governing the construction of these mining and dumping slot connectors can be found in Appendix 3.2 and Appendix 3.3.

Haul availability is set directly in the settings. This functionality is used where haul roads have been physically removed as mining has progressed. By assigning a 'closed' status to road availability and establishing links between ramps and the subsequent mining phase, the tool facilitates accurate simulation of operational changes. This capability ensures streamlined haulage operations even when road connections are interrupted due to ongoing mining operations. However, it is crucial to bear in mind certain limitations while using the tool for this study. Even though the tool provides significant flexibility and enables weekly opening and closure of track sections, a simplified method was chosen to provide an adequate level of detail for this study. The simulation was focused on ensuring that every truck passes every trolley line on the way to the waste dump. Furthermore, the consistency of haulage availability has been maintained uniformly across all cases, ensuring homogeneity in the designated haulage route for each scenario.

The following stage involves determining the sections in which the trolley lines will be implemented. Initially, the selected haulage road sections are saved as filters, and then stored in the Scenario Settings along with the trolley lines' start and end dates. Figure 3-6 illustrates the trolley lines integrated for these cases, while Table 3-7 lists the parameters of each individual trolley line.

Figure 3-6 Trolley line positions in the pit



Note. Trolley lines according to "Case 2" as shown in Table 3-7

As illustrated in Table 3-7, the simulations encompassed the application of trolley lines in two distinct scenarios: Case 1 featured diesel-electric trucks, whereas Case 2 involved battery-electric trucks. In Case 2, the simulation encompassed the entirety of the nine trolley lines. Apart from Trolley Line 3 (illustrated in blue) and a segment of Trolley Line 5 (illustrated in yellow-green), which extend beyond the pit area, all trolley lines were strategically positioned on inclines. Trolley Line 3 and a portion of Trolley Line 5 necessitated placement on level terrain to align with the specified energy requisites.

In Case 1 involving diesel-electric trucks, the simulation exclusively incorporated trolley lines on inclines. This selection stems from the fact that the advantages conferred by trolley lines on level stretches are notably diminished in contrast to those on inclines, primarily due to reduced engine loading. Furthermore, the trolley line imposes a restricted maximum speed of 30 km/h upon the trucks, considerably diminishing operational efficiency relative to the unrestricted 50 km/h attainable in diesel mode without trolley line integration. Moreover, the cost-benefit equilibrium for trolley lines on level sections is comparatively lower.

For the Base Case and Case 3 with battery-electric haulage trucks, the trolley lines were deactivated for the simulation.

Table 3-7 Trolley line parameters

Trolley Name	Haul_ID	Start Date	End Date	Case 1 (m)	Case 2 (m)
Trolley 1	Ramp_N_00_1590-1741_T	01.01.2024	29.10.2050	1,512	1,512
Trolley 2	Ramp_Dump_1751-1895_T	01.01.2024	29.10.2050	1,430	1,430
Trolley 3	Haulage_N_00_W_T	01.01.2024	29.10.2050	0	1,011
Trolley 4	Ramp_S_02_(2)_T	01.01.2024	01.04.2026	1,178	1,178
Trolley 5	Ramp_S_03_(2)_T	01.01.2028	01.01.2032	854	2,087
Trolley 6	Ramp_N_02_1470-1590_T	01.04.2028	29.10.2050	1,059	1,059
Trolley 7	Ramp_S_04_1725-1835_T	01.10.2033	29.10.2050	1,117	1,117
Trolley 8	Ramp_S_04_1620-1695_T	01.10.2037	29.10.2050	757	757
Trolley 9	Ramp_N_03_1380-1470_T	01.10.2039	29.10.2050	874	874
Sum				8,782	11,026

Note. Adjustments between the cases on Trolley Lines 3 and 5

In the Destination and Material Mapping settings, the mined material is assigned to the appropriate destination, from the mixed mining blocks, the waste volume is assigned to the waste dump and the ore volume is assigned to the crusher, and the parameters shown in Table 3-8 are set.

The strategy for minimizing cycle time was selected, serving as the choice for a dumping strategy. This approach sets the quickest possible cycle time for every potential material type situated within a mining block.

Table 3-8 Destination and material mapping input

From	To	Volume Field	Truck Type	Swell Factor to Truck	Swell Factor to Dump	Spot Load Time (min)	Spot Dump Time (min)	Rolling Resistance (%)
Mixed	Waste	Waste Volume	Hitachi EH5000AC-3	1.2	1.2	3	2	3
Mixed	Ore	Ore Volume	Hitachi EH5000AC-3	1.2	1.2	3	2	3

Note. Based on best practice

The simulation generates a range of standard reports through Deswik, encompassing comprehensive simulation outcomes. The output parameters pertaining to the computed haulage roads are presented in Appendix 3.4. Furthermore, Deswik.CAD's layer control interface generates an additional layer that displays all the computed haulage roads for the LOM. Specific attributes associated with these generated haulage roads are provided in

Appendix 3.5. Notably, the mine under examination in this study encompassed a total of 29,535 thousand distinct haulage roads.

3.3 Energy Calculation

This chapter outlines the precise methodology used to determine energy consumption in different scenarios, forming a solid basis for comparing the proposed mining activities. The following sections provide both the input data and the assumptions that underpin these calculations, followed by the systematic energy assessment for the different cases.

3.3.1 Input Data and Assumptions

The resulting attributes from the generated simulations and the spatial data of the objects are the basis for the energy calculation. The attributes shown in Table 3-9 are from the generated haul roads from the simulation. The attributes in Table 3-10 were generated from the created haul roads using the *Interactive Cycle Time* tool, which shows the fuel requirements of the haul cycles.

Table 3-9 Simulation output attributes

Input Parameters	Unit
CycleTime	min
CycleTimeLoaded	min
CycleTimeUnloaded	min
DistanceLoaded	m
DistanceUnloaded	m
Finish	yyyy/mm/dd hh:mm
FromID	[stage]_[bench]_[I]_[J]
Start	yyyy/mm/dd hh:mm
ToID	[bench]_[I]_[J]
ID_Trucked	[FromID]-[ToID]

In the next phase, the haulage cycles were systematically broken down into segments using the *Interactive Cycle Time* tool. Within their respective ID_Trucked grouping, these segments were sequentially labelled, starting with number one. The assignment of the numbering was archived using the attribute Segment. At the same time, the attributes listed in Table 3-11 were linked to the designated segments. In conjunction with the distinct attributes, further "Global Constants" have been established within Deswik.CAD, these are listed in Appendix 3.6.

Table 3-10 Interactive cycle time output attributes

Quick Calculation Output	Unit
CYCLETIME_WITHTKPH	min
DZ	m
DZMAX	m
FUEL	L
FUEL_LOADED	L
FUEL_LOADED_WITHTKPH	L
FUEL_UNLOADED	L
FUEL_UNLOADED_WITHTKPH	L
FUEL_WITHTKPH	L
SPOT AND DUMP TIME	min
TIME LOADED	min
TIME UNLOADED	min
TRUCK	name

Table 3-11 Segment export output attributes

Segment Export Output	Unit
ID_Trucked	[FromID]-[ToID]
MAX VELOCITY LOADED	max. km/h
MAX VELOCITY UNLOADED	max. km/h
TIME LOADED	min
TIME UNLOADED	min
TRUCK	name
VELOCITY LOADED	avg. km/h
VELOCITY UNLOADED	avg. km/h
Segment	N

Table 3-12 shows the specific weights of the different truck configurations chosen for the cases. The payload of each truck configuration is the difference between the truck weight and the gross weight limit of 500 tonnes. The pantographs have a dead weight of 7 tonnes and the battery was assumed to weigh 15 tonnes.

Using the *Attributes From Formula* tool, further attributes were generated from the attributes of the segments and the spatial data of the objects with the use of formulas. The additional attributes are presented in Appendix 3.7 - Appendix 3.9. Attributes that do not play a crucial role in the energy calculations were created to support the iterative process and to optimise the enclosure designs.

Table 3-12 Specific weights of trucks and components

Type	Weight (t)
Trucks	
EH5000AC-3 diesel-electric	204
EH5000AC-3 diesel-electric + pantograph	211
EH5000AC-3 battery-electric + pantograph	209
EH5000AC-3 battery-electric	202
Truck + Payload	500
Other Components	
Pantograph	7
Battery	15
Catenary Poles	4

Note. The battery and the catenary poles are based on assumptions

3.3.2 Deswik Fuel Calculation Validation

To verify Deswik. LHS fuel calculations, fuel consumption was computed for each segment and then summed in the "ID_Trucked" group. The resulting fuel consumptions were subsequently compared with the fuel parameters from the simulation.

For the calculation of fuel consumption, two approaches were used, an energy-based calculation and a force-based calculation. Assumptions were made based on the haulage road characteristics, average speed, and maximum speed of the segments to determine whether the truck accelerates or decelerates on each corresponding segment. The disparity between the calculated acceleration or deceleration distance and the segmental length was used to calculate the maximum speed. Thus, the calculation of fuel consumption per segment was separated into acceleration, maintaining constant speed, and deceleration, which were then combined.

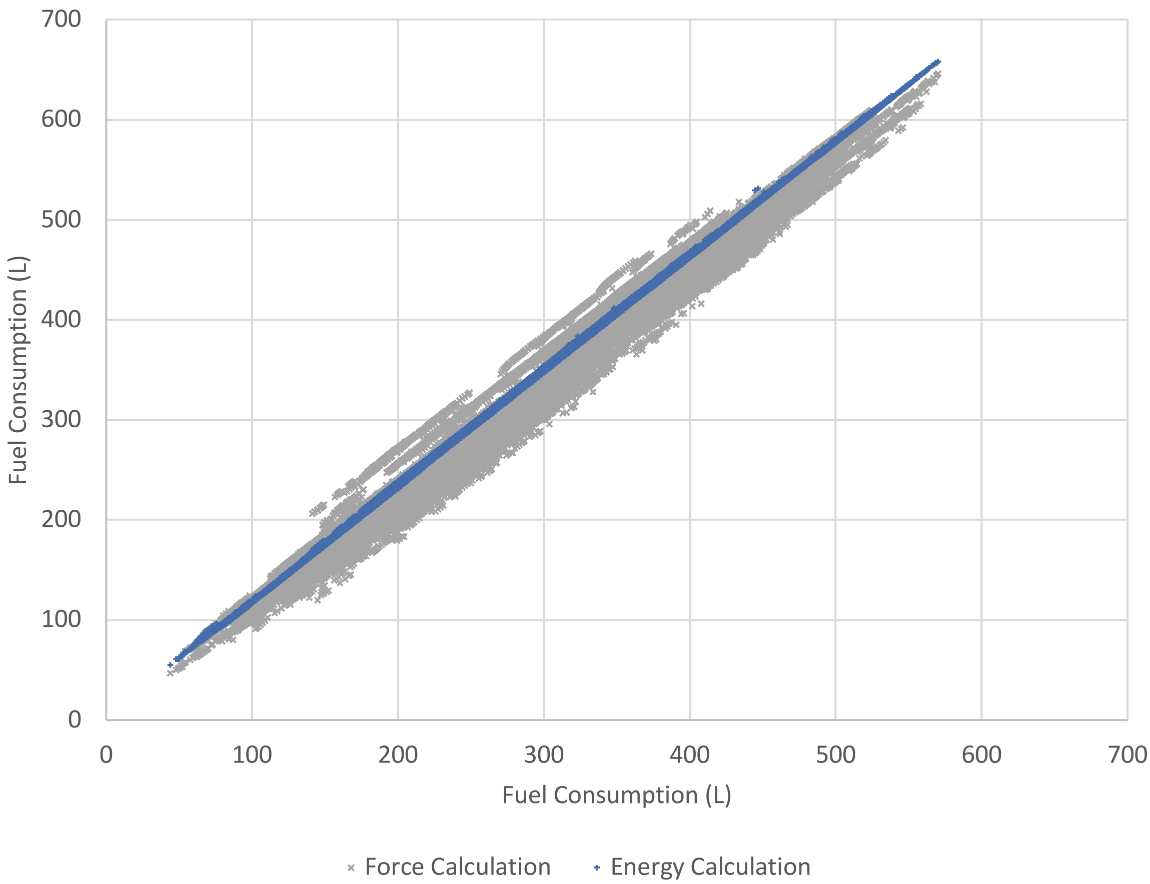
In the energy calculation method outlined in Appendix 3.10, the energy needed to drive the segment was calculated considering the factors of weight, gradient and rolling resistance. For this thesis, air resistance was disregarded. Using the engine's fuel efficiency, the energy requirement can be converted to fuel consumption.

The force calculation outlined in Appendix 3.11 method calculates the various forces acting on the truck. These forces are then used to determine the power required to overcome them. The rimpull curve (refer to Appendix 3.12) enables the calculation of the percentage of the overall power required. To determine the fuel consumption, the minimum fuel consumption is added to the determined percentage of the maximum fuel consumption.

The scatter plot illustrated in Figure 3-7 shows the results of the validation process for the Deswik fuel calculation method using both energy and force calculations. Data points marked with a grey "x" denote the results obtained from the Force Calculation. A noticeable correlation exists with the Deswik calculation, but a distinct variance is also present. This variation may be attributed to underlying assumptions regarding the hauling behaviour of the trucks, which subsequently affect the calculation.

Conversely, data points generated through the Energy calculation are denoted by a blue "+". These results show a similar correlation to the Force Calculation, though with significantly less variation. This observation emphasizes the increased reliability associated with the Energy calculation method.

Figure 3-7 Fuel consumption validation results



The outcomes derived from both calculation methodologies exhibit a positive variance in relation to Deswik's fuel calculations. Specifically, the outcomes of the energy calculations, on average, exhibit a factor of 1.17 higher than those of Deswik. Nevertheless, these findings support the assertion that Deswik's fuel calculations can be regarded as reliable and suitable for facilitating the comparative analysis of the theoretical models within this thesis. It is assumed that Deswik calculations are based on input parameters from calibrations and validations with real-world data. Deswik.LHS is considered an industry standard used by many mining companies and professionals. The fuel consumption results from Deswik allow this study to be better aligned with industry practices and standards.

3.3.3 Base Case: Conventional Diesel Operation

For the base case, the simulation was run with conventional diesel-electric trucks. The aggregate fuel requirement across various operations within a year was summed up to obtain the annual demand, from which the LOM demand could be calculated.

3.3.4 Case 1: Diesel-Electric Trucks with Trolley Assist

For the energy calculation in the first case, a distinction was made between diesel and electricity consumption. As in the Base Case scenario, the first step was to add up the fuel consumption for each action over the year to calculate the annual demand. The force required to overcome a 10% incline at a speed of 17 km/h with a fully loaded truck was then determined. This calculation employed the Force method, which involved calculating the Rolling Resistance Force and Slope Force to determine the overall Force to overcome. The nominal power was then obtained by multiplying the Force with the velocity, and efficiency factors were applied to derive the effective power.

The "Time on Trolley" for each action across all nine trolley lines was aggregated and converted from minutes to hours in the report. By multiplying the necessary power by "Time on Trolley" and the required cycles per action, the energy consumption in kWh can be calculated. The annual electricity demand was determined by adding up the electricity requirements for all the actions throughout the year, in the same way as the diesel demand.

3.3.5 Case 2: Battery-Electric Trucks with Trolley Assist

In Case 2, the energy calculation was performed in the context of a scenario involving a battery-electric truck. As described in chapter 3.3.1, the transport routes generated by the scenario tool were divided into segments based on their respective "ID_Trucked" group. As there was no diesel consumption in this particular case, the energy calculation was carried out using the Set from Formula function in the Deswik software. Subsequently, the energy calculations were attributed directly to the segments. Appendix 3.13 contains detailed information on the attributes and their respective calculations.

In the initial step, calculations are conducted for force, power, and energy. Subsequently, based on the parameters of gradient, speed, and the energy's polarity, the supplementary energy essential for the auxiliary system is incorporated, accounting for the appropriate efficiency considerations.

In the subsequent stage, an evaluation is performed through the use of conditional IF functions to determine whether the requisite energy within the given segment originates from the trolley line, the battery, or if the battery exclusively undergoes regeneration. In cases where the segment is equipped with a trolley line, the first step encompasses the calculation of the power derived from the trolley line, while the remaining portion of the available 8000kW power is denoted as "T_Charge." This value signifies the quantity of kWh by which the segment's battery has been charged. The attribute labelled "Battery_Delta" quantifies the amount of energy either charged to or consumed by the battery during the segment's operation. The cumulative value of "Battery_Delta" can subsequently serve to illustrate the battery's performance throughout the entirety of the haulage route. Additionally, these results provide insights into the battery's required capacity. Attributes such as

- Battery_Discharge_Power,
- Battery_Trolley_Charge_Power, and
- Regeneration_Charge_Power

convey the power levels at which the battery undergoes charging and the power needed from the battery. The C-rate can be calculated based on these characteristics, depending on the battery's capacity.

In the calculation of the actual annual energy requirement, the deduction of surplus energy demand unutilized by the Battery Management System (BMS) during practical operations was carried out in the final step. This involved determining the average surplus supply derived from the mean of all 29.535 haulage cycles and subsequently subtracting it from the energy provision originating from the trolley line.

3.3.6 Case 3: Battery Trucks with Stationary Charging

The energy calculation in the third case is based on the calculations made in the second case. During the simulation, all trolley lines were deliberately deactivated, resulting in the speed calculations relying solely on the rim pull curve of a conventional diesel-electric truck. Due to the specific constraints of the IF functions, only the battery formulae were used, while the catenary formulae were not considered. The haul cycle includes both the required energy (B_Eff_Total_Energy) to be supplied by the battery and the recovered energy (R_Charge).

After assigning attributes to the segments, the dataset of 1.02 million segments was exported as a .csv file. Then, in Excel, the attributes of these segments were summarised within their respective "ID_Trucked" groups and the cumulative battery status was calculated, representing the total energy demand. The sum of all transport operations within a year was then aggregated to determine the annual energy demand.

3.4 CO_2 Emission Calculation

This chapter addresses the emissions calculation process, a key aspect of understanding the carbon footprint associated with each operational scenario. Expanding on the groundwork established in the preceding chapter entitled "Energy Calculation," this section not only clarifies the approach implemented for emissions calculation, but also outlines the basic data sources and critical assumptions underlying these calculations.

3.4.1 Input Data and Assumptions

Table 3-13 shows the input parameters and assumptions used to calculate emissions. The emission rates are taken directly from sources or are derived from such sources. The overall parameters are case-specific and have been calculated based on simulation results.

Table 3-13 CO_2 emission calculation input parameters

Name	Value	Unit
Carbon Emission Rates		
Diesel	2.80	kg CO_2/L
Electricity	0.52	kg CO_2/kWh
Battery	1,860	kg CO_2/kWh
Steel	1.85	kg CO_2/kg
Plug-In Charger	800	t CO_2/Charger
Substation	800	t CO_2/Substation
General Parameters		
Battery Life	20,000	Cycles
Trucks	-	Number
Substations	-	Number
Catenary Poles	-	Number
Plug-In Charger	-	Number

Note. Value Sources: Diesel emissions with an applied factor of 1.05, to include life cycle emissions according to [65]; Electricity value decreases by 15 grams per year [61]; Battery [66]; Steel [67]; Substation and Plug-In Charger assumptions based on [68]

The emissions calculations were divided into scopes for each case. Table 3-14 shows the emission sources that have been considered within each scope in this thesis. In the analysis of Scope 3, particular attention was paid to the emission contributors introduced by the electrification methods, which have the most significant impact. Depending on the approach used, there may be differences in the demand for trucks due to differences in efficiency. In addition, the analysis included the consideration of batteries; despite their potential to reduce diesel consumption, the Scope 3 emissions associated with their production should not be underestimated. The calculations also included a life expectancy of 20,000 cycles. Finally, the additional infrastructure required for electrification was considered.

Table 3-14 Considered emissions sources per case

Cases	Scope 1	Scope 2	Scope 3
Base Case	Diesel	-	Truck Manufacturing
Case 1	Diesel	Electricity	Truck Manufacturing, Substations, Catenary Poles
Case 2	-	Electricity	Truck Manufacturing, Battery + Swaps, Substations, Catenary Poles
Case 3	-	Electricity	Truck Manufacturing, Battery + Swaps, Plug-In Chargers

Table 3-15 demonstrates the components of the trolley line setups in Case 1 and Case 2. For the diesel-electric Case 1, a single substation capable of delivering 8,000 kW was assumed, permitting two trucks to be served simultaneously. To determine the number of trucks that could be served by the trolley line at one time, the 3 minute loading time was divided by the 4 excavators, giving 45 seconds between trucks. Given a trolley line speed of 17 km/h, this equates to 212 metres. As a result, the system has been designed to withstand substantial loads. The distance between trucks is typically greater due to higher speeds on the flat sections before reaching the ramp. The necessary number of sub-stations can be determined by dividing the number of trucks using the trolley line by two.

