Investigation of decarbonization options for load and haul equipment in quarry mining with case study Ipoh quarry, Malaysia

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TU Delft

Investigation of decarbonization options for load and haul equipment in quarry mining with case study Ipoh quarry, Malaysia

By

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PREFACE

This thesis presents the results of research conducted by Thibaud Kegels on decarbonization options for load and haul equipment in quarrying operations. The research was conducted under the supervision of Dr. Masoud S. Shishvan (TU Delft), and Mark Scrutton (Imerys) in Paris, France. This research was completed as a requirement for the degree in Master of Applied Earth Sciences (European Mining Course) at TU Delft.

Title	:	Which decarbonization options for load and haul equipment in a quarrying operation are the most viable in terms of technical feasibility, cost-effectiveness and environmental impact, and how can they be implemented in quarry mining?	
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Abstract

The importance of decarbonization in various industries is growing significantly, especially when it comes to LHD equipment in the minerals and metals industry. Conventional diesel load and haul (LHD) equipment used in quarrying and mining operations have drawbacks that result in the emissions of hydrocarbon and greenhouse gases that need to be reduced to reach the Net Zero Emissions scenario. Decarbonization options that could replace diesel equipment include battery electric vehicles, green hydrogen, and alternative fuels. This project aims to give an overview of current and near future available decarbonization methods and to analyse the environmental benefit, cost effectiveness and technological feasibility of these alternatives to diesel fuel. The case study used to simulate and compare the three different decarbonization options is a mountaintop marble quarry based in Ipoh, Malaysia. A comparison has been made with Ipoh located in Malaysia and a hypothetical situation of Ipoh located in France to show the true potential of decarbonization as Malaysia does not incentivize businesses to reduce emissions due to their subsidies on the use of fossil fuel. Malaysia's energy mix consist of primarily unabated fossil fuels.

The proposed workflow involves an extensive literature review of current and near-future decarbonisation technologies to replace diesel equipment and to create a haulage network based on block model data using the software Xpac Quarry solutions and its Haulnet package. Diesel equipment is imported from the Quarry solutions database and used as a base case to compare BEV and trolley assist simulations. Hydrogen and HVO fuel consumption have been calculated manually to obtain NPVs and associated emissions. An investigation into required infrastructure and energy requirements has been done to accurately define costs and resulting total CO2eq emissions.

The results indicate that replacing diesel at Ipoh with any of the decarbonization methods will result in a negative NPV as the infrastructure requirements need extensive capital investment of which the payback period often exceeds the life of mine. The least expensive method to implement HVO fuels, followed by BEVs and green hydrogen. Furthermore, it has been found that using BEVs instead of diesel at Ipoh is more environmentally polluting because producing 1 kWh of electricity is more polluting than producing the same energy worth of diesel. Green hydrogen is the least polluting method with no greenhouse gas emissions associated with it, followed by alternative fuels. When investigating the technological feasibility of the three main decarbonization options, hydrogen is the furthest away of being technologically feasible as from now. No green hydrogen using water electrolysers has been produced at an industrial scale, and a lack of technical expertise and infrastructure is present regarding distribution, transportation, and storage. Currently, no hydrogen LHD equipment is commercially available currently, and the same applies to BEVs that could replace the current equipment used at Ipoh. To bridge this gap, alternative fuels are the best option, but the market is competitive, and supply is limited. This project has given a good overview of current possibilities and clearly shows today's options for decarbonisation and where industries stand with respect to infrastructure and equipment.

1. Introduction

Decarbonization is a pressing issue in today's world as the burning of fossil fuels is a major contributor to greenhouse gas emissions and climate change. The mining industry, which is a significant consumer of fossil fuels, must play a crucial role in the transition to a low-carbon economy. Decarbonizing the mining industry is not only a moral imperative but also a business opportunity. The reduction of greenhouse gas emissions, energy efficiency, and the use of renewable energy sources are key components of sustainable development and can help the mining sector to be more competitive and resilient in the long term.

