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LIST OF ABBREVIATIONS AND ACRONYMS

ABBREVIATION	DESCRIPTION
BMS	Battery Management Systems
BEV	Battery Electric Vehicle
CAPEX	Capital expenditures
CO_2-eq	Carbon Dioxide Equivalent
DINAMINE	Digital and Innovative Mine of the Future
EMX	EnergyModelsX
FELMICA	Felmica Minerals Industries S.A. (Portugal)
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse gas
GMG	Global Mining Guidelines Group
ISM-PM	Integrated Smart Mine Planning and Managing (system)
MEU	Million Euros
MIM	Mine Information Model
MWD	Measuring While Drilling
NPC	Net Present Cost
NIC	National Institute of Chemistry (Slovenia)
OPEX	Operational Expenditures
SKALAND	Skaland Graphite AS (Norway)
SINAS	SINTEF AS (Norway)
SINH	SINTEF Helgeland (Norway)
TEA	Techno-Economic Assessment
TCO	Total Cost of Ownership
WP	Work Package

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SUMMARY

The European economy relies heavily on critical raw materials that support rapidly growing sectors such as electric mobility, renewable energy, and digital technologies. Demand for key materials is expected to rise significantly in the coming decades. However, many European mining operations still rely on resource-intensive processes and often conventional processes, which can limit productivity, reduce resource efficiency, and contribute to environmental impacts. Strengthening Europe's resilience and competitiveness therefore requires a transition toward more efficient, digital, and sustainable mining operations.

In this context, the DINAMINE project addressed these challenges by developing innovative solutions for smarter and more sustainable mining. The project focused on enabling data-driven, automated, and safer mining operations through technologies for real-time measurements and integrated system control. As part of project work package 3 (WP3), Task 3.4 specifically targeted the topic of transition to low- and zero-emission mining transport systems, by assessing and optimising carbon-neutral transport solutions, including the evaluation of power demand, infrastructure constraints, and total cost of ownership for technologies such as battery-electric systems.

This document constitutes project deliverable 3.4 (D3.4) and presents the key activities required to develop and propose optimal low-to-zero-emission transport solutions tailored for small and medium-sized mining operations. It provides a structured framework for identifying, assessing, and recommending sustainable transportation strategies that align with environmental objectives and operational efficiency.

The deliverable includes a detailed description and model setup of the transport alternatives and boundary conditions considered for each demonstration site within the techno-economic assessment (TEA). It also presents the final evaluation of both the current and alternative transportation options, including their techno-economic performance, CO_2 emissions, and relevant safety considerations.

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1 INTRODUCTION

1.1 CONTEXT AND AIM OF THE PROJECT

Mineral raw materials are strategically important for the European economy, supporting rapidly expanding value chains such as electric mobility, renewable energy systems, and digital technologies. Demand for several critical materials is expected to increase significantly in the coming decades, driven by the energy transition and digitalisation. However, European mining operations face several structural challenges, including relatively high production costs, declining ore grades in some regions, and reliance on established, resource-intensive processes that can limit productivity and resource efficiency. These factors, combined with environmental and regulatory constraints, contribute to a growing gap between domestic supply and projected demand. Addressing these challenges requires a transition toward more efficient, digitalised, and environmentally responsible mining operations, supported by innovation and improved system integration [3].

In this context, the DINAMINE project developed and demonstrated a holistic mine management approach based on digitalisation of mining operations and advanced sensing technologies. At the core of the project is the Integrated Smart Mine Planning and Management (ISM-PM) system, which integrates advanced sensors, hardware, software, and intelligent data analytics tools to enable real-time monitoring and optimisation of mining operations. The system provides mine-to-port visibility of operational performance, environmental footprint, maintenance needs, productivity, and resource recovery.

DINAMINE also addresses the integration of automation, robotisation, and advanced analytics to improve operational safety and productivity. The project conducted energy-efficient-site studies to identify best practices for carbon-neutral logistics and transport, energy efficient mineral processing, and improved waste and tailings management and valorisation. With a particular focus on the needs of European small- and medium-sized mining enterprises, the project develops scalable tools that support more selective, efficient, and sustainable extraction.

The technologies and methodologies are tested and demonstrated under real operational conditions at two European mining sites: an open-pit feldspar mine in Portugal and an underground graphite mine in Norway together with their associated processing plants. These demonstrations contribute to advancing a more digital, sustainable, and competitive European mining sector.

1.2 PURPOSE OF THIS DOCUMENT

This document constitutes Deliverable 3.4 of Task 3.4 within the DINAMINE project. It presents the key activities carried out to develop and evaluate optimal low- to zero-emission transport solutions tailored to small and medium-sized mining operations. The document also defines the scope and methodological framework for the Techno-Economic Assessment (TEA) of zero-emission mass transport solutions at the two project mining sites.

The document provides a detailed description and model setup of the transport alternatives and boundary conditions considered for each demonstration site. It also presents the assessment of both the current and alternative transportation options, including their techno-economic performance including CO_2 emissions, and relevant safety considerations, within a structured framework that evaluates environmental performance, operational feasibility, and economic viability.

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1.3 DOCUMENT STRUCTURE

The content of this document is structured as follows:

- Section 2 outlines the objectives;
- Section 3 describes the methodology, including the data gathering, optimisation model, and safety considerations for the TEA of mining transport;
- Section 4 presents the safety considerations;
- Section 5 introduces the case studies;
- Section 6 describes an analysis of the case studies;
- Section 7 presents the results of the assessment;
- Section 8 presents the discussions; and
- Section 9 provides the main conclusions and perspectives.

2 OBJECTIVES

2.1 WORK PACKAGE OBJECTIVES

Work Package (WP) 3 in the DINAMINE project aims to enable data-driven, automated, and safer mining operations by developing technologies for real-time rock mass characterisation, intelligent excavation design, and integrated safety systems. This includes optimising drill-and-blast practices and improving excavation stability through the combination of machine vision, Measuring While Drilling (MWD) data, and geological information from the Mine Information Model (MIM) (Task 3.1). In addition, WP3 targets the automation and digital integration of drilling equipment, allowing a robotised jumbo drill to adapt drilling patterns in real time based on updated geological and operational data (Task 3.2). The work package also focusses on real-time safety monitoring and risk assessment, providing continuous evaluation of rock stability and generating dynamic risk maps to support decision-making in mining operations (Task 3.3).

A further key activity is to support the transition towards sustainable and low-emission mining transport systems, by assessing and optimising carbon-neutral transport solutions (Task 3.4). This task evaluates power demand, infrastructure constraints, and total cost of ownership for alternative transport technologies (battery and hydrogen systems), providing recommendations for cost-effective and reliable zero-emission transport in mining operations.

2.2 TASK OBJECTIVE

The objective of Task 3.4 is to provide recommendations for optimal low- to zero-emission transport solutions in small and medium-sized mining operations. To achieve this, SINAS, with support from NIC, analysed power demand profiles and maintenance requirements associated with key mass transport activities in mining. The analysis is intended to be based on operational data collected at the SKALAND and FELMICA sites and to cover transport activities underground, in-pit, and between the mine and the processing plant.

In parallel, SINAS, with the support of NIC, assessed the power and fuel supply capacities at the demonstration sites in order to identify potential infrastructure constraints or bottlenecks that may affect the implementation of low- to zero-emission transport technologies.

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Building on these analyses, a TEA of alternative mass transportation solutions was conducted using the EMX optimisation model. The model is intended to account for site-specific energy conditions and to evaluate suitable technological options, primarily battery-electric solutions, based on reliability-driven design and selection of haulage and hoisting systems. Safety considerations are also addressed qualitatively within the assessment.

As part of the task, a comprehensive state-of-the-art review on the use of hydrogen in the mining sector was conducted, resulting in the submission of a review article led by NIC, in collaboration with SINAS and SINH (Lokar et al.) [7]. The article covers four main areas:

1. hydrogen production, transportation, and storage;
2. hydrogen applications in mining;
3. hydrogen safety in mining environments; and
4. modelling the role of hydrogen in mining systems.

While hydrogen-based transport solutions are within the broader scope of Task 3.4, they are not explicitly included in the techno-economic modelling presented in this deliverable due to data limitations and the current maturity of available case-specific inputs. The hydrogen-related work is therefore intended to provide background and support future extensions of the analysis rather than to inform the quantitative results presented herein.

While all topics are relevant to the task, the modelling and safety aspects are particularly important, as they provide key inputs for the techno-economic and safety assessments carried out within the task.

Following the completion of the review, significant progress had been made in defining the scope and methodology for the TEA of zero-emission mass transport solutions at the two project mining sites.

3 METHODOLOGY

In this section, the overall methodology of the Techno-Economic Assessment and Safety Issues is presented. The section is divided into three main parts, as shown in Figure 1. The first methodology component consisted of scoping and data gathering, described in Section 3.1, which provided the necessary boundary conditions and input data to the quantitative Techno-Economic Assessment (methodology is described in Section 3.2 for the overall approach and Section 3.3 for the model description) and, finally, a qualitative Safety Assessment (methodology is described in Section 3.4) that evaluates safety issues of alternative vehicles in the mine.

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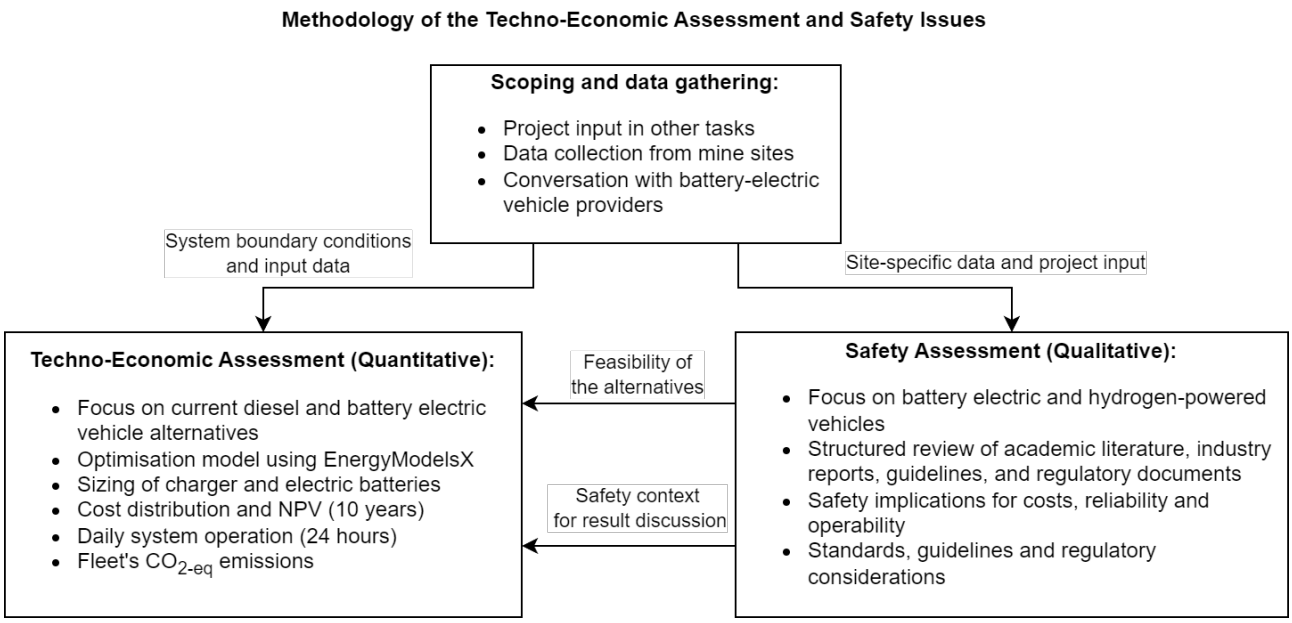

Figure 1 Overall methodology for the Techno-Economic Assessment and Safety Issues, including the three main parts (Scoping and data gathering, the quantitative Techno-Economic Assessment and the qualitative Safety Assessment) as well as the main information flow between these activities that show how the assessments are integrated.

Even though hydrogen-based transport solutions are relevant to the scope of Task 3.4, we leave it out of the quantitative techno-economic assessment. As we investigated, hydrogen technology is still far from commercially available for the mining sector, and the focus of the analyses presented is the next five years. Specifically, loaders and dumpers are still not completely developed for commercial use[1], compared to the availability of several commercial BEV models for the mining sector. Nevertheless, as part of the task we contributed to review of the hydrogen role in mining (Lokar et al.) [7], as mentioned above, and we see potential in the use of hydrogen in the mining sector in the longer term. We therefore invite the reader to read the article for an updated review of this topic. Thus, the quantitative techno-economic assessment focusses on the current diesel-based fleet and battery-electric alternatives.

The safety assessment was evaluated only qualitatively. One way to assess it quantitatively could be via explicit costs associated with new safety equipment required by battery-technology operation (e.g. regarding fire hazards), or by evaluating reduction in ventilation needs due to the replacement of diesel vehicles. However, it was not possible to gather relevant data to quantify these effects.

3.1 COPING AND DATA GATHERING

The first phase of the mine decarbonisation assessment followed a structured approach combining problem scoping and data collection. The objective was to define the boundaries of the study, identify feasible zero-emission alternatives, and gather the information required to support a robust techno-economic evaluation. The scope of the analysis was defined based on previous work within the project, particularly Task 4.1 - Real

[1] For example, Volvo mentioned in personal communications that they developed a hydrogen-driven dumper, but it was considered to be in the pre-pilot phase.

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time feed – output control / monitoring (including carbon footprint calculations), which helped identify the main emission sources and relevant operational processes.

The initial phase focussed on identifying battery electric vehicles suitable for decarbonisation, mapping their duty cycles, routes, energy consumption, and maintenance requirements. Giving the discussion with the partners and the vehicles producers, we focussed on battery-electric alternatives (listed in Appendix), as the most feasible options in the next few years. In addition, some cable-electric vehicles are listed in the Appendix, whole Hydrogen-powered options have been listed in the review article ([2]). Two site visits were conducted to understand the operational context of the mines better. These visits enabled the development of a preliminary representation of the system boundaries and main operational processes for both sites. The proposed scope was subsequently discussed with the mine partners to ensure that the analysis reflected the practical and operational realities of the two case studies.

Current energy use at each site was also assessed, including grid connections, fuel types, refuelling logistics, and maintenance practices. Furthermore, the site-specific potential for renewable energy deployment and hydrogen integration was discussed with the partners, including safety considerations. These phases enabled the pre-selection of feasible zero-emission alternatives (see Appendix) that could realistically operate in the specific mining environments at FELMICA and SKALAND.

Following the scoping phase, a comprehensive data collection phase was implemented. Data were gathered from multiple sources, including site visits, existing project datasets, and direct input from the mine partners. Initial data needs were defined by establishing tables of key parameters required for the analysis. These parameters were then populated using available information from existing project activities, particularly Task 4.1.

To ensure consistent and systematic data reporting, structured Excel templates were developed. These templates were designed to collect additional information not already available within the project and to ensure comparability between the two mining sites. They included diagrams summarising the main subprocesses, lists of vehicles within the scope of the TEA, and three categories of information for each vehicle: cost and energy data, safety data, and emissions data.

Regular discussions with project partners helped clarify data requirements, review the collected information, and address remaining data gaps. In cases where specific parameters were not available from the mining sites, estimated values or reasonable ranges from relevant literature, technical reports, and industry references were used. These assumptions allowed the dataset to be completed while maintaining transparency regarding the level of uncertainty associated with certain inputs.

The data collection phase, coordinated by SINAS, provided the essential inputs for the subsequent techno-economic and safety assessments, ensuring that the evaluation of decarbonisation options was both comprehensive and tailored to the operational realities of each mining site.

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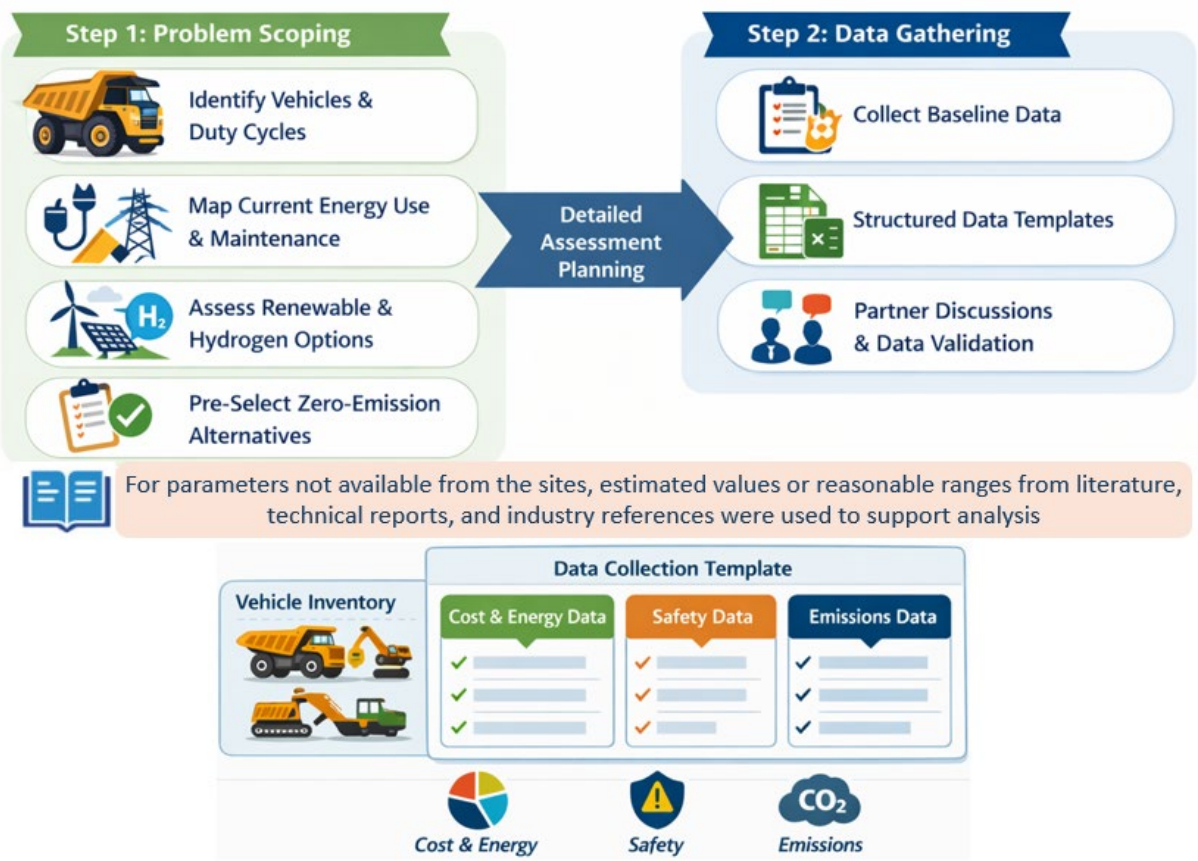

Figure 2 Scoping and data collection structure for the techno-economic assessment of mine-site decarbonisation.

Figure 2 presents the structured approach used to define system boundaries and collect the data required for the analysis. Step 1: (Problem scoping) identifies vehicles suitable for decarbonisation, maps current energy use and infrastructure, evaluates renewable and hydrogen options, and pre-selects feasible zero-emission alternatives while considering safety requirements. Step 2 (Data gathering) compiles baseline operational data from site visits and project activities using structured Excel templates and partner consultations to validate and complete the dataset. For parameters not available from the sites, estimated values or reasonable ranges from literature, technical reports, and industry references were used to support the analysis while maintaining transparency regarding associated uncertainties. The collected information is organised into cost and energy, safety, and emissions data, which form the basis for the subsequent techno-economic and safety assessments.

3.2 OVERALL TEA STRUCTURE

TEAs are analytical tools for evaluating the technical feasibility and economic viability of technologies. By integrating technical and economic parameters, such as capital and operational costs, revenues, and material and energy flows, TEAs enable a comprehensive comparison of alternative solutions and help identify the most cost-effective options. In this context of DINAMINE task 3.4, the approach is particularly relevant for comparing low-emission transport alternatives with conventional fossil fuel–based systems.

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The objective of the assessment is to analyse, over a long-term horizon (10 years in this case), the technical as well as the economic and safety implications of low-emission mass transport solutions at the FELMICA and SKALAND mining sites. To support this analysis, an optimisation model of the mine energy system is being developed, capturing power and fuel supply conditions, existing and potential infrastructure, and the transport vehicles responsible for mass haulage within the mine and between the mine and the processing plant.

The assessment compares the technical performance and economic viability of the current transport systems with optimally designed low-emission alternatives. These alternatives may involve investments in new vehicle technologies (e.g. battery-electric or hydrogen-powered vehicles) as well as the development of supporting infrastructure, including additional renewable energy generation, hydrogen production facilities, and stationary energy storage systems.

The optimisation model is based on the open-source energy system optimisation model EnergyModelsX[2], extended with a vehicle-routing module to capture operational constraints such as charging times and energy storage capacity. The model also enables the evaluation of Scope 1 and Scope 2 CO_2-equivalent emissions, allowing comparison between current and alternative solutions and the inclusion of emission constraints or penalties in the analysis. As part of the TEA, this modelling approach is applied to develop site-specific representations of the FELMICA and SKALAND mining operations. A general overview of the typical input and output of the EnergyModelsX model is shown in Figure 3.

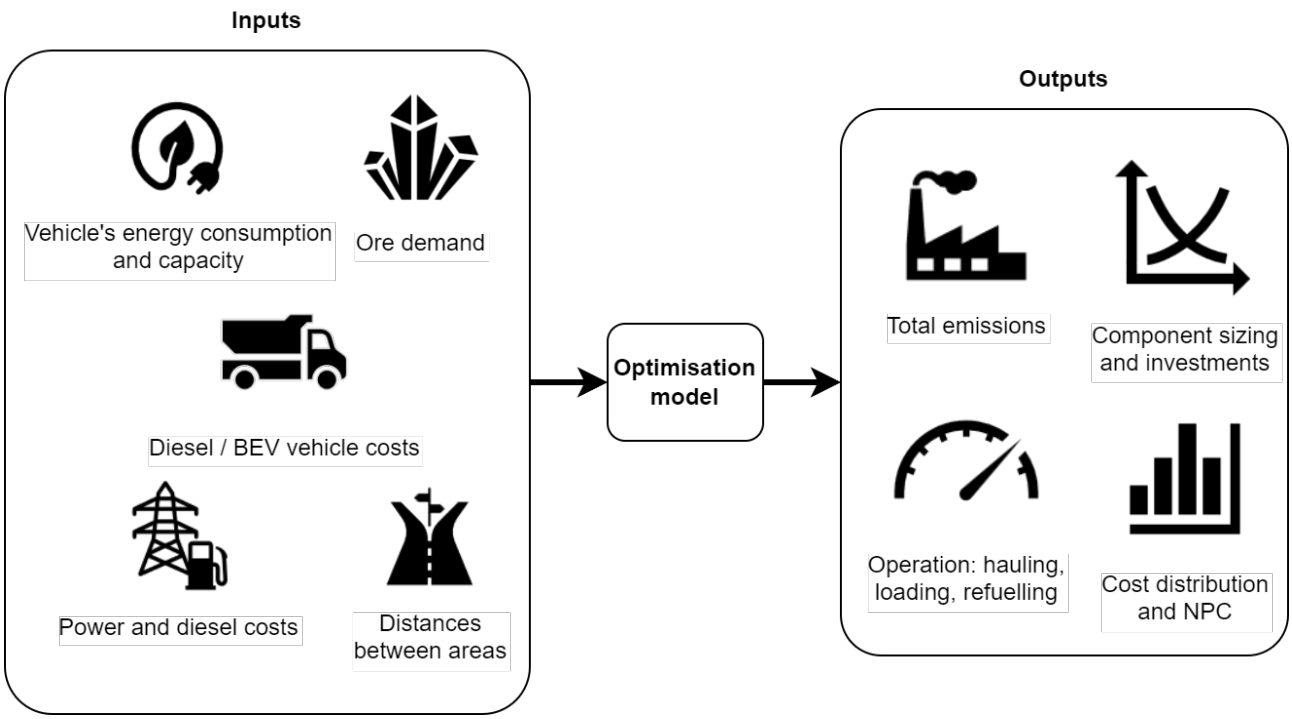

Figure 3 Simple example of the optimisation structure employed in the zero-emission transportation Techno-Economic Assessment

[2] https://github.com/EnergyModelsX

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Transitioning to low- or zero-emission transport solutions in mining operations affects not only the vehicles and machinery themselves but also the broader value chain required to supply alternative energy carriers, such as electricity or hydrogen, at the mine and/or processing plant. Consequently, the first step in the TEA is to clearly define the system boundaries and value chains included in the analysis.