In contrast, the battery-electric Case 2 requires a dedicated substation for each truck using the trolley line due to the added charging needs. The number of catenary poles is determined by 40 metres spacing between them. It is noteworthy that during the acquisition process, the calculations take into account the reuse of substations and catenary poles from Trolley Lines 4 and 5 for the new trolley lines.

Table 3-15 Trolley line components for case 1 and 2

	Case 1		Case 2	
	Substations	Catenary Poles	Substations	Catenary Poles
Trolley 1	4	38	7	38
Trolley 2	4	36	7	36
Trolley 3	-	-	5	26
Trolley 4	3	30	6	30
Trolley 5	2	22	10	53
Trolley 6	3	27	5	27
Trolley 7	3	28	5	28
Trolley 8	2	19	4	19
Trolley 9	2	22	4	22
Sum	23	222	53	279

The study assessed the requirement for plug-in chargers by calculating the duration necessary to recharge the energy expended during each haulage cycle. This duration was subsequently incorporated into the overall driving time. By dividing the charging time by the total time, the percentage of trucks necessitating charging was determined. The analysis revealed that 30% of the trucks are in a continuous state of recharging. Additionally, it was assumed that a Plug-In Charger system comprises a sub-station with the capacity to simultaneously charge three trucks.

3.4.2 Calculation process

To compute emissions stemming from diesel consumption, the calculated consumption derived from the Deswik simulation was employed in both the base case and case 1. Subsequently, the calculated diesel consumption was multiplied by the diesel emission rate.

For Scope 2 emissions, the energy consumption values calculated in the previous chapter in kWh were multiplied by the CO_2 emissions per generated kWh. As a baseline value for the year 2024, the Australian average of 0.52 $kgCO_2/kWh$ from the year 2022 was employed.

For the production of the trucks, as part of the scope 3 emissions, the number of trucks was determined by the required annual truck hours. The assumed annual truck hours divided by the 5800 annual working hours of the EH5000AC-3 truck gives the required number of units. It was also considered that the trucks have a life expectancy of 75,400 hours before they need to be replaced. Since the truck is mainly made of steel, the empty weight was multiplied by the emissions to produce steel to calculate the emissions.

In the electrical infrastructure context, it was assumed that the catenary poles would be steel made. The total weight of all catenary poles was calculated using the emission rate linked to steel production. The emissions associated with the trolley substations and plug-in chargers were also calculated based on the mentioned assumptions.

To calculate the emissions from the battery, the first step was to determine the annual energy consumption per truck in kWh. Then, the number of charge-discharge cycles required to consume the total converted kWh was calculated. As the operational lifespan is expected to be 20,000 cycles, the annual proportion of this lifespan could be determined. During the emissions calculation process, the next step involved offsetting the annual installation of batteries against the determined percentage of their total lifespan. This was then multiplied by the emission factor associated with battery production.

Although this simplified calculation approach omits the direct consideration of battery Nonetheless, it precisely calculates the emissions linked with battery replacement through the LOM.

3.5 Financial Modelling

In the pursuit of environmentally sustainable mining practices, the assessment of costs associated with potential carbon reduction strategies is of central importance. This chapter offers a thorough undiscounted cost analysis of the three different electrification cases for minimising CO_2 emissions in a conventional truck and shovel operation. All monetary values in this analysis are in Australian Dollars (AU$). This chapter presents the cost assumptions and the methods for calculating the operating expenses (OpEx) and the capital expenditures (CapEx) for the different approaches. The objective is to enable a comprehensive comparison of economic feasibility and environmental sustainability.

3.5.1 Cost Input Data and Assumptions

The CapEx costs for the various scenarios were determined by utilizing the capital values as presented in Table 3-16. This data is derived from a Cost Estimator Guide and assumptions *[69]*. Table 3-16 provides a compilation of the capital values associated with the machinery and infrastructure components necessary for the respective scenarios.

For the calculation of the OpEx costs, the capital costs listed in Table 3-17 have been used. The costs associated with diesel and electricity represent the average expenditure observed in mining operations across Australia. The operating costs for the diesel-electric truck include operating labour, lubricants, maintenance labour, maintenance components, wear-related items, and tyre costs, as detailed in Appendix 3.14.

Table 3-16 Capital values associated with the machinery and infrastructure

Mining Fleet Component	Value	Unit
Haulage Trucks		
Diesel Truck	7,500,000	AU$
Diesel Truck + Pantograph	7,800,000	AU$
Battery Truck + Pantograph	7,800,000	AU$
Battery Truck + Plug-In	7,800,000	AU$
Electricication Components		
Truck Pantograph retrofit	1,562,500	AU$
Truck Battery retrofit	3,125,000	AU$
Substation	2,656,250	AU$
Trolley Line	3,125,000	AU$/km
Plug-In Charger	2,656,250	AU$
Battery	1,000,000	AU$

Note. Based on assumptions and MEC Mining internal information

By excluding maintenance and spare parts for the diesel engine, the running costs for the battery electric truck were conservatively estimated to be 15% lower.

Table 3-17 Operational expenses input values

OpEx Cost	Value	Unit
Diesel	0.73	$/L
Electricity	0.35	$/kWh
Truck diesel-electric	328.37	$/h
Truck battery-electric	279.11	$/h

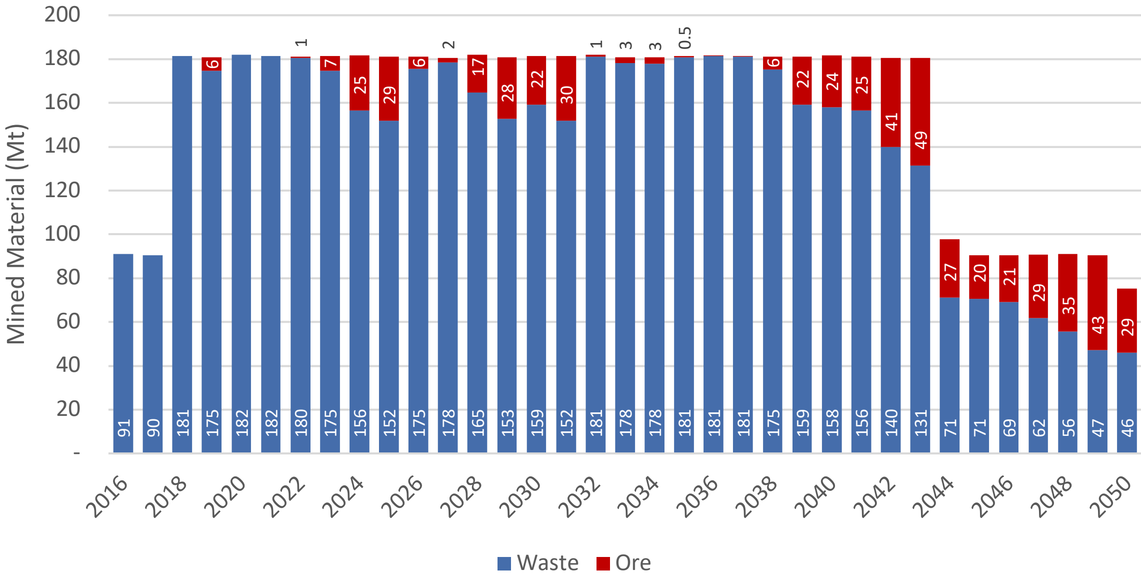
Note. Based on assumptions and MEC Mining internal information

4 Case Study

This chapter provides the results of a comprehensive analysis of the electrification scenarios for haulage trucks in open pit mining. The purpose of this chapter is to present the CO_2 emissions and financial implications associated with the transition from conventional diesel haulage trucks to the different scenarios. Initially, the results for each case are presented, outlining the respective emissions and financial results. Following this, this chapter provides a detailed comparative analysis, comparing the results of each case. Finally, the chapter concludes by highlighting aspects that were not considered within the scope of this work.

Figure 4-1 demonstrates the material movement over the LOM, a parameter primarily influenced by shovel selection. Consistency in shovel set-up across all cases ensures uniform material movement, with only the number of trucks required varying between the different scenarios. Mine procedures employ four shovels during the first two years, causing an annual materials movement of approximately 90 Mt. From 2018 onwards, the mining capacity was increased through the deployment of four extra shovels operating simultaneously in a separate stage, increasing the annual mining capacity to 180 Mt. The waste to ore ratio varies over time due to geological and operational factors, although this study does not focus on the specific materials extracted. Starting in 2044, the last phase of operations will return to using four shovels, resulting in a decrease in extracted materials to 90 Mt.

Figure 4-1 Material movement over LOM



Note. All numbers are given in Mt

4.1 Base Case: Conventional Diesel Operation

This subchapter provides an overview of the CO_2 emissions and financial analysis results derived from the base case. The base case serves as a reference point against which the other scenarios are assessed. Currently, the conventional truck and shovel technique, which makes use of diesel-electric haulage trucks, is the predominant method utilised in most mines.

4.1.1 CO_2 Emission Calculation

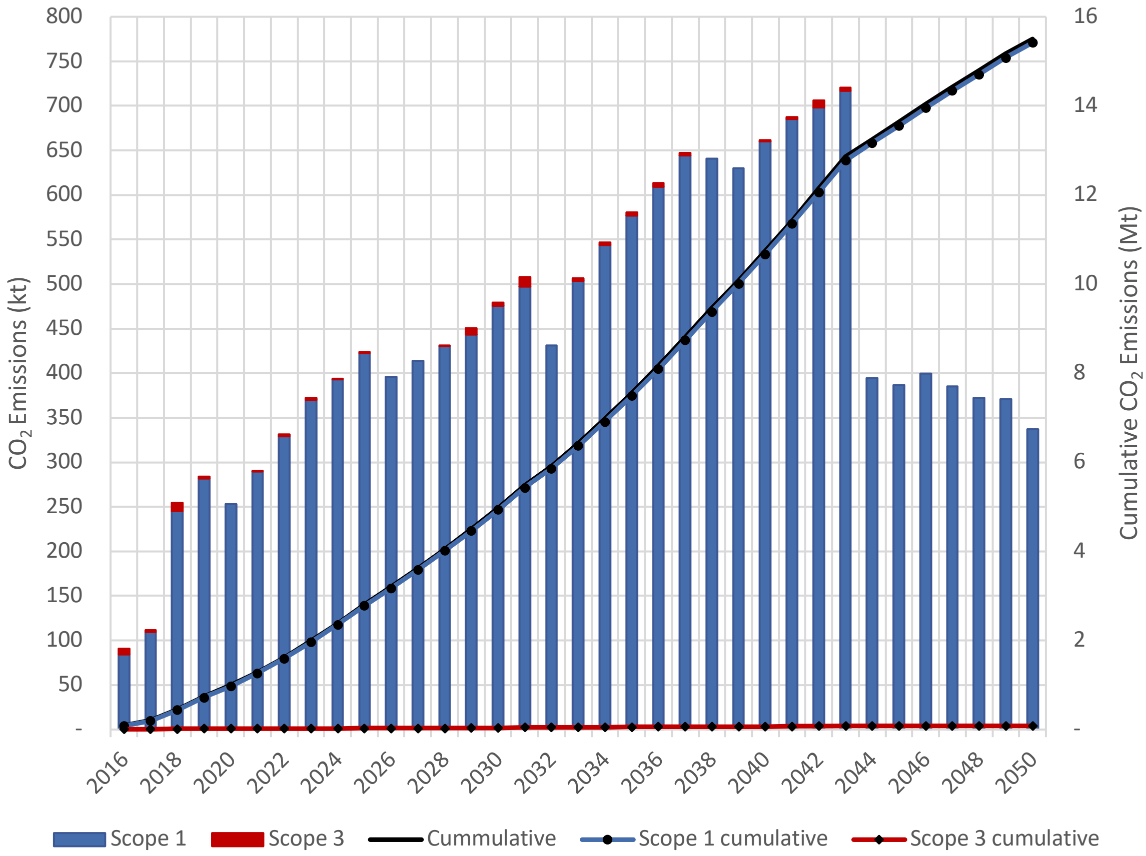
Figure 4-2 presents the CO_2 emission results of the base case. The X-axis denotes the years within the LOM, while the left Y-axis describes the values of the columns by representing the CO_2 emissions in tonnes. On the other hand, the right Y-axis represents the cumulative CO_2 emissions in tonnes over the years, describing the lines in the diagram. The columns are classified based on emissions categorized in Scope 1 (blue) and Scope 3 (red). As the haulage trucks in the base case do not consume electricity at any time, Scope 2 (light blue) is only included in the graphs of the other cases. Total cumulative CO_2 emissions are shown in black, Scope 1 in blue with a dot, and Scope 2 in red with a diamond. Cumulative CO_2 emissions for Scope 2 are displayed using a light blue line marked with a cross.

The chart shows that the majority of the columns indicate Scope 1 emissions, with Scope 3 emissions accounting for only a small proportion. Specifically, for the years between 2024 and 2028, as well as 2044 and 2050, there are almost exclusively Scope 1 emissions. Similarly, other outliers consist entirely of Scope 1 emissions. Scope 3 emissions exhibit their greatest intensity in the early years and in the period from 2029 to 2043, despite constituting only a minimal proportion of total emissions.

During the initial two years of operation, CO_2 emissions are minimal, ranging from 80 to 110 kt. It is shown that annual emissions increase steadily from 2018, with around 250 kt of CO_2 emissions, to 2043, with around 725 kt. By 2044, they fall to just under 400 kt, and by 2050 they are reduced to around 340 kt.

Examining the total cumulative CO_2 emissions, it can be seen that the cumulative Scope 1 emissions are almost identical to the total cumulative emissions line. As for the LOM cumulative Scope 3 emissions, at 83 kt they represent only about one percent of total emissions. The total emissions over the LOM amount to approximately 15.5 Mt of CO_2.

Figure 4-2 Base Case: Annual CO_2 emissions over LOM



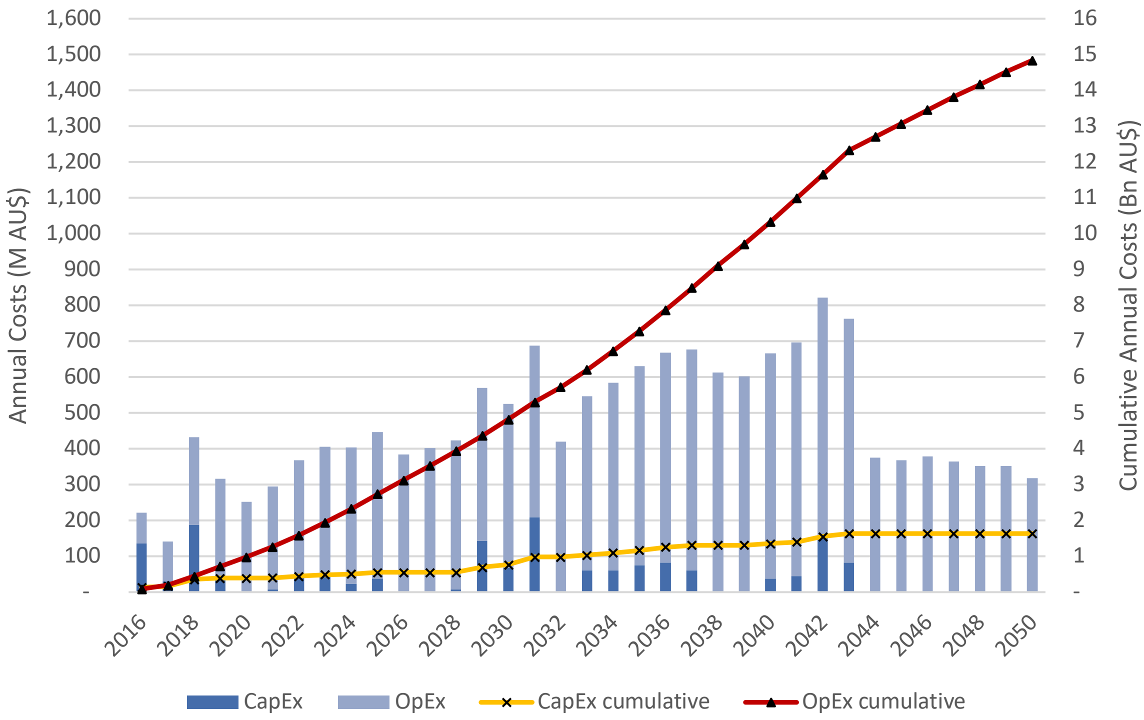
4.1.2 CapEx and OpEx Cost Calculation

Figure 4-3 presents the results of the modelled CapEx and OpEx costs. The X-axis represents the years of the LOM from 2016 to 2050. The left Y-axis describes the annual costs in AU$ and refers to the columns in the graph. The Y-axis on the right indicates the cumulative annual costs in AU$ and refers to the lines shown. Both the CapEx (blue) and OpEx (light blue) costs have been distinctly labelled for the columns. The cumulative CapEx costs are represented by the yellow line marked with crosses, while the cumulative OpEx costs are represented by the red line marked with triangles.

Looking at the columns over the LOM, it is noticeable that the annual costs rise steadily from about $200 million to about $800 million, with a few outliers from the initial year to 2043. In 2044, the costs fall to around $375 million per year and only fall slightly until 2050. The larger share of the annual costs comes from the OpEx costs. CapEx costs are more sporadic and less uniform.

The comparison between cumulative costs clearly demonstrates that the line of cumulative OpEx costs rises much more steeply than that of CapEx costs. In total, CapEx costs amount to \$1.6 billion over the LOM, while OpEx costs amount to \$14.8 billion.

Figure 4-3 Base Case: Annual CapEx and OpEx costs over LOM



Note. A figure for the respective components of the OpEx costs is provided in Appendix 4.1

4.2 Case 1: Diesel-Electric Trucks with Trolley Assist

In this section, we present the comprehensive results of the study on the electrification potential of trucks using a diesel-electric drive system with additional trolley lines. Case 1 is a scenario in this study that investigates a technology that bridges the gap between the conventional diesel approach and electrification that has already been tested and adopted in a few mines.

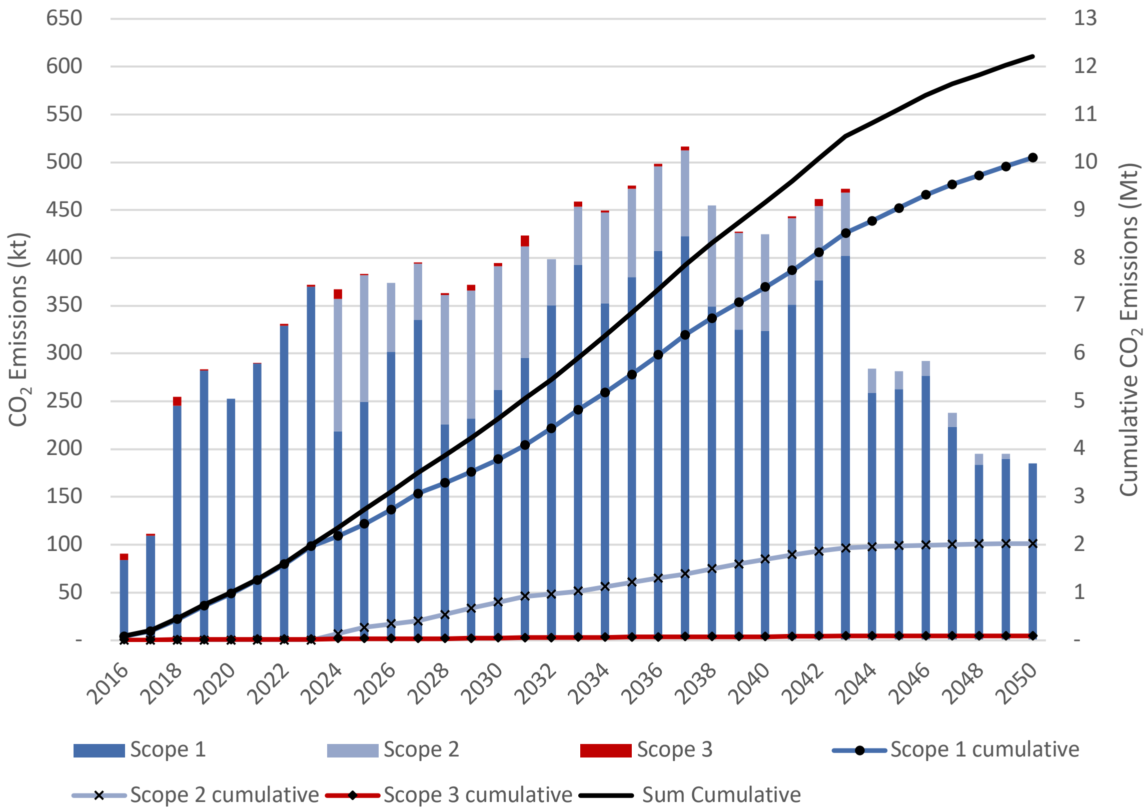
4.2.1 CO_2 Emission Calculation

The CO_2 emission outcomes of the haulage truck powered by diesel-electric drive combined with trolley lines are shown in Figure 4-4. The least amount of CO_2 emissions is observed during the initial two years, with roughly 80 kt and 110 kt. CO_2 emissions escalated to 250 kt in 2018 and continued to rise at a steady pace until 2037, reaching approximately 520 kt. Between 2038 and 2043, emissions persist at a relatively consistent level of around 450 kt. From 2044 onwards, the recorded tonnage drops below 300 kt and by 2050, it falls to approximately 180 kt.