The proposed master thesis project aims to investigate the potential of decarbonization techniques for loading and haulage equipment in the quarrying industry. The research will focus on identifying and evaluating the various decarbonization options available for load and haul equipment and assessing their feasibility in a real-world quarrying operation. The goal of the research is to provide insights and recommendations on how to reduce the carbon footprint of the quarrying industry, which is an essential step towards achieving a sustainable and low-carbon future.

Therefore, the research on decarbonization of load and haul techniques in quarries will add valuable insights to the mining industry on how to reduce their carbon footprint and contribute to the global efforts of reducing greenhouse gas emissions.

1.1 Hypothesis

Hypothesis: decarbonization options for quarry load and haul equipment include battery electric vehicles and alternative fuels. Whilst the cost for alternative fuels is significantly lower than BEVs due to the required infrastructure and change of fleet for electrifying diesel equipment. BEVs offer the lowest environmental impact, whereas alternative fuels still result in GHG emissions.

1.2 Objectives and research questions

Goal: the goal of the master thesis project is to deliver a scoping level study to clarify and document the current and near future landscape and potential of decarbonised quarry load and haul technologies in extractive operations. An investigation of suitable site selection to for the implementation of different decarbonized quarry load and haul technologies will be performed. The aim of the research is to establish an existing baseline then modelling and scoping form a financial and technological perspective, implementation of the selected decarbonized quarry load and haul technology on the site.

Objectives: The specific objectives for this project include:

1. Fully understand and compare different decarbonisation options for load and haulage equipment.
2. Assess the feasibility of implementing decarbonization options considering factors such as cost and technical requirements.

3. New insights into how the implementation of decarbonization options for load and haul equipment can contribute to reducing the carbon footprint of the quarrying and mining industry. How much CO2 can be saved and how does this translate financially?
4. Financial and technological aspects of the implementation of a chosen technology, providing an understanding of the costs, benefits, and challenges of these techniques.
5. Long-term mine plan, the research will develop a strategic long-term mine plan, including new decarbonized quarry load and haul technologies. This will provide a roadmap for the quarrying industry on how to reduce its carbon footprint and become more sustainable in the long term.

Research questions: this study plans to address the following research question:

Which decarbonization options for load and haul equipment in a quarrying operation are the most viable in terms of technical feasibility, cost-effectiveness, and environmental impact, and how can they be implemented in quarry mining?

Sub-research question:

- What are current and near future decarbonization options for load and haul equipment in quarry mining operation and how do the technical specification and performance of these options compare?
- What is the cost-effectiveness of each option, and how does it vary based on the scale of implementation?
- What is the potential environmental impact of each option, and how does it compare to conventional methods.
- What are the potential issues and challenges associated with the implementation of decarbonization technologies in quarry mining operations?
- What steps need to be taken to ensure the successful implementation of decarbonization technologies in quarry mining operations?

1.3 Methodology

The initial step will be to review available and near future decarbonised Quarry load and haul technologies including researching and working with OEMs to define technologic characteristics such as vehicle weights, charging / refill capacities and times, electricity / fuel expenditure, electricity generated from energy available at the wheels for regenerative braking, etc…. This first step to the thesis also includes an extensive literature review.

Following this will be a phase of operational and planning familiarisation of current Imerys extractive operations to identify which extractive operation I will be focussing my research on. This is also important to determine how the mine operates, what the planning strategy of the operation site is and what the strategic plans are.

The next step will be to match available and near future individual decarbonised Quarry load and haul technologies with their potential in the chosen operation(s).

Finally using existing mine planning and scheduling data, establishing a baseline, and recommending optimisations then modelling the financial and technological aspects to scoping level of implementation of the chosen technologies in their chosen sites. The study should allow a scoping level quantification and roadmap of future steps to be drawn up. Different scenarios will be made to calculate saved CO2 emissions.