The overall scope of the assessment covers the energy system of the mine and the associated processing plant, with a particular focus on mass transport operations and the supporting energy infrastructure. This includes the technologies required to supply, store, and distribute energy carriers to vehicles and machinery. The current diesel-based operation is used as a benchmark scenario, against which different low-emission transportation alternatives are evaluated.

The TEA is formulated as an optimisation-based energy system model that evaluates the economic performance of alternative configurations over a multi-year planning horizon. The objective is to estimate the net present cost (NPC) of different technology pathways to assess the economic feasibility of carbon-neutral transport solutions. This includes the costs of all vehicles and energy technologies considered by the scope, but we do not include any revenues. Within this framework, the optimisation identifies both investment and operational decisions that minimise system costs while satisfying operational constraints.

Investment decisions focus on determining the optimal sizing and deployment of system components, including energy generation technologies, storage systems, charging or refuelling infrastructure, and alternative vehicles or machines. Operational decisions, on the other hand, evaluate typical days or weeks of operation under different technology scenarios. These operational simulations consider factors such as fuel or electricity consumption, refuelling or charging times, vehicle utilisation patterns, and hourly operating costs.

The operational behaviour of alternative vehicles and machines is based on existing operational patterns observed at the mining sites. These patterns are used as input assumptions and are adjusted within the model to reflect the requirements of alternative technologies, such as more frequent charging cycles or modified scheduling of transport operations.

To represent the physical structure of the system, the mine and the processing plant are modelled as separate operational areas connected by transport routes. Trucks transport extracted material from the mine to the processing plant, and the energy technologies required to support this operation are represented as nodes within each area. This structure enables the modelling of energy supply, storage, and demand interactions across the different parts of the site. Figure 4 and Figure 5 illustrate the system scope defined for the FELMICA and SKALAND case studies, respectively. In both cases, the system boundaries include the main operational components of the mining site: the extraction area, the processing plant, and the transport connections between them. The diagrams show how material flows from the mine to the processing facility through transport operations, while energy supply technologies are integrated to support these activities.

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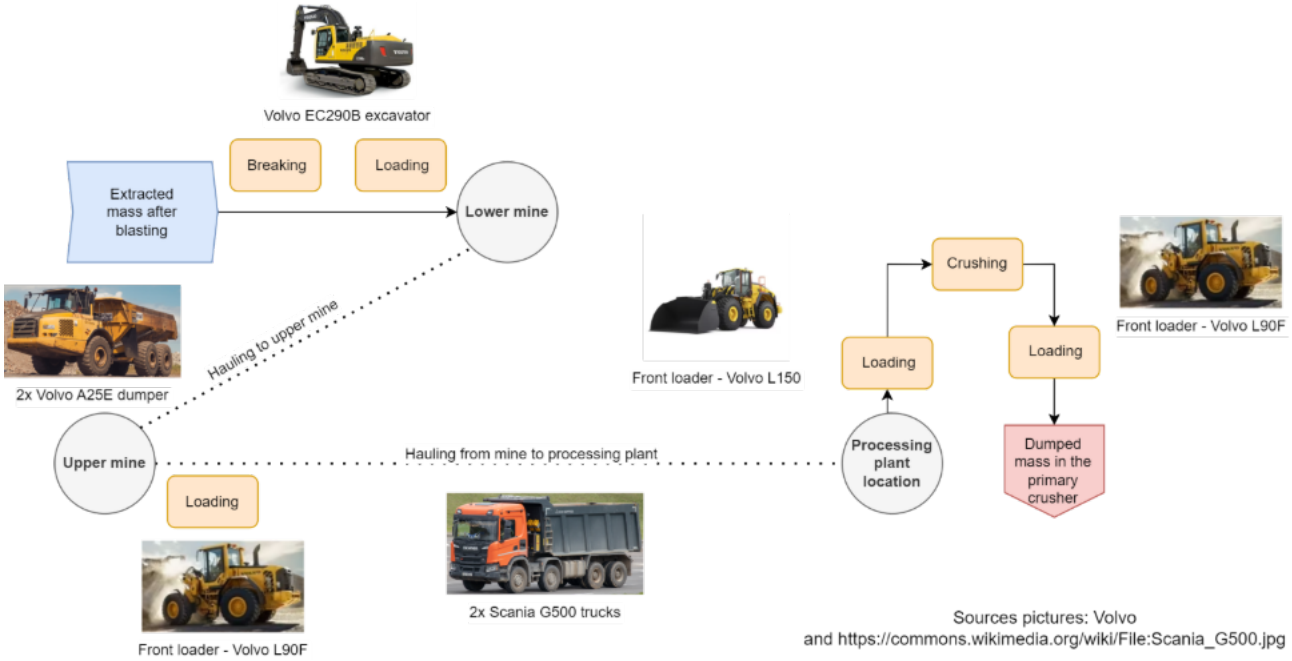

Figure 4 The system scope defined for the FELMICA.

Within each operational area, the relevant equipment and energy technologies are represented as interconnected nodes, enabling the modelling of energy generation, storage, and consumption across the system. This representation allows the analysis of how different energy technologies and transport solutions interact with mining and processing operations. The system structure therefore provides a framework for evaluating alternative energy configurations and transport options, and for assessing their techno-economic and environmental performance within the overall mining operation.

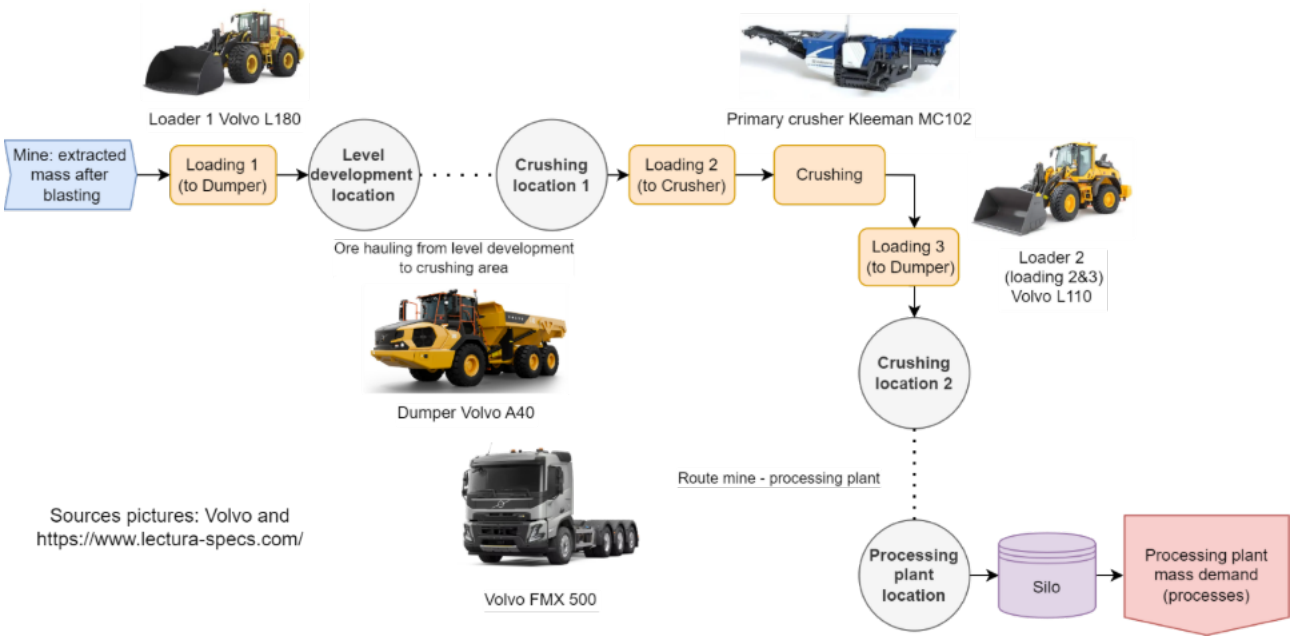

Figure 5 The system scope defined for the SKALAND.

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The operational activities in both case studies are represented through a set of subprocesses corresponding to the main stages of the mining workflow, including drilling, blasting, loading, hauling, and material processing. These subprocesses are performed using different types of heavy-duty vehicles and equipment. For example, drilling rigs are used for rock drilling prior to blasting, excavators or loaders are used to load blasted material, and dumpers or trucks transport the extracted material from the mine to the processing plant. At the processing facility, additional loaders and support equipment handle the material during crushing, sorting, or other processing operations.

Although the overall system structure is similar for both case studies, the specific configuration of subprocesses and vehicles differs depending on the operational characteristics of each site. The FELMICA case study includes equipment such as drilling rigs, excavators, dumpers, loaders, and transport trucks operating between the extraction area and the processing plant, while the SKALAND case reflects its own operational setup through adapted vehicle types and transport configurations. This modelling approach makes it possible to analyse the energy demand and operational performance of different vehicle technologies, including conventional diesel equipment and potential low- or zero-emission alternatives such as electric or hydrogen-powered vehicles.

3.3 MODELLING APPROACH

3.3.1 ENERGYMODELSX

The TEA is based on the EnergyModelsX (EMX) framework, an open-source energy system modelling toolbox developed by SINAS[2]. EMX is implemented in Julia using the JuMP optimisation framework. EMX is a flexible platform capable of representing complex energy systems across different spatial and temporal scales. The framework is supported by the TimeStruct package [1], which enables a consistent representation of multi-horizon time structures, capturing both short-term operational dynamics (e.g. hourly resolution) and long-term strategic decisions (e.g. investment planning over several years).

To capture both long-term planning and short-term operational dynamics, the model adopts a multi-horizon time structure. Long-term strategic periods represent investment decisions, such as the deployment and sizing of generation technologies, energy storage systems, and transport equipment. Within each strategic period, short-term operations are represented through typical or representative weeks for different seasons, with an hourly resolution. This approach enables the analysis to capture variations in energy demand, operational patterns, and resource availability, while linking investment decisions to detailed system operation. By combining long-term planning with high-resolution operational modelling, the TEA accounts for the different cost components associated with the transition from conventional diesel vehicles to low-emission alternatives. An example of this multi-horizon structure used in the TEA is presented in *Figure 6*.

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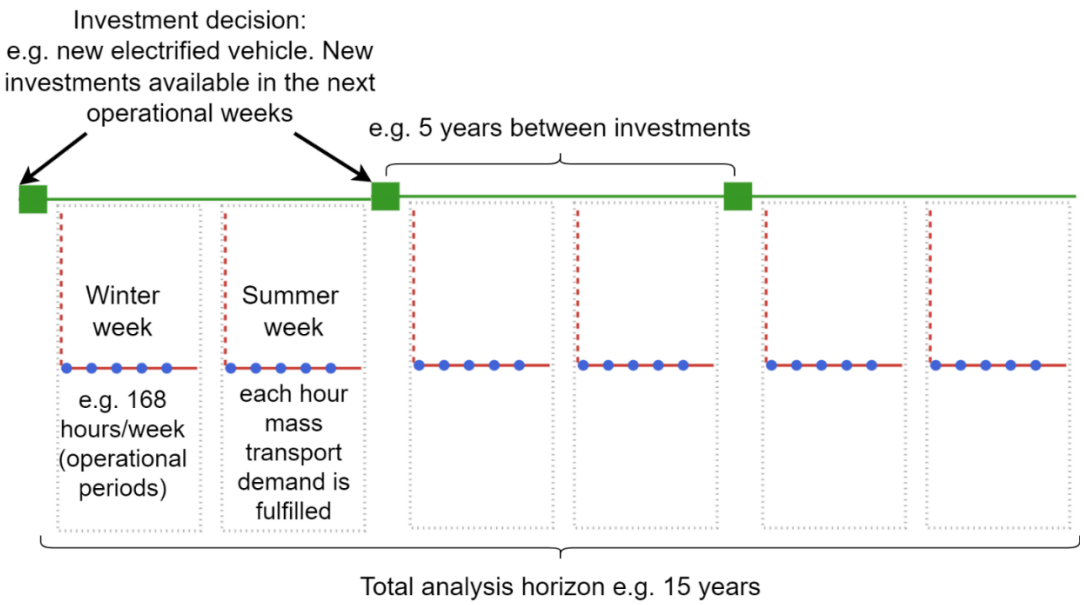

Figure 6 Example of the time horizon consider for the Techno-Economic Assessment of low emission mass transport in FELMICA and SKALAND. It is a two-level horizon, with long-term strategic periods (3 periods of 5 years each), and each of these strategic periods have two representative weeks (summer, winter) with hourly resolution (168 hours/week). All these parameters are completely flexible and are adjusted depending on available data and the focus of the analysis.

At its core, EMX represents the energy system as a network of interconnected nodes and links. Nodes correspond to system components such as energy sources, sinks, conversion technologies, storage units, and infrastructure elements, while links represent energy and material flows between them. Each node is defined by a set of techno-economic and operational constraints, including capacity limits, efficiencies, costs, and emissions. This modular structure allows the integration of multiple energy carriers (e.g. electricity, diesel, hydrogen) and supports the co-optimisation of energy supply, infrastructure, and end-use technologies.

The model also enables investment modelling, with options for discrete, continuous, or semi-continuous capacity expansion decisions. By default, the optimisation minimises total system costs, including both operational expenditures and, when relevant, capital investments. Through this approach, EMX identifies cost-optimal strategies for energy system design and operation, while simultaneously accounting for GHG emissions and key aspects of system performance, such as the ability to meet transport demand, ensure operational feasibility, and maintain efficient use of energy resources. As such, it provides a robust basis for TEA by linking infrastructure choices and operational strategies to economic and environmental outcomes. Figure 7 illustrates EnergyModelsX, showing its typical inputs, optimisation model, and the range of outputs generated by the model.

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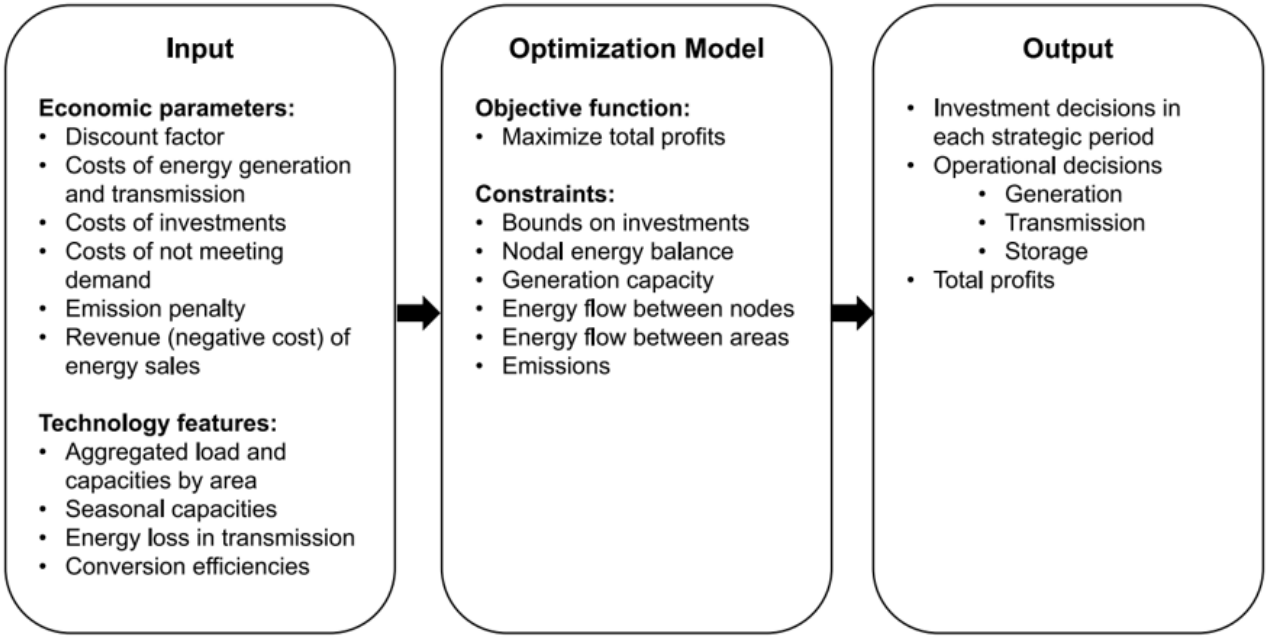

Figure 7 EnergyModelsX's typical inputs, optimisation model and outputs that the model provides, from [21]

3.3.2 ENERGYMODELSTRANSPORT

EMX is adapted to represent the specific characteristics of the FELMICA and SKALAND mining systems, in line with the system boundaries and scoping defined in Section 6 below. For both case studies, the sites are modelled as multi-area systems (e.g. mine and processing plant) connected through transport activities, which constitute the primary focus of the decarbonisation analysis. To model vehicle routing, a novel EMX expansion was developed during the task's work: EnergyModelsTransport.

EnergyModelsTransport allows to model vehicle routing into the energy system, accounting for energy consumption, emissions when vehicles are in movement, and connections to different locations to charge and discharge materials and fuel. Figure 8 displays a small example of the new elements added by the expansion EnergyModelsTransport, which will serve as a guideline to explain the expansion's additions.

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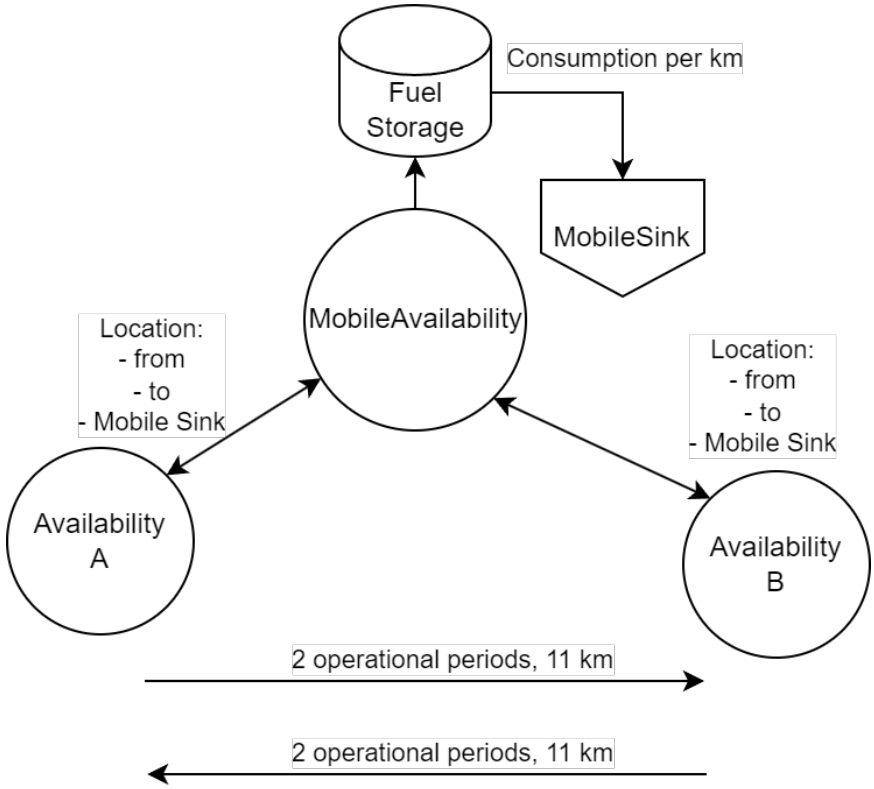

Figure 8 Representation of an example of the new elements of the EMX expansion EnergyModelsTransport showing a vehicle defined by a MobileAvailability Node, with a Fuel Storage and a MobileSink, representing fuel consumption while moving. The vehicle moves between two places A & B (represented by two regular Availability nodes from EMX, 11 km apart from each other and taking 2 operational periods (e.g. 20 minutes) to go from one of the places to the other.

This expansion provides first of all new nodes. MobileAvailability represents an availability node associated with a vehicle (it moves between other nodes and can have other nodes associated, like fuel storage or power train). MobileSink is a specific type of sink that represents energy consumption when a vehicle is moving. It also includes a new type of structure in EMX called "Locations": these are a new structure that couples a MobileAvailability node, another node and a MobileSink representing the vehicle moving between availability nodes. Finally, a new type of EnergyModel is needed, including the network data with distances and time duration between the different spatial points (Availability A and B in the example).

At SKALAND, the model represents two main nodes the underground mine and the processing plant connected by a transport link corresponding to the 11 km haulage route. At FELMICA, the system includes the open-pit mine and the processing plant located approximately 92 km apart, with transport demand characterised by lower frequency but longer-distance truck operations. In both cases, diesel-based transport is used as the baseline scenario.

The EMX model incorporates:

- Vehicle technologies (diesel and battery-electric) as transport options,
- Energy supply options, including grid electricity and diesel fuel supply

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- Infrastructure components, such as charging stations, ore storage, and refuelling systems.

The optimisation simultaneously determines:

- Investment decisions, such as sizing of energy infrastructure and accounting for investment costs of the baseline and alternative vehicles,
- Operational strategies, including energy use, refuelling/charging schedules, and transport activity patterns across operational time periods.

By applying EMX in this way, the TEA evaluates and compares alternative decarbonisation pathways for mining transport at both sites, quantifying costs, emissions, energy requirements, and system implications, while accounting for site-specific operational conditions and constraints.

3.3.3 OPTIMISATION MODEL

The optimisation model aims to identify cost-optimal low- to zero-emission transport solutions by minimising the total system cost expressed as NPC. The model evaluates alternative configurations of vehicles and energy infrastructure, determining their optimal sizing and operation under real-world constraints.

The model incorporates technical and operational constraints, such as energy demand, transport requirements, infrastructure availability, and site-specific limitations. It ensures that transport performance is maintained while identifying the most economically efficient solution.

The output provides the optimal combination of technologies and infrastructure, along with associated costs, enabling comparison of decarbonisation options based on their economic viability through NPC minimisation.

3.4 METHODOLOGY FOR SAFETY APPROACH

In addition to site-specific data and project inputs, the safety assessment was investigated by a structured review of academic literature, industry reports, guidelines, and regulatory documents. Relevant publications were identified through targeted searches in databases such as Google Scholar and ScienceDirect using keywords related to mining safety, battery-electric vehicles, hydrogen systems, hazards, and risk mitigation. This multi-source approach ensured that the safety assessment combines theoretical knowledge with practical experience and current industry practices. Besides, consultations with the safety experts were conducted.

The safety assessment was performed as a structured, comparative analysis within the TEA structure. The objective was to identify, classify, and evaluate safety risks associated with conventional diesel systems and alternative low- and zero-emission transport technologies, specifically battery-electric (BEV) and hydrogen-powered (FCEV) vehicles, in mining environments.

The methodology is based on a hazard identification and risk categorisation approach. Risks were systematically mapped across the three technology types to evaluate how the safety profile changes with the transition to low-emission solutions. This comparative framework enabled the identification of risk trade-offs, highlighting both the reduction of traditional diesel-related hazards and the emergence of new risks associated with electrification and hydrogen systems. The results were structured into comparative tables summarising risks, safety requirements, and their relative impact across technologies. The assessment further considered site-specific conditions, distinguishing between open-pit FELMICA and underground SKALAND mining environments. Finally, safety implications were evaluated in relation to infrastructure needs, safety systems, and workforce requirements. In this way, safety is treated as an integral component of feasibility assessment, directly linked to cost, reliability, and operability within the overall TEA structure.

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4 SAFETY CONSIDERATIONS

While techno-economic assessments traditionally focus on cost, efficiency, and productivity, safety plays a critical and often underrepresented role in determining the feasibility of alternative transport solutions. In underground and open-pit mining environments, safety is not only a regulatory requirement but also a key factor influencing operational continuity, workforce protection, and infrastructure design. To frame the safety assessment, it is first necessary to briefly outline the key advantages and limitations of battery-electric and hydrogen-powered vehicles compared to diesel, as these directly influence their risk profiles and safety requirements.