Until 2024, emissions primarily comprise of Scope 1 emissions, with a proportion of Scope 3 emissions that is insignificant and almost negligible. Thereafter, from 2024 until 2034, the emissions also include a percentage of approximately 20-30% from Scope 2 emissions. From 2044, the emissions comprise exclusively of Scope 1 and Scope 2, with the proportion of Scope 2 emissions declining to approximately 5%.

Through the LOM, a total of 12.2 Mt of CO_2 is emitted, of which 83% belong to Scope 1, 17% to Scope 2 and less than 1% to Scope 3.

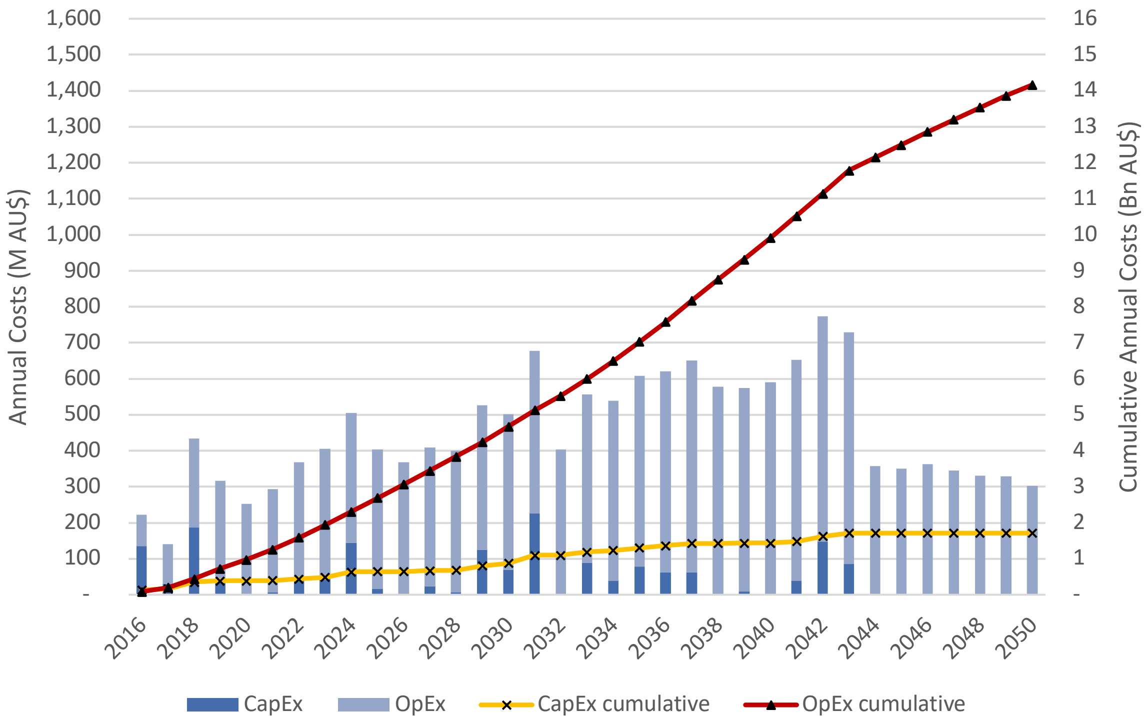
Figure 4-4 Case 1: Annual CO_2 emissions over LOM



4.2.2 CapEx and OpEx Cost Calculation

The calculated CapEx and OpEx costs, depicted in Figure 4-5, show a relatively steady but small increase in annual costs. Between 2016 and 2043, expenditures increase from approximately \$200 million to approximately \$750 million per year. Costs decrease to around \$350 million from 2044 onwards and fall to \$300 million by 2050. OpEx costs constitute the majority of the annual costs. CapEx costs are sporadic and spread unevenly over the LOM. From 2044 onwards, solely OpEx costs incur. CapEx costs amount to \$1.7 billion throughout the LOM, while OpEx costs amount to \$14.1 billion.

Figure 4-5 Case 1: Annual CapEx and OpEx costs over LOM



Note. Figures for the respective components of the CapEx and OpEx costs are provided in Appendix 4.2 and 4.3

4.3 Case 2: Battery-Electric Trucks with Trolley Assist

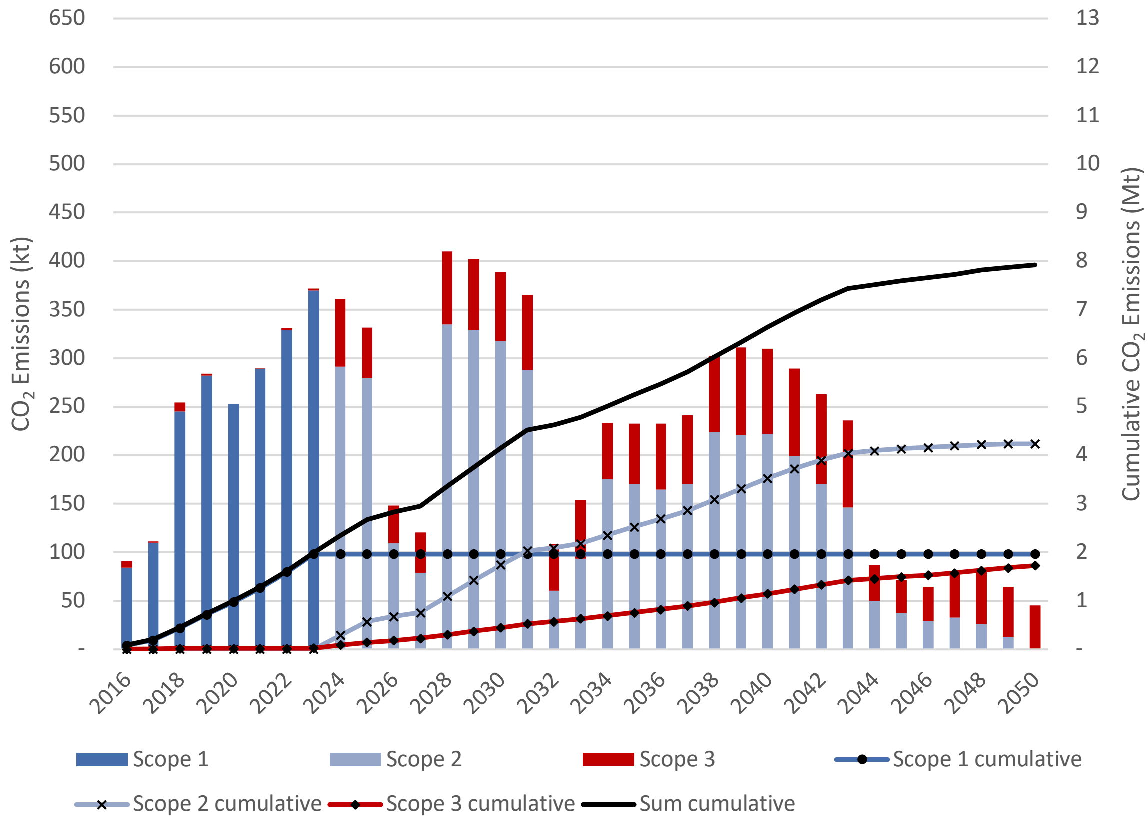
This section presents the findings of Case 2, which investigates the incorporation of battery-electric trucks into the existing trolley assist infrastructure. While trolley lines have been established in some mines, the introduction of battery electric trucks is a disruptive technology that is still in the development phase and only prototypes currently exist.

4.3.1 CO_2 Emission Calculation

Figure 4-6 presents the results of the CO_2 emissions of the battery electric truck with Trolley Assist. Annual emissions reveal significant variability over the years. From 2016 to 2024, the emissions increase steeply from 80 kt at the beginning to about 375 kt. Throughout these eight years, emissions mostly comprise of Scope 1 emissions with only a slight proportion attributed to Scope 3 emissions. From 2024 onwards, only Scope 2 and Scope 3 emissions will be emitted. The emissions values for 2023 are only surpassed in a few instances, with emissions ranging between 100 and 400 kt. Notably, in 2026, 2027, 2032 and 2033, annual emissions fall to a very low level of less than 150 kt, in contrast to the previous and following years.

Between 2024 and 2043, 20-30% of the emissions will be made up of Scope 3 emissions. Beginning in 2024, this proportion will increase annually, ultimately reaching 100% by 2050.

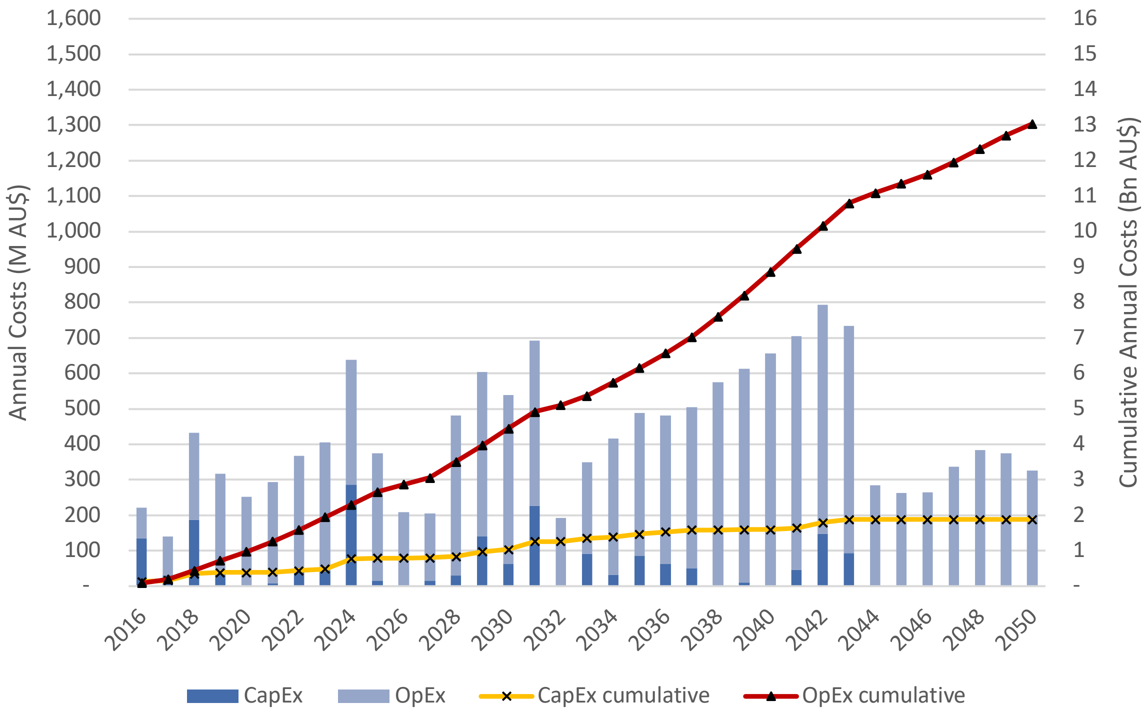
Figure 4-6 Case 2: Annual CO_2 emissions over LOM



4.3.2 CapEx and OpEx Cost Calculation

The CapEx and OpEx costs presented for this case are shown in Figure 4-7. The annual costs for this case show greater variation over the years, with no steady increase in costs over the years. However, there are three separate cost increases, interrupted by lower costs of approximately \$200 million in 2026 - 2027 and 2032. The year with the highest costs is 2042 with almost \$800 million, of which about 20% are CapEx and 80% OpEx. The share of CapEx costs in total costs is also very high in 2016, 2018, 2024, 2029, 2031 and 2042, with shares of up to 50%. Over the LOM, CapEx costs amount to \$1.8 billion and OpEx costs to \$13 billion.

Figure 4-7 Case 2: Annual CapEx and OpEx costs over LOM



Note. Figures for the respective components of the CapEx and OpEx costs are provided in Appendix 4.4 and 4.5

4.4 Case 3: Battery-Electric Trucks with Stationary Charging

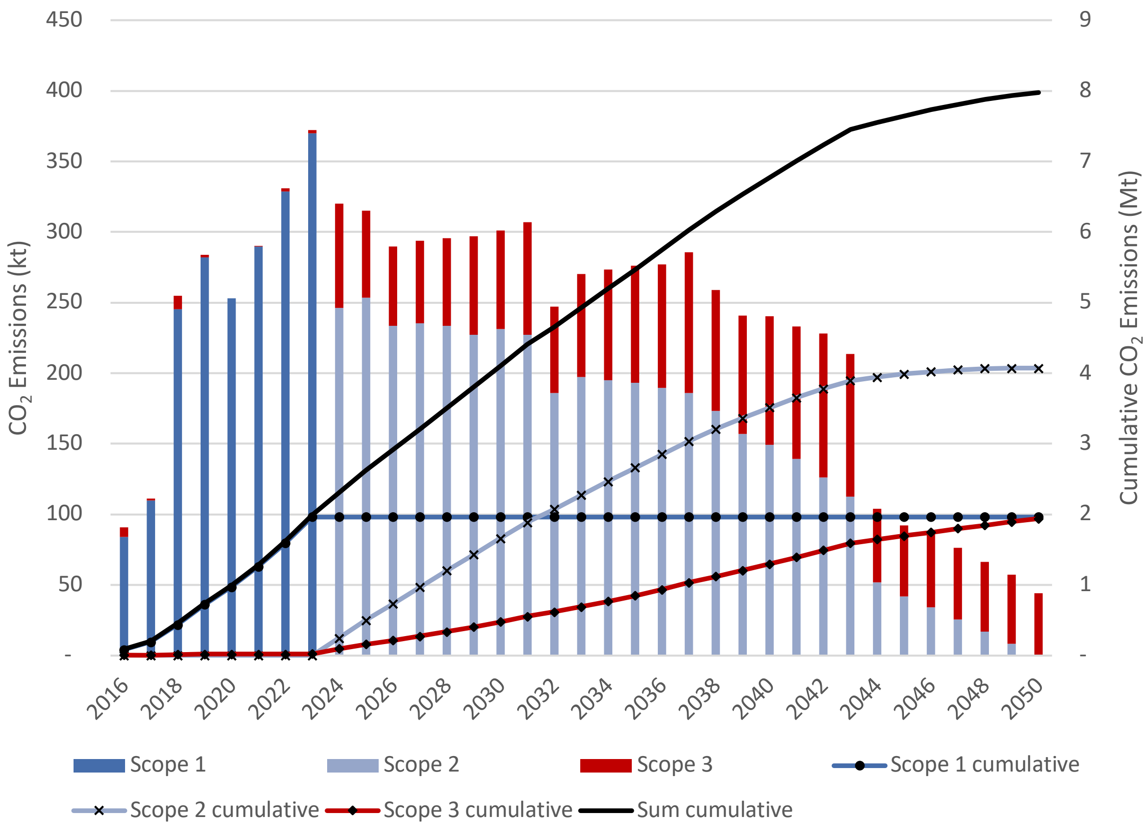
Case 3 examines the implementation of battery-electric trucks operating without trolley lines and relying on stationary charging infrastructure. This approach represents a fully self-contained electrification system, in contrast to the trolley assist systems investigated in the previous cases.

4.4.1 CO_2 Emission Calculation

Figure 4-8 presents the annual CO_2 emissions over the LOM. The initial two years are very low with annual emissions between 80 and 110 kt. Subsequently, between 2019 to 2023, the CO_2 emissions surge from 250 kt to approximately 370 kt. In the first eight years of the operation, the CO_2 emissions predominantly consist of Scope 1 emissions (99%) and Scope 3 emissions (1%). However, the CO_2 emissions were solely attributed to Scope 2 and Scope 3 from 2024 onwards. Between 2024 and 2043, annual emissions will decrease as a result of the yearly reduction in Scope 2 emissions. Nevertheless, during this same period, both absolute and proportional increases in Scope 3 emissions will occur. In the last phase of the LOM, Scope 2 emissions continue to decrease until the annual emissions in 2050 are exclusively Scope 3 emissions.

In this scenario, almost 8 Mt of CO_2 emissions are released through the LOM. Scope 1 and 3 each constitute approximately 25% of the total, equating to just under 2 Mt of CO_2. Scope 2 emissions represent around 50% of the total, amounting to approximately 4 Mt of CO_2.

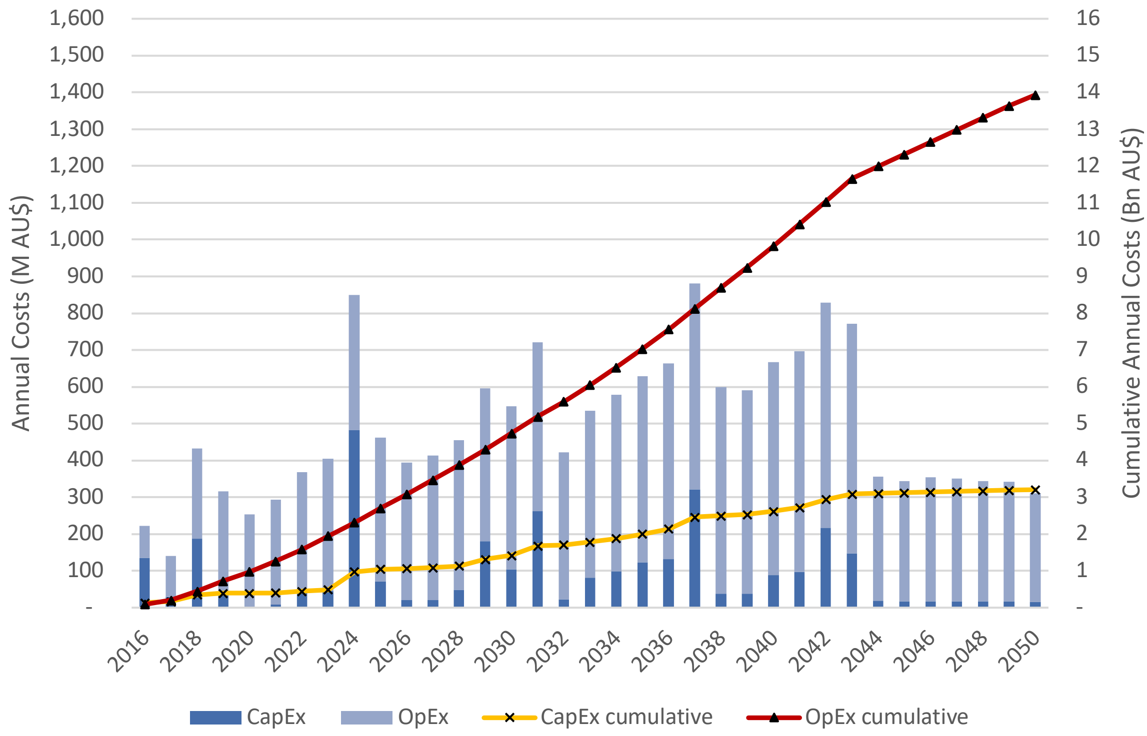
Figure 4-8 Case 3: Annual CO_2 emissions over LOM



4.4.2 CapEx and OpEx Cost Calculation

The annual expenses depicted in Figure 4-9 increases relatively steadily from \$200 million to \$800 million between 2016 and 2043. The portion of CapEx costs demonstrate lower values and greater variations across the years. Notably, enormous expenses occur in 2024, 2031, 2037, 2042, and 2043, with values of up to more than \$800 million per year. These elevated expenses during this period resulted from exceptionally high CapEx expenditures, while the OpEx expenses remained relatively constant. The cumulative annual OpEx expenses indicate this trend. The annual costs remain constant at approximately \$350 million from 2044 to 2050, with just minimal CapEx costs being incurred during this period.