Using software provided by Imerys, the final product will be a strategic long-term mine plan including new decarbonised Quarry load and haul technologies. A case study with different scenarios for the mine plan will be made. This will include looking at optimizing CAPEX, CO2 saved, Net Present Value and a profit comparison by implementing the new decarbonised Quarry load and haul technologies in the mine plan optimization.

1.4.1 Scope

The scope of this thesis project is to investigate the potential of decarbonization techniques for loading and haulage equipment in the quarrying industry. The research will focus on identifying and evaluating various decarbonization options available for load and haul equipment and assessing their feasibility in a real-world quarrying operation. The research will include the following elements:

Literature review: A comprehensive review of existing literature on decarbonization options for load and haul equipment in the quarrying industry, including electric and hybrid vehicles, alternative fuels, and energy storage systems.

Data collection and analysis: Collection and analysis of data on the current state of load and haul equipment in a quarrying operation, including vehicle weights, charging/refill capacities and times, electricity/fuel expenditure, and electricity generated from energy available at the wheels for regenerative braking. Imerys will provide data regarding fuel consumption per activity.

Feasibility assessment: An assessment of the feasibility of implementing decarbonization options in a real-world quarrying operation, considering factors such as cost, technical requirements, and regulatory compliance.

Carbon footprint reduction: An estimation of how the implementation of decarbonization options for load and haul equipment can contribute to reducing the carbon footprint of the quarrying industry.

Financial and technical aspects: Modelling and scoping the financial and technological aspects of implementation of the chosen technologies, providing an understanding of the costs, CO2 saved, tax benefits and other challenges of these techniques.

Long-term mine plan: development of a strategic long-term mine plan, including new decarbonized quarry load and haul technologies, providing a roadmap for the quarrying industry on how to reduce carbon footprint and become more sustainable in the long term.

1.4.2 out of scope

The following points will be considered out of scope for this project:

- actual implementation of decarbonization techniques
- In-depth analysis of specific decarbonization technologies or components, such as battery technology, hydrogen fuel cells, or renewable energy systems.
- Detailed design or engineering calculations for specific decarbonization measures.
- Analysis of the broader political and regulatory environment for decarbonization in the mining industry, beyond the specific context of the quarry mining operation in question.
- Detailed financial analysis or cost projections for the implementation of decarbonization technologies, beyond a high-level cost-benefit analysis.
- Detailed analysis of the social and cultural impacts of decarbonization measures

1.5 thesis outline

The thesis will start with a comprehensive literature review of current and near future decarbonization technologies. This will include battery electric vehicles, hydrogen and alternative fuels. The following chapter will talk about a roadmap to implementation for battery electric vehicles. Furthermore, the decarbonization technologies mentioned in the literature review will be assessed using a case study quarry site based in Malaysia. This chapter will look at NPV, CO2, and costs associated with said technologies. Finally, the thesis will end with a discussion of the results as well as a conclusion.

2. Literature review

This chapter will discuss electric and battery electric vehicles (BEVs), hydrogen and alternative fuels as a decarbonization option for LHD equipment in the mining industry. Subchapter 2.1 will investigate battery electric vehicles (BEV) as well as trolley assists, electrochemical energy storage systems and considerations for usage of BEVs. Chapter 2.2 will discuss hydrogen technology, fuel cell systems and the (green) hydrogen market. Chapter 2.3 will talk about alternative fuels including biodiesel, hydrogenated vegetable oils (HVO), alcohols like ethanol, methanol, and butanol.

2.1 BEV and electrification

There exist four different types of electric vehicles. Fully battery electric vehicles are the first type. This type of electric vehicle relies on an on-board battery system that supplies the car with energy. Secondly, diesel/electric vehicles have been in commercial usage for longtime. This type of vehicle relies on both diesel and a battery system for the supply of energy to the car. Fuel cell vehicles are the third type of electric vehicle. This vehicle requires a fuel cell that converts hydrogen into electricity instead of relying on a battery. Lastly, there are hybrid electric vehicles that employ two of the above-mentioned types of vehicles: diesel/electric, fuel cell/battery, or diesel/fuel cell. However, the latter of the three is not commercially available. For this chapter, the focus will rely solely on battery vehicles.