4.1.1 BATTERY ELECTRIC VEHICLES

Battery electric vehicles (BEVs) in underground mining offer clear advantages over diesel, primarily by eliminating exhaust emissions (CO, NOx, DPM), which creates a significantly safer and healthier working environment with lower noise, heat, and odour levels, while also drastically reducing ventilation and cooling requirements one of the major cost drivers in deep mines which can translate into significant reductions in both capital and operational expenditure [22]. This translates into lower operational costs, improved working conditions, and potential productivity gains due to better torque characteristics, fewer moving parts, and regenerative braking. In contrast, diesel vehicles are robust, energy-dense, and operationally flexible (no charging downtime), but they impose high ventilation demands, generate harmful emissions, and increase heat load, which limits deep mining efficiency and raises both CAPEX and OPEX. However, BEVs also introduce several disadvantages. Their lower energy density compared to diesel limits operating range and requires careful charging strategies. They require significant upfront investment in electrical infrastructure and charging systems. In addition, they introduce new safety risks such as battery fires, thermal runaway, and toxic gas release. Operational challenges must also be addressed, including workforce training and maintenance of high-voltage systems [4].

BEVs benefits are also supported by empirical evidence from field trials. For instance, a study conducted at the Kittilä mine in Finland reported significant improvements in air quality, as well as reductions in noise and heat exposure when battery-electric vehicles replaced diesel equipment. In addition, mine workers reported improved working conditions and overall satisfaction, highlighting the positive impact of BEVs on occupational safety and comfort [5]. These trends are also widely recognized in recent literature, which highlights the growing adoption of battery-electric vehicles in underground mining due to their environmental and operational advantages [6].

4.1.2 HYDROGEN-POWERED VEHICLES

Hydrogen-powered vehicles (FCEVs) in mining sit between diesel and battery-electric systems: compared to diesel, they can achieve major emission reductions (up to 60–95 %) while maintaining similar operational characteristics such as long range and fast refuelling, which makes them particularly suitable for heavy-duty and remote applications where diesel traditionally dominates. Relative to battery-electric vehicles, hydrogen offers higher energy density and longer range with shorter refuelling times, avoiding charging downtime and making it more flexible for continuous operations; however, BEVs still outperform hydrogen in terms of efficiency, lower operating complexity, and reduced ventilation requirements in underground environments. The main disadvantages of hydrogen are currently economic and infrastructural: vehicle and fuel costs remain significantly higher than both diesel and electric (often 20–68 % more expensive), with limited refuelling infrastructure and immature supply chains, meaning large-scale viability is unlikely before 2030 without strong policy support. Additionally, hydrogen introduces specific safety challenges (e.g. storage, leakage, explosion risk) and requires new operational competencies [7].

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Given these differences in operational characteristics, the transition from diesel to battery-electric and hydrogen-powered vehicles is not only a technological shift but also a transformation of the underlying safety paradigm. Each technology introduces distinct hazard profiles and requires adapted risk management strategies, which must be systematically evaluated within the techno-economic framework.

Safety considerations are embedded in the techno-economic assessment of alternative transportation options by systematically identifying the specific risks and safety requirements associated with each technology, including diesel, battery-electric, and hydrogen systems. These safety considerations are then evaluated in terms of their impact on total cost of ownership (TCO), as well as on system reliability and operability, for instance through the need for additional infrastructure, enhanced fire protection systems, or increased ventilation capacity. To ensure consistency and credibility, the assessment is further grounded in recognized standards and guidelines, which provide a structured framework for evaluating and managing safety across different transport technologies.

4.1.3 SAFETY RISKS AND REQUIREMENTS

Introducing BEVs and FCEVs into the mining environment can introduce new risks, reintroduce previously well-managed hazards, and mitigate others that are traditionally associated with diesel-based systems. Table 1 provides a structured overview of the key safety risks, associated requirements, and their relative impact across diesel, battery-electric, and hydrogen vehicle technologies. It highlights that while diesel systems are primarily characterized by exhaust emissions and fuel fire risks, electrified and hydrogen-based systems shift the risk profile toward electrical hazards, thermal runaway, and gas-related explosion risks. Additionally, hydrogen introduces specific safety challenges (e.g. storage, leakage, explosion risk), as similar hazard scenarios, including hydrogen leaks, jet fires, and explosion risks, have been identified in recent studies assessing hydrogen-based energy systems on industrial sites [17].

Field studies have demonstrated that the elimination of exhaust emissions and reduction of noise and heat exposure can substantially improve occupational health conditions, thereby mitigating long-standing safety concerns related to air quality and worker fatigue [5]. These risk categories and associated mitigation measures are further aligned with industry guidelines, such as the Global Mining Guidelines Group (GMG) Recommended Practices for Battery Electric Vehicles [4], which provide a structured framework for hazard identification, risk management, and safe integration of BEVs in underground mining operations. Consequently, the nature of required safety measures also changes from ventilation-driven controls in diesel operations to electrical protection systems, battery management, and gas detection and handling systems in alternative technologies.

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Table 1 Risks, Safety requirements and Impact across vehicle technologies.

	Diesel	Battery-electric (BEVs)	Hydrogen (FCEVs)
Main risks	- Fire and explosion risk from fuel - Exposure to exhaust gases (CO, NOx) - Engine overheating	- Electrical shock - Thermal runaway / battery fire - High-voltage hazards - Chemical leakage from battery cells	- Hydrogen leaks (flammable and explosive) - High-pressure storage hazards - Cold burns from liquid hydrogen
Safety requirements	- Proper ventilation in enclosed spaces - Fire suppression systems (foam, dry chemical) - Regular engine maintenance - Personal protective equipment (PPE)	- High-voltage insulation and labeling - Battery management systems (BMS) - Fire suppression systems suitable for lithium-ion batteries - Emergency disconnect systems - PPE for high-voltage handling	- Hydrogen sensors and leak detection - Ventilation systems - Pressure relief devices - Staff training for hydrogen handling - Explosion-proof electrical equipment
Impact	- Fuel storage tanks - Fuel delivery infrastructure - Exhaust treatment systems (filters, catalytic converters)	- Charging stations with safety systems - Battery storage and disposal facilities - Fireproof containment areas	- Hydrogen production, storage or refueling stations - Dedicated ventilation and safety zones

Lithium-ion battery fires represent a complex, multi-stage hazard characterized by thermal runaway, gas release, and potential explosion scenarios. Quantitative risk assessments have shown that battery fire development depends on a combination of triggering factors (e.g. mechanical damage, overcharging), propagation mechanisms within battery cells, and environmental conditions such as ventilation and confinement. These characteristics make battery-related incidents fundamentally different from conventional fuel fires and require specialized detection, suppression, and emergency response strategies. Furthermore, the interaction between heat generation, flammable gas release, and confined underground environments can significantly amplify the severity of battery fire events, highlighting the importance of integrated safety system design [8]. In addition, lithium-ion battery failures can release toxic and hazardous gases, such as carbon monoxide and hydrogen fluoride, which pose significant risks to personnel, particularly in confined underground environments, further complicating emergency response and evacuation procedures [9]. In addition to battery-related hazards, operational procedures such as battery swapping introduce a wide range of additional risks, including mechanical hazards (e.g. crushing, falling objects, and instability during handling), electrical risks, and human–machine interaction risks, particularly in confined underground environments [10].

The classification of risks and safety requirements presented in Table 1. is consistent with industry best practices, including the GMG guidelines, which identify key hazard areas such as high-voltage systems, battery thermal management, charging infrastructure, and emergency response procedures [4]. Table 2 further compares the technologies from a safety performance perspective, emphasizing the trade-offs between environmental performance, hazard types, and maturity of safety solutions. While BEVs and FCEVs demonstrate clear advantages in terms of emissions and reduced exposure to diesel particulate matter, they introduce fewer familiar risks that require new safety strategies and competencies. FCEVs involve specific

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challenges related to gas handling, leak detection, and explosion prevention, whereas BEVs require careful management of high-voltage systems and battery-related failure modes. Overall, the comparison illustrates that no technology is inherently risk-free; rather, each shifts the safety burden in different ways, requiring tailored mitigation approaches and influencing operational practices and infrastructure design.

Table 2 Safety technology comparison.

Aspect	Diesel	Battery-electric (BEVs)	Hydrogen (FCEVs)
Air quality	Poor (emissions)	Very good	Very good
Fire hazard	Fuel fire	Chemical fire	Explosive gas
Ventilation	Highly required	Moderate	Required for H_2 removal
Training	Standard	New (high-voltage, batteries)	New (hydrogen, explosion risk)
Heat / Noise	High	Low	Low
Tech. maturity	Very high	Medium (developing)	Low (in mining)

The qualitative assessment presented in Table 2 is supported by empirical observations from underground mining operations. Field trials with battery-electric vehicles have confirmed substantial improvements in air quality, along with lower noise and heat levels compared to diesel equipment, reinforcing the classification of BEVs as a safer option in terms of working environment conditions [5].

4.1.4 SAFETY IMPLICATIONS FOR COST, RELIABILITY AND OPERABILITY

Safety requirements have a direct and measurable impact on the techno-economic performance of transport systems in mining. For diesel-based operations, safety is strongly linked to ventilation demand, which represents a significant portion of both capital and operational expenditure, particularly in deep underground mines. In contrast, BEVs can significantly reduce ventilation demand, leading to substantial savings in both capital and operational expenditure. These reductions can partially offset the additional costs associated with charging infrastructure, electrical grid upgrades, and fire protection systems tailored to lithium-ion batteries. FCEVs, while offering operational flexibility like diesel, require substantial additional investments in hydrogen production, storage, and refuelling infrastructure, as well as advanced safety systems for leak detection, ventilation, and explosion prevention.

Beyond cost implications, safety measures also influence system reliability and operability. For example, battery management systems (BMS) and thermal monitoring improve safety but add system complexity and maintenance requirements. In addition, the implementation of BEVs in underground mining introduces operational challenges related to charging infrastructure, energy management, and equipment availability, which can indirectly affect safety by influencing operational planning and system reliability [11]. Similarly, hydrogen systems require continuous monitoring and strict operational protocols, which may affect uptime and require specialized personnel. Diesel systems, although technologically mature and operationally robust, impose constraints through ventilation dependency and exposure-related risks. Overall, safety considerations are inherently connected to system design choices and should be evaluated as an integral component of the TCO, rather than treated as an external or separate constraint. The transition towards electrified mining systems

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is part of a broader decarbonisation strategy, where operational changes extend beyond individual machines to encompass fleet composition, infrastructure, and energy management at the mine level [12]. This system-level perspective is increasingly reflected in industrial practice, where the transition to electrified fleets is implemented holistically, as demonstrated by projects such as the Sandvik – Rana Gruber collaboration in Norway, involving the deployment of multiple types of battery-electric mining equipment within a single operation [13].

4.1.5 STANDARDS, GUIDELINES, AND REGULATORY CONSIDERATIONS

The standardization of BEVs in mining is still in an early stage and is currently supported by a combination of general electrical safety standards and emerging industry-specific guidelines. Existing frameworks such as IEC 60204-1 and IEC 60204-11 address the safety of electrical equipment in machinery, while the ISO 14990 series provide requirements for electrical safety in earth-moving equipment. In addition, Canadian standards such as CSA M421-16 (Use of electricity in mines) and CSA M424 (Underground mining mobile equipment) offer guidance on the safe integration of electrical systems in mining environments. Complementing these, the GMG has developed Recommended practices for battery-electric vehicles in underground mining, representing one of the most comprehensive industry-driven frameworks addressing the specific safety challenges of BEVs. These guidelines cover key aspects such as risk assessment, battery safety, charging systems, emergency response, and operational procedures, and are widely recognized as a reference point for the safe implementation of BEVs in mining [4]. In this context, standards such as IEC 61851-23 and IEC 60364-7-722 are relevant for defining safety requirements related to charging infrastructure and electrical installations supporting BEV deployment. However, the overall regulatory landscape remains fragmented, and further development and harmonization of standards will be required as BEV deployment in mining continues to expand. In addition, aspects of functional safety (e.g. ISO 13849 or IEC 61508) and battery-specific safety (e.g. thermal runaway prevention and standards such as IEC 62619) are increasingly relevant, particularly due to the integration of battery management systems and high-voltage components. In underground environments, consideration of explosive atmospheres (e.g. IEC 60079 series) may also be required.

The standardization of hydrogen technologies in mining is more complex and remains in a developing stage, drawing on a broad combination of mining regulations, explosion protection directives, and hydrogen-specific standards. At the regulatory level, mining safety is governed by established national frameworks (e.g. MSHA in the United States, Mines Regulations in the UK, and equivalent legislation in Australia, Sweden, Peru, and South Africa) as well as European directives such as 92/91/EEC and 2006/21/EC, which address worker safety and environmental protection in extractive industries. Due to the explosive nature of hydrogen, additional regulatory layers are required, particularly those related to hazardous atmospheres, such as EU Directives 2014/34/EU (ATEX equipment) and 1999/92/EC (ATEX workplace safety). These are complemented by international standards including the IEC 60079 series for electrical equipment in explosive atmospheres, EN 1127 for explosion prevention (with specific provisions for mining), and the ISO/IEC 80079 series for equipment used in underground environments. Beyond general explosion safety, a dedicated set of hydrogen-specific standards governs production, storage, detection, and fuelling, such as ISO 19880 for hydrogen refuelling stations, ISO 14687 for fuel quality, ISO 22734 for hydrogen production via electrolysis, and ISO 26142 for hydrogen detection systems. Additional guidance, including ISO/TR 15916 and CGA G-5.5, addresses system-level safety considerations and venting design. Overall, the regulatory landscape for hydrogen is extensive but fragmented, reflecting the need to integrate both mining-specific and hydrogen-

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specific safety requirements, with further harmonization required as deployment in mining applications advances [7].

FELMICA mine; site-specific regulatory considerations:

For open-pit mining operations in Portugal, the regulatory framework for the safe use of transport equipment, including diesel and emerging electric technologies, is primarily based on national transposition of European legislation. A key legal instrument is Decree-Law No. 50/2005 (DL 50/2005), which transposes Directive 2001/45/EC and establishes minimum safety and health requirements for the use of work equipment by workers. This regulation defines employer responsibilities regarding equipment suitability, maintenance, inspection, and operator training, ensuring safe operation across mining activities [16]. In addition, broader EU legislation such as the Machinery Regulation (EU) 2023/1230 applies to all machinery placed on the market, including mining vehicles, requiring compliance with essential health and safety requirements. Depending on site-specific conditions, particularly in areas where explosive atmospheres may occur, the ATEX Directive 2014/34/EU may also be relevant. Compared to underground mining, open-pit operations generally do not involve constraints related to ventilation and confined spaces; however, safety considerations remain critical, particularly in relation to equipment operation, traffic management, and the integration of new technologies such as battery-electric or hydrogen-powered vehicles. Overall, the regulatory framework in Portugal provides a structured basis for safe equipment use, while allowing flexibility for the adoption of alternative transport technologies in mining.

SKALAND mine; Site-specific regulatory considerations:

For underground mining operations in Norway, the regulatory framework governing electrical and battery-electric machinery is based on a combination of European legislation, international standards, and national laws. At the European level, the EU Machinery Regulation (EU) 2023/1230 establishes essential health and safety requirements for machinery, while ISO 19296 specifies safety requirements for mobile machines operating underground. In environments where explosive atmospheres may be present, the ATEX Directive 2014/34/EU applies, ensuring that equipment is designed and certified for safe use under such conditions. At the national level, oversight is provided by the Norwegian Directorate of Mining with the Commissioner of Mines at Svalbard, which enforces compliance with applicable safety regulations in mining activities. Electrical safety is further governed by the Norwegian Electrical Supervision Act (*El-tilsynsloven*), which aims to prevent hazards related to electrical installations and equipment, including risks to life, health, and property [14]. In addition, specific requirements for underground operations are addressed in regulations such as the "*Forskrift for brannvern i gruver og annen virksomhet under jord*," which defines fire protection measures in mines and other subsurface activities [15]. Together, these frameworks create a comprehensive, albeit multi-layered, regulatory environment for the safe deployment of electrical and battery-electric machinery in Norwegian underground mining.

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5 CASE STUDY OVERVIEW

This section presents the two demonstration sites FELMICA (Portugal) and SKALAND (Norway), used to apply the TEA framework described in Section 4. These case studies represent two contrasting mining contexts, underground mining with short-distance transport and open-pit mining with long-distance transport and are used to evaluate the feasibility of low-emission transport solutions within the defined system boundaries and optimisation model.

5.1 FELMICA

FELMICA is a producer of lithium-bearing feldspar primarily used in the ceramic industry. Within the scope of the DINAMINE project, the analysis focusses on operations at the Gonçalo open pit mine (Guarda) and the associated processing plant in Mangualde, located approximately 92 km apart in Portugal. Figure 9 shows an overview of the FELMICA mining site and processing plant.

Figure 9 Overview of the FELMICA mining site (left) and processing plant (right).

5.1.1 MINING AND TRANSPORT OPERATIONS

The Gonçalo site is an open-pit mining operation comprising four pits (Pit-1 to Pit-4), of which Pit-1 is currently used for waste rock storage. The ore body consists of a mixture of feldspar types white, yellow, and pink which are visually distinguished on-site based on their mineral composition.

Mining activities are carried out using a drill-and-blast method for fresh rock, while overburden and weathered materials are removed using an excavator. The operation is relatively compact, relying on a single drilling unit and excavator. Benches typically have a height of approximately 10 m and a width of 6–10 m.

Following blasting, the extracted material is loaded and transported by two 25-tonne dumpers to a temporary stockpile within the mine. At this stage, the material is also visually sorted according to colour. A front-end loader then transfers the ore to 30-tonne road trucks, which transport it to the processing plant located approximately 92 km away.

Under normal operating conditions, 2–3 truckloads per day are transported, although higher short-term volumes may occur following blasting events, which typically take place every two weeks. The transported material has a maximum particle size of approximately 800 mm.

5.1.2 PROCESSING OPERATIONS AND ENERGY USE

At the Mangualde processing plant, the material undergoes several stages, including primary crushing, screening, optical sorting, magnetic separation, and dry milling. After initial crushing and size classification,

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the material is sorted based on colour using optical sorting systems. White feldspar is mainly used in ceramics, while pink feldspar contains lithium and can be directed toward higher-value applications.

Further processing includes magnetic separation, where metallic impurities are removed (approximately 30% of the material in certain streams), followed by dry milling, which reduces particle size down to approximately 45 microns. The plant produces multiple products, including:

- Fine crushed feldspar (<10 mm),
- Intermediate products (10–40 mm), and
- Lithium-rich feldspar fractions.

5.2 SKALAND

The Trælen mine, operated by Skaland Graphite AS, is located on the island of Senja in northern Norway, between Tromsø and the Lofoten archipelago. It is the largest producer of high-grade natural flake graphite in Europe, with an annual production of approximately 40,000 tonnes of ore and 10,000–12,000 tonnes of graphite concentrate. The deposit consists of graphitic gneiss with an average carbon content of around 25%, and total resources are estimated at approximately 1.84 million tonnes. SKALAND aims to increase production of concentrate within the next years, targeting applications in battery anode materials. Figure 10 presents an overview of the mine and processing plant location, along with the underground mining structure and associated plant facilities.

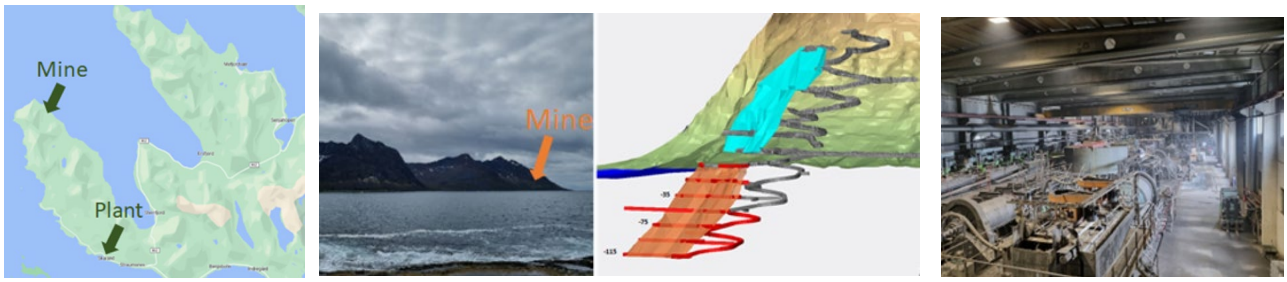

Figure 10 View of the mine and processing plant location (left), underground mining structure (middle), and processing plant facilities (right).

5.2.1 MINING AND TRANSPORT OPERATIONS

The Trælen mine is an underground operation with mining activities distributed across multiple sublevels and ongoing development to access deeper zones. Ore extraction involves drilling and blasting, followed by loading using remotely operated equipment and transport via dumpers to an underground primary crusher. From there, the material is transferred by road trucks to the processing plant. The processing plant is located approximately 11 km from the mine, and ore is transported via a combination of gravel and regional roads (fylkesvei 862). Transport conditions are relatively challenging due to road quality, although winter conditions can improve drivability. On average, around 12 truckloads per day, each carrying approximately 16 tonnes, are transported between the mine and the plant.

5.2.2 PROCESSING OPERATIONS AND ENERGY USE

At the processing plant in SKALAND, the ore undergoes a sequence of crushing, grinding (autogenous and pebble mills), flotation, drying, screening, and packaging. The plant processes approximately 35,000 tonnes of ore annually, producing around 10,000 tonnes of final graphite products with carbon content up to 98%. These products are classified into different grades (e.g., flake, medium, fine, and powder) depending on

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customer requirements. The facility includes laboratory capabilities and a dedicated harbour for international shipping, with shipments typically dispatched every three weeks. Tailings are thickened and deposited in a nearby fjord.

6 ANALYSIS OF THE TWO CASES

Framing and scoping focus on mass transport vehicles and the relevant energy infrastructure, with each technology represented as a single "node." The defined scope establishes which processes to include or exclude within the mine, the processing plant, and the transport links between them.

One challenge in the definition of the assumptions was defining the data. The project team received good insight into the main activities of the mine operations and developed a wrapper to connect to the API of the ISM-PM system to better estimate the energy consumption and displacement of the current fleet. Due to delays in establishing some of the real-time sensor infrastructure, this could not be part of the analysis, and some few but important data points, such as the vehicle's energy consumption or actual distances travelled by the dumpers in the mine, were based on more general assumptions like average historical values. Another important assumption was the power consumption of the battery-electric vehicles, which was based on a rough equivalence that 1 litre of diesel is equal to 3 kWh consumption by an electric vehicle, provided by Volvo in personal communication. This consumption can however change with the type of vehicle, road profile and elevation difference between locations.

Building on this scope and the available data, the CAPEX and OPEX assumptions were defined separately for the existing diesel fleet and the battery-electric alternatives. For the existing diesel fleet, CAPEX data were primarily based on information provided by the SKALAND and FELMICA mines, reflecting their current operating conditions and diesel-powered equipment. Where mine-specific CAPEX data were unavailable or incomplete, assumptions were developed based on historical or representative values and discussed and verified with mine representatives to ensure consistency with the actual operating context, e.g. we assumed the same CAPEX of the truck in SKALAND for the two trucks in FELMICA. The OPEX in SKALAND was mostly provided by the mine based on operation & maintenance costs. However, they don't own all of the vehicles, so we had to make some assumptions for estimated non-energy OPEX values. FELMICA provided their operation costs including diesel consumption, so we estimated a 4% of fixed, non-energy OPEX, which would provide a similar number to the OPEX at SKALAND. All these assumptions are explained on each item in Table 3 and Table 5.

For the battery-electric alternatives, CAPEX and OPEX estimates were developed based on information obtained through discussions with Volvo and representatives of the two mines, together with relevant market and industry data for commercially available electric vehicles. The only exception is the electric crusher, since it would be grid connected (not battery-electric) and thus assumed the same CAPEX as the diesel one. OPEX estimates incorporated assumptions regarding energy consumption, operating conditions, maintenance and other relevant cost components. Where mine-specific cost data for electric vehicles were unavailable, CAPEX was estimated using appropriate CAPEX premiums and industry reference values.