Figure 4-9 Case 2: Annual CapEx and OpEx costs over LOM



Note. Figures for the respective components of the CapEx and OpEx costs are provided in Appendix 4.6 and 4.7

4.5 Results

In this subsection, the emissions and financial outcomes of all scenarios are presented in a broad and comparative way. Visual representations have been carefully designed to compare each scenario with the base case, permitting a nuanced evaluation of the environmental and economic repercussions of our electrification scenarios.

4.5.1 Emitted CO_2 Emissions

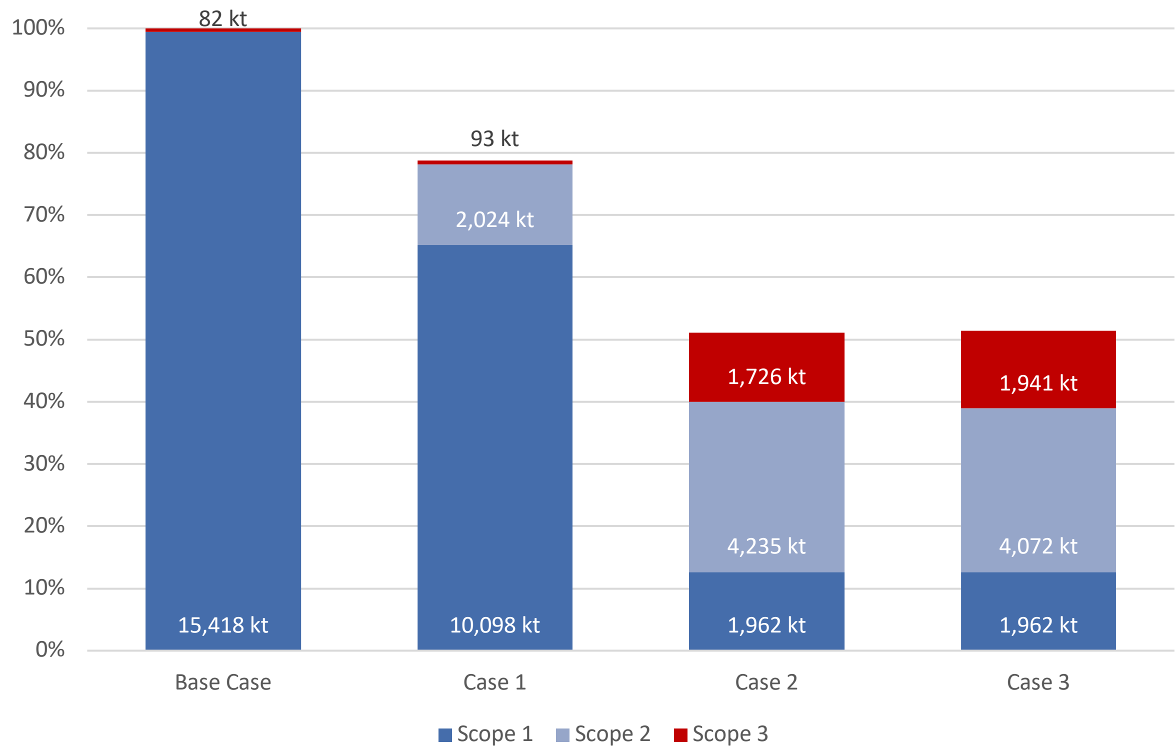
The figure 4-10 shows the CO_2 emissions of the three cases in relation to the base case. The columns on the x-axis are from left to right in the order Base Case, Case 1, Case 2 and Case 3. The y-axis presents the CO_2 emissions as a percentage relative to the Base Case. Each column is then classified into Scope 1 (blue), Scope 2 (light blue), and Scope 3 (red) emissions with subdivisions specifying the absolute CO_2 emissions in kilotonnes.

In the given scenario, 15.5 Mt of CO_2 emissions are generated by the LOM in the base case. Among those emissions, 15.418 kt result from Scope 1 emissions, and 82 kt occur due to Scope 3 emissions. As a result, Scope 1 emissions are responsible for 99.5% of the total CO_2 emissions in the base case. Scope 2 emissions are not represented in the base case.

The CO_2 emissions of Case 1 amount to 12,213 kt over the LOM, a 21% reduction compared to the base case. Scope 1 emissions, accounting for the majority (82%) of the Base Case, are mostly similar. Scope 2 emissions amount to 17%, equating to 2.024 kt. In comparison, Scope 3 emissions are nearly identical to the base case, differing by only 10 kt.

The emissions of both battery-electric options are nearly identical, emitting only 7.9 Mt, 49% less than the base case. Scope 1 emissions constitute approximately 24%, with Scope 2 emissions at roughly 53%, and Scope 3 emissions making up about 27%.

Figure 4-10 CO_2 emissions relative to the base case

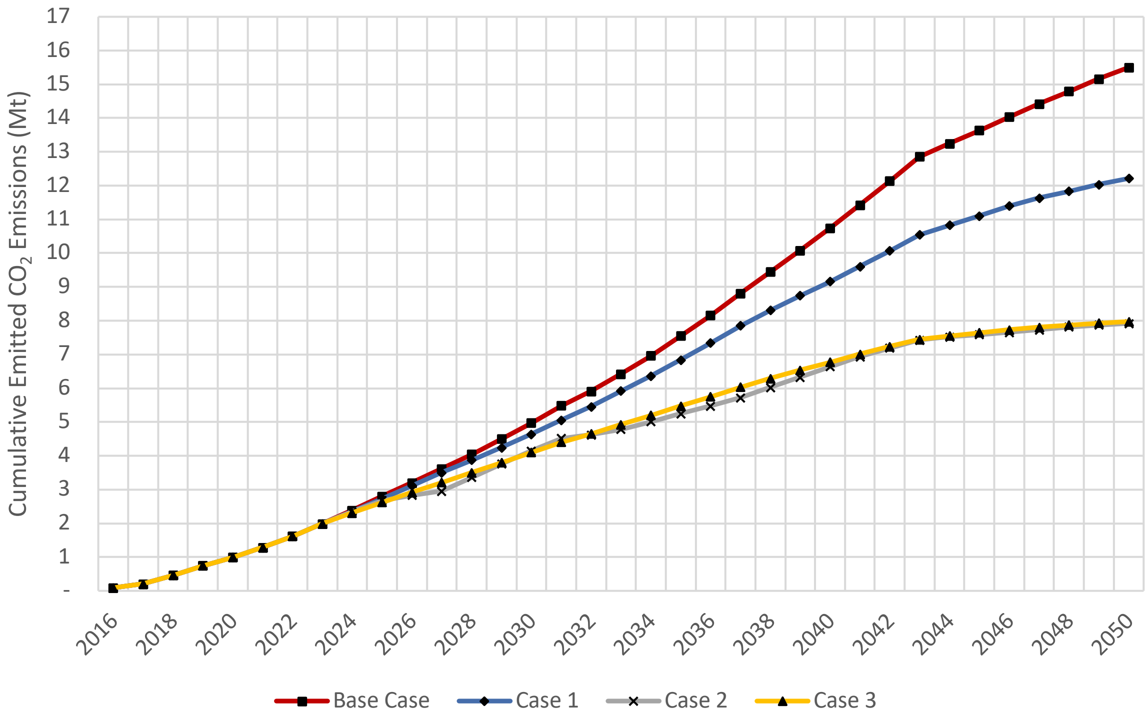


Note. Base Case: diesel-electric; Case 1: diesel-electric trolley assist; Case 2: battery-electric trolley assist; Case 3: battery-electric stationary charging

The cumulative CO_2 emissions over the 34 years are shown in Figure 4-11. Years are marked on the x-axis, while annual CO_2 emissions in tonnes are shown on the y-axis.

The base case, shown with a red line and squares, shows convex growth until 2042 and then linear growth with flattened growth. The results from Case 1 (yellow with diamond) follow a similar pattern from 2024 onwards, with a lower growth rate than the Base Case. The emissions from Case 2 and Case 3 (grey with crosses and yellow with triangles) follow an identical pattern over the years. From 2032 onwards, the growth rate is significantly lower than in the other cases. In the last 7 years, the growth rate has almost stagnated.

Figure 4-11 Total cumulative CO_2 emissions



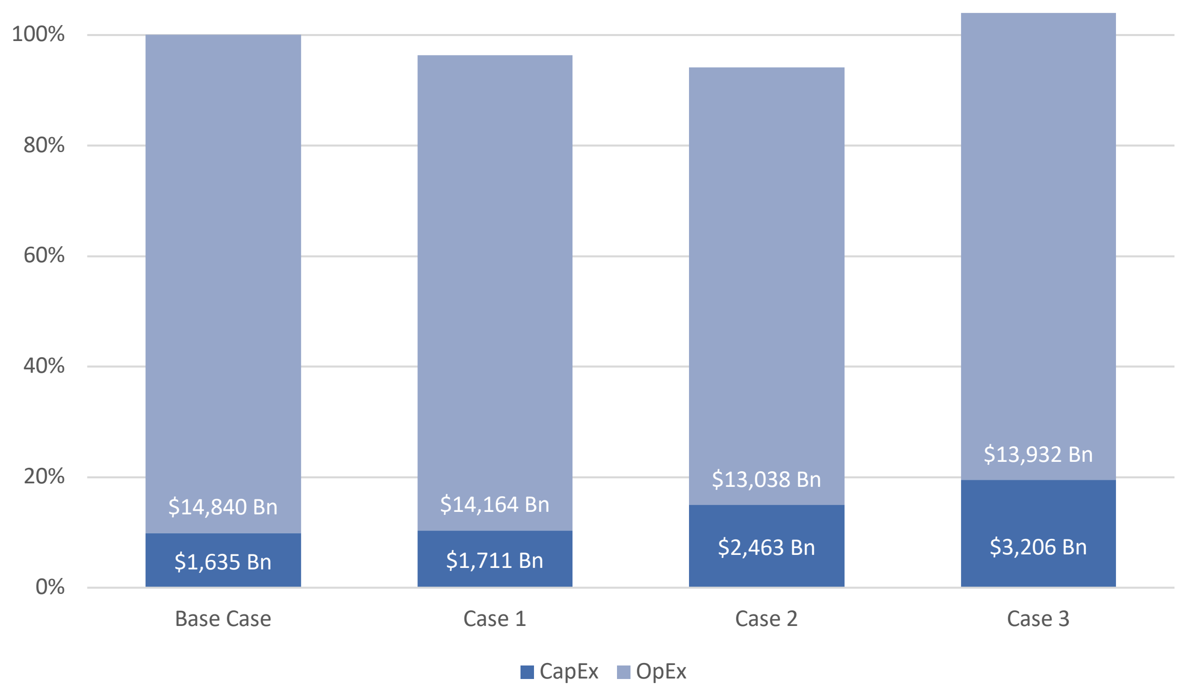
Note. Base Case: diesel-electric; Case 1: diesel-electric trolley assist; Case 2: battery-electric trolley assist; Case 3: battery-electric stationary charging

4.5.2 Cost Breakdown

Figure 4-12 displays the CapEx and OpEx throughout the LOM for each case in relation to the base case. The costs in the base case amount to $16.4 billion. CapEx represents 10% with $1.6 billion, while OpEx accounts for 90% with $14.8 billion.

The costs for Case 1 are 3.5% lower than those of the Base Case, despite CapEx costs being $100 million higher. In addition, OpEx costs are approximately $700 million lower. For Case 2, total costs decrease by 6%. CapEx in this scenario is $800 million higher, whereas OpEx is $1.8 billion lower than in the base case. In the final case, total costs increase by 4%. CapEx of $3.2 billion is twice as high as in the base case, while OpEx of $13.9 billion is 7% lower than in the base case.

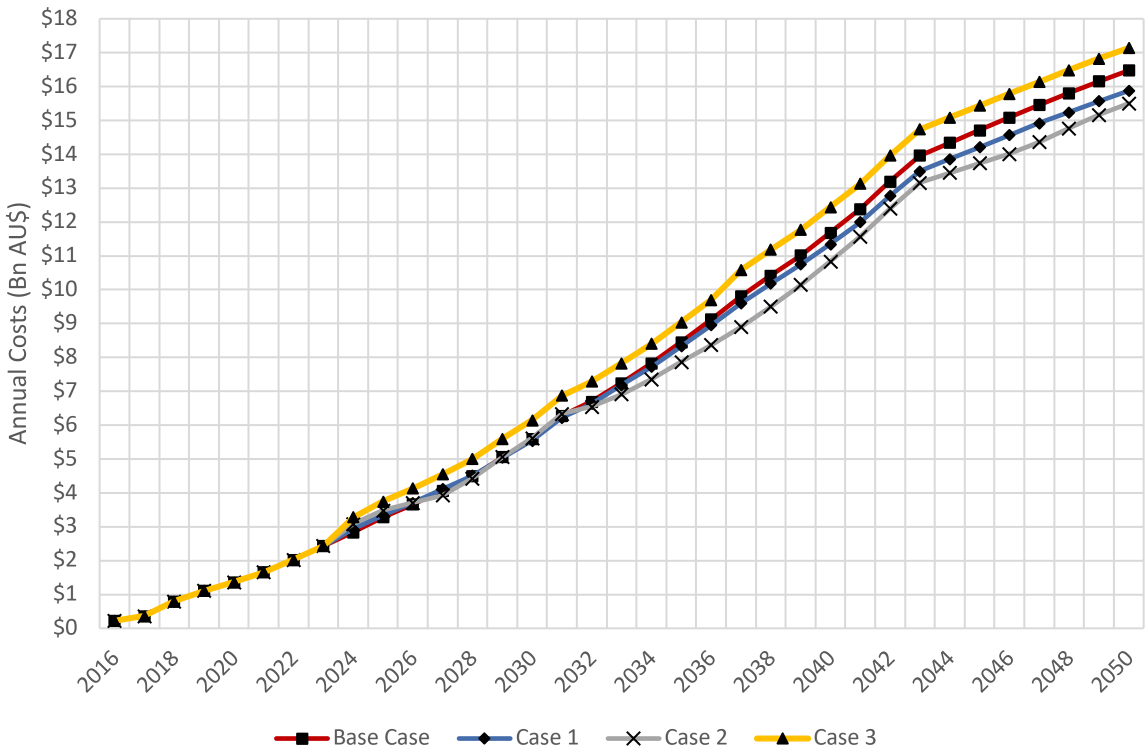
Figure 4-12 Case study CapEx and OpEx cost relative to the base case



Note. Base Case: diesel-electric; Case 1: diesel-electric trolley assist; Case 2: battery-electric trolley assist; Case 3: battery-electric stationary charging

Figure 4-13 displays the overall cumulative costs of the four cases. It is noticeable that the costs for the Base Case and Case 1 (red with squares and blue with diamonds) are very similar until 2035, after which they start to diverge. The expenses for Case 2, (grey with crosses) are almost identical to those for the base case and Case 1 until 2031, after which the expenses increase over the years at a lower growth rate. From the beginning of electrification, the expenses for Case 3 (yellow with triangles) surpass those of the other instances, and this disparity remains constant throughout the LOM.

Figure 4-13 Comparison of total cumulative costs

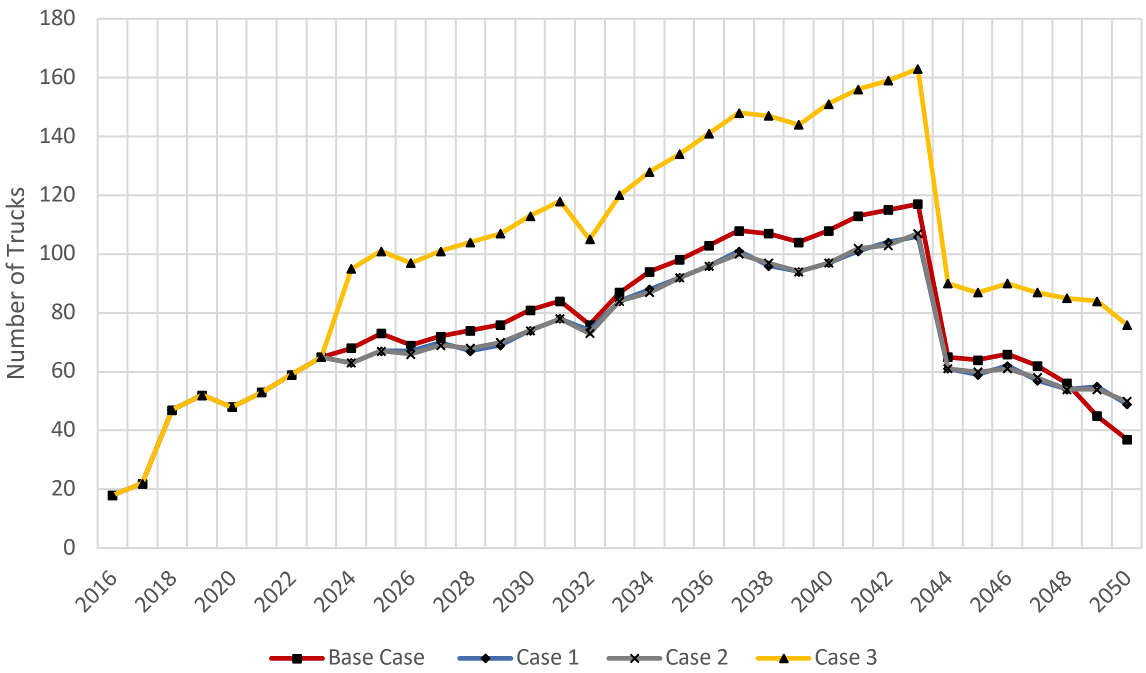


Note. Base Case: diesel-electric; Case 1: diesel-electric trolley assist; Case 2: battery-electric trolley assist; Case 3: battery-electric stationary charging

4.5.3 Haulage Trucks

Figure 4-14 shows the required number of trucks per year over the LOM. The x-axis represents the years and the y-axis the quantity. From 2024, when the electrification of trucks begins, the largest deviation in truck demand is seen in case 3 (yellow with triangles). The demand for trucks is significantly higher than in the base case (red with squares), peaking at 163 trucks in this case. The two lines for Case 1 and Case 2 (blue with diamonds and grey with crosses) are overlaid and show identical demand, which is consistently around 10 trucks lower than in the base case. The highest demand is 107 trucks. Only in the last two years is the lowest number of trucks required in the base case.

Figure 4-14 Required trucks by case over LOM



Note. Base Case: diesel-electric; Case 1: diesel-electric trolley assist; Case 2: battery-electric trolley assist; Case 3: battery-electric stationary charging

5 Discussion

This chapter delves into the analysis of prior findings. The CO_2 emissions of the scenarios are examined, and the pathways to carbon-neutral mining offered by the different electrification strategies are identified. Economics of each approach are then evaluated. Furthermore, this chapter critically reviews the limitations of this thesis and offers recommendations for future research in this field.

This work provides new insights into the feasibility and impact on CO_2 emissions of electrified haulage trucks. The results can be related to the research of J. V. Cruzat and M. A. Valenzuela [4] and L. Lindgren et al. [10].

In their 2018 study, J. V. Cruzat and M. A. Valenzuela [4] analysed the advantages of trolley assist systems for diesel-electric mining trucks, comparing idealised cycles with field records. He discovered fuel savings of 28% overall and 80% on the ramp with the trolley line, in a sample of 30 trucks. This paper found that, under the given assumptions, the diesel-electric trolley assist method led to 40% fuel savings over the LOM. Using a Hitachi 5000AC-3, the direct fuel savings in this research were even higher, reaching 90%. Furthermore, an elevation speed increase of 44% was accomplished on an idealised ramp with gradients ranging between 0% and 12%. Moreover, a rise of 58% was observed through the Trolley Line on ramps featuring a gradient of 10% in this study. The potential to decrease the lorry fleet by 7% by means of increased efficiency was also found in this work to be 4.6% over the LOM.