Battery vehicles are an important decarbonization technology. Looking at OEMs like Caterpillar or Mercedes or Volvo, there is an increase in products being demonstrated and becoming available on the market. Battery vehicles are becoming more and more popular. Below a list of advantages of using battery vehicles:

- BEVs offer a safer, healthier, and cleaner working environment.
- Full elimination of CO, CO_2, NO_x, SO_x, hydrocarbons, and particulate matter emissions.
- They offer reduced noise, heat, and odour levels.
- Significant reduction in ventilation requirements due to decrease in heat and no emissions.

A significant operational and capital cost in the mining and quarrying industry, especially in underground working environments, is allocated to ventilation requirements. The deeper the mine, the larger the need for ventilation to create a workable and survivable working environment. Ventilation is costly and electricity intensive, it also requires cooling infrastructure. A reduction in ventilation requirements will lead to a significant reduction in capital and operation expenditure and can lead to larger economic viability.

- The removal of exhaust from vehicles allows for airflow to be reused, further reducing ventilation requirements.
- Significant GHG emissions reduction due to no exhaust and reduction in power consumption from ventilation requirements.
- There is a reduction in refrigeration costs due to a decrease in heat loading and friction braking.

- BEVs are not idle at rest and allow for regenerative braking.
- BEVs offer higher productivity due to the usage of electric traction motors. Electric traction motors allow for low-speed torque enhancing acceleration, enhanced vehicle responsiveness and traction control.
- BEVs have fewer moving parts in their structure than diesel vehicles, so less maintenance and heat generation.

However, BEVs also have disadvantages associated with it:

- Several constraints can be applied to using battery vehicles, such as infrastructure, maintenance, electric power demand and operational requirements.
- Consideration of charging in mine planning and scheduling as well as the installation of charging infrastructure on the mine/quarry site.
- Diesel has a higher energy density and volume specific energy than currently used batteries for BEVs. Even considering energy losses from diesel combustion, transmissions and gearboxes, diesel represents a higher energy content than BEVs.
- There is no standardization of battery charging infrastructure and methods.
- Not all systems can support the extra power demand BEVs require, especially on remote sites with diesel generators.
- Recycling and disposal of batteries at their end-of-life also pose an environmental and technical issue.

2.1.1 Performance and productivity considerations

Electric vehicles can contribute to enhancing performance, ultimately leading to increased productivity (higher tonnage mined) and greater revenue. For instance, the available ventilation capacities typically influence the size of diesel engines and may restrict the fleet size based on vehicle performance. However, this constraint doesn't apply to BEVs. In the case of BEVs, units with the same payload capacity can be equipped with more powerful electric drives, resulting in improved equipment performance in terms of breakout/lifting capacity, acceleration, and speed. Of course, this improvement hinges on the mill's capacity to handle increased throughput.

Nevertheless, it's important to consider the potential impact of charging times or battery swapping durations on these performance enhancements. To ensure that BEV implementations align with the mine's expectations, a thorough investigation into these impacts on overall productivity should be conducted.

If a transition to BEVs is being considered, it's crucial to conduct data collection well in advance. This includes gathering data related to ventilation capacities, equipment performance, and analysing both diesel and BEV options. This pre-arrival data collection phase helps establish a baseline for comparison. Once the equipment is on-site, ongoing data collection becomes essential to monitor operational performance and validate the anticipated benefits. Additionally, the collected data can serve as a basis for simulations before the actual implementation of BEVs into the mining operation.