FELMICA

Figure 11 presents the main mass transport vehicles and subprocesses included within the defined TEA scope for the FELMICA case, covering operations from ore extraction at the open pit mine to transport and initial processing at the plant.

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The process begins with ore extraction following blasting events, which typically occur approximately once every two weeks. Each blasting cycle enables the handling of around 20 dumper loads per day and 2–3 truckloads per day. The blasted material is first fragmented by an excavator (EC380E) into transportable sizes and loaded into dumpers (A25E). These dumpers transport the material to a higher section of the mine, where visual sorting by colour (e.g. white and darker feldspar) is performed.

The sorted ore is then loaded using a loader (L90F) onto road trucks, which transport the material over a distance of approximately 92 km (around 1 hour travel time) to the processing plant. This long-distance transport segment represents the primary mass transport flow in the TEA and is therefore a key focus for decarbonisation.

At the processing plant, the material is unloaded and fed into the system using a loader (L150), which supplies the primary crusher. The crusher reduces large ore into coarse fragments, after which the material is transferred via conveyor belts and screened by size. Fractions smaller than 10 mm are classified as waste, while material in the 10–40 mm range is retained as product.

Within the TEA model, these subprocesses are represented as sequential handling and transport stages, each associated with specific equipment, energy consumption, and operational constraints. The long-haul truck transport defines the transport demand to be met by alternative technologies; while loading and handling equipment contribute to the overall energy demand and operational structure of the system.

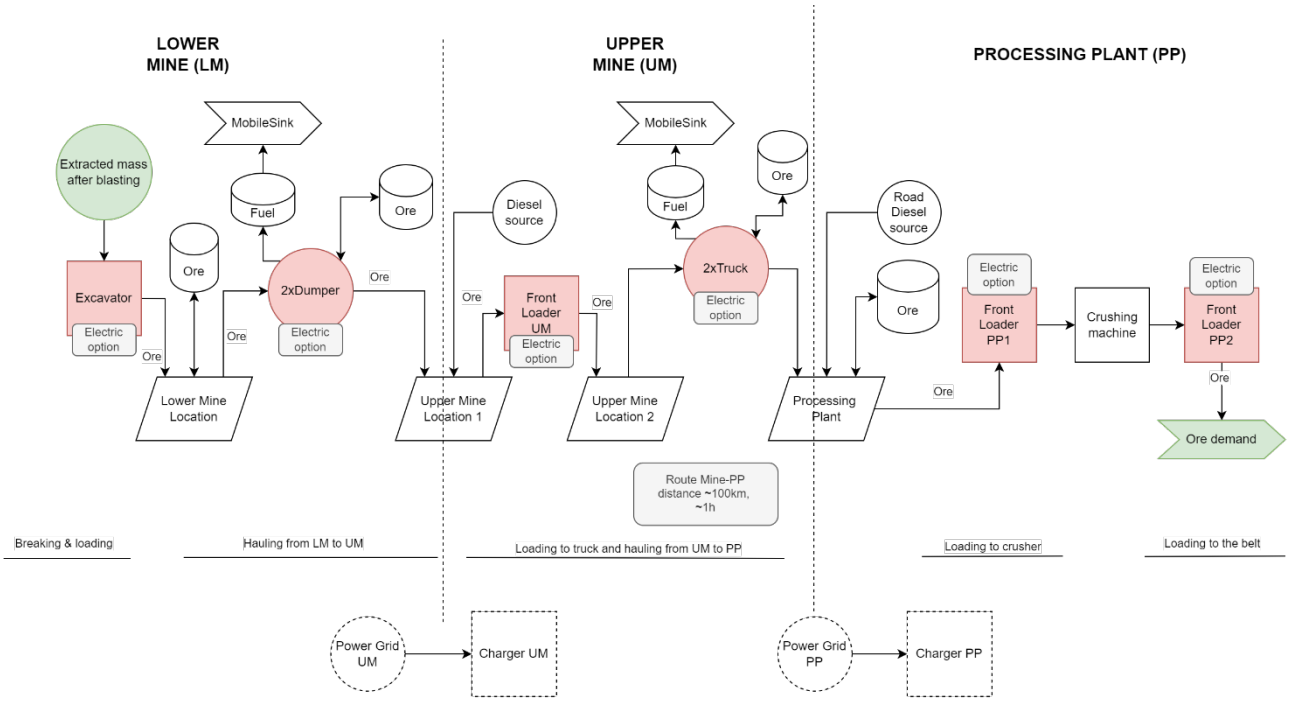

Figure 11 TEA diagram modelled for the FELMICA case. In green the general scope is defined: from mass extraction at the lower mine to the delivery of ore at the conveyor belt at the processing plant. The red blocks represent the vehicles considered, where excavator and loaders are considered fixed (movement is not modelled) and dumpers and trucks are modelled as mobile vehicles in the model. Diesel sources and

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alternative power grid and electric charger (in dashed lines at the bottom of the diagram) are in addition connected to all vehicle nodes.

Based on information gathered during the site visits in Task 3.4, together with previous analyses conducted in Task 4.1 on carbon footprint assessment, the main mass transport vehicles operating at the FELMICA site have been identified.

Looking at the details of each technology, different techno-economic data is required for each technology and for the general analysis. The data used is presented in *Table 3*. We assume 204 tonnes demand of ore to the conveyor belt per day (based on the blasting scheduling of 2000 tonnes every two weeks), to be delivered during 12h, and the time resolution is 20 minutes. Based on later feedback from FELMICA, the more common operation demand is around 60 tonnes/day at the conveyor belt, with an operation of 8h per day instead of 12h. To correct this deviation of normal operation, we ran a new case with these updated operations. The results are presented in Appendix 2 in Section 12. We can therefore assume that the results presented in the next section for FELMICA represent a situation with higher operation demand, and longer operating shifts. These two operation modes will provide a more nuanced view on costs and emissions of the current fleet and the alternative electrified mass transport vehicles.

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Table 3 Data and assumptions used in the Techno-Economic Assessment for FELMICA

Parameter	Value	Unit	Description
Current Dumper Volvo A25E (Diesel)			
OPEX	14000	€/y	Based on FELMICA
CAPEX	350000	€/vehicle	FELMICA
Charging capacity	36.12	MWh/h	Charges completely in 10 minutes
Capacity level	4.28	MWh	400 litres (10.7 kWh/L) https://www.volvoce.com/-/media/volvoce/global-site/products-and-services/past-products/documents/09-articulated-haulers/05-volvo/v-a25e/v-a25e-a30e-21b1003154-2007-12.pdf?v=_XxHPw
Electric Dumper (alternative battery model)			
OPEX	14000	€/y	Assumption 4% CAPEX/year, same as diesel dumper
CAPEX	647500	€/vehicle	82.5% CAPEX premium over diesel dumper
Capacity level	0.25	MWh	
Current Truck Vovlo FMX 540 (Diesel)			
Non-energy OPEX	11200	€/y	Assumption 4% CAPEX/year
CAPEX	280000	€/vehicle	SKALAND data
Charging capacity	55.86	MWh/h	Charges completely in 10 minutes
Capacity level	9.31	MWh	varies depending on model 150-870 litres: https://resource.digitaldealer.com.au/pdf/131070992052435eba4da0c121122376.pdf
Electric truck (alternative battery model)			
OPEX	1200	€/y	Assumption same as diesel truck
CAPEX	532000	€/vehicle	90% CAPEX premium over diesel truck
Capacity level	0.5	MWh	

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Current Excavator Volvo EC380E (Diesel)			
OPEX	340	EUR/tonne /h/year	Assumption 4% CAPEX, FELMICA 45000 EUR/year (including diesel) for 121.5 t
Energy/fuel consumption	0.00465	MWh/t	Based on FELMICA
CAPEX	8500	EUR/t/h	Based on FELMICA: 340000 EUR for 40 t/h
Electric excavator (alternative)			
OPEX	340	EUR/tonne /h/year	Same as diesel, assumption 4% CAPEX
CAPEX	16150	EUR/t/h	90% CAPEX premium
Loader UM - Volvo L90F			
OPEX	160	EUR/tonne /h/year	assumption 4% CAPEX (diesel separatedly).
Energy consumption	8	l/h	Based on FELMICA
CAPEX	4000	EUR/t/h	160000 EUR for a L90F, FELMICA
Electric loader (alternative)			
OPEX	160	EUR/tonne /h/year	EUR/tonne/h/year, assumption 4% CAPEX (electric), same as diesel loader
CAPEX	7600	EUR/t/h	90% CAPEX premium over diesel loader
Loader PP1 – L150 BrittagemF (Diesel)			
OPEX	280	EUR/tonne /h/year	Assumption 4% CAPEX (diesel separately), 50000 EUR/year including diesel L90F, Based on FELMICA
CAPEX	7000	EUR/t/h	280000 EUR for a 40 t/h loader
Loader PP1 – L150 BrittagemF (Electric)			
OPEX	280	EUR/tonne /h/year	
CAPEX	13300	EUR/t/h	90% CAPEX premium over diesel loader

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Loader PP2– L90F OS (Diesel)			
OPEX	160	EUR/tonne /h/year	Assumption 4% CAPEX (diesel separately). 12000 EUR/year including diesel L90F, Based on FELMICA
CAPEX	4000	EUR/t/h	160000 EUR for a 40 t/h loader
Loader PP1 – L150 BrittagemF (Electric)			
OPEX	160	EUR/tonne /h/year	same as diesel, assumption 4% CAPEX
CAPEX	7600	EUR/t/h	90% CAPEX premium over diesel loader

Table 4 shows the energy-related assumptions in FELMICA. We do not consider limitations in power or diesel access.

Table 4 Energy assumptions FELMICA

Parameter	Value	Unit	Description
Diesel price	102.8	EUR/MWh	Data From FELMICA, 1.1 EUR/l
Power price	138	EUR/MWh	FELMICA, average 2025 including tariffs, scaled to a daily power profile (11.04.2025)
Charger relative CAPEX	5000000	EUR/MW	fast charging, based on 3 M$ for 0.6 kW [21]
Estimated consumption conversion for electric vehicles	3	kWh electric/l diesel	Rough estimation in conversations with Volvo

6.1 SKALAND

Figure 12 presents the main mass transport vehicles and subprocesses included within the defined TEA scope for the SKALAND case, covering operations from underground extraction to transport to the processing plant.

Following extraction and primary crushing underground, the ore is transported to the surface using a loader (L180) to a load–dumper transfer point. A dumper (A40) then transports the material from the stope to the first crushing stage. Subsequently, a loader (L110) transfers the crushed material to a secondary crushing area. From this point, road trucks transport the ore to the processing plant.

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In the TEA model, these subprocesses are represented as sequential transport and handling stages, each associated with specific vehicle types, energy consumption profiles, and operational constraints. The road transport segment constitutes the main mass transport flow considered for decarbonisation and is therefore modelled explicitly as a demand for transport services (e.g. tonne-kilometres) to be fulfilled by alternative vehicle technologies.

The processing plant is located approximately 11 km from the mine, and transport occurs via a combination of gravel and regional roads, and we assume a 20-minute displacement time.

Each vehicle type is characterised in the model by parameters such as energy use per trip, loading capacity, operational availability, and refuelling or charging requirements, allowing the optimisation model to determine both the optimal technology choice and the associated infrastructure and operational strategy required to meet the transport demand.

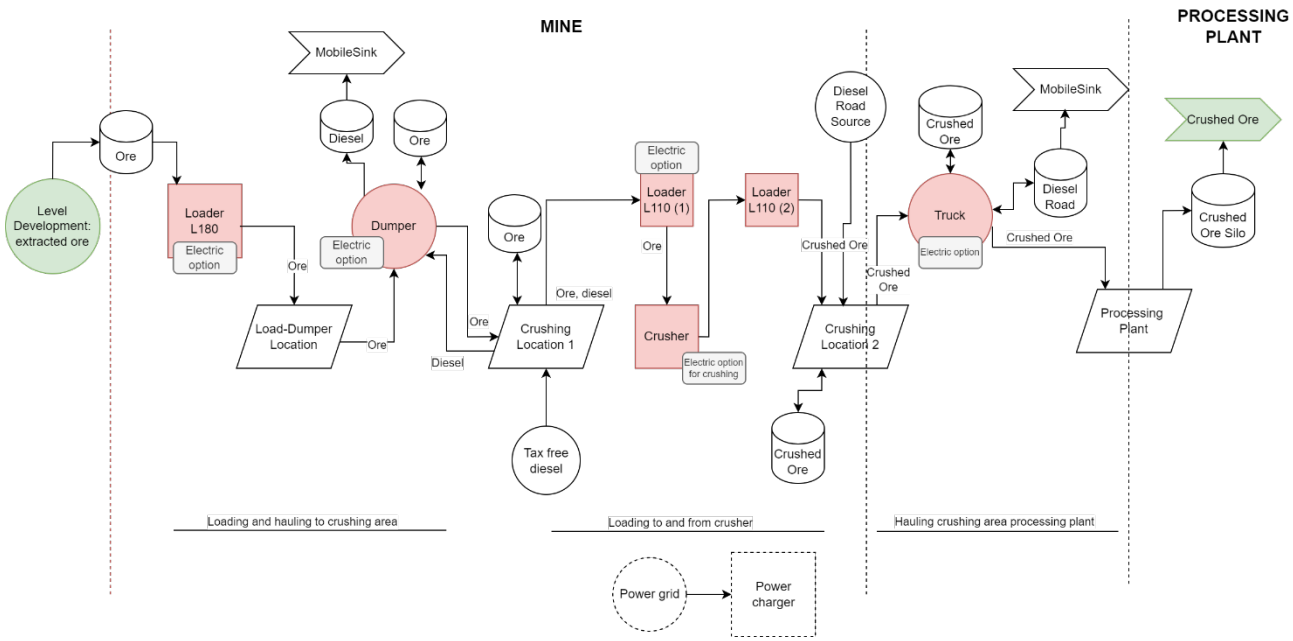

Figure 12 TEA diagram modelled for the SKALAND case. In green the general scope is defined: from mass extraction at the mine to the delivery of ore at the conveyor belt at the processing plant. The red blocks represent the vehicles considered, where crusher and loaders are considered fixed (movement is not modelled) and the dumper and truck are modelled as mobile vehicles in the model. Diesel sources and alternative power grid and electric charger (in dashed lines at the bottom of the diagram) are in addition connected to all vehicle nodes, where road diesel is only used by the road truck. The two nodes associated to L110 are just a modelling mechanism to handle the two different products Ore and Crushed ore.

Based on insights obtained from the site visits conducted in Task 3.4, together with previous work carried out in Task 4.1 on carbon footprint assessment, the main mass transport vehicles operating at the SKALAND site have been identified. Table 5 provides an overview of the data and assumptions used in the TEA for SKALAND. We assume for the representative day that 156 tonnes of crushed ore are sent to the processing plant, during 24h, that is 6.5 tonnes/h, and the time resolution is 10 minutes.

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Table 5 Data and assumptions used in the Techno-Economic Assessment for SKALAND

Parameter	Value	Unit	Description
Dumper – Volvo A40 (A30)			
OPEX	16800	€	Non-energy OPEX, 1400 EUR/month SKALAND
CAPEX	400000	€	Based on SKALAND
Charging capacity	36.12	MWh/h	Charges completely in 10 minutes
Capacity level	6.02	MWh	563 litres (10.7 kWh/L): https://resource.digitaldealer.com.au/pdf/131070992052435eba4da0c121122376.pdf
Electric dumper			
OPEX	16800	€	Same as the diesel dumper
CAPEX	730000	€	Based on diesel 400000 EUR per vehicle, 82.5% CAPEX premium (truck)
Capacity level	0.25	MWh	
Truck – Volvo EMX540			
OPEX	16800	€	Non-energy OPEX, 1400 EUR/month SKALAND
CAPEX	280000	€	Based on SKALAND
Charging capacity	55.86	MWh/h	Charges completely in 10 minutes
Capacity level	9.31	MWh	varies depending on model 150-870 litres: https://resource.digitaldealer.com.au/pdf/131070992052435eba4da0c121122376.pdf
Electric truck			
OPEX	16800	€	Same as the diesel dumper
CAPEX	532000	€	Based on diesel 280000 EUR per vehicle, assumption 90 % CAPEX premium for electric version based on https://www.ausimm.com/globalassets/communities/branches/sydney/mine-electrification--what-technology-is-available-now-and-how-do-the-costs-stack-up-sarah-devries.pdf

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Capacity level	0.5	MWh	varies depending on model 150-870 litres: https://resource.digitaldealer.com.au/pdf/1310709920524 35eba4da0c121122376.pdf
Loader Volvo L110 (diesel)			
OPEX	420	EUR/tonne /h/year	SKALAND 1400 EUR/month or 16800 EUR/year for 40 t/h loader
CAPEX	8750	EUR/t/h	8750 EUR/t/h for a 350000 EUR loader of estimated 40 t/h capacity. Based on SKALAND
Electric Loader L110			
OPEX	420	EUR/tonne /h/year	SKALAND 1400 EUR/month or 16800 EUR/year for 40 t/h loader
CAPEX	16625	EUR/t/h	8750 EUR/t/h for a 350000 EUR loader of estimated 40 t/h capacity
Crusher			
OPEX	138.27	EUR/tonne /h/year	Estimation for now, 16800 EUR/year for a 121.5 t/h crusher
CAPEX new vehicle	5761.31	EUR/t/h	700000 EUR for a 121.5 t/h crusher. Based on SKALAND
Electric crusher			
OPEX	138.27	EUR/tonne /h/year	Estimation for now, 16800 EUR/year for a 121.5 t/h crusher
CAPEX new vehicle	5761.31	EUR/t/h	700000 EUR for a 121.5 t/h crusher
Loader Volvo L180 (diesel)			
OPEX	420	EUR/tonne /h/year	SKALAND 1400 EUR/month or 16800 EUR/year for 40 t/h loader
CAPEX	17500	EUR/t/h	700000 EUR for a 40 t/h loader. Based on SKALAND

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Electric Loader L180			
OPEX	420	EUR/tonne /h/year	SKALAND 1400 EUR/month or 16800 EUR/year for 40 t/h loader
CAPEX	29750	EUR/t/h	70 % CAPEX premium for electric (LHD), based on 700000 EUR from https://www.ausimm.com/globalassets/communities/branches/sydney/mine-electrification--what-technology-is-available-now-and-how-do-the-costs-stack-up-sarah-devries.pdf

Table 6 below shows the energy-related assumptions for SKALAND. We do not assume constraints in power or diesel access.

The current model does not explicitly include grid or network capacity as binding optimisation constraints. However, available data for SKALAND indicate a defined maximum capacity, and the model results show that the simulated power demand and peak loads remain below this limit. Battery degradation effects and phased (staggered) deployment of BEVs are also not explicitly represented. The analysis assumes fully available battery capacity and an immediate fleet transition, which simplifies the modelling but may underestimate long-term operational costs and infrastructure requirements.

Table 6 Energy assumptions SKALAND

Parameter	Value	Unit	Description
Diesel price (tax free)	153.27	EUR/MWh	ca. 18 NOK/liter wo VAT (from commercial prices from the Norwegian provider CircleK), 11 NOK/eur (1.64 EUR/l), 10.7 kWh/kg
Diesel price (road truck)	170	EUR/MWh	ca. 20 NOK/liter wo VAT (from commercial prices from the Norwegian provider CircleK), 11 NOK/eur (1.82 EUR/l), 10.7 kWh/kg
Power price	16	EUR/MWh	Average, spot price profile from 21.03.2026 for NO4 + tariff on low voltage (6.7 EUR/MWh)
Charger relative CAPEX	5000000	EUR/MW	Fast charging, based on 3 M$ for 0.6 kW [18]
Estimated consumption conversion for electric vehicles	3	kWh electric/l diesel	Rough estimation in conversations with Volvo

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7 TEA RESULTS

In this section, the results of the TEA model are presented. The analysis compares the baseline scenario, where transport operations rely exclusively on diesel-powered vehicles, with alternative scenarios based on battery-electric vehicles (BEVs). We model the trucks and dumpers as fully mobile vehicles, as described in the previous section, whereas excavator, loaders and crusher are modelled as static processes to allow the solvability of the problem.

As there are several models available in the market, and we do not want to base the analyses on specific models, two types of BEV scenarios are considered: one based on existing commercially available battery capacities, and another in which the optimisation model determines the minimum required battery size needed to meet the transport demand and ensure material delivery to the processing plant. For the dumper, we assume a net capacity of 250 kWh (Volvo A30 has a total capacity of 270 kWh [19]). For the road truck, we assume a standard 500 kWh net capacity (Volvo FM models show up to 540 kWh total battery capacity [20]).

Due to the complexity of the optimisation problem, particularly the large number of binary decision variables, since the optimisation problem is a so called Mixed-Integer Linear Problem (MILP), which combine binary variables (with a value of 0 or 1) with linear formulations, which are, very simplified, summations of decision variables (x_1, x_2) modified by constant parameters (c_1, c_2, b), e.g. $x_1 \cdot c_1 + x_2 \cdot c_2 = b$. These binary variables are associated with vehicle routing and operational scheduling (when and where each mobile vehicle, i.e. trucks and dumpers), are located, if they are moving or not, how long it takes to arrive to the next location etc, and they can increase the complexity of the problem exponentially. In addition, these binary decisions influence the rest of the variables of the problem (e.g. storage level, refuelling, loading etc.) This makes the problems computationally very demanding.

To approach this computation issues, a maximum solving time of at least 6 hours per scenario was imposed for all cases, with two exceptions for FELMICA for the electric battery cases (12 and 18h) to make sure that the model cannot find better solutions in reasonable solving times. In some cases, especially for the diesel baseline scenario, relatively large optimality gaps (up to 40%) were observed, whereas the battery-electric scenarios generally achieved lower gaps (below 5% for SKALAND, but up to 22% for FELMICA, even after extending the solving time to 18 hours). The optimality gap represents the difference between the best solution found by the model and the theoretical best (optimal) solution; a higher gap means there is more uncertainty on how close the result is to the true optimum. Despite the increase in solving time (even testing several days), the solutions do not change, so even though one cannot define them as mathematically optimal, they are the best feasible solutions that the model can provide for the modelled system. Table 7 summarises the computational performance of the model, including solving times and optimality gaps for each scenario, providing an indication of solution quality and model tractability. These computational challenges to confirm that the solution is mathematically proven as optimal are primarily driven by the combinatorial complexity of vehicle movement decisions between locations. This is particularly remarkable in the FELMICA case study due to the presence of multiple interacting vehicles (e.g. four mobile units) compared to the two mobile units (one dumper and one truck) in SKALAND.

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Table 7 Computational performance of the optimisation model across scenarios, including solving time and optimality gap

Case	**Solving time (s)**	**Achieved gap (%)**
FELMICA Base Case	21600	40.16
FELMICA electric fixed battery size	64800	22.11
FELMICA electric optimised battery size	43200	18.25
SKALAND Base Case	43200	28.19
SKALAND electric fixed battery size	21600	3.46
SKALAND electric optimised battery size	21600	3.08

In the following sections, the results for both sites are presented.

7.1 FELMICA

This section presents the results of the techno-economic analysis for the FELMICA case study, also structured around three distinct scenarios to evaluate the impact of transport system electrification. One important change compared to the real operation of the mine is that in this analysis, the two trucks operate exclusively between the Gonçalo mine and processing plant. In the real operation, the trucks collect ore from different mines. The time resolution is 20 minutes, and the operation horizon is 24 hours. For the cost distribution and emissions, the values of this day of operation are upscaled to be representative for the operation of the mine in the medium-long term (10 years).

The first scenario represents the diesel baseline, in which all mobile equipment operates using conventional diesel technology. This case serves as the reference against which alternative configurations are compared in terms of operational performance, costs, and emissions.

The second scenario explores battery-electric alternatives, where relevant vehicles are replaced with battery-electric counterparts using representative, commercially available battery capacities mentioned above. Also, the size of the charger is defined by the model. This scenario assesses the feasibility and performance of electrification under realistic technological assumptions.

The third scenario considers battery-electric alternatives with battery sizing, in which the model determines the minimum required battery capacities needed to meet operational constraints while ensuring demand fulfilment for the mobile vehicles, that is the two dumpers and the two trucks. This allows for a more flexible and system-driven evaluation of battery requirements and their impact on overall performance.