L. Lindgren et al. [10] conducted a research study examining the technical and financial viability of battery electric trolley assist trucks through simulation. The simulation comprised five driving cycles that represented standard operations at the Aitik copper mine located in northern Sweden. The feasibility tested at a small scale in this study has been confirmed through simulating the entire LOM in this work. The financial analyses cannot be compared due to geographical disparities and associated cost assumptions. Nonetheless, both studies demonstrate cost savings from implementing diesel-electric and battery-electric trolley assistance systems. In both studies, the impact of the electrification of haulage trucks on CO_2 emissions was not investigated.

This thesis represents a significant advance in the field of research, as it operates in a context that has been rarely investigated. Despite the existence of several studies on the feasibility of diesel-electric and battery-electric haulage trucks powering through trolley lines, comprehensive assessments of CO_2 emissions over the complete LOM of open pit mining continue to be limited. The absence of comparable literature emphasises the uniqueness of this research's contribution. This research represents a pioneering initiative, providing one of the first and possibly only extensive analyses of CO_2 emissions generated by various electrification technologies implemented in the mining sector. This work is important as it not only fills a research gap but also offers valuable guidance for developing sustainable practices in the mining industry.

5.1 Comparison of Emissions

The study findings indicate that by electrifying haulage trucks over the LOM period, a significant decrease in CO_2 emissions can be achieved in a large open pit mine. The base case scenario shows that 99.5% of emissions originate from the internal combustion engines of the trucks, while the assumed Scope 3 emissions linked to truck manufacturing have a negligible impact.

In Case 1, the installation of trolley lines at the beginning of electrification in 2024 resulted in a significant reduction of 40% in diesel consumption, coupled with a corresponding decrease of 40% in Scope 1 emissions. To achieve this outcome, the simulation integrated trolley lines in a manner that trucks were connected to them for approximately 20% of their operational cycle time. Strategically positioning trolley lines on ramps is crucial for maximizing their benefits.

Although the inclusion of additional trolley line segments on flat roads could theoretically lower emissions further, this would yield a suboptimal benefit-cost ratio. This is because reducing the driving speed of trucks on trolley lines to 30 km/h is necessary for safety reasons, representing a 20 km/h reduction compared to diesel operation. Achieving higher emission reductions would result in reduced operational efficiency, requiring the deployment of additional trucks to compensate for this loss, as well as incurring infrastructure costs associated with extra trolley lines. It should be noted that the Scope 3 emissions associated with additional trolley line infrastructure do not significantly differ from those observed in the base case throughout the LOM.

For both Case 2 and Case 3, there are negligible disparities in the CO_2 emissions released during the LOM. Upon analysis of the LOM for Case 2, it is apparent that, during the periods of 2026-2027 and 2032-2033, the scope 2 emissions demonstrate lower values. However, in comparison to Case 3, higher values are observed in the remaining years. This inconsistency can be linked to the unsophisticated scheduling methodology applied in this research. In a practical operational setting, the integration of trolley lines would require significant adaptation in the schedule of different stages. Despite this, the results from the LOM analysis indicate that emissions typically level out over time, which is statistically significant, especially when compared to Case 3. Cumulative Scope 1 emissions are uniform, as they only relate to the period before electrification in both instances. Since battery-electric trucks are used in these scenarios, the emissions from 2024 onwards consist solely of Scope 2 and Scope 3. It is worth noting that in Case 2, Scope 2 emissions are more than two times greater compared to Case 1.

In Case 1, while maintaining an approximate speed of 17 km/h, trucks on the ramp draw 3.4 MW from the trolley line. Similarly, the battery-electric trucks employed in Case 1 are also utilized in Case 2. However, to fulfill their operational requirements and charge their batteries, the trucks in Case 2 are supplied with 8 MW from the trolley line. To guarantee a sufficient energy supply for the trucks, a total of 2.3 km more trolley line infrastructure is required in Case 2.

When comparing the Scope 2 emissions of the two battery-electric scenarios, it is noticeable that Case 2 has an additional 163 kilotonnes of emissions. As identical routes and cycles were undertaken in both scenarios, this disparity can be attributed to the increased empty weight of the battery-electric trucks equipped with pantographs. This results in reduced payload capacity and requires more frequent execution of certain cycles compared to the previous case. However, the slight increase in weight without any load leads to greater energy recovery. However, this does not compensate for the discrepancy.

In the battery-electric scenarios, it is seen that Scope 3 emissions are up to 20 times higher than in Case 1, with approximately 94% of the emissions attributed to the batteries. This increase in emissions is due to the stationary charging method used in the plug-in concept, which diminishes the operational efficiency of each vehicle. On average, about 28% of the fleet is involved in the charging process at the same time. To address this challenge, Case 3 requires a truck demand that is approximately 50% higher than in Case 2.

The calculation of CO_2 emissions relies heavily on assumed emissions from electricity generation. The calculations described in the results section used a baseline value of 0.52 kgCO_2/kWh, representing the emissions attributed to the Australian energy mix in 2022. This assumption is then subject to an annual decrease of 0.02 kgCO_2 per kWh, in line with the goals of the Paris Agreement. It is hypothesized that electricity production will be completely free from CO_2 emissions by 2050. These emissions averages per kilowatt-hour for Australia are significant in serving as a suitable starting point for comparative analysis within the scope of this study.

It is crucial to assess how diverse emission assumptions impact the comparative consequences of the scenarios. In regions with elevated CO_2 emissions per kilowatt-hour (CO_2/kWh), outcomes of the different cases are likely to converge towards the Base Case. However, battery-electric cases would be subject to more adverse effects due to proportionally higher Scope 2 emissions. In a situation where carbon-neutral electricity becomes available from 2024 onwards, Case 1's CO_2 emissions could drop by an additional 16.5%. This would result in a total saving of 34% over the LOM compared to the Base Case. Further reductions in CO_2 emissions would not be achievable due to the diesel engine.

The use of CO_2-neutral electricity could significantly affect cases 2 and 3. In these cases, half of the emissions result from electricity generation via the LOM. Therefore, cases 2 and 3 have the potential to reduce CO_2 emissions by around 75% if battery-electric trucks are used, compared to the base case.

It is important to note that the assumptions and parameters used in this study are based on prevailing market conditions and technologies available at the time of publication. However, it must be recognised that both the battery industry and renewable energy sector are constantly evolving and subject to technological advancement. Recent advancements and breakthroughs hold the potential to rapidly supersede the fundamental premises on which this study is based, consequently impacting the results.

The batteries are responsible for approximately 93% of the scope 3 emissions. It is estimated in this scenario that the batteries will need to be replaced after around 4.2 - 4.8 years, based on their expected life of 20,000 charging cycles. The utilization of batteries with extended life expectancies could, therefore, result in significant reductions in Scope 3 emissions in Cases 2 and Case 3. Considering the potential development of the battery market to provide batteries with a life expectancy of up to 40,000 charge cycles, it becomes conceivable that in simulated Scenarios 2 and 3 an 80% reduction in CO_2 emissions over the LOM can be achieved compared to the base case.

5.2 Economic Comparison

In order to examine the economic viability of the three scenarios compared to traditional diesel operation, CapEx and OpEx were modelled over the entire LOM. The analysis only considered costs directly related to the electrification of haulage vehicles, and therefore only included those costs that were subject to change. In the reference scenario, the LOM results in a total cost of $16.5 billion, of which 10% is CapEx and 90% is OpEx. Diesel-related costs account for approximately 66% of the total OpEx.

In the initial scenario, implementing diesel-electric trolley assist trucks leads to a 3.5% decrease in total costs. However, this comes at the cost of increased CapEx linked to retrofitting the trucks and establishing trolley line infrastructure. Despite a drop in truck acquisition expenses due to reduced demand, CapEx remains higher than the Base Case. The reduction in OpEx is due to the substitution of diesel with electricity, which is a more cost-effective energy source, and the reduced size of the operational fleet.

CapEx in Case 2 have increased by 50% compared to the Base Case. This rise is due to higher retrofit costs compared to Case 1, as well as expenses related to battery acquisition. Despite diesel usage being eliminated in this scenario starting from 2024, OpEx only show a relatively modest decrease. This can be attributed to the truck's considerable electricity demand.

The high demand for trucks due to stationary recharging and the associated battery distribution make the final case particularly investment intensive, which ultimately results in the most economically expensive scenario. Despite considering the reduced operating expenses as compared to the standard case, this disparity persists without compensation.

Electricity is a more cost-effective energy source, leading to predictable results. The greater the substitution of diesel with electricity, the higher the potential for savings. Although the initial CapEx is substantial, financial viability is achieved in this case study after a period of seven years in both Case 1 and Case 2. By contrast, Case 3 does not exhibit economic viability due to the significant need for more trucks.

The financial analysis is based on input parameters that are contemporary with the publication of this thesis. Therefore, a cautious approach is necessary when evaluating the feasibility of mining projects. It is crucial to acknowledge that fluctuating diesel and electricity costs may significantly affect the cost calculations. Considering the inherent uncertainty in accurately forecasting these costs, this paper assumes that they will remain constant throughout the entire LOM. Based on the underlying data, it can be concluded that, considering relevant financial aspects, Case 2 presents itself as the preferred option for the simulated operation in question. The main reasons for this decision are the full electrification of the operation and the resulting reduction in the need for trucks due to the increased efficiency of the trolley line infrastructure.

The financial analysis may experience swift transformations fuelled by emerging technologies in the battery industry. Batteries with extended life will not only have the potential to reduce emissions, but also to minimise capital expenditure in the latter two scenarios. Additionally, the forthcoming improvements in fast-charge technologies represent another influential factor affecting the financial aspect. These innovations have the potential to increase charging capacities, resulting in fewer trolley line metres or plug-in chargers, potentially leading to cost reductions. However, it is important to note that the implementation of higher charging rates will require the expansion of the electrical infrastructure throughout the mine, which will result in significant additional expenses.

5.3 Limitations

This chapter examines the limitations and constraints encountered during this research to provide transparency and context for interpreting findings.

Data availability limitations were identified in two specific areas within this study. Firstly, there was a lack of comprehensive cradle-to-gate LCA for trucks. In response to this limitation, a simplification approach was taken, weight calculations were performed using emissions data derived from steel production. It is recognised that the actual emissions associated with truck production and delivery are much more complex than this simplified representation. However, it is important to emphasise that this simplification remained consistent across all the scenarios considered, thereby facilitating a consistent and fair comparison across different parameters.

Second, the cost analyses were based on a cost guideline, mainly because battery electric trucks were not on the market at the time of the study. As a result, cost estimates were based on assumptions. In addition, it is important to recognise that these cost estimates depend on factors such as the manufacturer, the size of the mine and the potential number of trucks ordered.

The main limitation encountered in the simulation of the cases was the transition from diesel to electric operation. In this context, a simplification within the simulation framework was necessary to facilitate an abrupt transition from diesel to electric, as opposed to the gradual transition that would occur in actual operational settings. For example, Case 2 assumed the accelerated installation of trolley lines. In practice, trolleys approaching the end of their life would remain in diesel mode until they could be replaced by battery electric counterparts. To speed up the integration of trolley lines, newer diesel-electric trucks could first be retrofitted with pantographs. This would be followed by the replacement of diesel engines with batteries. It will be important to consider the age of the vehicles in this process to ensure that the cost of retrofitting remains economically viable.

A transition phase would have a negative impact on CO_2 emissions due to the extended use of diesel throughout the LOM, thereby reducing the effectiveness of electrification throughout the

LOM. However, the CapEx would be spread over several years, making electrification financially viable.

Further consideration should be given to non-modelled adjustments in mine design. When incorporating trolley lines into an ongoing operation, it is often necessary to extend the width of the ramps by approximately 5 metres to accommodate the installation of trolley line support poles. Depending on the location of the ramp within the mine, this involves the excavation and removal of a significant amount of additional material. The emissions and costs associated with this additional blasting and increased truck hours have not been included in this study.

In cases where the mine is already at a significant depth and the ramp is located along the pit wall, widening the ramps may require leaving ore behind. While such a change would result in emission reductions, it would also result in financial losses. As the inclusion of emissions and costs associated with mine design changes depends on many factors, some of which are not explicitly defined in this study, these additional emissions and costs have not been included in the analysis.

5.4 Future Research and Recommendations

According to the research findings, electrifying haulage fleets and incorporating sustainable energy sources offer promising pathways for mining companies to significantly reduce their carbon footprint and adopt more environmentally responsible practices. In the context of these findings, the following research points provide practical strategies and areas of investigation for companies and mining engineers.

The first step is to further investigate the optimisation of the transition period from a comprehensive financial perspective at the highest level. Examining the best allocation of capital resources during this transition period can achieve such optimisation. Prioritisation should be applied to specific investments to strategically distribute the financial burden and achieve the greatest immediate benefits from implemented strategies. In-depth case studies should also be utilised to explore different financing options and assess the feasibility of funding through equity, debt, or potential government subsidies.

A crucial aspect of maximizing the advantages of electrifying haulage trucks concerns the energy mix's composition. Hence, it is relevant to investigate the feasibility and economic viability of proprietary hybrid renewable energy technologies. Significantly, within the Australian context, the integration of smart grid technologies in conjunction with solar panels and energy storage has the potential to improve energy management, facilitate load balancing and promote seamless grid integration. Thus, a comprehensive investigation into the distinct mine parameters necessary to generate a strong return on investment is required. Especially for remote mining operations in Australia, these considerations are important in the drive to reduce carbon emissions.

Based on the research methods employed and the study findings, clear and practical action recommendations can be derived. These recommendations are intended to guide mining companies in effectively advancing the electrification of their haulage fleets.

1. Analysis of status quo: It is crucial to identify the areas within the mine where the highest levels of diesel consumption occur. Additionally, a comprehensive evaluation of long-term mine planning is necessary, including investigating which ramps are best suited to implementing trolley lines, taking into account their extended operational life and traffic capacity. In many cases, the main surface ramps that lead to the waste dump are feasible options. It is crucial to evaluate the current power supply infrastructure to identify potential areas for improvement.
2. Electrification of Haulage Trucks: The electrification process should be conducted in a phased manner. In the first stage, the trucks ought to be converted to diesel-electric trolley assist. Subsequently, the ramps identified in the first phase could be fitted with trolley lines. Once the trolley network can consistently support the functioning of battery-electric trucks, the transition to these trucks can be made gradually.
3. CO_2-neutral electricity: Depending on the mine's situation, concepts should be developed to ensure that the electricity used is as environmentally friendly as possible and has the lowest possible carbon footprint. The approach of an on-site renewable energy grid mentioned above could be considered.
4. Mine Planning Optimization: The electrification of trucks necessitates adjustments to both short-term and LOM mine planning. These adjustments will cover modifications to mine design as well as the scheduling of different mining phases.
5. Training and education: This section concerns training requirements for truck operators and maintenance personnel. To avoid accidents and critical failures of the trolley line system, it is imperative that operators receive specific training for trolley line operation. Due to the higher speeds involved, operators need to undertake intensive training to improve their driving skills. Furthermore, technical staff need to be trained to acquire the necessary skills to deal effectively with the intricacies of new electrical technologies.
6. Continuous Evaluation and Optimization: It is recommended that a continuous monitoring system is implemented to gather data that can be used to optimise operations

and strategies. Additionally, market conditions should be consistently evaluated to enable the integration and exploitation of emerging innovations.

6 Conclusion

The objective of this thesis was to investigate the impact of different truck electrification systems on Scope 1, 2 and 3 CO_2 emissions and the financial viability over the life of the mine compared to conventional diesel operation. The study investigated the use of diesel-electric trucks with trolley assist, battery electric trucks with trolley assist and battery electric trucks with stationary charging.

The results of the diesel-electric trolley assist system showed that switching to electric drive with trolley lines on the ramps was a significant improvement. An average trolley time of 20% of the cycle time saved 40% of the Scope 1 emissions over the LOM. The additional Scope 2 emissions, by assuming the energy mix, could in this case save 22% CO_2 emissions over the LOM with an additional cost reduction of 3.5%.

As expected, the CO_2 emission savings over the LOM were almost identical in the two battery-electric cases. The total substitution of diesel by electricity saved 49% of the CO_2 emissions over the LOM in both cases. There was a clear difference between the two battery-electric cases in terms of profitability: the combination with trolley lines saved 6% in costs over the LOM, while the use of a stationary charging system resulted in a 4% increase in costs due to lower efficiency.

This quantitative study has demonstrated the impact of the different electrification methods on the different scopes and how emissions change with the transition from conventional to electrified operation. In the first case of diesel-electric trolley assist, emissions were mainly shifted from Scope 1 to Scope 2. Due to the more efficient electric motors, total emissions were reduced.

In the battery-electric cases, the switch to electricity only as an energy source causes a significant redistribution of emissions, not only are the missing Scope 1 emissions absorbed by additional Scope 2 emissions, but the high demand for new equipment and batteries increases the Scope 3 emissions over the LOM by about 23 times compared to the Scope 3 emissions from the base case. Nevertheless, it could be shown that in each case, considering the whole years, there is no payback time, as electrification directly reduces CO_2 emissions.

It was also shown that the use of trolley lines could reduce costs by increasing efficiency, with a payback time of around eight years in this scenario, while stationary charging is more costly due to the high equipment requirements.

References

[1] "ABB eMine™ Trolley System. Transition your mining hauling trucks from diesel to electric." ABB in Mining. [Online Video]. https://www.youtube.com/watch?v=qcsuOYznFHw (accessed 09/08/2023).

[2] Department of Climate Change, Energy, the Environment and Water, "Australia’s emissions projections 2022," Canberra, 2022.

[3] H. Bao, P. Knights, M. Kizil, and M. Nehring, "Electrification Alternatives for Open Pit Mine Haulage," *Mining,* vol. 3, no. 1, pp. 1-25, 2023.

[4] J. V. Cruzat and M. A. Valenzuela, "Modeling and evaluation of benefits of trolley assist system for mining trucks," *IEEE Transactions on Industry Applications,* vol. 54, no. 4, pp. 3971-3981, 2018.

[5] G. Bourne, A. Stock, W. Steffen, P. Stock, and L. Brailsford, "Australia's rising greenhouse gas emissions," 2018.

[6] W. A. Hustrulid, M. Kuchta, and R. K. Martin, *Open pit mine planning and design*, 3rd ed. CRC Press, 2013.

[7] E. Hay, M. Nehring, P. Knights, and M. Kizil, "Ultimate pit limit determination for semi mobile in-pit crushing and conveying system: a case study," *International Journal of Mining, Reclamation and Environment,* vol. 34, no. 7, pp. 498-518, 2020.

[8] A. Soofastaei, E. Karimpour, P. Knights, and M. Kizil, "Energy-efficient loading and hauling operations," *Energy Efficiency in the Minerals Industry: Best Practices and Research Directions,* pp. 121-146, 2018.

[9] "Australian Energy Update 2022," Australian Government - Department of Climate Change, Energy, the Environment and Water, Canberra, 2022.

[10] L. Lindgren, A. Grauers, J. Ranggård, and R. Mäki, "Drive-Cycle Simulations of Battery-Electric Large Haul Trucks for Open-Pit Mining with Electric Roads," *Energies,* vol. 15, no. 13, p. 4871, 2022.

[11] M. Taplin, "The history of tramways and evolution of light rail," *Light Rail Transit Association,* 1998.

[12] F. Kesicki, "The third oil price surge–What’s different this time?," *Energy Policy,* vol. 38, no. 3, pp. 1596-1606, 2010.

[13] T. Adams. "An introduction to trolley-assist haulage systems." Globalroadtechnology.com. https://globalroadtechnology.com/trolley-assist-haulage-systems/ (accessed 01/07/2023).

[14] "CAT Trolley Assist System - For ultra-class electric drive mining trucks," Caterpillar, 2021.

[15] R. Muralidharan, T. Kirk, and T. Blank, "Pulling the Weight of Heavy Truck Decarbonization: Exploring Pathways to Decarbonize Bulk Material Hauling in Mining," *Rocky Mountain Institute: Basalt, CO, USA,* 2019.

[16] K. Uno, K. Imaie, K. Maekawa, G. Smith, A. Suyama, and J. Hatori, "Development of mining machinery and future outlook for electrification," *Hitachi Review,* vol. 62, no. 2, pp. 99-106, 2013.

[17] J. Mazumdar, "Performance improvement of mining haul trucks operating on trolley systems," in *2011 IEEE Industry Applications Society Annual Meeting*, 2011.

[18] SIEMENS AG, "SIMINE Haul Truck - How to execute material transport at lowest cost per ton," 2019.

[19] B. M. Al-Alawi and T. H. Bradley, "Review of hybrid, plug-in hybrid, and electric vehicle market modeling studies," *Renewable and Sustainable Energy Reviews,* vol. 21, pp. 190-203, 2013.