As mentioned in the previous section, the operation of FELMICA in these analyses is different from the normal operation of the mine and processing plant, where we assume here a larger demand (204 tonnes/day) and operation hours (12h). Appendix 2 in Section 12 provides alternative results for FELMICA, changing the

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demand to 60 tonnes/day to be delivered during an 8-hour shift, more in line with today's operation. The same scenarios and results are evaluated and the main different discussed in that Appendix.

7.1.1 BASE CASE DIESEL

In the case of FELMICA we have assumed only operation during 12 hours during the day, both in the mine and processing plant. The model for this case can be summarised as follows:

minimise: $\sum CAPEX_{dieselvehicles} + OPEX_{dieselvehicles} + OPEX_{taxfreediesel} + OPEX_{roaddiesel}$

subject to:
$$- \textit{capacity contraints: vehicle operation and fuel availability}$$
$$- \textit{material and energy flow constraints}$$
$$- \textit{diesel vehicle mobility constraints}$$

Figure 13 displays ore delivered to the processing plant, ore stored at the processing plant and ore extracted from the mine. The figure represents some of the main mass flows (left y-axis, in tonnes/h). The red line represents the flow to the conveyor belt in the processing plant (Ore_Sink), that is the final ore demand. In purple we represent the ore deficit at the conveyor belt (Ore_Sink_deficit), which means in which periods there is a deviation from the demand and for all these analyses in this section this value is zero (all demand is fulfilled). The blue line represents when the material is extracted from the lower mine (SourceMinedOre_LowerMine) to start the transport to the upper mine and processing plant. This line is a just model decision variable and does not follow any actual blasting process. We also represent one of the ore storages at the processing plant, assumed by the model to be able to store 300 tonnes of ore (right y-axis, black dashed line, Storage_Ore_max) whereas the actual mass stored is represented by the green line (Storage_Ore). This type of plot has the same structure for all three cases, both in FELMICA and SKALAND below.

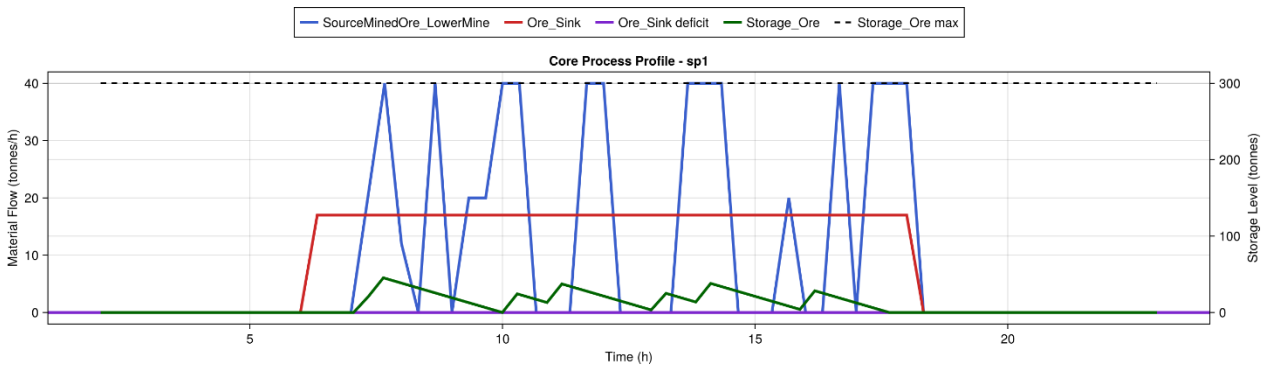

Figure 13 Main operation variables for the diesel base case of FELMICA. The ore delivered is marked as CrushedOre Sink, whereas any deficit is shown by CrushedOre Sink deficit, which is 0 as all demand is delivered. The extracted Ore is shown by SourceMinedOre and the modelled ore storge capacity at the processing plant is shown by the dashed line, whereas its state of charge is represented by the green line (Storage_Ore).

One can immediately notice that there is some ore extraction at the end of the day, when the storage ore has already been depleted and it is enough to fulfil the demand. This is caused by how the storage modelling works. We impose a cyclic storage, that is that for each operation horizon (here 24 hours), the stored material or fuel in the first period of the day has to be the same than the last period at the end of the day. But the model can

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decide the initial storage material or fuel, whether it starts with the storages full, empty, or something in between. This is done to avoid that the model utilises the storages unrealistically to provide an economic advantage of starting the day with a full storage and then leave it empty at the end of the day. An example of this enforcement of a cyclic storage can be observed in the next figure, Figure 14.

If we look at the ore transport of dumper and truck, Figure 14, the two vehicles alternate to deliver both from lower to upper mine, and especially from the mine to the processing plant, where the large distance of 92 km requires coordination between the two trucks to ensure constant availability of ore at the processing plant.

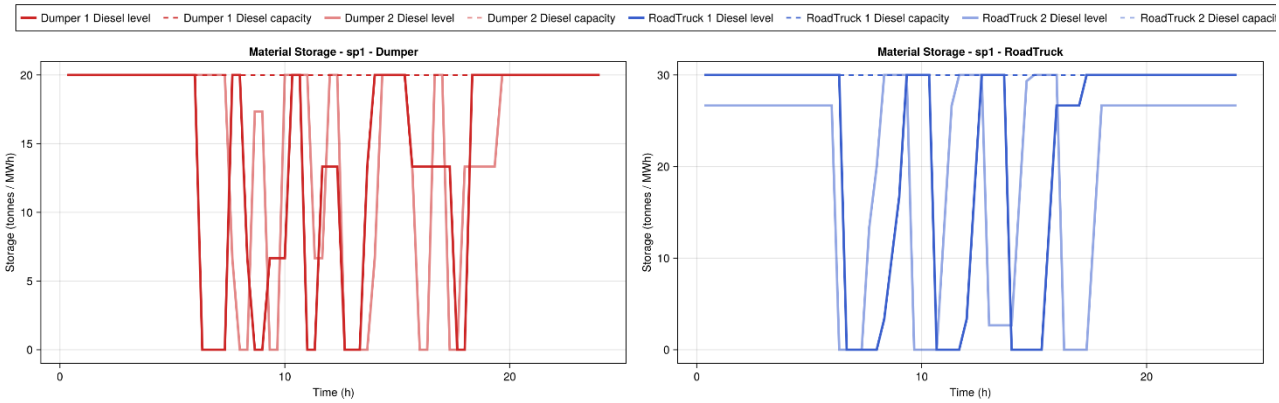

Figure 14 Cargo level of the ore storage of the 2 diesel Dumpers (left) and the 2 Trucks (right) for the FELMICA diesel base case, where the dashed line represents the ore storage capacity.

Regarding the total cost of the system, where NPC for 10 years of operation is 11.32 MEUR, the main contributor is, as in SKALAND, the diesel consumption, especially the one consumed by the trucks, since they need to transport ore for 92 km. The total cost distribution is displayed in Figure 15.

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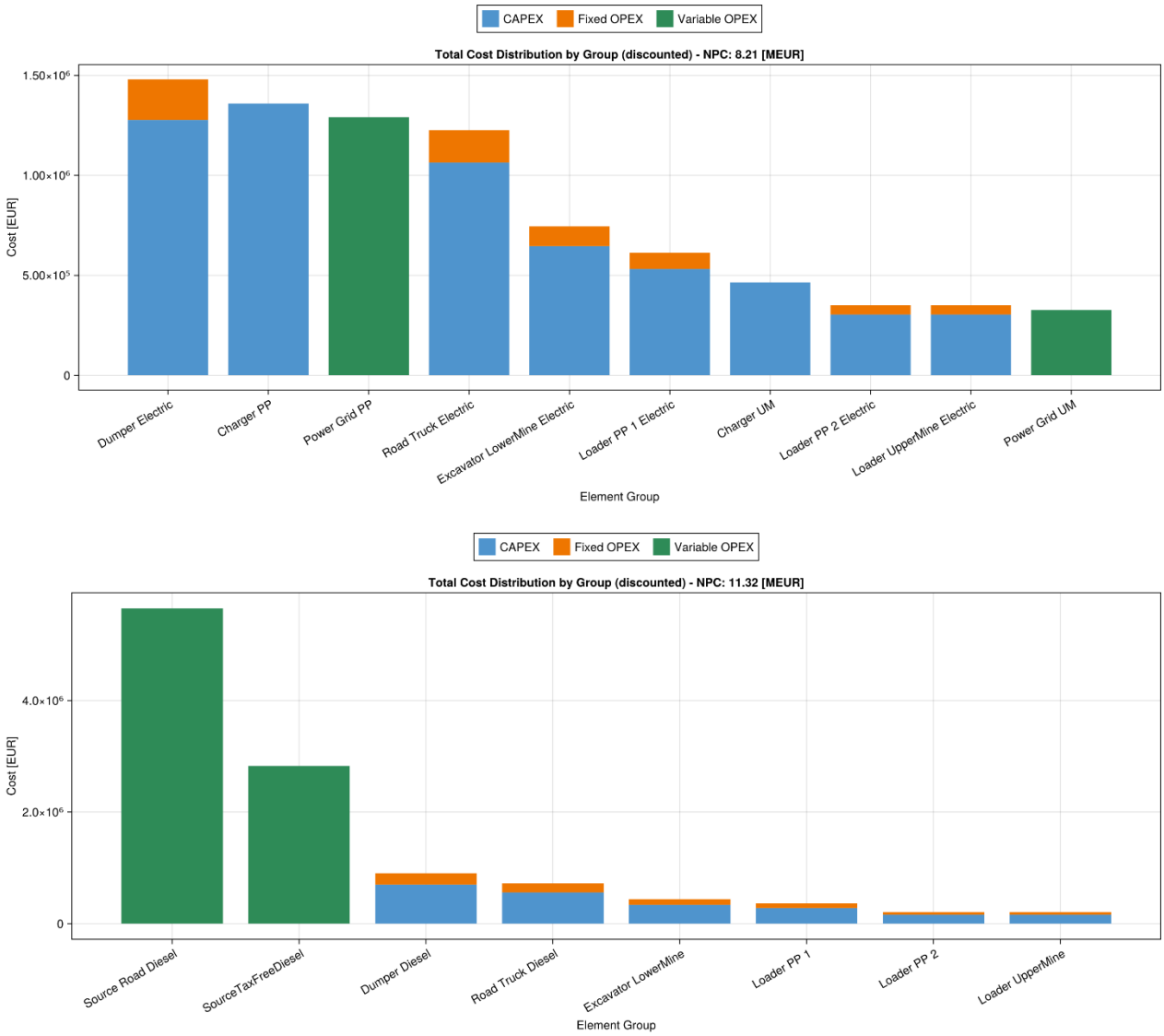

Figure 15 Total cost of the diesel base case for FELMICA, divided per type (CAPEX, fixed and variable OPEX) and per vehicle and energy source. The two trucks and dumpers are grouped together into one column

The yearly emissions are displayed in Figure 16. They amount to 447 ktonnes CO2-eq per year, and following the total costs, it is the road truck that contributes to the largest emissions. Note that these figures need to be considered cautiously, as we assume that the 24 hours of representative operation scale up to provide yearly values, whereas in reality, operation and thus emissions can vary from day to day. Comparing with the work done in the Carbon Footprint report (in Task 4.1 - Real time feed – output control / monitoring), based on historical data, we can observe that the main contributors are the road trucks, dumpers and excavator as well, but in the Carbon Footprint report the loaders play a smaller role than in this TEA analysis (only 5%). That is why it is important to focus on the general trends of the TEA analysis rather than exact numbers, given the number of simplifications required.

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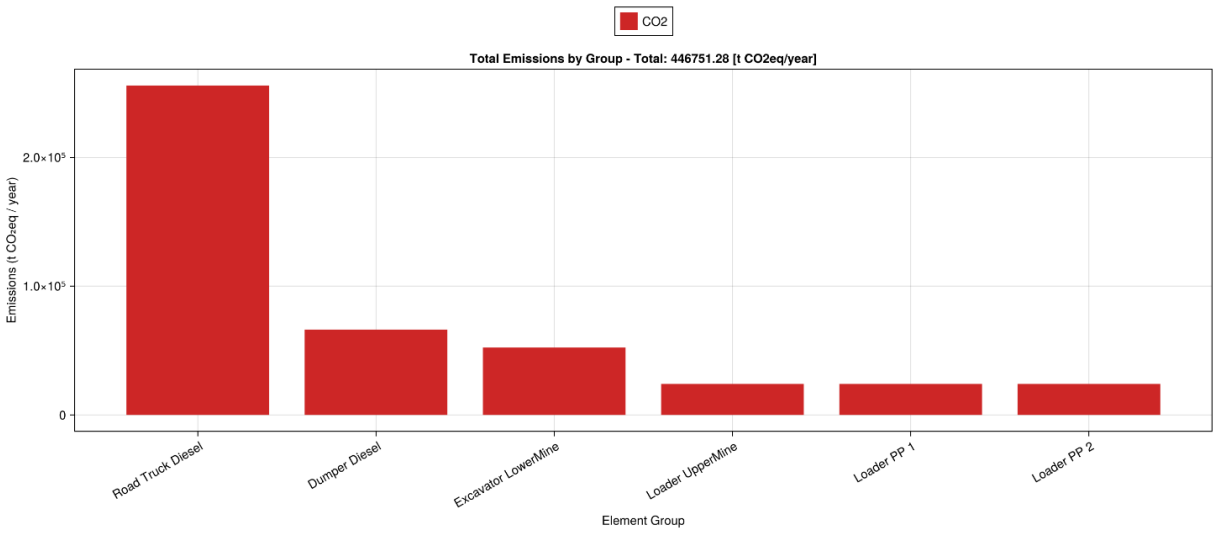

Figure 16 Yearly emissions per vehicle for the FELMICA diesel base case. The two trucks and dumpers are grouped together into one column

7.1.2 ELECTRIC ALTERNATIVES

If all vehicles in FELMICA are replaced by battery-electric alternatives, the overall operation of the system remains similar with small changes in scheduling, but probably due to the model having multiple options with the same costs. This model for this case can be represented as follows:

minimise: $\sum CAPEX_{el,vehicles} + OPEX_{el,vehicles} + OPEX_{grid} + CAPEX_{charger}$

subject to:
- $capacity\ contraints: el.vehicles, power\ availability,\ charger\ capacity$
- $material\ and\ energy\ flow\ constraints$
- $el.vehicle\ mobility\ constraints$

Figure 17 show the main operation profile of the system. In terms of power consumption, the peak is approximately 272 kW, and there is no activity during the night due to lack of operation, except for certain periods for recharging the dumpers and trucks. As mentioned above, the extracted mined ore does not necessarily need to align with the ore storage at the processing plant due to how storage is modelled: starting storage level in the first operation period must be the same as the storage level at the last period. That means the storages can start loaded and then refilled at the end of the day.

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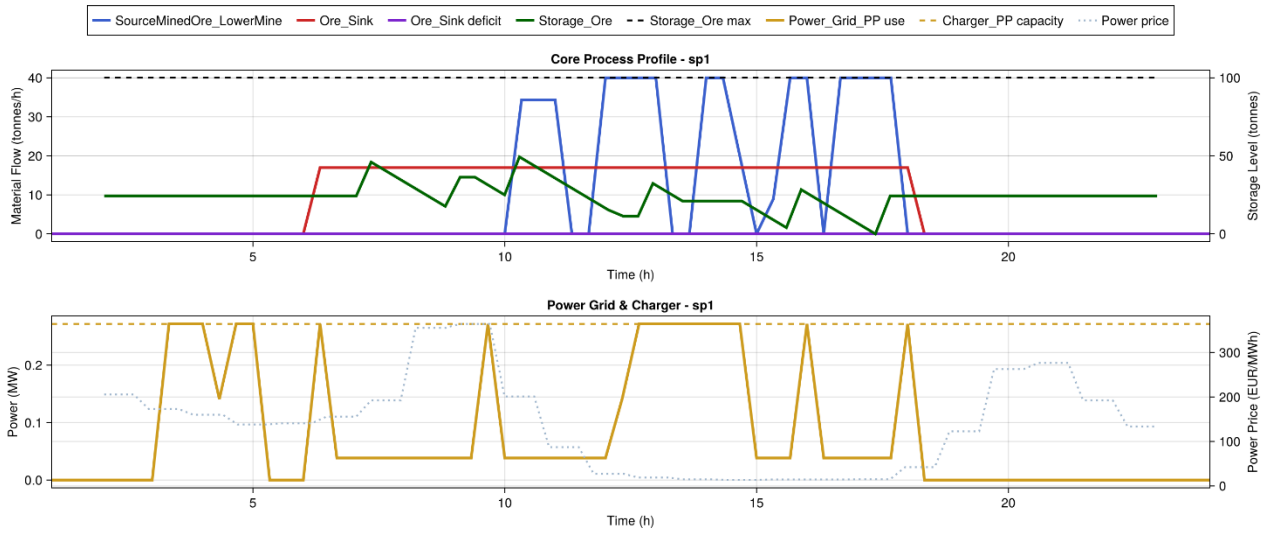

Figure 17 Main operation variables for the electric alternatives case of FELMICA. The ore delivered is marked as CrushedOre Sink, whereas any deficit is shown by CrushedOre Sink deficit, which is 0 as all demand is delivered. The extracted Ore is shown by SourceMinedOre and the modelled ore storge capacity at the processing plant is shown by the dashed line, whereas its state of charge is represented by the green line (Storage_Ore). Below the power consumption is represented.

Similarly to the diesel base case, delivery and load of ore alternates between the two dumpers and trucks, as shown in Figure 18. Figure 19 shows, on the other hand the state of charge and maximum capacity of the batteries of the two electric dumpers and trucks. It seems that the dumpers are less limited than the trucks by the battery storage, which is rather reasonable considering the long distances that the trucks need to cover.

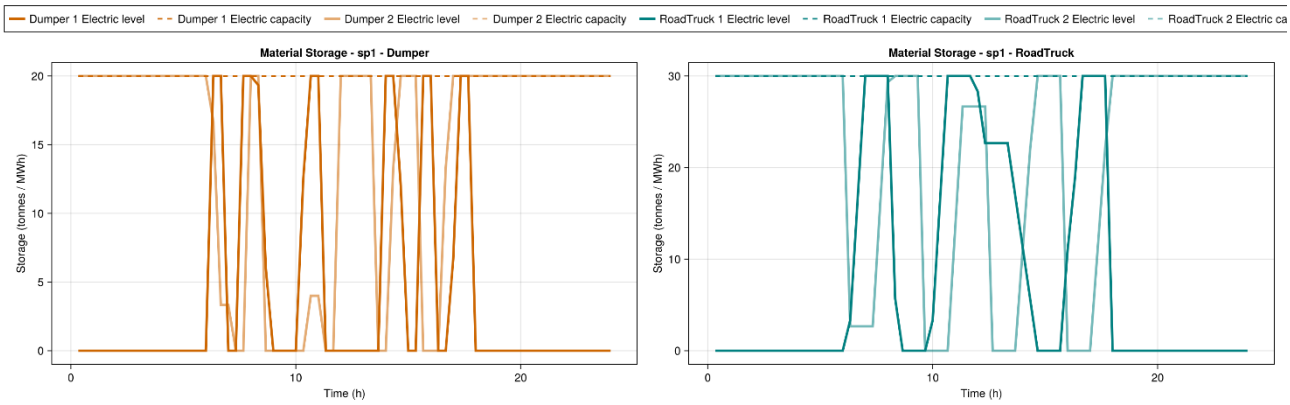

Figure 18 Cargo level of the ore storage of the 2 battery-electric Dumpers (left) and the 2 Trucks (right) for the FELMICA electric alternatives case, where the dashed line represents the ore storage capacity.

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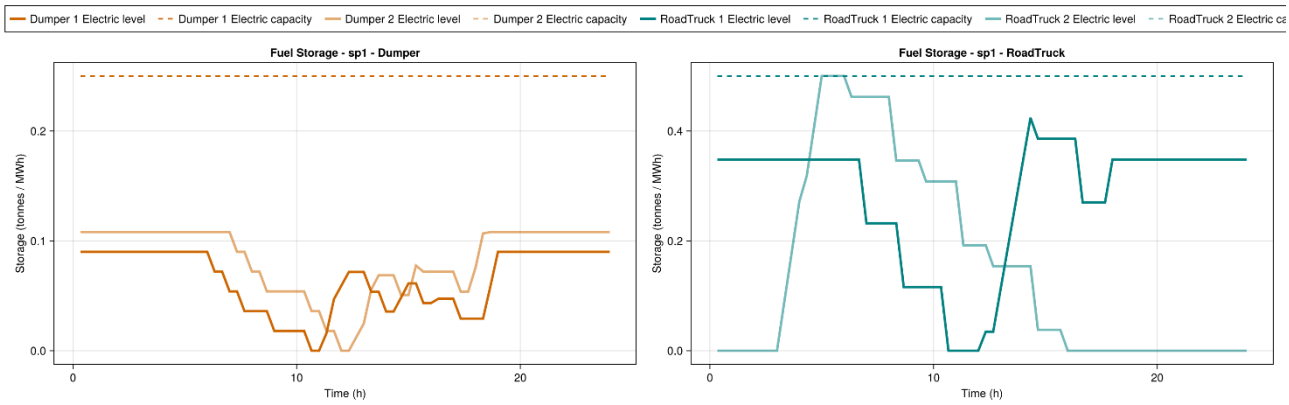

Figure 19 State of charge of the 2 battery-electric Dumpers (left) and the 2 Trucks (right) battery storage (MWh) for the FELMICA diesel base case, where the dashed line represents the ore storage capacity.

Finally, Figure 20 shows the NPC of the system and the cost distribution of the modelled system. The majority of the costs are taken by the electric dumpers, the charging equipment and electricity costs at the processing plant and by the electric trucks. Compared to the diesel base case, it represents a 27.3% reduction in the net present value. This is mostly driven by the higher energy efficiency replacing diesel by electricity, together with lower fuel costs, although the cost reduction is considerably lower than in the case of SKALAND, since electricity price are higher (138 EUR/MWh compared to 16 EUR/MWh assumed for SKALAND).

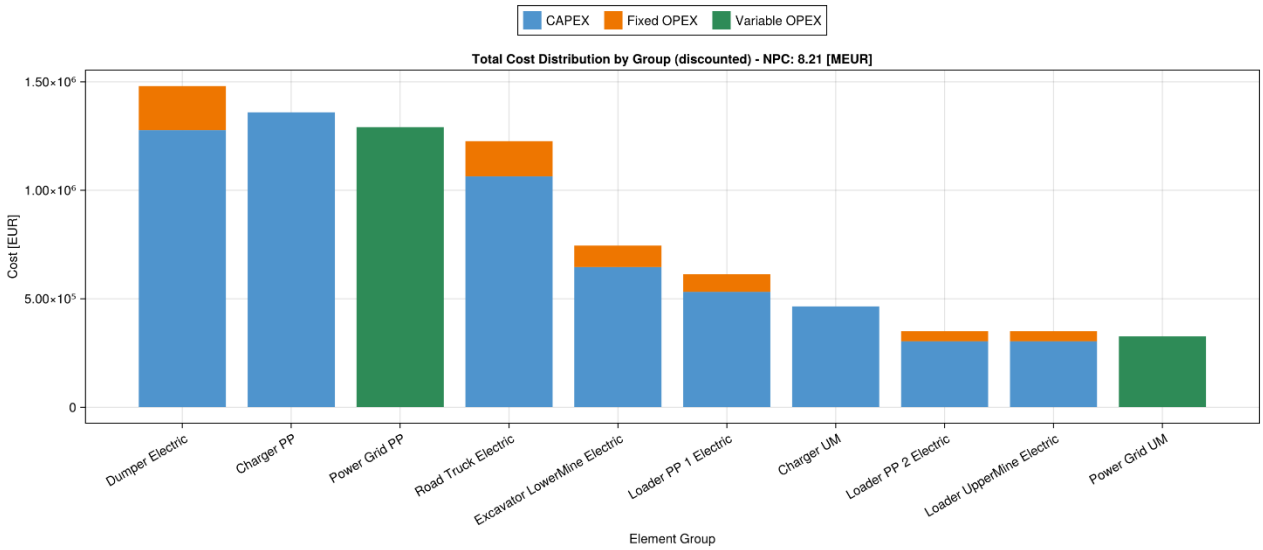

Figure 20 Total NPC and cost of the electric alternatives case for FELMICA, divided per type (CAPEX, fixed and variable OPEX) and per vehicle and fuel/energy source. Dumpers and trucks grouped together into one column.

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7.1.3 ELECTRIC ALTERNATIVES WITH BATTERY SIZING

In this case the battery of the vehicles is decided by the model against a penalty (100 EUR/MWh, on top of the CAPEX premium of the battery-electric vehicles) to avoid over dimensioning. Compared to a constraint in maximum capacity (which is also included, 3 MWh), a penalty will avoid that large and heavy batteries will be preferred without any economic consequence for the price, making the solution overly positive. The model of this case is described as:

Minimise: $\sum CAPEX_{el.vehicles} + OPEX_{el,vehicles} + OPEX_{grid} + CAPEX_{charger} + Penalty_{batteryCAPEX}$

Subject to: $- \; capacity\ contraints: BEV\ vehicles, power\ availability, charger\ \&\ battery\ capacity$
$- \; material\ and\ energy\ flow\ constraints$
$- \; Electric\ vehicle\ mobility\ constraints$

Looking at the general process, shown in Figure 21, the power peak is reduced to 212 kW (compared to 272 kW in the previous case with fixed batteries.

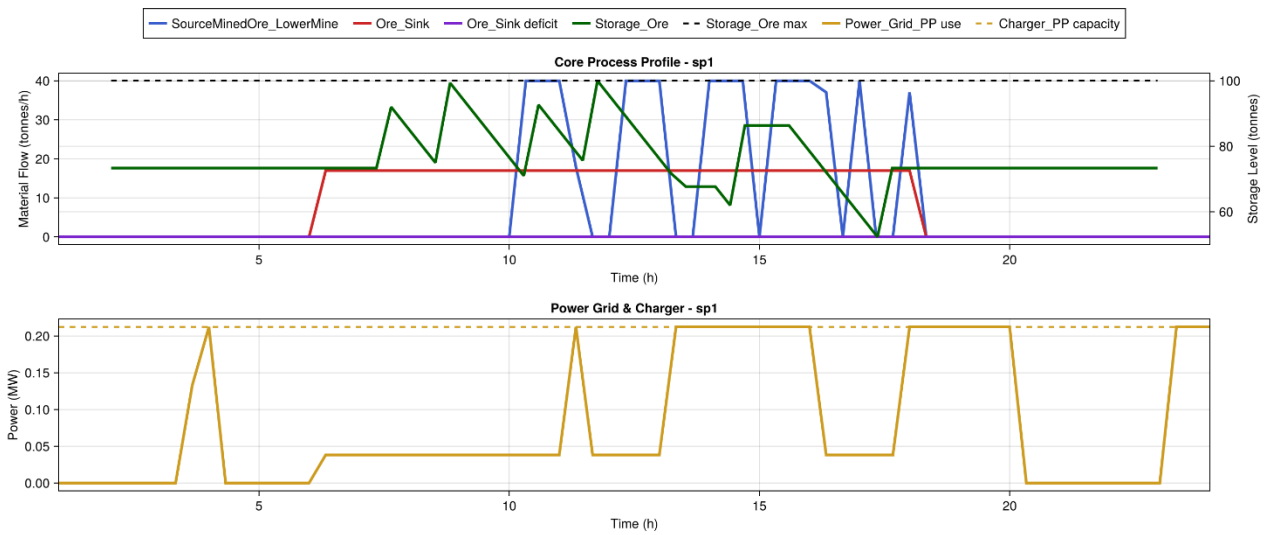

Figure 21 Main operation variables for the electric alternatives with battery sizing case of FELMICA. The ore delivered is marked as CrushedOre Sink, whereas any deficit is shown by CrushedOre Sink deficit, which is 0 as all demand is delivered. The extracted Ore is shown by SourceMinedOre and the modelled ore storge capacity at the processing plant is shown by the dashed line, whereas its state of charge is represented by the green line (Storage_Ore). Below the power consumption is represented.

Regarding battery size and charging, the model confirms that the dumpers' operation does not require large batteries, and the model suggests sizes below 100 kWh, as shown in Figure 22. For the trucks, on the other hand, larger batteries than the assumed standard model (700 kWh for truck 2) would benefit the overall economics of this case.

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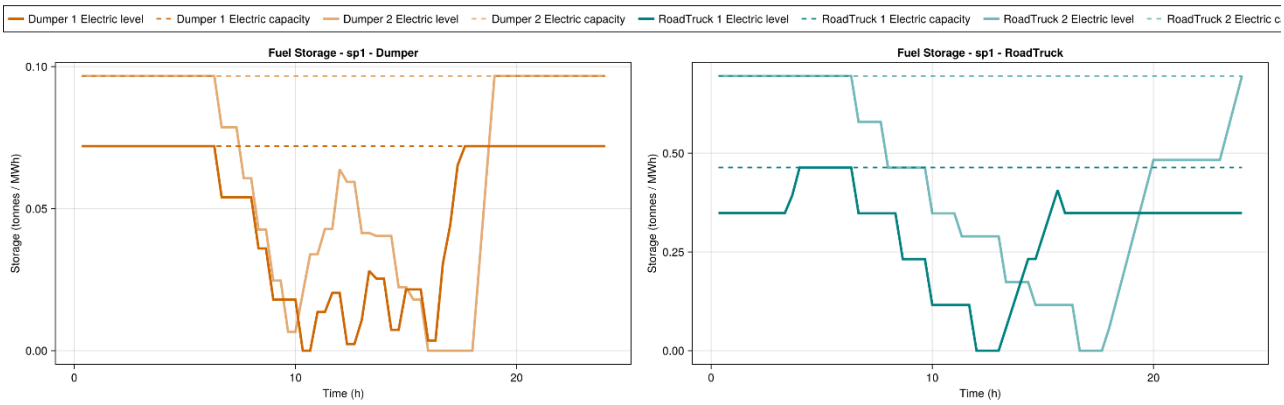

Figure 22 State of charge of the battery storages of the 2 battery-electric Dumpers (left) and the 2 Trucks (right) for the FELMICA electric alternatives with battery sizing case, where the dashed line represents the ore storage capacity.

Given these changes in battery size and charge, one can see a reduction of 4% reduction compared to the case of fixed batteries, as shown in the total cost figure in Figure 23.

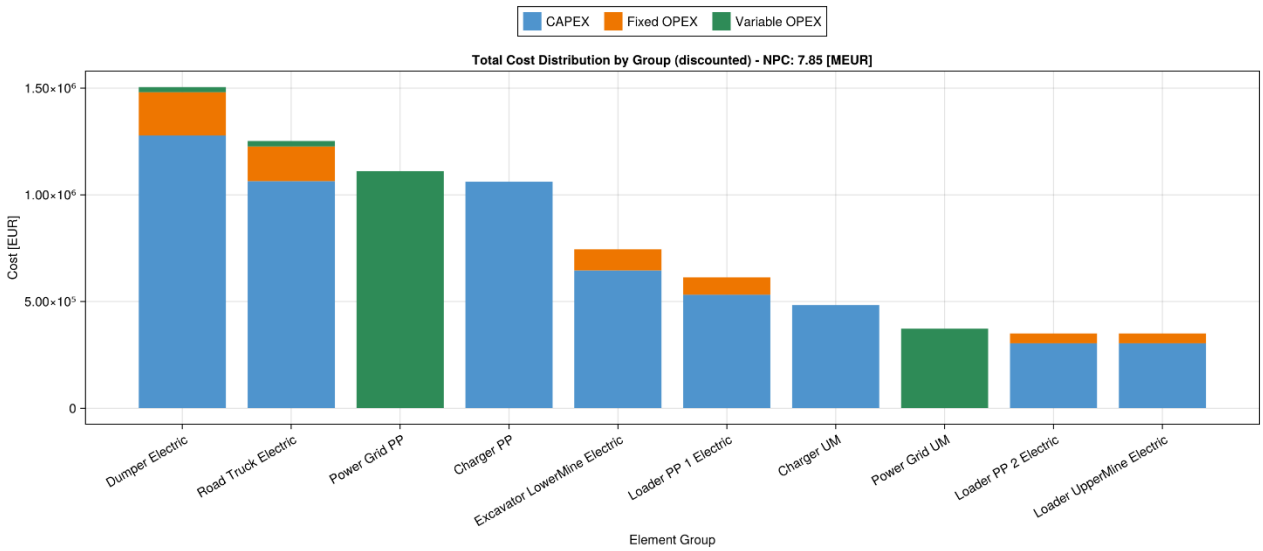

Figure 23 Total cost of the electric alternatives with battery sizing case for FELMICA, divided per type (CAPEX, fixed and variable OPEX) and per vehicle and energy source.

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7.2 SKALAND

This section presents the results of the techno-economic analysis for the SKALAND case study, following the same scenario structure and methodological approach as described for the FELMICA case. The analysis is based on a time resolution of 10 minutes over a 24-hour operational horizon. For cost distribution and emissions, the results are extrapolated to represent medium- to long-term mine operation (10 years).

As in the FELMICA case, three scenarios are considered. The first scenario represents the diesel baseline, in which all mobile equipment operates using conventional diesel technology and serves as the reference for comparison. The second scenario evaluates battery-electric alternatives, where relevant vehicles are replaced with battery-electric counterparts using representative, commercially available battery capacities, with charger sizing determined by the model.

The third scenario also follows the same principle as in the FELMICA case, with battery capacities optimised by the model. However, in the SKALAND case, this optimisation is applied specifically to the main transport vehicles (the dumper and the truck), reflecting the structure and operational characteristics of the system. This allows for a system-driven assessment of battery requirements and their impact on overall performance.

7.2.1 BASE CASE DIESEL

In terms of operation, the SKALAND case is characterised by a continuous (24/7) operation of the processing plant, while mining activities are typically limited to daytime operation (12-hour shifts). This means that the intermediate storage (silo) must be sufficiently filled during the day to ensure a continuous supply of ore to the processing plant during nighttime hours. Making a considerable simplification of the actual mathematical formulation, the optimisation problem of this base case can be described as follows:

minimise: $\sum CAPEX_{dieselvehicles} + OPEX_{dieselvehicles} + OPEX_{taxfreediesel} + OPEX_{roaddiesel}$

subject to:

$$- \; capacity\ contraints: vehicle\ operation\ and\ fuel\ availability$$
$$- \; material\ and\ energy\ flow\ constraints$$
$$- \; diesel\ vehicle\ mobility\ constraints$$

The operational dynamics for a representative day are illustrated in Figure 24, where 10 truck deliveries take place during the daytime period, ensuring that the total demand is fully satisfied. This is a bit lower than the current operation of the mine, with 12 truck deliveries.

Figure 24 presents the main operational variables for the diesel baseline scenario at SKALAND. The material flows measured in tonnes/h include the ore delivered to the processing plant, represented by “CrushedOre Sink” (red line), while any unmet demand is indicated by “CrushedOre Sink deficit” (purple) which remains at zero, confirming that all demand is fulfilled. The extracted ore is shown as “SourceMinedOre” (in blue), Finally, we represent the silo’s capacity in a dashed black line (Storage_Silo_max), and the actual stored ore in green (Storage_Silo), both measured as tonnes in the right y-axis.

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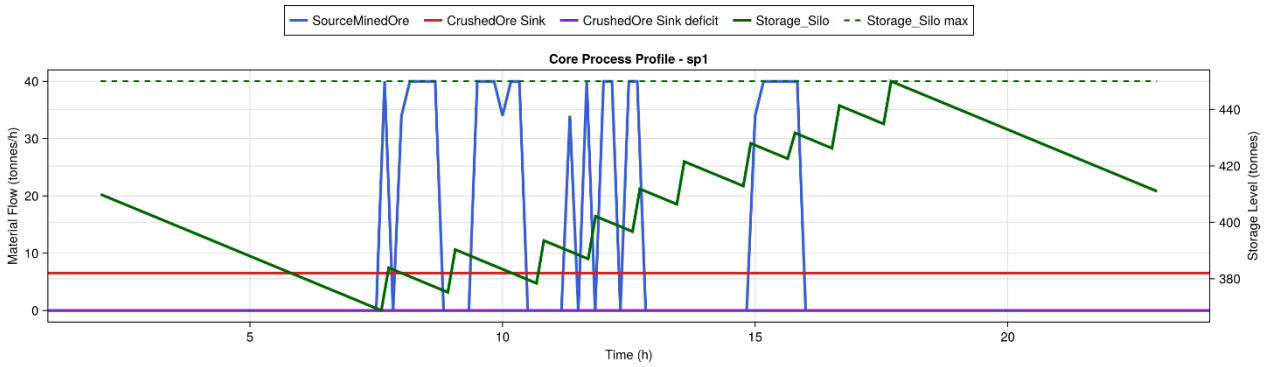

Figure 24 Main operational variables for the diesel baseline scenario at SKALAND, including ore supply (SourceMinedOre), delivered demand (CrushedOre Sink), unmet demand (CrushedOre Sink deficit), and silo capacity and state of charge (Storage_Silo).

The material storage utilisation of the dumper and truck provides additional insight into the operational behaviour of the system, as illustrated in Figure 25. Due to its slightly higher material capacity, the dumper requires fewer trips, whereas the truck performs approximately 10 delivery cycles to meet the transport demand.

Figure 25 shows the evolution of the material storage levels (state of charge) for the diesel dumper (left) and truck (right) in the SKALAND baseline scenario. In both cases, the dashed line represents the maximum storage capacity, allowing a clear comparison between utilisation levels and operational patterns.

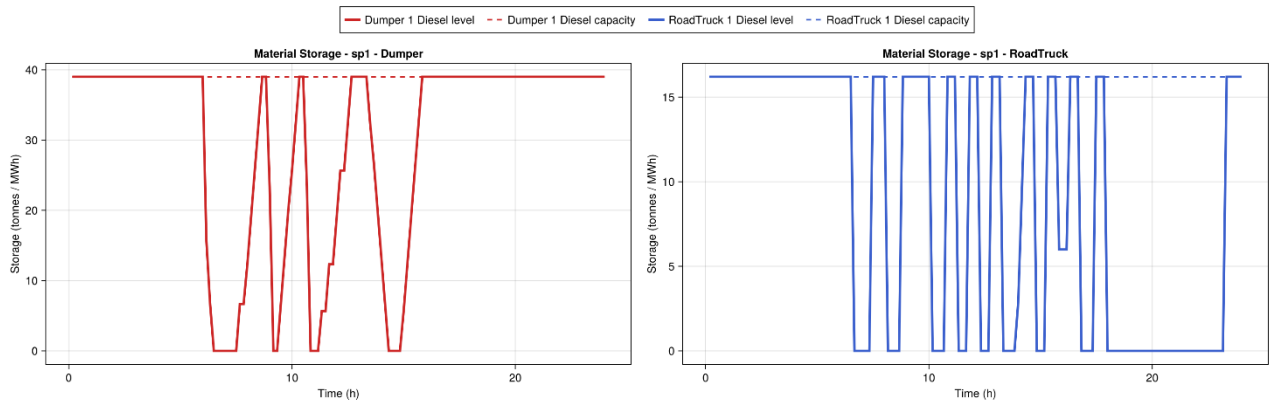

Figure 25 Cargo level of the ore storage of the diesel dumper (left) and truck (right) in the SKALAND baseline scenario, with dashed lines indicating maximum storage capacity.

Figure 26 presents the cost distribution by vehicle type and cost category. Diesel fuel clearly represents the dominant cost component, driven primarily by the consumption of tax-free diesel used in loaders, crushers, and dumpers. The total NPC over the 10-year analysis period amounts to 12.61 million euros.

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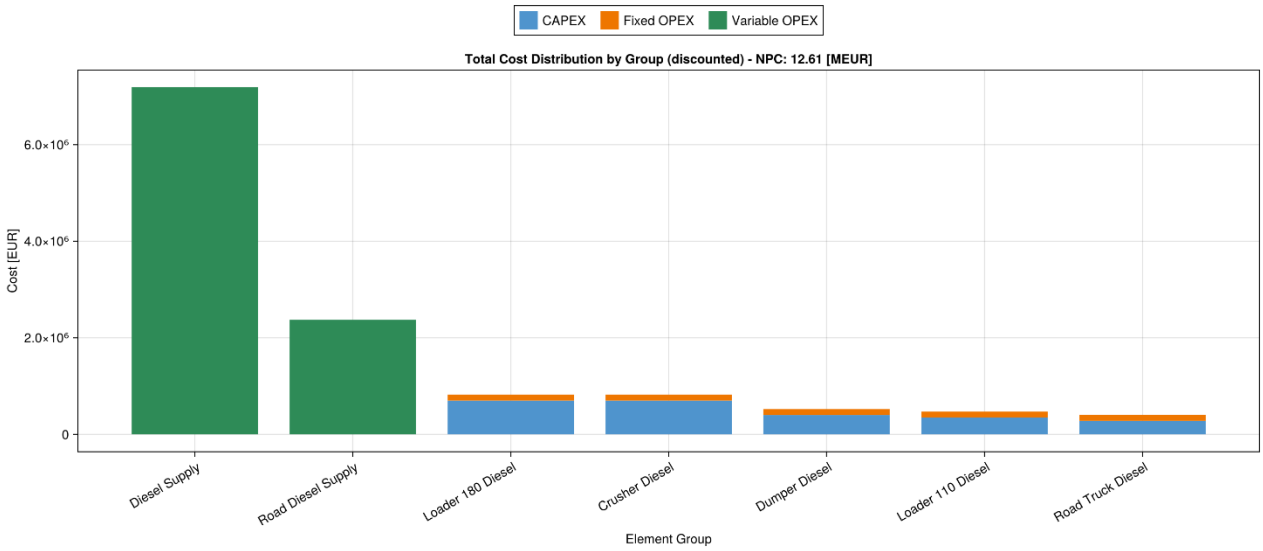

Figure 26 Total cost breakdown of the diesel baseline scenario at SKALAND by cost category (CAPEX, fixed and variable OPEX) and by vehicle and energy source, here diesel (Diesel Supply is tax free diesel and Road Diesel the regular diesel used by the Truck).

It should be noted, however, that these results are subject to uncertainty, as they rely on multiple assumptions related to both cost parameters and operational conditions. Therefore, the results should be interpreted with caution, with greater emphasis placed on identifying overall cost trends and comparing relative differences between the diesel baseline and battery-electric alternatives, rather than focussing on absolute cost values.

Finally, the emissions analysis shows that the road truck is the largest contributor, accounting for approximately one third of the total annual emissions of around 1 million tonnes of CO_2-equivalent estimated by the model. Loaders represent the second highest source of emissions, followed by the dumper and the crusher. The distribution of CO_2 emissions across the different equipment types is illustrated in Figure 27. Note that these emissions consider the result of the modelled day and upscale to obtain yearly values. For a more detailed analysis based on historical data, view Carbon Footprint report (in Task 4.1 - Real time feed – output control / monitoring). This is why it is important to focus on the general trends of the TEA analysis (which align with the carbon footprint work of the project) rather than exact numbers, given the number of simplifications required.

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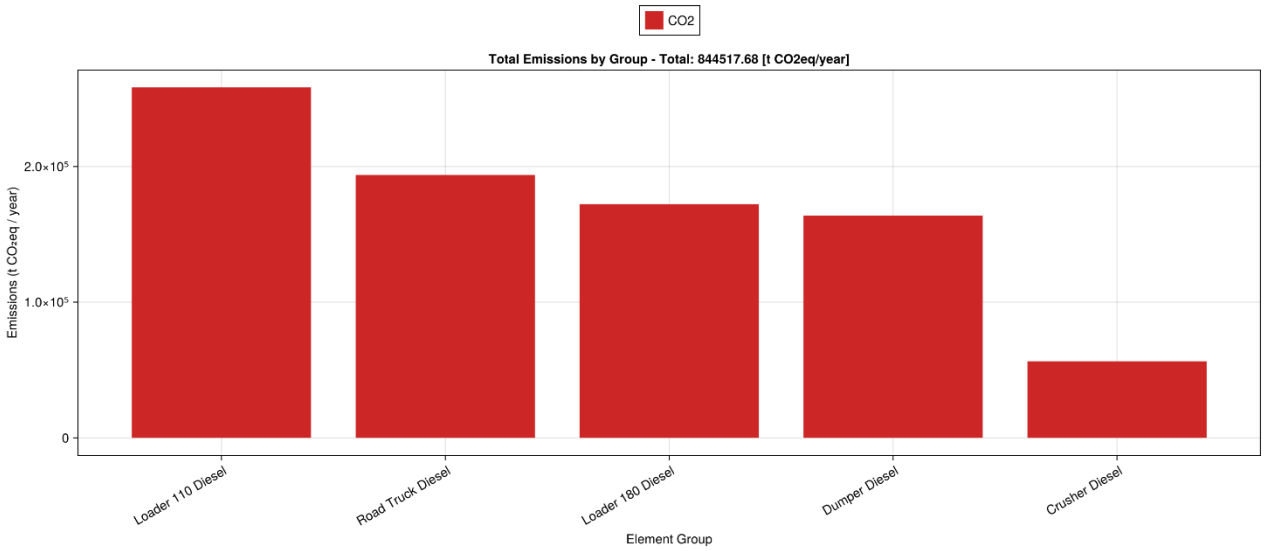

Figure 27 Annual vehicle emissions for the SKALAND diesel baseline scenario

7.2.2 ELECTRIC ALTERNATIVES

In this case we only allow battery electric vehicles with fixed battery sizes that substitute the existing diesel fleet. In addition, the model sizes the power charger needed to provide power to the electric vehicles. This case can be described as follows:

minimise: $\sum CAPEX_{el,vehicles} + OPEX_{el,vehicles} + OPEX_{grid} + CAPEX_{charger}$

subject to:
$$- capacity\ contraints: el.vehicles, power\ availability,\ charger\ capacity$$
$$- material\ and\ energy\ flow\ constraints$$
$$- el.vehicles'\ mobility\ constraints$$

When all the vehicles are replaced with battery-electric alternatives, the operation remains largely unchanged, with a constant power demand of 57.8 kW, corresponding to the installed charger capacity for the vehicles. It should be noted, however, that loaders and the crusher are modelled as fixed equipment, and their energy use (including diesel consumption in the reference setup) is distributed throughout the day. In addition, 10 truck deliveries are completed daily, ensuring that the full ore demand is met. The resulting operational profile is shown in Figure 28. It can be observed that deliveries may happen before ore extraction. This is caused by how storage is modelled: all storage (dumper, trucks, silo and other intermediate storage) must have the same state of charge at the beginning and end of the operational horizon, here one day. This can clearly be seen for example in Figure 29.

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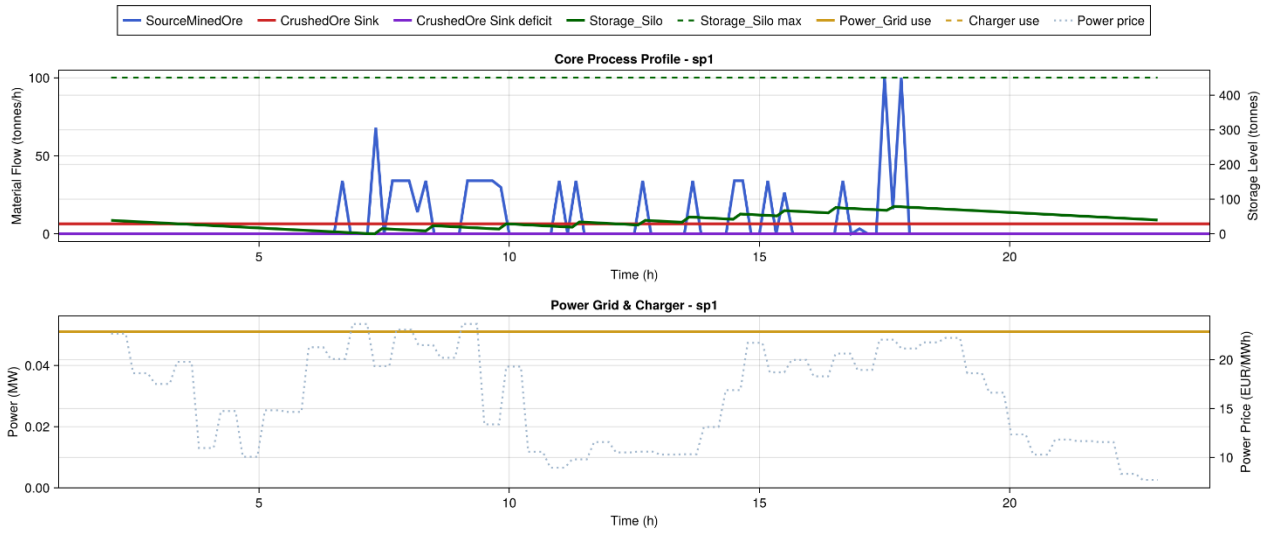

Figure 28 Main operational variables for the SKALAND electric case. Crushed ore delivered is shown as CrushedOre Sink, with any deficit indicated by CrushedOre Sink deficit (zero, as demand is fully met). Extracted ore is represented by SourceMinedOre, and silo capacity is shown by the dashed line, while its state of charge is shown by the green line (Storage_Silo). Power consumption is displayed at the bottom.