[20] B. Watson. "Caterpillar successfully demonstrates first battery electric large mining truck and invests in sustainable proving ground." Caterpillar Inc. https://www.caterpillar.com/en/news/corporate-press-releases/h/caterpillar-succesfully-demonstrates-first-battery-electric-large-mining-truck.html (accessed 14/07/2023).
[21] "Fortescue welcomes the arrival of Australia’s first prototype battery system designed for a zero-emission battery electric mining haul truck." Fortescue Metals Group Ltd. https://www.fmgl.com.au/in-the-news/media-releases/2023/01/16/fortescue-welcomes-the-arrival-of-australia’s-first-prototype-battery-system-designed-for-a-zero-emission-battery-electric-mining-haul-truck (accessed 14/07/2023).
[22] "Hitachi names First Quantum in Zambia as battery trolley mining truck partner." TEAM Publishing Ltd. https://im-mining.com/2023/03/01/hitachi-names-first-quantum-in-zambia/ (accessed 14/07/2023).
[23] "Liebherr T 274. The new 305 tonne payload truck." Liebherr-International Deutschland GmbH. https://www.liebherr.com/en/can/products/mining-equipment/mining-trucks/t-274/t-274.html (accessed 21/07/2023).
[24] S. M. Rezvanizaniani, Z. Liu, Y. Chen, and J. Lee, "Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility," *Journal of power sources,* vol. 256, pp. 110-124, 2014.
[25] M. Lelie *et al.*, "Battery management system hardware concepts: An overview," *Applied Sciences,* vol. 8, no. 4, p. 534, 2018.
[26] Y. Wang *et al.*, "A comprehensive review of battery modeling and state estimation approaches for advanced battery management systems," *Renewable and Sustainable Energy Reviews,* vol. 131, p. 110015, 2020.
[27] A. T. Hamada and M. F. Orhan, "An overview of regenerative braking systems," *Journal of Energy Storage,* vol. 52, p. 105033, 2022.
[28] N. Beutler, "Plug in mines: World’s first fully automated charging system for mining trucks," *ABB Review 02/23,* vol. Volume 2, 2023.
[29] D. Gleeson. "Fortescue kicks off battery-electric truck testing in the Pilbara." International Mining. https://im-mining.com/2023/08/01/fortescue-kicks-off-battery-electric-truck-testing-in-the-pilbara/ (accessed 01.10.2023.
[30] S. Solomon, *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC*. Cambridge university press, 2007.
[31] M. McNutt, "Climate change impacts," vol. 341, ed: American Association for the Advancement of Science, 2013, pp. 435-435.
[32] J. Turner *et al.*, "Antarctic climate change and the environment: an update," *Polar record,* vol. 50, no. 3, pp. 237-259, 2014.
[33] N. B. Grimm *et al.*, "The impacts of climate change on ecosystem structure and function," *Frontiers in Ecology and the Environment,* vol. 11, no. 9, pp. 474-482, 2013.
[34] M. K. Van Aalst, "The impacts of climate change on the risk of natural disasters," *Disasters,* vol. 30, no. 1, pp. 5-18, 2006.
[35] J. E. Hansen and M. Sato, "Paleoclimate implications for human-made climate change," in *Climate change: Inferences from paleoclimate and regional aspects*: Springer, 2012.
[36] S. Mohammed *et al.*, "An overview of greenhouse gases emissions in Hungary," *Journal of Cleaner Production,* vol. 314, p. 127865, 2021.

[37] A. Lindley and A. McCulloch, "Regulating to reduce emissions of fluorinated greenhouse gases," *Journal of fluorine chemistry,* vol. 126, no. 11-12, pp. 1457-1462, 2005.
[38] "Global Warming Potential Values," Greenhouse Gas Protocol.
[39] "Global warming potential values of hydrofluorocarbon refrigerants." Australian Government - Department of Climate Change, Energy the Environment and Water. https://www.dcceew.gov.au/environment/protection/ozone/rac/global-warming-potential-values-hfc-refrigerants (accessed 30/07/2023).
[40] K. P. Shine, "The global warming potential—the need for an interdisciplinary retrial," *Climatic Change,* vol. 96, no. 4, pp. 467-472, 2009.
[41] C. Böhringer, "The Kyoto protocol: a review and perspectives," *Oxford Review of Economic Policy,* vol. 19, no. 3, pp. 451-466, 2003.
[42] "For a livable climate - Net-zero commitments must be backed by credible action." United Nations. https://www.un.org/en/climatechange/net-zero-coalition (accessed 30/07/2023).
[43] "The Paris Agreement." United Nations Framework Convention on Climate Change. https://unfccc.int/process-and-meetings/the-paris-agreement (accessed 30/07/2023).
[44] M. AK-BHD, "WMO Greenhouse Gas Bulletin," *World Meteorological Organization: Geneva, Switzerland,* vol. 15, 2019.
[45] H. Ritchie, M. Roser, and P. Rosado, "CO_2 and greenhouse gas emissions," *Our world in data,* 2020. Available: https://ourworldindata.org/co2-emissions?utm_source=tri-city%20news&utm_campaign=tricity%20news%3A%20outbound&utm_medium=referral. (accessed 04/07/2023).
[46] P. Friedlingstein *et al.*, "Global carbon budget 2021," *Earth System Science Data,* vol. 14, no. 4, pp. 1917-2005, 2022.
[47] D. ISO, "Greenhouse Gases—Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals (ISO 14064-1: 2018); German and English version EN ISO 14064-1: 2018. 2019," *International Organization for Standardization, Geneva, Switzerland,* 2006.
[48] "Quarterly Update of Australia's National Greenhouse Gas Inventory - December 2022," Australian Government Department of Climate Change, Energy, the Environment and Water, 2022.
[49] "Australia's whole-of-economy Long-Term Emissions Reduction Plan," Australian Government Department of Industry, Science, Energy and Resources, 2021.
[50] Greenhouse Gas Protocol Initiative, "A corporate accounting and reporting standard," *World Resources Institute and World Business Council for Sustainable Development,* 2004.
[51] "About Us - Greenhouse Gas Protocol provides standards, guidance, tools and training for business and government to measure and manage climate-warming emissions." Greenhouse Gas Protocol https://ghgprotocol.org/about-us#:~:text=What%20is%20GHG%20Protocol%3F,value%20chains%20and%20mitigation%20actions. (accessed 08/07/2023).
[52] Greenhouse Gas Protocol, "Corporate value chain (scope 3) acounting and reporting standard - a supplement to the GHG protocol corporate accounting and reporting standard," *World Resources Institute and World Business Council for Sustainable Development,* 2004.

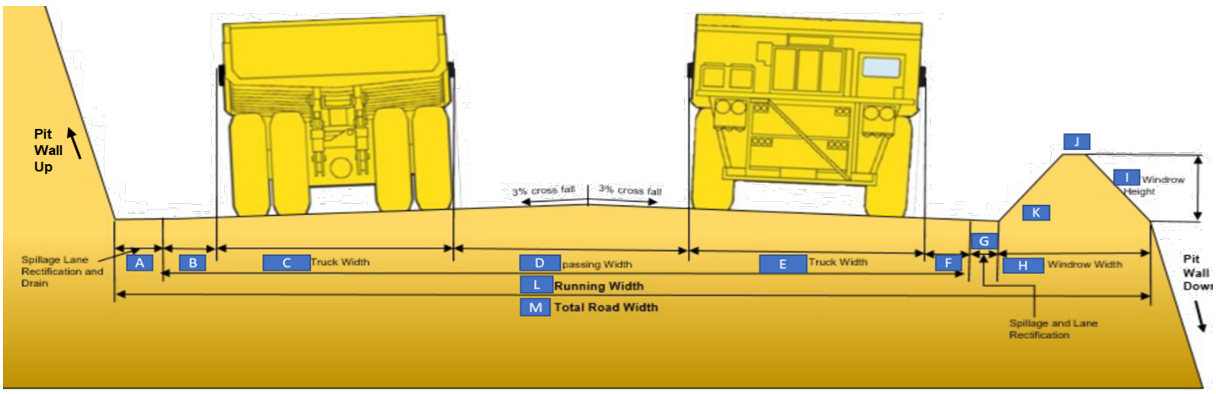
[53] Greenhouse Gas Protocol, "Technical Guidance for Calculating Scope 3 Emissions," 2013.
[54] "National Electricity Market." Australian Government - Departement of Climate Change, Energy, the Environment and Water. https://www.energy.gov.au/government-priorities/energy-markets/national-electricity-market-nem#:~:text=The%20NEM%20is%20a%20wholesale,not%20connected%20to%20the%20NEM. (accessed 08/09/2023).
[55] Energy Networks Australia, "Guide to Australia's Energy Networks," 2019.
[56] "South West Interconnected System transformation." Australian Government - Infrastructure Australia. https://www.infrastructureaustralia.gov.au/map/south-west-interconnected-system-transformation (accessed 08/09/2023).
[57] "Northern Territory remote community power generation program." Australian Government - Infrastructure Australia. https://www.infrastructureaustralia.gov.au/map/northern-territory-remote-community-power-generation-program (accessed 09/08/2023).
[58] "Hybrid power generation for Australian off-grid mines," Australian Renewable Energy Abency, 2018.
[59] V. Balaji and H. Gurgenci, "Search for optimum renewable mix for Australian off-grid power generation," *Energy,* vol. 175, pp. 1234-1245, 2019.
[60] M. Henrio, O. van der Ende, G. Motta, and R. K. Ray. "Electrifying mines could double their electricity demand." McKinsey & Company. https://www.mckinsey.com/industries/metals-and-mining/our-insights/electrifying-mines-could-double-their-electricity-demand#/ (accessed 16/06/2023).
[61] Electricity Maps ApS. "Australia." Electricity Maps ApS,. https://app.electricitymaps.com/zone/AU (accessed 04/09/2023).
[62] A. Strazzabosco, J. H. Gruenhagen, and S. Cox, "A review of renewable energy practices in the Australian mining industry," *Renewable Energy,* vol. 187, pp. 135-143, 2022.
[63] W. R. Abdellah, C. Hirohama, A. Sainoki, A. R. Towfeek, and M. A. Ali, "Estimating the Optimal Overall Slope Angle of Open-Pit Mines with Probabilistic Analysis," *Applied Sciences,* vol. 12, no. 9, p. 4746, 2022.
[64] R. Thompson, "10.6 Design, construction, and maintenance of haul roads," in *SME Mining Engineering Handbook, Volume 1*: Society for Mining, Metallurgy, and Exploration, 2011, pp. 957-977.
[65] E. Furuholt, "Life cycle assessment of gasoline and diesel," *Resources, Conservation and recycling,* vol. 14, no. 3-4, pp. 251-263, 1995.
[66] R. Yin, Y. Yang, Y. Yang, and Z. Chen, "Life cycle assessment of the lithium titanate batteries used for electric vehicles," *China Environmental Science,* vol. 38, no. 6, pp. 2371-2381, 2018.
[67] C. Hoffmann, M. Van Hoey, and B. Zeumer. "Decarbonization challenge for steel." McKinsey & Company. https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel (accessed 04/09/2023).
[68] H. Serres, "Life Cycle Assessment of typical projects of the distribution power network: Assessment, Improvement & Recommendations," 2022.
[69] InfoMine USA, Inc. "Mine and Mill Equipment Costs: An Estimator's Guide," 2016.

Appendices

Appendix 3.1

Table 6-1 (Appendix) Parameters employed for calculating the ramp width

Road Parameters Hitachi EH5000AC-3		Input	Unit
Lane Configuration		Double	Type
Angle of Repose		37.00	Deg
Running Width Factor (based on lane config)		3.50	factor
A	Inside - Spillage, Rectification & Drain	2.00	m
B	Inside - Contingency	3.00	m
C	Inside - Truck Width	9.36	m
D	Passing Width	3.00	m
E	Outside - Truck Width	1.00	m
F	Outside - Contingency	3.00	m
G	Outside - Spillage, Rectification & Drain	1.00	m
H	Outside - Windrow Width	5.09	m
I	Windrow Height	1.50	m
J	Windrow Flat Top Width	1.60	m
K	Rill Angle	45.00	Deg
L	Running Width	32.76	m
M	Total Road Width	40.85	m



Appendix 3.2

Table 6-2 (Appendix) Regulations and limitations of the mining slot connectors

Description	Block	Haul Road	Connection Type	Tolearnce Up	Tolearnce Down	Set Gradient (%)	Add Distance	Connection Position
Stage 00	Stage = 0	Stage=00	Nearest within Vertical Tolerance	15	-15	10	50	Bottom
Stage 01	Stage = 1	Stage=01	Nearest within Vertical Tolerance	10	-10	10	50	Bottom
Stage 02	Stage = 2	Stage=02	Nearest within Vertical Tolerance	10	-10	10	50	Bottom
Stage 03	Stage = 3	Stage=03	Nearest within Vertical Tolerance	10	-10	10	50	Bottom
Stage 04	Stage = 4	Stage=04	Nearest within Vertical Tolerance	10	-10	10	50	Bottom
Stage 04 and higher	Stage = 4 AND Bench >= 1845	Stage=04	Nearest within Vertical Tolerance	7	-100	10	50	Bottom

Appendix 3.3

Table 6-3 (Appendix) Regulations and of the dumping slot connectors

Rule	Block	Haul Road	Connection Type	Tolearn ce Up	Tolearnce Down	Set Gradient (%)	Add Distance	Connection Position
1	Stage = 00-04 AND Material = Waste	Stage=00-04	Nearest within Vertical Tolerance	2	-2	10	20	Top
2	Material = Ore	<No Filtering>	Nearest within Vertical Tolerance	35	-35	10	20	Bottom
3	<Unconnected>	Stage=00-04	Nearest within Vertical Tolerance	13	-13	10	20	Top

Appendix 3.4

Table 6-4 (Appendix) Output attributes pertaining to the computed haulage roads

Parameter	Discription
ID	The identifier for this action.
FROM ID	The identifier of the mining block for this action.
TO ID	The identifier of the dump block for this action.
START DATE	The start date for this action.
END DATE	The finish date for this action.
TYPE	The type of material dumped in this action.
DUMPED VOLUME	The loose volume of material dumped in this action.
REMAINING VOLUME	The remaining volume of the dump block specified in the To ID column.
CYCLETIME	The cycle time, in minutes, for this action
CYCLETIME LOADED	The truck cycle time, in minutes, for haul from source to destination, including spot load time and spot dump time for this action.
CYCLETIME UNLOADED	The truck cycle time, in minutes, for return haul from destination back to the source for this action.
DISTANCE LOADED	The one-way haul distance from source to destination for this action.
DISTANCE UNLOADED	The one-way haul distance from destination back to source for this action.
FUEL ALGORITHM1 PER CYCLE	The fuel, in liters, used per cycle for this action.
NUMBER CYCLES	The number of cycles represented by this action.
FUEL ALGORITHM1	The total fuel, in liters, used in this action.
DZ	The total change in elevation between the mining block and the dump block as illustrated in the following image.
TRUCK	The name of the truck used for this haul.
TRUCK BCM CAPACITY	The BCM (Bank Cubic Meter) capacity of the truck as specified in the Deswik Truck file.
SWELLFACTOR	The value specified in the Swell Factor To Dump field on the Destination Mapping tab of the Scenario dialog.
SWELLFACTOR TO TRUCK	The value specified in the Swell Factor To Truck field on the Destination Mapping tab of the Scenario dialog.
DZMAX	The maximum change in elevation between the mining block and the dump block as illustrated in the DZ field above.
DENSITY	The density value used for this action.
BANK VOLUME	The bank or unswollen volume or material dumped in this action.
DUMPED MASS	The mass of material dumped in this action.
VOLUME FIELD	The attribute that defines the material volume as specified in the Volume Field field on the Destination Mapping tab of the Scenario dialog.
TRUCK BCM HAULED PER CYCLE	The BCM (Bank Cubic Meter) volume hauled per cycle.
TRUCK MASS HAULED PER CYCLE	This should equal the Truck Mass Capacity for hauled cycles, but should return '0' if draglines or conveyors are used.
TRUCK MASS CAPACITY	The truck payload weight of the truck as specified in the Deswik Truck file.
TRUCK LCM CAPACITY	The LCM (Loose Cubic Meter) capacity of the truck as specified in the Deswik Truck file.
FUEL ALGORITHM1 LOADED	The fuel, in liters, used on loaded hauls for this action.
FUEL ALGORITHM1 UNLOADED	The fuel, in liters, used on unloaded hauls for this action.
SOURCE MATERIAL	The source material as specified in the From field on the Destination Mapping tab of the Scenario dialog.

DESTINATION MATERIAL	The destination material as specified in the To field on the Destination Mapping tab of the Scenario dialog.
SCHEDULE ID	The identifier of the schedule task that represents the source of this haul action.
TRUCK HOURS	The number of truck hours for the haul.
NO. TRUCKS	The number of trucks used for this haul.
HAUL ROAD	The identifier of the haul road that the material was hauled on.
RETURN HAUL ROAD	The identifier of the haul road taken by the truck to return from the destination to the source.
MiningVertex	The vertex index on the haul path polyline where the mining slot connector links to the main haul path when driving from source to destination.
DumpingVertex	The vertex index on the haul path polyline where the dumping slot connector links to the main haul path when driving from source to destination.
DumpBlockVertex	The vertex index on the haul path polyline where the dumping slot connector ends at the dump block.
FromMiningBlockToHaulString	The time taken, in minutes, to travel from the mining block to the haul road.
AlongHaulStringFromMiningBlock	The time taken, in minutes, to travel along the haul road between the points where the mining block and dump block slots connect to it.
FromHaulStringToDumpBlock	The time taken, in minutes, to travel from the haul road to the dump block.
FromDumpBlockToHaulString	The time taken, in minutes, to travel from the dump block to the haul road.
AlongHaulStringFromDumpBlock	The time taken, in minutes, to travel along the haul road between the points where the mining block and dump block slots connect to it.
FromHaulStringToMiningBlock	The time taken, in minutes, to travel from the haul road to the mining block.
CycleTimeNoTKPH	The cycle time calculated without TKPH.
CycleTimeWithTKPH	The cycle time calculated with TKPH.
LOADED TIME	The portion of the cycle time spent in a loaded state.
UNLOADED TIME	The portion of the cycle time spent in an unloaded state.
FILL TIME	The portion of the cycle time spent loading.
DUMP TIME	The portion of the cycle time spent dumping.
TKPH WITH TKPH	The TKPH of the haul after speeds have been altered to bring the TKPH within the tolerance value of the tire TKPH rating.
TKPH NO TKPH	he TKPH of the haul before speeds were altered to reduce the TKPH of the haul.
MAXIMUM SPEED LOADED	The maximum speed on loaded hauls for this action.
MAXIMUM SPEED UNLOADED	The maximum speed on unloaded hauls for this action.
DISTANCE ON TROLLEY	The distance that the truck is powered by the trolley system.
TIME ON TROLLEY	The truck time per cycle, in minutes, that the truck is powered by the trolley system.
MAX ENERGY DELIVERABLE ON TROLLEY	This is the maximum power drawn by the truck per cycle, in kWh.
DENSITY FIELD	The attribute that defines the material density as specified in the Density Field (Wet) on the Destination Mapping tab of the Scenario dialog.
Distance By Trolley [Trolley Name]	The haulage distance traveled by a specific trolley.
Time By Trolley [Trolley Name]	The amount of time (mins) that a specific trolley is operational.
Max Energy Deliverable By Trolley [Trolley Name]	The product of the maximum voltage and maximum amperage of a specific trolley as specified in the scenario settings.