Understanding the operation of the electric batteries in the truck and loader is useful, and Figure 29 illustrates their state of charge over time. Overall, both are primarily discharged during daytime operation and recharged at night, with occasional short charging events during the day.

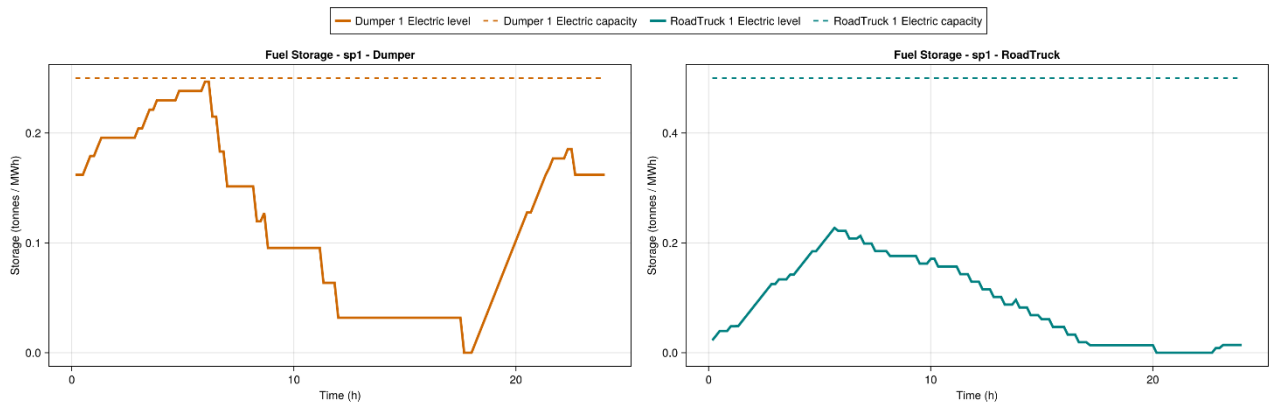

Figure 29. State of charge and capacity of the electric dumper (left) and truck (right) batteries (MWh) in the SKALAND electric alternative case

From an overall cost perspective, replacing diesel vehicles with battery-electric alternatives leads to a substantial reduction in NPC, decreasing from 12.6 MEUR in the base case to 5.0 MEUR in the battery-electric scenario. This occurs despite higher capital expenditures, as battery-electric vehicles are assumed to have a 70–90% CAPEX premium relative to their diesel counterparts (see Figure 30). The reduction in NPC is primarily driven by lower energy consumption and the relatively low electricity prices in Northern Norway, both of which contribute to significantly reduced long-term operating costs in the modelled system.

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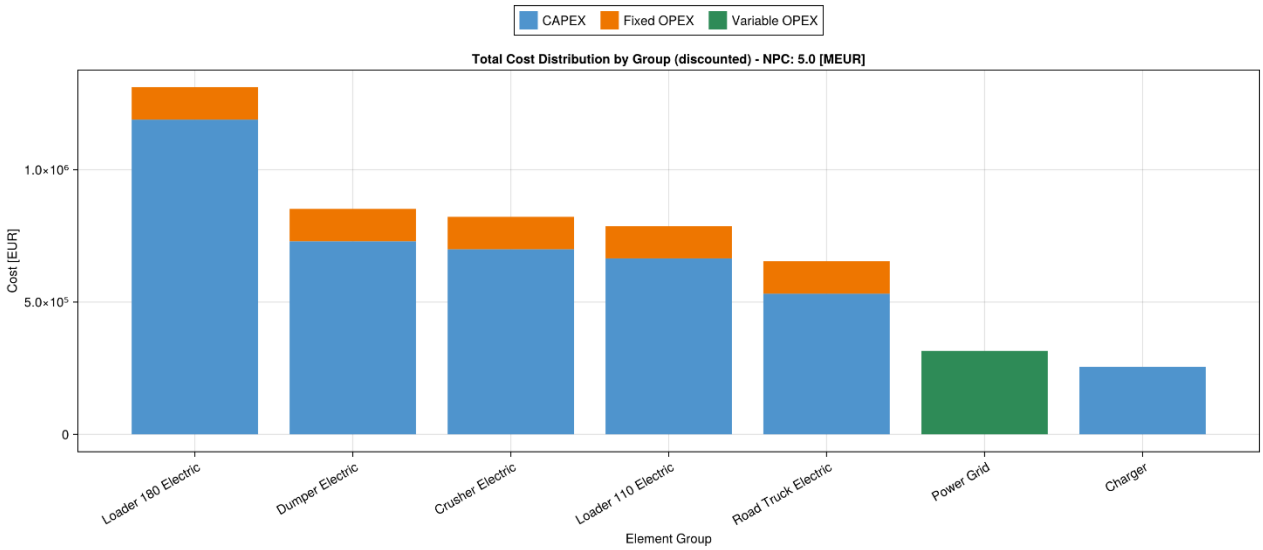

Figure 30 Total cost breakdown for the SKALAND electric alternative case, disaggregated by cost type (CAPEX, fixed OPEX, and variable OPEX) and by vehicle and energy source.

Since the model only accounts for process emissions and excludes upstream emissions, the total CO_2-equivalent emissions of the mass transport system are assumed to be 0 tonnes per year.

7.2.3 ELECTRIC ALTERNATIVES WITH BATTERY SIZING

In this final case variant, the battery sizes of both the dumper and the truck are optimised by the model, while charging is restricted to night-time and lunch periods to ensure that the resulting capacities are not undersized. The optimisation problem can be summarised as follows:

minimise: $\sum CAPEX_{el,vehicles} + OPEX_{el,vehicles} + OPEX_{grid} + CAPEX_{charger} + Penalty_{batteryCAPEX}$

subject to: $- capacity\ contraints: el.vehicles, power\ availability, charger\ \&\ battery\ capacity$
$- material\ and\ energy\ flow\ constraints$
$- el.vehicles'\ mobility\ constraints$

The optimised battery capacities are 237.8 kWh for the dumper and 268.9 kWh for the truck, assuming full utilisation of the available capacity (implying that actual installed batteries would likely be slightly larger). These values are consistent with the assumptions used in earlier cases, aligning with the previously considered sizes of 250 kWh and 500 kWh, respectively. Figure 31 presents the corresponding state of charge profiles. It should be noted that no additional cost is assigned to battery sizing, as this is included within the vehicle CAPEX; instead, a small penalty is applied to discourage excessive oversizing.

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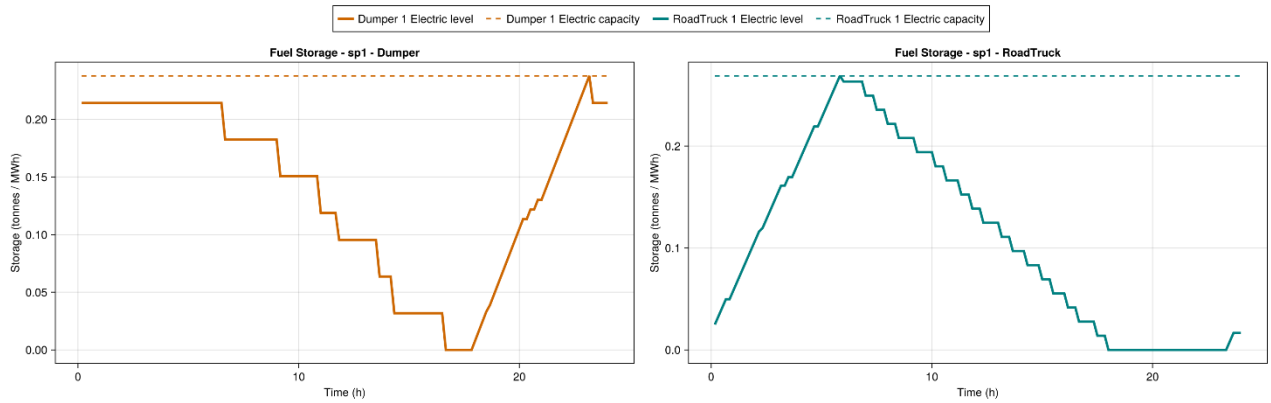

Figure 31 State of charge and battery capacity (MWh) of the electric dumper (left) and truck (right) in the SKALAND electric alternative case with model-optimised battery sizing.

Regarding the cost distribution, the NPC decreases slightly from 5.0 in the case with fixed batteries to 4.98 MEUR, and the overall cost breakdown is therefore very similar, as shown in Figure 32.

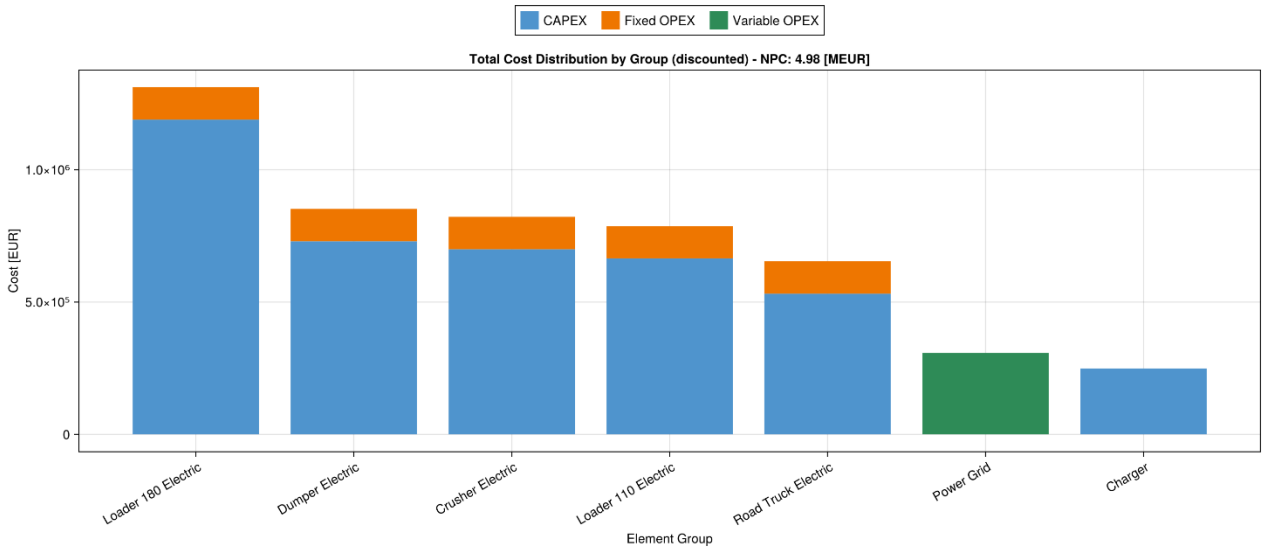

Figure 32 Total cost breakdown for the SKALAND electric alternative with battery sizing, disaggregated by cost type (CAPEX, fixed OPEX, and variable OPEX) and by vehicle and energy source.

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8 DISCUSSION

The results of the TEA analysis highlight several important insights regarding the transition from diesel-based to battery-electric transport systems across both the FELMICA and SKALAND case studies, demonstrating that electrification is technically feasible under different operational conditions.

It should, however, be emphasised that the quantitative results obtained for the SKALAND case should be interpreted with caution and not considered as definitive values. The analysis relies on several assumptions, including CAPEX premiums for electric vehicles, electricity and diesel prices, and simplified process representations. These assumptions introduce uncertainty in the results, and while the overall trends are considered robust, the exact numerical outcomes may vary under different conditions.

SKALAND case:

From an operational perspective, the electrification of the vehicle fleet at SKALAND does not significantly alter the system's ability to meet production requirements. In all scenarios, including both fixed and optimised battery capacities, the system consistently satisfies the daily ore demand, with 10 truck deliveries ensuring continuous plant operation. This indicates that battery-electric vehicles (BEVs) can provide a direct substitute for diesel-powered transport under the given operating conditions.

A key operational feature is the reliance on intermediate storage to balance the mismatch between daytime mining activities and continuous (24/7) processing plant demand. The silo plays a critical role in maintaining system stability, particularly during nighttime hours when no mining occurs. This operational logic remains fully preserved under electrification, indicating that BEVs can be integrated into the system without necessitating any structural changes.

Battery behaviour further supports the feasibility of electrification. Vehicles are primarily discharged during daytime operation and recharged at night, with only minor daytime charging events. This charging strategy reduces peak power demand and avoids the need for fast-charging infrastructure. The battery sizing optimisation results (237.8 kWh for the dumper and 268.9 kWh for the truck) closely match commercially available capacities in the case of the dumper and being below in the case of the road truck, reinforcing the practicality of the solution. Economically, the transition leads to a substantial reduction in NPC (from 12.6 MEUR to 5.0/4.98 MEUR), driven mainly by lower energy costs and high efficiency of electric systems, particularly under the favourable electricity prices in Northern Norway.

FELMICA case:

In contrast, the FELMICA case presents a more constrained and energy-intensive transport system, characterised by longer transport distances (up to 92 km) and fully daytime operations (no night shift). While electrification remains technically feasible, the operational dynamics differ more noticeably compared to the diesel baseline. The system continues to meet all ore demand in all scenarios, confirming feasibility. However, due to the long-haul distances, coordination between vehicles becomes more critical, particularly for trucks transporting ore between the mine and the processing plant. Unlike SKALAND, where storage plays a buffering role, FELMICA relies more heavily on continuous logistics coordination, making the system more sensitive to vehicle availability and performance. Battery behaviour in FELMICA highlights stronger constraints. While dumpers require relatively small battery capacities (below 100 kWh), trucks are significantly more energy-constrained due to long-distance transport. The results show that increasing truck

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battery capacity beyond standard assumptions (e.g. up to ~700 kWh) can improve system performance and economics. This underlines the importance of site-specific design and suggests that standard battery configurations may not always be optimal.

Power demand is also more variable, with peak loads reaching approximately 272 kW in the fixed battery case and reduced to 212 kW when battery sizes are optimised. While a more detailed assessment of network capacity constraints and the costs and risks associated with custom-designed BEVs would further strengthen the analysis, these results already demonstrate that battery sizing influences not only vehicle performance but also the resulting infrastructure demand profile.

From an economic perspective, electrification still results in cost reductions, but to a lesser extent than in SKALAND. The NPC decreases by approximately 27%, mainly due to higher electricity prices (138 EUR/MWh compared to 16 EUR/MWh in SKALAND) and higher overall energy demand. Battery optimisation provides an additional but modest improvement (~4%), indicating that optimisation is more relevant in constrained systems like FELMICA than in more flexible ones like SKALAND.

Cross-case insights:

Comparing both cases highlights several general trends. First, electrification is technically feasible across different mining configurations, but its performance and benefits are highly site dependent. Factors such as transport distance, operational schedule, and electricity price strongly influence both technical and economic outcomes.

Second, energy costs are the dominant driver of economic performance. While CAPEX increases significantly for electric vehicles, these costs are outweighed by reductions in operating expenses, particularly in regions with low electricity prices. However, in cases with higher electricity costs or energy-intensive transport (as in FELMICA), the economic advantage is reduced.

Third, battery sizing plays a different role depending on system constraints. In flexible systems (SKALAND), standard battery sizes are sufficient, while in constrained systems (FELMICA), optimisation can improve performance and reduce infrastructure requirements.

From an environmental perspective, the electric scenarios reduce on-site CO_2 emissions, underscoring the decarbonisation potential of electrification at the point of use. However, a complete assessment should also account for upstream and system-level emissions associated with other transport modes and processes involved in material and product flows, which may influence the overall environmental impact beyond the site boundary. Across both case studies, this corresponds to a full reduction of direct (process) emissions, meaning that the transition to battery-electric vehicles can potentially reduce nearly 100% of yearly operational CO_2 emissions associated with diesel use. While the exact annual emission values depend on site-specific fuel consumption, the results clearly demonstrate the significant mitigation potential in both FELMICA and SKALAND. However, it should be noted that upstream emissions, including electricity generation and battery production, are not included in the analysis and could affect the overall environmental performance [23].

Several limitations should be considered when interpreting these results. The optimisation model exhibits relatively large optimality gaps in some scenarios due to the computational complexity of vehicle routing and scheduling decisions. Additionally, safety-related costs are not included due to a lack of available data. These

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may include investments in fire protection systems, monitoring technologies, ventilation adjustments, and workforce training.

While the optimality gaps remain relatively high in some cases, the stability of the solutions over extended solving times supports their validity for comparative techno-economic insights.

Building on the reflections from T3.4, safety considerations fundamentally influence the feasibility and implementation of low- and zero-emission transport systems. The transition from diesel to battery-electric and hydrogen-powered technologies shifts the risk landscape from well-understood emission- and ventilation-related hazards to new challenges associated with high-voltage systems, battery safety, and, in the case of hydrogen, explosion risks. While electrification reduces traditional hazards such as emissions, heat, and noise and may also reduce ventilation requirements, particularly in underground mining, these benefits must be balanced against the introduction of new safety requirements and associated costs.

At the same time, the elimination of diesel exhaust emissions can significantly reduce ventilation requirements, leading to notable reductions in ventilation-related CAPEX and OPEX. This dual effect, introducing new safety challenges while reducing existing ones highlights the need for a balanced, system-level perspective. Safety should therefore be explicitly integrated into techno-economic assessments, as it directly influences total cost of ownership, system reliability, and operational continuity.

Furthermore, the evolving and fragmented regulatory landscape emphasises the need for harmonised standards and system-level approaches to ensure safe and scalable deployment of alternative transport technologies across different mining contexts.

9 CONCLUSIONS AND PERSPECTIVES

The study compared the investment in a new diesel fleet with the investment in a new battery-electric fleet to assess their respective economic and environmental performance, for each of the mine operation cases. The results indicate that, even though the transition to a battery-electric fleet may require higher initial CAPEX, battery-electric alternatives can provide long-term economic benefits through lower operating costs. The magnitude of these benefits is, however, influenced by site-specific conditions, including electricity and diesel prices, transport distances, vehicle utilisation, and operating conditions. The analysis did not determine the optimal timing for replacing the existing diesel vehicles with battery-electric alternatives; rather, it evaluated the economic implications of the two fleet options under comparable conditions while maintaining current demand and production levels.

The assessment provides a positive indication of the economic and environmental potential of mine transport electrification under the conditions analysed. At the same time, the results should be interpreted in the context of the assumptions and system boundaries applied in the study. Electrification enables mining operations to maintain production performance while eliminating on-site CO_2 emissions and reducing operating costs, particularly in regions with low electricity prices. At the same time, the results highlight that system design including battery sizing, charging strategies and infrastructure, must be adapted to local conditions to achieve optimal performance.

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Factors such as battery degradation, charging infrastructure requirements, and other operational constraints were not fully represented and may influence the long-term performance and cost of electric fleets. Nevertheless, within the scope of this assessment, the findings indicate that battery-electric fleet alternatives can meet the transport requirements and maintain current production levels while improving the economic and environmental performance of mine transport. Future work could further strengthen the assessment by incorporating these factors and evaluating their impact on long-term fleet performance, costs, and investment decisions.

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11 APPENDIX 1: LIST OF ELECTRIC VEHICLES

Loaders:

- Epiroc: Scooptram ST10 G, Scooptram ST14 SG, Scooptram ST14 SG
- Volvo Construction Equipment: Volvo L90 Electric, Volvo L120 Electric, Volvo L20, Volvo L25
- Sandvik: Toro® LH625iE, Toro® LH514iE, LH409E, Toro® LH518iB
- Caterpiller: R1700 XE
- Liebherr: Liebherr L 507 E
- Komatsu: Komatsu WX04B

Dumpers:

- Volvo Construction Equipment: Volvo A40 Electric, Volvo A30 Electric
- Sandvik: Sandvik TH550B
- Epiroc: Minetruck MT42 SG
- Komatsu: 930E Power Agnostic

Trucks:

- Volvo Trucks: Volvo FMX Electric, Volvo FM Electric, Volvo FE Electric, Volvo FH Electric W/Wo Areo, Volvo FM Electric Low Entry, Volvo FL Electric
- Sandvik: TH550B
- Scania: to configure

Excavators:

- Volvo Construction Equipment: EWR150 Electric, EC230 Electric, EW240 ElectricMaterial Handler, EC18, ECR18, ECR25
- Komatsu: PC4000-11E

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12 APPENDIX 2: ALTERNATIVE RESULTS FELMICA

In this appendix we add a new round of results of the FELMICA case, after adjusting the operations based on feedback from FELMICA. In this case, the demand at the conveyor belt goes down to 60 tonnes/day, spread along 8 hours. This has several consequences in the case. Since the demand is considerably lower than the 204 tonnes/day for 12 hours operation assumed in the main results of the report. This implies that only one dumper and one truck are needed, making the problem considerably easier to compute. In the following subsections we present briefly the results for the three scenarios evaluated: base case using diesel, electric alternatives, and electric alternatives with battery sizing. Please consult Section 7.1 to clarify the details of what each figure represents.

12.1 DIESEL BASE CASE

Similarly to the FELMICA cases in Section 7.1, the results are displayed in Figure 33, Figure 34, Figure 35 and Figure 36.

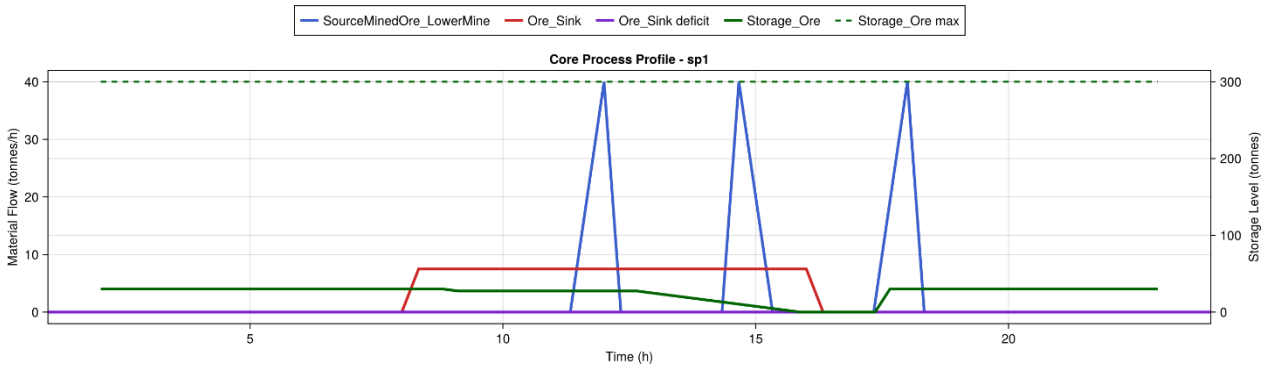

Figure 33 Main operation of the diesel base case of FELMICA with 60 tonnes/day demand during 8h

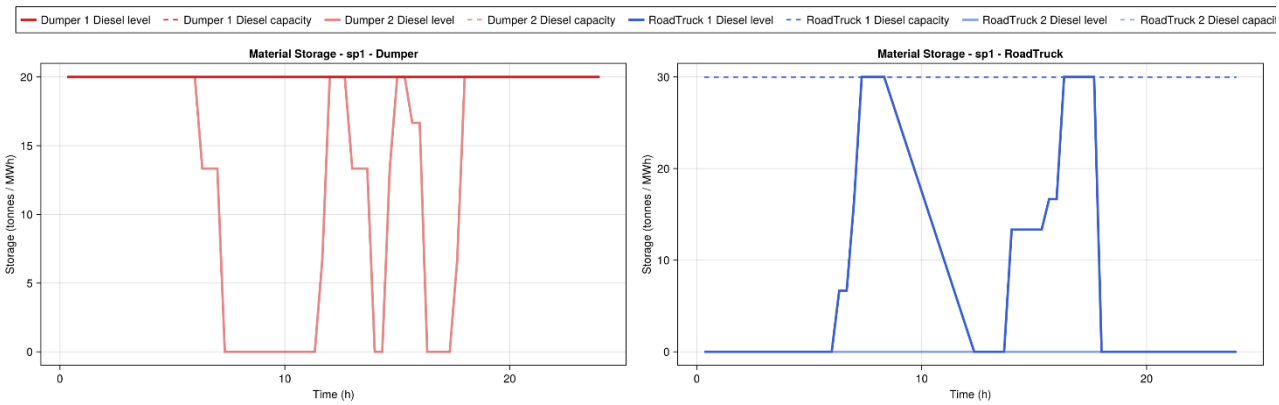

Figure 34 Material storage cargo for the diesel dumper (left) and truck (right) for the diesel base case of FELMICA with 60 tonnes/day demand during 8h

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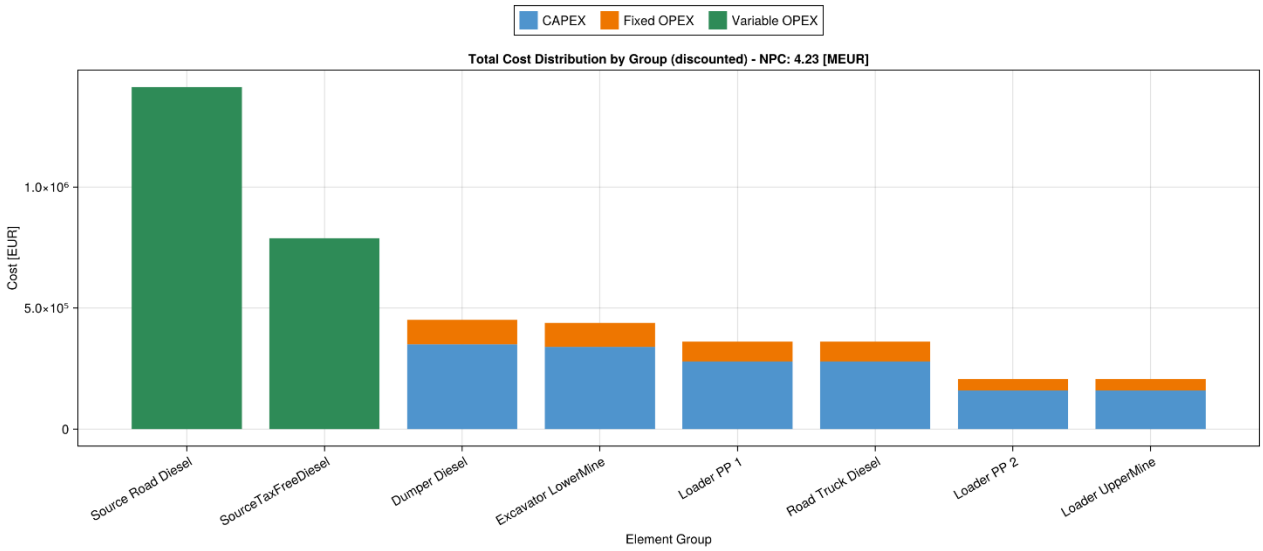

Figure 35 Cost distribution and NPC for the diesel base case of FELMICA with 60 tonnes/day demand during 8h

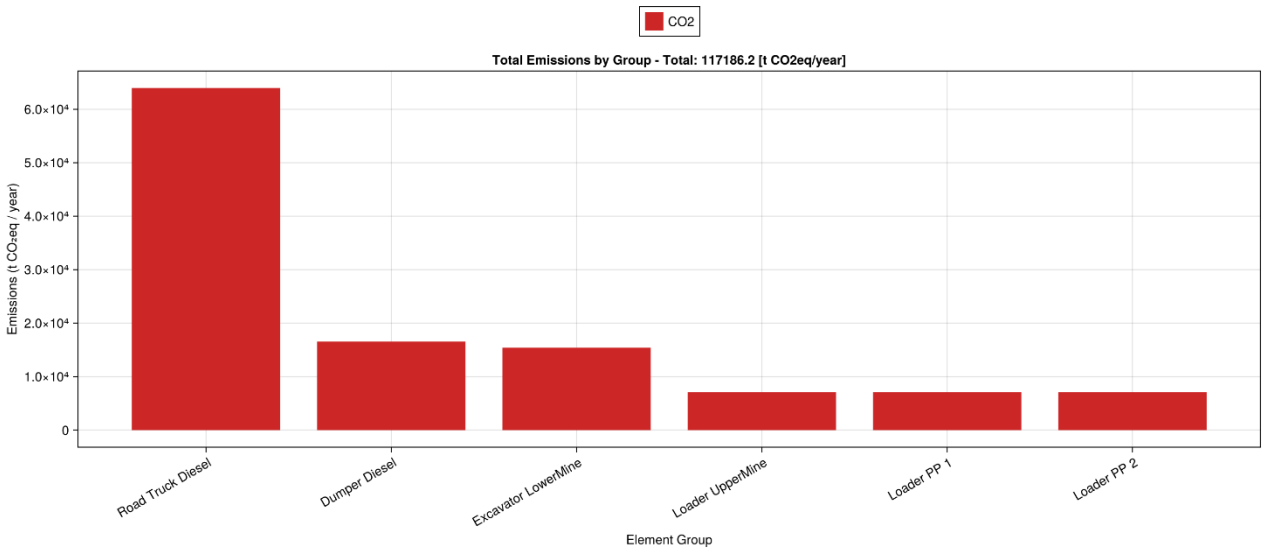

Figure 36 Yearly emissions per vehicle and total for the diesel base case of FELMICA with 60 tonnes/day demand during 8h

The main comment of this case, is the considerable reduction in NPC (from 11.32 to 4.23 MEUR), due to reduced ore demand (a 70% reduction compared to the standard results of Section 7.1.1), which makes that only one dumper and one truck are needed (thus reducing investment costs) and operational costs related to fuel consumption are reduced due lower mass transportation. Emissions also are considerably lower than the main diesel base case for FELMICA, going from to 446 to 117 kt/year

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12.2 ELECTRIC ALTERNATIVES

The main results of this scenario are presented in Figure 37, Figure 38, Figure 39 and Figure 40.

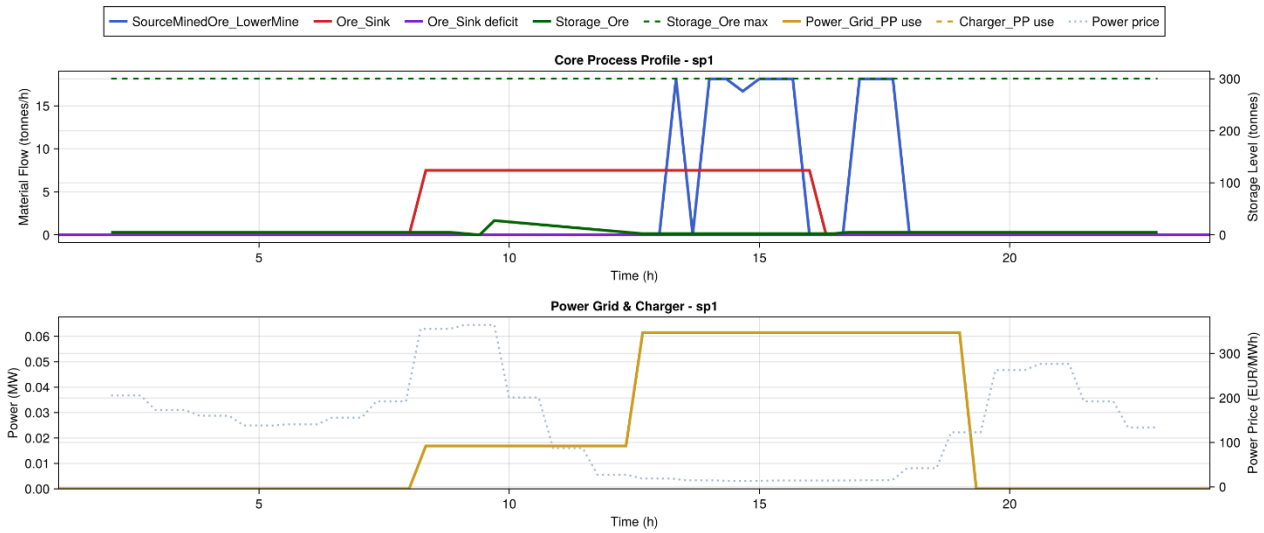

Figure 37 Main operation of the electric alternatives' scenario of FELMICA with 60 tonnes/day demand during 8h

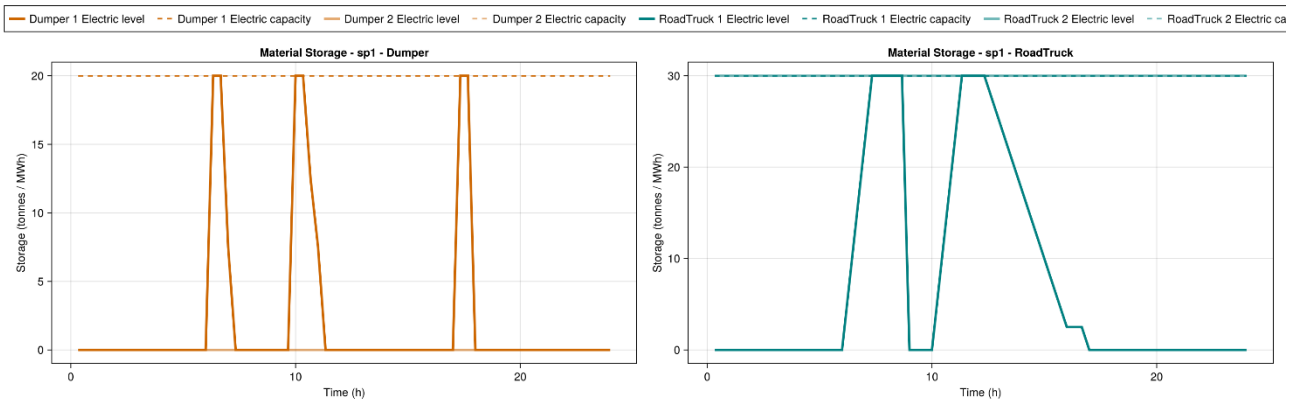

Figure 38 Material storage cargo for the electric dumper (left) and truck (right) for the electric alternatives' scenario of FELMICA with 60 tonnes/day demand during 8h

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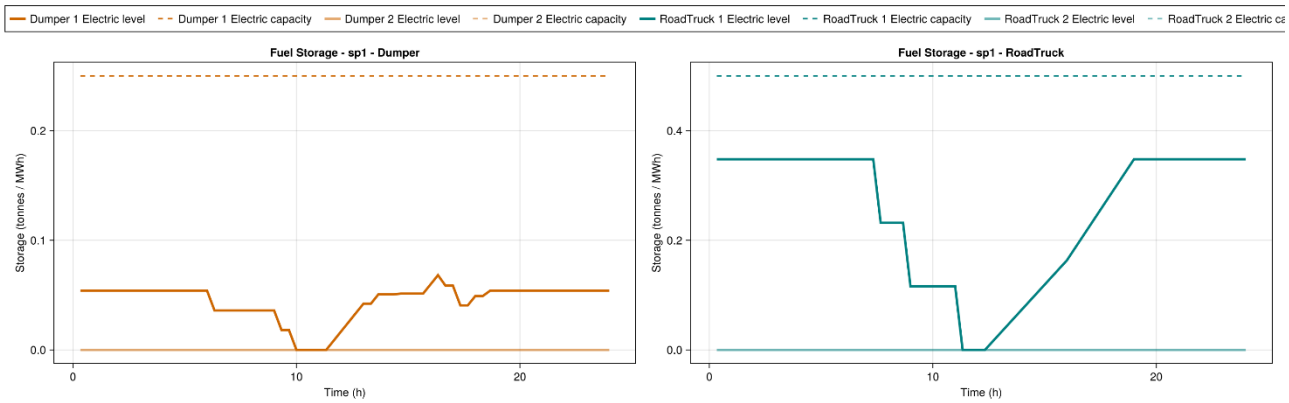

Figure 39 State of charge of the batteries of the electric dumper (left) and truck (right) for the electric alternatives' scenario of FELMICA with 60 tonnes/day demand during 8h

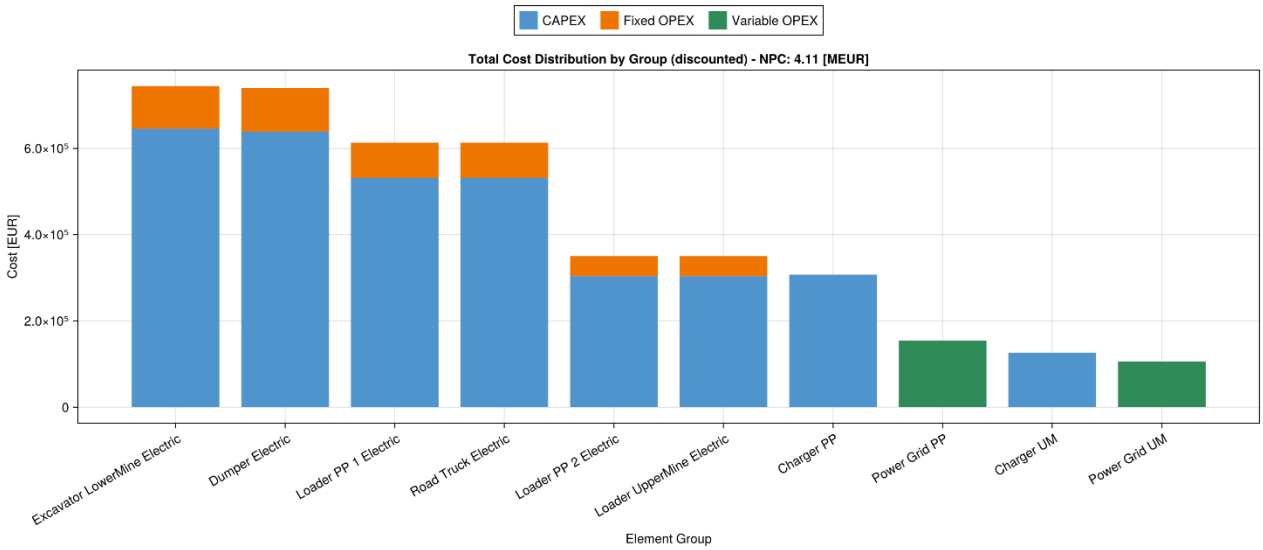

Figure 40 Cost distribution and NPC for the electric alternatives' scenario of FELMICA with 60 tonnes/day demand during 8h

The main comment of this scenario is the reduction in NPC (only 3%) compared to the equivalent diesel base case. This is because the electric alternatives' scenario has the advantage of lower fuel costs and, having less demand in this case, the cost reduction is rather limited.

12.3 ELECTRIC ALTERNATIVES WITH BATTERY SIZING

Figure 41, Figure 42, Figure 43, Figure 44 summarise the results of this scenario.

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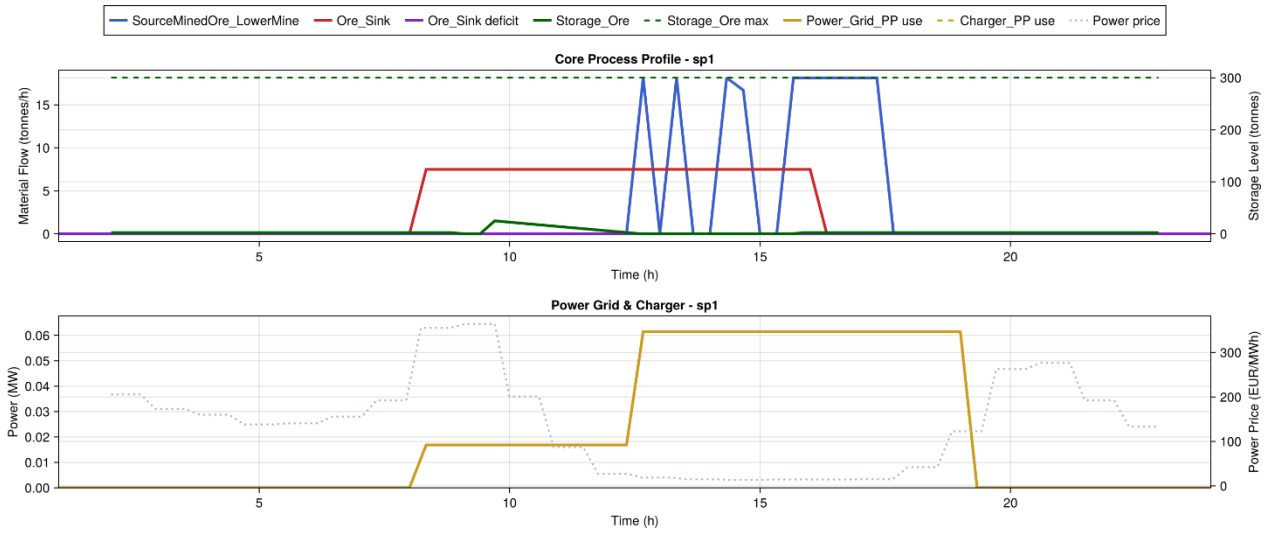

Figure 41 Main operation of the electric alternatives with battery sizing scenario of FELMICA with 60 tonnes/day demand during 8h

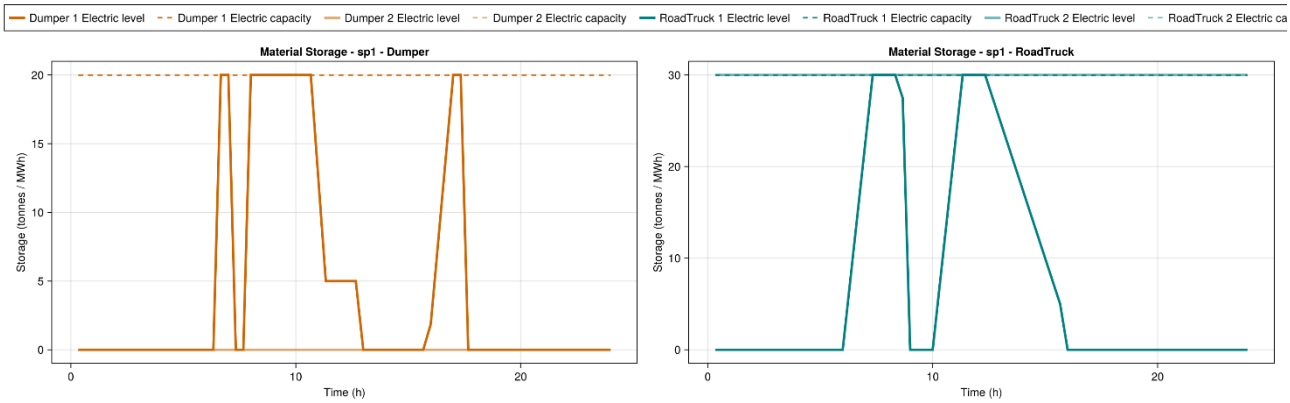

Figure 42 Material storage cargo for the electric dumper (left) and truck (right) for the electric alternatives with battery sizing scenario of FELMICA with 60 tonnes/day demand during 8h

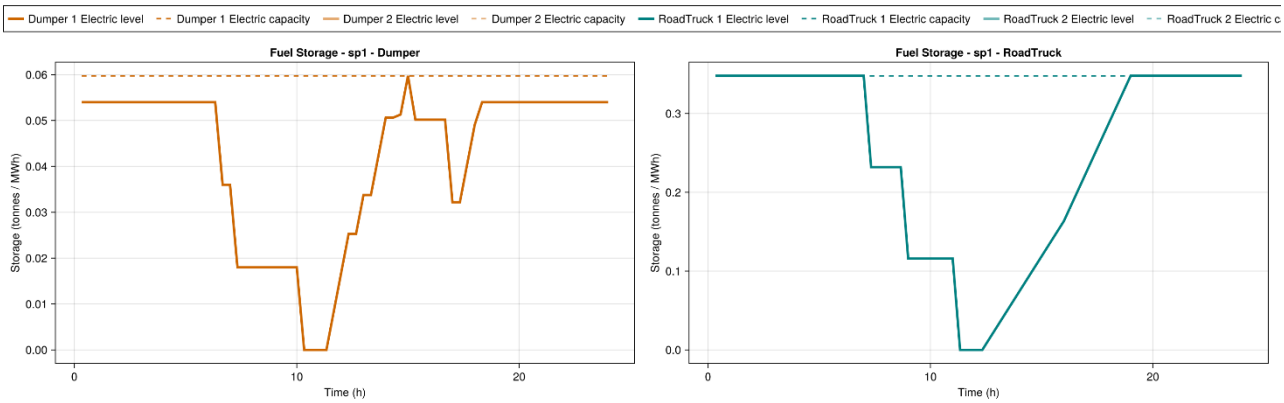

Figure 43 State of charge of the batteries of the electric dumper (left) and truck (right) for the electric alternatives with battery sizing scenario of FELMICA with 60 tonnes/day demand during 8h

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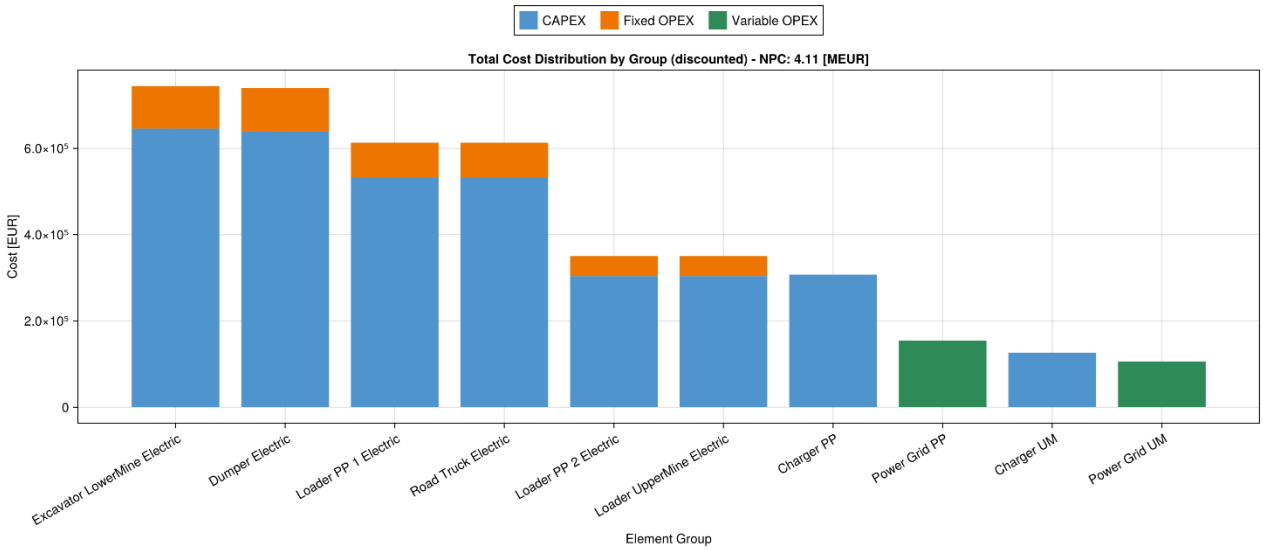

Figure 44 Cost distribution and NPC for the electric alternatives with battery sizing scenario of FELMICA with 60 tonnes/day demand during 8h

The main comment is the battery size (60 kWh for the dumper and 348 kWh), which is considerably lower than commercial batteries and the equivalent FELMICA scenario presented in 7.1.3, and that the smaller batteries do not contribute to a reduction in NPC compared to the previous scenario.

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