Appendix 3.5

Table 6-5 (Appendix) Specific attributes associated with generated haulage roads

Attribute	Filter	Formula
String Audit		
MaxGrade%	<No Filtering>	max(abs([*GradientMax_Per]),abs([*GradientMin_Per]))
Length	<No Filtering>	[*Length]
DeltaZ	<No Filtering>	[*ZMax]-[*ZMin]
XYZ		
X1	<No Filtering>	round(if([*StartPointX]-[*StartPointY]/100000000<[*EndPointX]-[*EndPointY]/100000000,[*StartPointX],[*EndPointX]),0)
Y1	<No Filtering>	round(if([*StartPointX]-[*StartPointY]/100000000<[*EndPointX]-[*EndPointY]/100000000,[*StartPointY],[*EndPointY]),0)
Z1	<No Filtering>	round(if([*StartPointX]-[*StartPointY]/100000000<[*EndPointX]-[*EndPointY]/100000000,[*StartPointZ],[*EndPointZ]),0)
X2	<No Filtering>	round(if([*StartPointX]-[*StartPointY]/100000000<[*EndPointX]-[*EndPointY]/100000000,[*EndPointX],[*StartPointX]),0)
Y2	<No Filtering>	round(if([*StartPointX]-[*StartPointY]/100000000<[*EndPointX]-[*EndPointY]/100000000,[*EndPointY],[*StartPointY]),0)
Z2	<No Filtering>	round(if([*StartPointX]-[*StartPointY]/100000000<[*EndPointX]-[*EndPointY]/100000000,[*EndPointZ],[*StartPointZ]),0)

Appendix 3.6

Table 6-6 (Appendix) Global Constants

Name	Value	Unit
General		
EH5000 kg Empty	202,000 - 211,000	kg
EH5000 kg Payload	298,000 - 289,000	kg
Auxiliary Power Required (EH5000)	212.7	kW
Rolling Resistance	3	%
Diesel fuel energy	10.6	kWh/L
Load time	180	s
Dump time	120	s
EH5000 Max Power	2,127	kW
acc_loaded	0.417	m/s^2
acc_unloaded	0.417	m/s^2
dec_loaded	-0.417	m/s^2
dec_unloaded	-0.417	m/s^2
Fuel_min	55.4	L/h

Fuel_max	554	L/h
Maximum Deceleration Rate	-0.417	m/s^2
Trolley Line Power	8,000	kW
Plug-In Charge Power	3,000	kW
Battery Capacity	1500	kWh
Main Efficiencies		
Diesel Engine	36.0	%
Electric Motor	92.0	%
Drive efficiency Diesel	85.8	%
Aux Efficiency Diesel	95.0	%
Drive efficiency Battery	85.4	%
Drive Efficiency Trolley	90.0	%
Auxiliary drive efficiency (trolley)	94.0	%
Auxiliary drive efficiency (battery)	89.0	%
Charge efficiency (trolley)	90.0	%
Charge efficiency (regeneration)	85.0	%
Battery charge discharge efficiency	97.5	%
Drive Components Efficiencies		
Alternator	96.0	%
Rectifier	99.5	%
Inverter	98.0	%
Wheel motor	96.0	%
Final drive	95.5	%
DC-DC	95.0	%

Appendix 3.7

Table 6-7 (Appendix) Attributes generated from the attributes of the segments and the spatial data (1/3)

Attribute	Filter	Formula
Speeds		
Status	<No Filtering>	if(CONTAINS([*Layer Name], "EMPTY")=TRUE,"EMPTY","LOADED")
Max Speed m/s	Loaded	[MAX VELOCITY LOADED]/3.6
Max Speed m/s	Empty	[MAX VELOCITY UNLOADED]/3.6
Min_Acc	<No Filtering>	If([End Speed m/s]*3.6*0.7>19,0.0004*([End Speed m/s]*3.6*0.7)^(2)-0.0409*([End Speed m/s]*3.6*0.7)+1.0343,-0.00000000000000005*([End Speed m/s]*3.6*0.7)+0.4167)
Min Speed m/s	<No Filtering>	([Length]-0.5*[Min_Acc]*([Time sec])^(2))/[Time sec]

<table>
<tr><td>End Speed m/s</td><td><No Filtering></td><td>IF(ISMAXIMUMOFGROUP("Route|*Layer Name","Segment")=TRUE,"0",IF([Segment] = 1, [Max Speed m/s],IF([Gradient]=0,[Max Speed m/s], IF([Gradient]<0,[Max Speed m/s],IF(AND([Gradient]>=0,PEEKOFFSET("Route","Segment",FALSE,"Gradient",1,0)>=[Gradient]),[Max Speed m/s],IF(AND([Gradient]>0,PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)<[Gradient]>PEEKOFFSET("Route|*Layer Name","Segment",TRUE,"Gradient",1,0)),PEEKOFFSET("Route|*Layer Name","Segment",TRUE,"Min Speed m/s",1,0),IF(AND([Gradient]>0, PEEKOFFSET("Route|*Layer Name","Segment",TRUE,"Gradient",1,0) > [Gradient] , [Gradient] > PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)),PEEKOFFSET("Route|*Layer Name","Segment",TRUE,"Max Speed m/s",1,0),0)))))))</td></tr>
<tr><td>Start Speed m/s</td><td><No Filtering></td><td>IF([Segment] = 1, 0,IF(AND([Gradient]=0,0>=PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(AND([Gradient]=0,PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",2,0)>PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)>0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(AND([Gradient]=0,PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",2,0)<PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)>0),[Min Speed m/s],IF(AND([Gradient]>0, PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)<=0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(AND(PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Segment",1,0)=1,[Gradient] >0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(AND([Gradient]>0, PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",2,0)>=PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)>=0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(AND([Gradient]>0,PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",2,0)<PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)>0),[Max Speed m/s],IF(AND([Gradient]<0, PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)<=0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Segment",1,0)=1, PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(AND([Gradient]<0, PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",2,0)>PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0)>0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Max Speed m/s",1,0),IF(AND([Gradient]<0,PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",2,0)<PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0),PEEKOFFSET("Route|*Layer Name","Segment",FALSE,"Gradient",1,0) >0),[Min Speed m/s],0))))))))))))</td></tr>
<tr><td>Time sec</td><td>Loaded</td><td>[TIME LOADED]</td></tr>
<tr><td>Time sec</td><td>Empty</td><td>[TIME UNLOADED]</td></tr>
</table>

Appendix 3.8

Table 6-8 (Appendix) Attributes generated from the attributes of the segments and the spatial data (2/3)

Attribute	Filter	Formula
Trucking		
Mass kg Empty	<No Filtering>	GC("EH5000 kg Empty")
Mass kg Payload	<No Filtering>	GC("EH5000 kg Payload")
Mass kg	Empty	[Mass kg Empty]
Mass kg	Loaded	[Mass kg Empty]+[Mass kg Payload]
Velocity_avg	Empty	[VELOCITY UNLOADED]
Velocity_avg	Loaded	[VELOCITY LOADED]
Time sec	Empty	[TIME UNLOADED]
Time sec	Loaded	[TIME LOADED]
Start_End_Points		
X1	<No Filtering>	[*StartPointX]
Y1	<No Filtering>	[*StartPointY]
Z1	<No Filtering>	[*StartPointZ]
X2	<No Filtering>	[*EndPointX]
Y2	<No Filtering>	[*EndPointY]
Z2	<No Filtering>	[*EndPointZ]
Length2D	<No Filtering>	[*Length2D]
Length3D	<No Filtering>	[*Length3D]
General		
Length	<No Filtering>	[*Length]
Gradient	<No Filtering>	Round([*GradientAve_Deg],2)
Route	<No Filtering>	[ID_Trucked]
Gradient%	<No Filtering>	Round([*GradientAve_Per],2)

Appendix 3.9

Table 6-9 (Appendix) Attributes generated from the attributes of the segments and the spatial data (3/3)

Attribute	Filter	Formula
Mass_5000_L	EH5000 AC3 Diesel	GC("EH5000 kg Empty")+GC("EH5000 kg Payload")
Mass_5000_E	EH5000 AC3 Diesel	GC("EH5000 kg Empty")
acc_5000	<No Filtering>	MIN(((IF([Velocity_Acc]>5.54774,699929*[Velocity_Acc]^(-1.001)*9.81,(-2387.6)*[Velocity_Acc]+134866*9.81))-(GC("Rolling resistance")*[Mass kg]*9.81)-([Mass kg]*9.81*SIN(RAD(0))))/[Mass kg],GC("acc_unloaded"))

dec_5000	<No Filtering>	MAX(((IF([Velocity_Dec]>19.553,-(962314*[Velocity_Dec]^(-0.906))*9.81*0.7,-(-11.956*[Velocity_Dec]+66714)*9.81*0.7))-(GC("Rolling resistance")*[Mass kg]*9.81)-([Mass kg]*9.81*SIN(RAD(0))))/[Mass kg],GC("dec_unloaded"))
max_acc	<No Filtering>	max([acc_5000]+SIN(RAD(-[*GradientAve_Deg]))*9.81,[acc_5000])
max_dec	<No Filtering>	min([dec_5000]-SIN(RAD([*GradientAve_Deg]))*9.81,[dec_5000])
time_acc	<No Filtering>	if([Start Speed m/s]>[End Speed m/s],0,([Max Speed m/s]-[Start Speed m/s])/[max_acc])
time_dec	<No Filtering>	if([End Speed m/s]>[Start Speed m/s],0,([End Speed m/s]-[Max Speed m/s])/[max_dec])
displacement_acc	<No Filtering>	if([Start Speed m/s]<[Max Speed m/s],[Start Speed m/s]*[time_acc]+0.5*[max_acc]*([time_acc])^2,0)
displacement_dec	<No Filtering>	if([Max Speed m/s]>[End Speed m/s],[Max Speed m/s]*[time_dec]+0.5*[max_dec]*([time_dec])^2,0)
delta_h_acc	<No Filtering>	if(or([*EndPointZ]>[*StartPointZ],[*EndPointZ]<[*StartPointZ]),SIN(RAD([*GradientAve_Deg]))*[displacement_acc],0)
delta_h_const	<No Filtering>	if(or([*EndPointZ]>[*StartPointZ],[*EndPointZ]<[*StartPointZ]),SIN(RAD([*GradientAve_Deg]))*([*Length]-[displacement_acc]-[displacement_dec]),0)
delta_h_dec	<No Filtering>	if(or([*EndPointZ]>[*StartPointZ],[*EndPointZ]<[*StartPointZ]),SIN(RAD([*GradientAve_Deg]))*[displacement_dec],0)

Appendix3.10

Table 6-10 (Appendix) Energy calculation

Attribute	Filter	Formula
Energy_Acc	<No Filtering>	if([Start Speed m/s]<[Max Speed m/s],((0.5*[Mass kg]*(([Max Speed m/s])^2-([Start Speed m/s])^2))+([Mass kg]*9.81*([delta_h_acc]))+([Mass kg]*9.81*GC("Rolling resistance")*[displacement_acc])),0)/3600/1000
Energy_Const	<No Filtering>	MAX((([Mass kg]*9.81*[delta_h_const])+([Mass kg]*9.81*GC("Rolling resistance")*([Length]-[displacement_acc]-[displacement_dec])) , 0)/3600/1000
Energy_Dec	<No Filtering>	if([Max Speed m/s]>[End Speed m/s],max(((0.5*[Mass kg]*(([End Speed m/s])^2-([Max Speed m/s])^2))+([Mass kg]*9.81*([delta_h_dec]))+([Mass kg]*9.81*GC("Rolling resistance")*[displacement_dec])),0),0)/3600/1000
Total_Energy_Acc	<No Filtering>	[Energy_Acc]+([time_acc]*GC("Auxiliary power required (EH5000)")/3600)
Total_Energy_Const	<No Filtering>	[Energy_Const]+(([Time sec]-[time_acc]-[time_dec])*GC("Auxiliary power required (EH5000)")/3600)
Total_Energy_Dec	<No Filtering>	[Energy_Dec]+([time_dec]*GC("Auxiliary power required (EH5000)")/3600)
Eff_Total_Energy_Acc	<No Filtering>	([time_acc]*GC("Auxiliary power required (EH5000)")/3600)/GC("Aux Efficiency Diesel")+[Energy_Acc]/GC("Drive Efficiency (diesel)")

Eff_Total_Energy_Const	<No Filtering>	(([Time sec]-[time_acc]-[time_dec])*GC("Auxiliary power required (EH5000)")/3600)/GC("Aux Efficiency Diesel")+[Energy_Const]/GC("Drive Efficiency (diesel)")
Eff_Total_Energy_Dec	<No Filtering>	([time_dec]*GC("Auxiliary power required (EH5000)")/3600)/GC("Aux Efficiency Diesel")+[Energy_Dec]/GC("Drive Efficiency (diesel)")
Fuel_Burn_Acc_(L)	<No Filtering>	[Eff_Total_Energy_Acc]/GC("Engine efficiency")/GC("Diesel fuel energy")
Fuel_Burn_Const_(L)	<No Filtering>	[Eff_Total_Energy_Const]/GC("Engine efficiency")/GC("Diesel fuel energy")
Fuel_Burn_Dec_(L)	<No Filtering>	[Eff_Total_Energy_Dec]/GC("Engine efficiency")/GC("Diesel fuel energy")
Segment_Fuel_Burn_(L)	<No Filtering>	[Fuel_Burn_Acc_(L)]+[Fuel_Burn_Const_(L)]+[Fuel_Burn_Dec_(L)]

Appendix 3.11

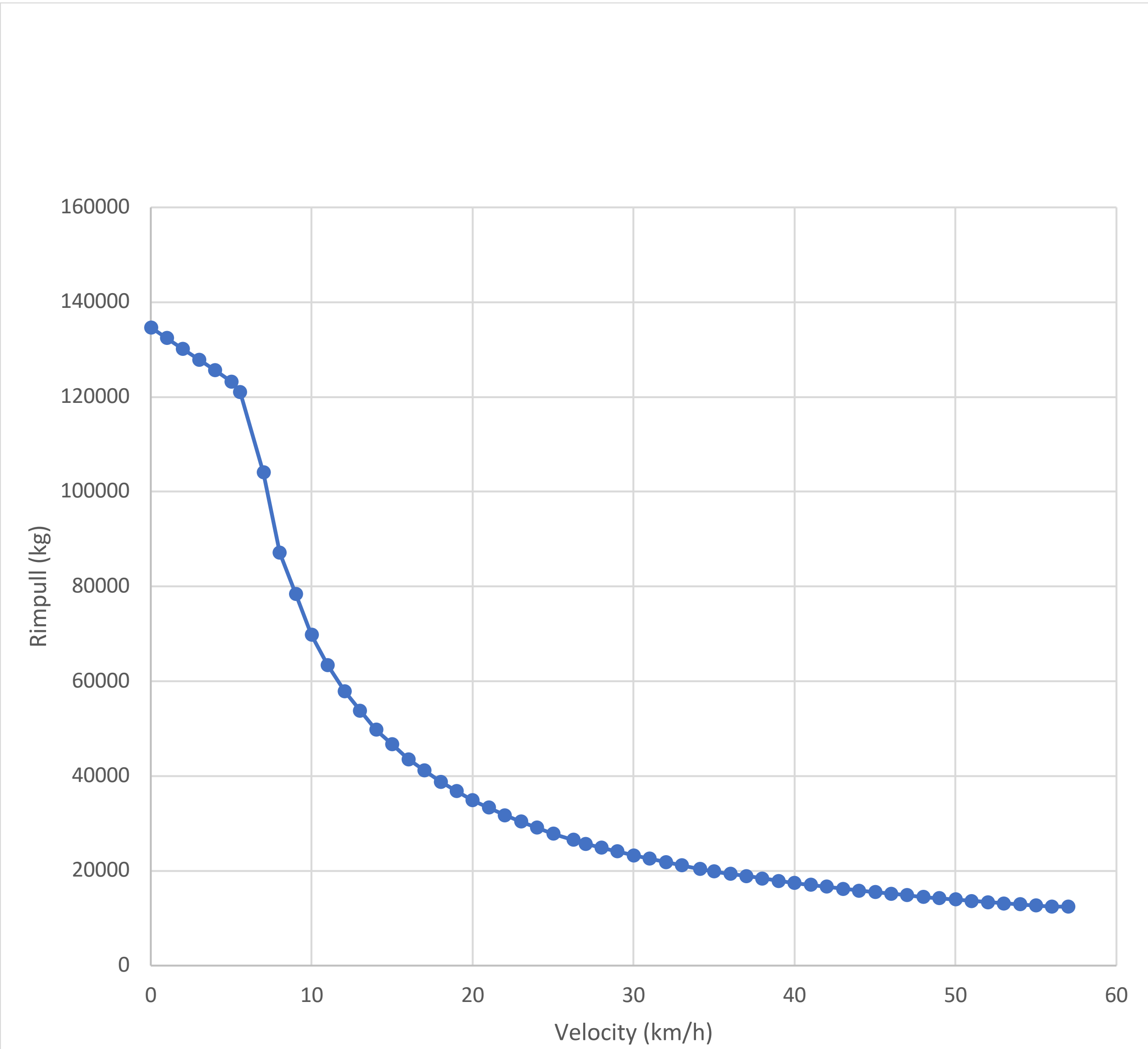
Table 6-11 (Appendix) Force calculation

Attribute	Filter	Formula
Force_Acc_(N)	<No Filtering>	if([Start Speed m/s]<[Max Speed m/s],max((((GC("Rolling resistance")*[Mass kg]*9.81)+([Mass kg]*9.81*SIN(RAD([*GradientAve_Deg]))))+([acc_5000]*[Mass kg])),0),0)
Force_Const_(N)	<No Filtering>	max(([Mass kg]*9.81*SIN(RAD([*GradientAve_Deg])))+([Mass kg]*9.81*GC("Rolling resistance")),0)
Force_Dec_(N)	<No Filtering>	if([End Speed m/s]<[Max Speed m/s],MAX((((GC("Rolling resistance")*[Mass kg]*9.81)+([Mass kg]*9.81*SIN(RAD([*GradientAve_Deg]))))+([dec_5000]*[Mass kg])),0),0)
Force_Acc	<No Filtering>	[Force_Acc_(N)]/9.81
Force_Const	<No Filtering>	[Force_Const_(N)]/9.81
Force_Dec	<No Filtering>	[Force_Dec_(N)]/9.81
Velocity_Acc	<No Filtering>	if([Start Speed m/s] < [End Speed m/s],(([Start Speed m/s]+[End Speed m/s])*0.5),0)*3.6
Velocity_Const	Loaded	IF(AND([Start Speed m/s] = 0, [End Speed m/s] = 0), [Max Speed m/s],IF([Start Speed m/s] = 0, [End Speed m/s],IF(AND(ISMAXIMUMOFGROUP("Route|*Layer Name","Segment")=TRUE,[*GradientAve_Per]>1),869.99*([*GradientAve_Per]/100)^(2) - 163.42*([*GradientAve_Per]/100) + 10.869,IF([End Speed m/s]=0,[Start Speed m/s],[End Speed m/s]))))*3.6
Velocity_Const	Empty	IF(AND([Start Speed m/s] = 0, [End Speed m/s] = 0), [Max Speed m/s],IF([Start Speed m/s] = 0, [End Speed m/s],IF(AND(ISMAXIMUMOFGROUP("Route|*Layer Name","Segment")=TRUE,[*GradientAve_Per]>1),-100.85*([*GradientAve_Per]/100)+16.982,IF([End Speed m/s]=0,[Start Speed m/s],[End Speed m/s]))))*3.6
Velocity_Dec	<No Filtering>	IF([Start Speed m/s] > [End Speed m/s], ([Start Speed m/s] + [End Speed m/s])*0.5, 0)*3.6
Throttle_Acc	<No Filtering>	IFERROR([Force_Acc]/IF([Velocity_Acc]>5.54774,699929*[Velocity_Acc]^(-1.001),(-2387.6)*[Velocity_Acc]+134866),0)

Throttle_Acc	<No Filtering>	IFERROR([Force_Const]/IF([Velocity_Const]>5.54774,699929*[Velocity_Const]^(-1.001),(-2387.6)*[Velocity_Const]+134866),0)
Throttle_Acc	<No Filtering>	IFERROR([Force_Dec]/IF([Velocity_Dec]>5.54774,699929*[Velocity_Dec]^(-1.001),(-2387.6)*[Velocity_Dec]+134866),0)
Fuel_Consump_Acc_(L)	<No Filtering>	if([Start Speed m/s]<[Max Speed m/s],((GC("Fuel_min")+[Throttle_Acc]*GC("Fuel_max"))/3600)*[time_acc],0)
Fuel_Consump_Const_(L)	<No Filtering>	((GC("Fuel_min")+[Throttle_Const]*GC("Fuel_max"))/3600)*([Time sec]-[time_acc]-[time_dec])
Fuel_Consump_Dec_(L)	<No Filtering>	if([End Speed m/s]<[Max Speed m/s],((GC("Fuel_min")+[Throttle_Dec]*GC("Fuel_max"))/3600)*[time_dec],0)
Segment_Fuel_Consump	<No Filtering>	[Fuel_Consump_Acc_(L)]+[Fuel_Consump_Const_(L)]+[Fuel_Consump_Dec_(L)]

Appendix 3.12

Figure 6-1 (Appendix) Rimpull curve



Appendix 3.13

Table 6-12 (Appendix) Detailed information on the attributes for battery energy calculation

Attribute	Filter	Formula
E_Force	<No Filtering>	[Mass kg]*9.81*SIN(RAD([*GradientAve_Deg]))+[Mass kg]*GC("Rolling resistance")*9.81
E_Power	<No Filtering>	([E_Force]*([Velocity_avg]/3.6))/1000
E_Energy	<No Filtering>	[E_Power]*([Time sec]/3600)
E_Total_Energy	<No Filtering>	IF(AND([Gradient]>5,[Velocity_avg]>14),[E_Energy]+((GC("Auxiliary Power Required (EH5000)")/0.94)*([Time sec]/3600)),IF([Gradient]<0,[E_Energy]+((GC("Auxiliary Power Required (EH5000)")/0.89)*([Time sec]/3600)),IF(AND([Gradient]>0,[Velocity_avg]<14),[E_Energy]+((GC("Auxiliary Power Required (EH5000)")/0.89)*([Time sec]/3600)),IF(AND([Gradient]>0,[Velocity_avg]>14,[Length]>160),[E_Energy]+((GC("Auxiliary Power Required (EH5000)")/0.89)*([Time sec]/3600)),IF([Gradient]=0,[E_Energy]+((GC("Auxiliary Power Required (EH5000)")/0.89)*([Time sec]/3600)),0)))))
B_Eff_Total_Energy	<No Filtering>	IF(AND([E_Total_Energy]>0,[Gradient]>0,[Velocity_avg]<15.5),[E_Total_Energy]/GC("Drive Efficiency Battery"),IF(AND([E_Total_Energy]>0,[Gradient]=0,[Velocity_avg]<28),[E_Total_Energy]/GC("Drive Efficiency Battery"),IF(AND([E_Total_Energy]>0,[Gradient]=0,[Velocity_avg]>31),[E_Total_Energy]/GC("Drive Efficiency Battery"),IF(AND([E_Total_Energy]>0,[Gradient]>0,[Gradient]<5),[E_Total_Energy]/GC("Drive Efficiency Battery"),IF(AND([E_Total_Energy]>0,[Gradient]>5,[Length]<85),[E_Total_Energy]/GC("Drive Efficiency Battery"),IF(AND([E_Total_Energy]>0,[Gradient]>5,[Length]>160),[E_Total_Energy]/GC("Drive Efficiency Battery"),IF(AND([E_Total_Energy]>0,[Gradient]>5,[Length]>85,[Velocity_avg]<15),[E_Total_Energy]/GC("Drive Efficiency Battery"),IF(AND([E_Total_Energy]>0,[Gradient]>5,[Length]<160,[Velocity_avg]<15),[E_Total_Energy]/GC("Drive Efficiency Battery"),0))))))))*(-1)
T_Eff_Total_Energy	<No Filtering>	IF(AND([E_Total_Energy]>0,[Velocity_avg]>15,[Gradient]>5,[Length]>85),[E_Total_Energy]/GC("Drive Efficiency Trolley"),IF(AND([E_Total_Energy]>0,[Gradient]=0,[Velocity_avg]>27,[Velocity_avg]<31,[Length]>170),[E_Total_Energy]/GC("Drive Efficiency Trolley"),0))*(-1)
R_Charge	<No Filtering>	IF(AND([E_Total_Energy]<0,[Gradient]<0),[E_Total_Energy]*GC("Drive Efficiency Battery")*GC("Battery charge discharge efficiency"),0)*(-1)
T_Charge	<No Filtering>	IF(AND([Gradient]>5,[Velocity_avg]>15,[Length]>85),(GC("Trolley Line Power")-(-[T_Eff_Total_Energy]/([Time sec]/3600)))*([Time sec]/3600),IF(AND([Gradient]=0,[Velocity_avg]>27,[Velocity_avg]<31,[Length]>170),(GC("Trolley Line Power")-(-[T_Eff_Total_Energy]/([Time sec]/3600)))*([Time sec]/3600),0))*GC("Battery charge discharge efficiency")*0.95

Battery_Delta	<No Filtering>	[R_Charge]+[T_Charge]+[B_Eff_Total_Energy]
Electricity_Used	<No Filtering>	IF(AND([Velocity_avg]>15,[Gradient]>5),(GC("Trolley Line Power")*([Time sec]/3600))/0.97,IF(AND([E_Total_Energy]>0,[Gradient]=0,[Velocity_avg]>27,[Velocity_avg]<31,[Length]>170),(GC("Trolley Line Power")*([Time sec]/3600))/0.97,0))
Battery_Status_cum	<No Filtering>	SUMOFGROUPINCREMENTAL("Route|*Layer Name","Segment",TRUE,"Battery_Delta")
Battery_Discharge_Power	<No Filtering>	(-[B_Eff_Total_Energy])/([Time sec]/3600)
Battery_Trolley_Charge_Power	<No Filtering>	[T_Charge]/([Time sec]/3600)
Regeneration_Charge_Power	<No Filtering>	[R_Charge]/([Time sec]/3600)

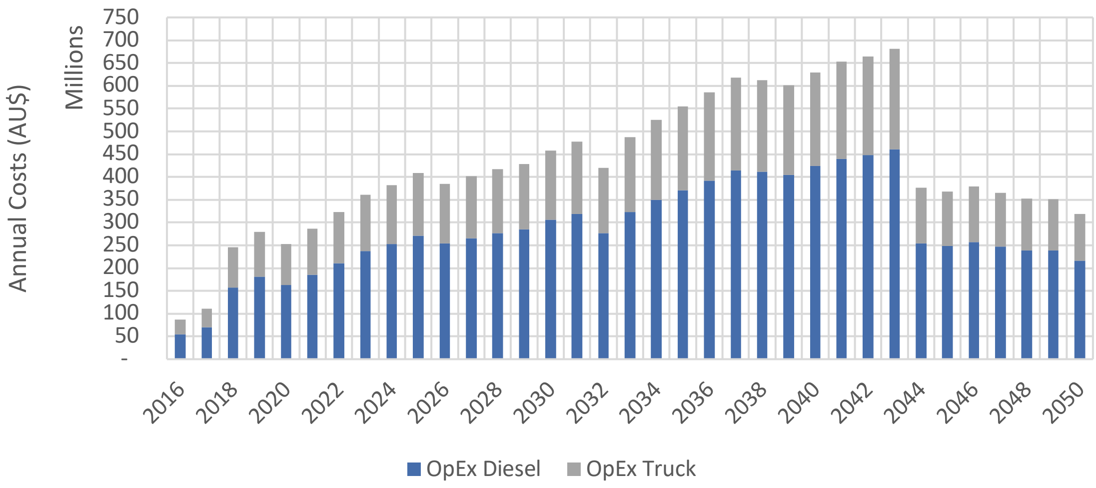
Appendix 3.14

Table 6-13 (Appendix) Detailed OpEx costs

Name	Diesel Truck (AU$/h)	Electric Truck
Operations Labour	155.20	-
Lubricants	20.42	-
Maintenace - Labour	6.10	-
Maintenace - Parts	78.15	-
Wear Components	13.50	-
Tyres	55.00	-
Total Operating Cost	328.37	279.11

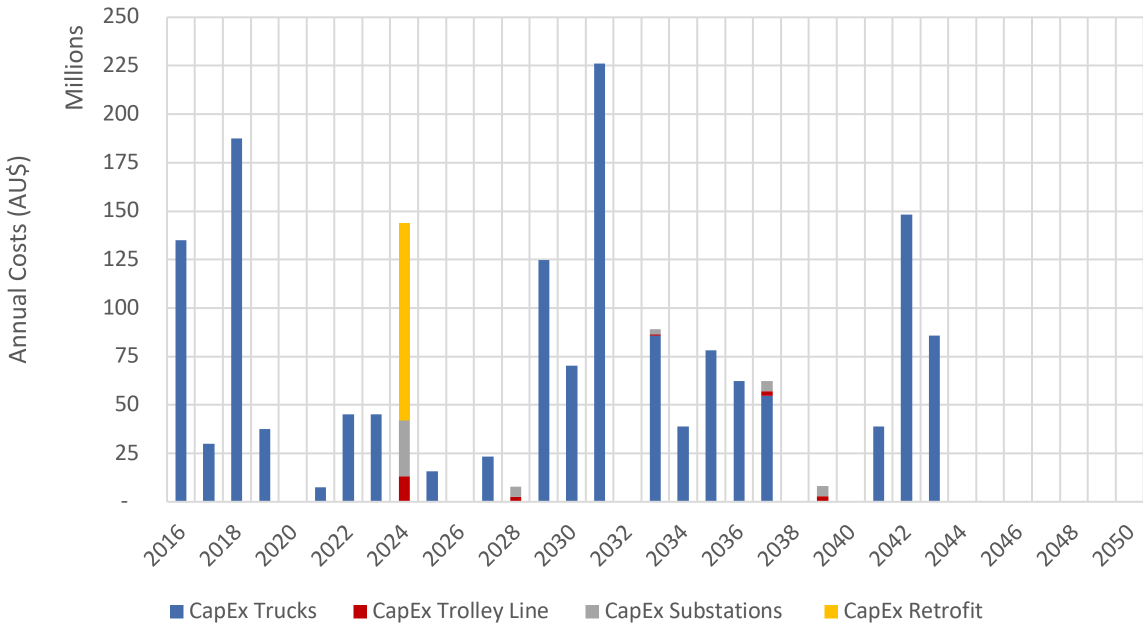
Appendix 4.1

Figure 6-2 (Appendix) Base Case: Breakdown of OpEx costs



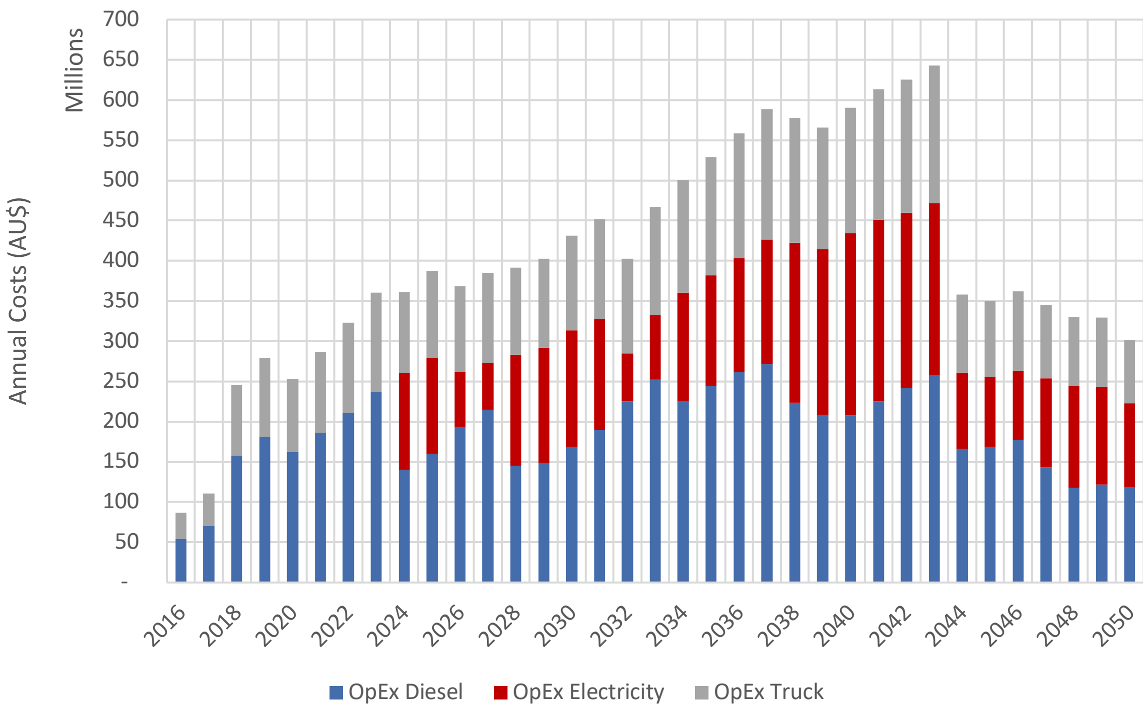
Appendix 4.2

Figure 6-3 (Appendix) Case 1: Breakdown of CapEx costs



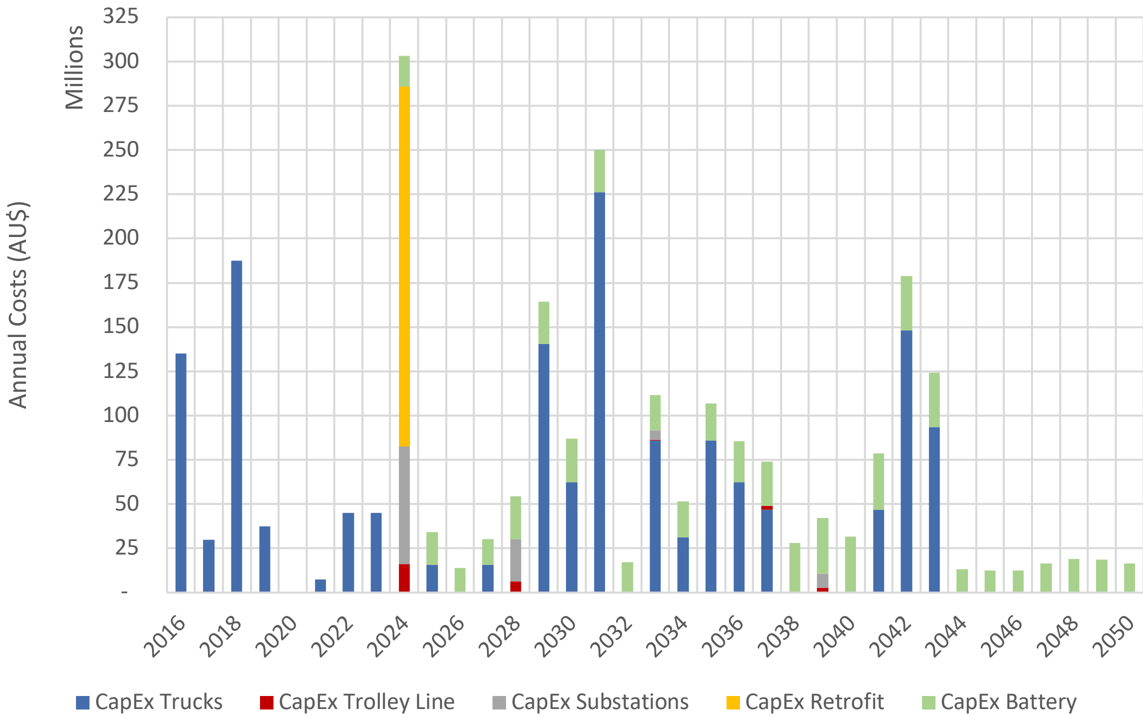
Appendix 4.3

Figure 6-4 (Appendix) Case 1: Breakdown of OpEx costs



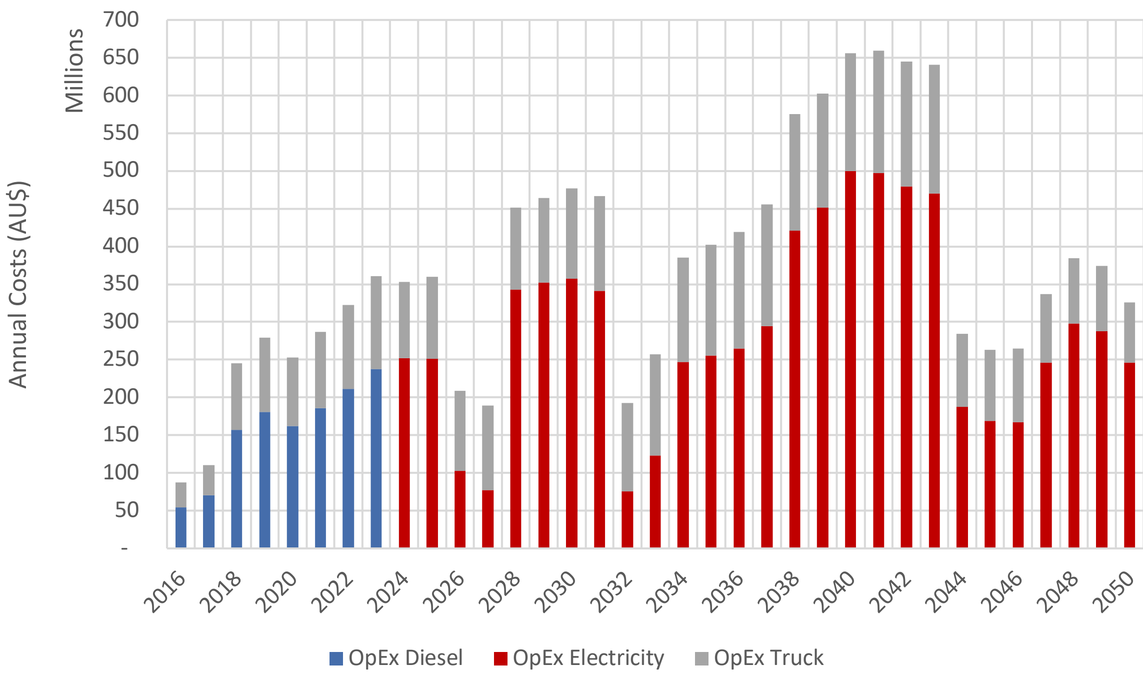
Appendix 4.4

Figure 6-5 (Appendix) Case 2: Breakdown of CapEx costs



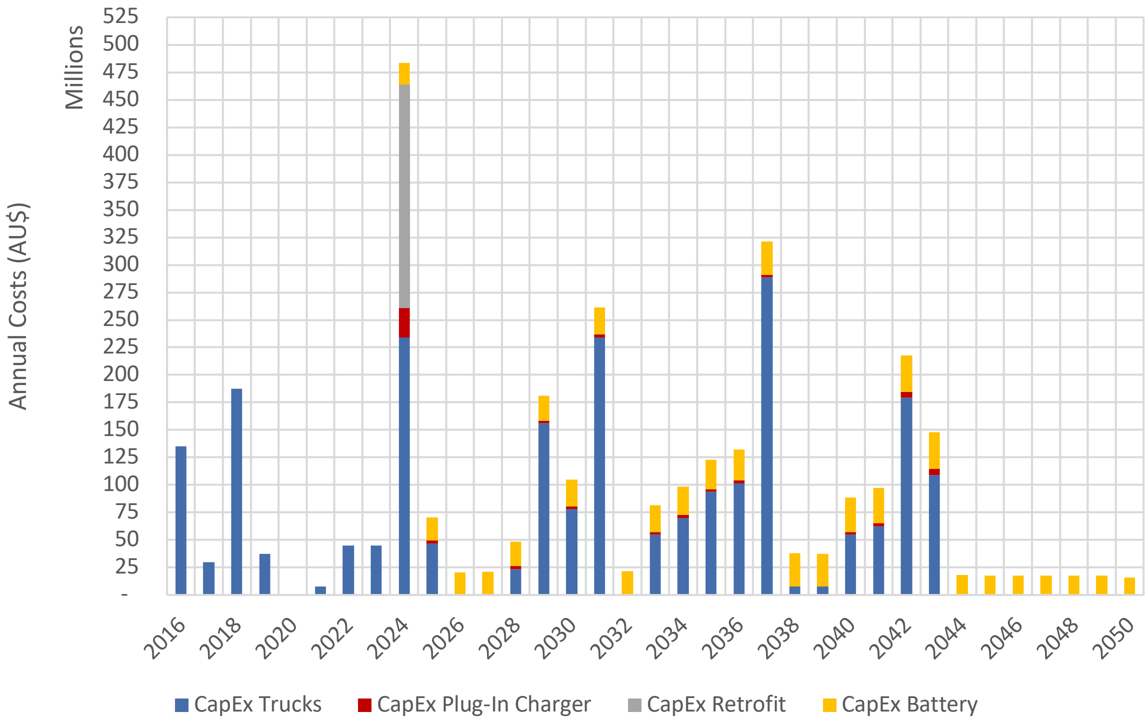
Appendix 4.5

Figure 6-6 (Appendix) Case 2: Breakdown of OpEx costs



Appendix 4.6

Figure 6-7 (Appendix) Case 3: Breakdown of CapEx costs



Appendix 4.7

Figure 6-8 (Appendix) Case 3: Breakdown of OpEx costs