2.1.2 Capital expenditure considerations

Infrastructure costs:

When it comes to infrastructure, it is important to distinguish between greenfield and brownfield projects. A brownfield project designed for diesel equipment, especially for underground operations, might not be able to accommodate the new infrastructure requirements for BEVs, such as maintenance areas, charging infrastructure and charging locations. The costs associated with instalment of new infrastructure can be a limiting factor for brownfield operations. This is not the case for greenfield projects. In greenfield scenarios, there's room to electrify the entire mining system by mixing different types of vehicles like BEVs, diesel hybrids, traditional diesel vehicles, tethered equipment, and trolley assist systems. This applies to both open pit and underground operations.

Vehicle and Battery costs:

The upfront cost (CAPEX) for batteries can vary depending on how you choose to pay for them. BEV costs can be quite substantial and could be part of your initial capital investment (CAPEX) or be spread out as operational expenses (OPEX) through rental or leasing agreements. As technology adapts and evolves, battery and electric components improve while costs tend to decrease. OEMs are continuously refining vehicle designs for better performance and cost efficiency. Regarding battery disposal, it's worth considering that batteries might find new applications before they need to be recycled.

Ventilation and Cooling Infrastructure:

Opting for BEVs could potentially lead to a reduced need for ventilation airflow. This, in turn, could allow for smaller ventilation shafts, access drifts, and fans. The potential to save costs becomes more feasible in all-electric greenfield mines, but it might be somewhat limited for brownfield or mixed-fleet mines. Considerations to consider:

- Is there room to reduce ventilation and cooling infrastructure?
- Can the ventilation plan undergo changes?
- Is the need for ventilation and cooling primarily driven by dilution of emissions, or are there other factors like radon and dust?

Electrical Infrastructure and Power Distribution:

Considering the availability of electrical energy throughout the entire mining cycle is crucial. It's also important to assess the impact of varying daily demand loads. Switching to BEVs could potentially affect the underground distribution system, potentially requiring power infrastructure upgrades. One should also look at how charging requirements and related infrastructure might impact the mine's overall power supply. If there are plans to expand the fleet size, which might alter charging demands, these considerations should also be factored in.

Cost Implications and Charging Philosophy:

The costs associated with implementing BEVs are substantial, and your charging strategy can play a big role in the overall total cost of ownership calculations. Apart from any changes needed in the electrical distribution system, you'll need to establish a comprehensive charger system (one charger per equipment or a setup with multiple equipment sharing one charger). Chargers generate localized heat, possible requiring additional ventilation. For new projects, carefully weighing total mine power requirements becomes crucial for making decisions about self-generation or utility connections. It's worth noting that as a general trend, most projects experience a drop in net power demand due to ventilation savings, which could lead to considerable capital savings.

2.1.3 Operational expenditure considerations

Energy requirements and costs:

Transitioning to BEVs comes with significant CAPEX but allows for a reduced OPEX. In addition, one crucial distinction between diesel and BEVs is the energy consumption for the same tasks. BEVs generally require less energy to perform the same task compared to diesel vehicles. This is primarily due to the higher efficiency of electric drivetrains. Electric motors have a higher energy conversion efficiency and provide instant torque, which means they can deliver power to the wheels more effectively. Diesel engines have various energy losses due to factors like internal friction, heat dissipation, and inefficient power transmission. Furthermore, ventilation demands are generally lower for BEVs. The reduction in heat for different weight classes of internal combustion engines (ICE) and BEV can be seen in the following figure. Heat generated in an underground mine by a diesel fleet accounts for 30-50 % of total heat generated. Ventilation and cooling costs account for 40-50% of underground mine power demand in a traditional ICE fleet operation. Reducing fleet generated heat will lead to significant savings.

Implementing BEVs requires a different power distribution strategy (both for greenfield and brownfield setups). Charging equipment becomes a 100% load during charging and drops to 0% when not charging, which results in spikes in power demand. This needs careful assessment and monitoring to understand its effects on existing infrastructure and protection systems. The need to charge BEVs results in changes regarding workflow and equipment availability as well. Considerations:

- How does the total mine power change after accounting for BEVs?
- How do power requirements fluctuate throughout the day?
- How can load rebalancing be achieved?
- What's the impact of different loads on power quality?
- What adaptations will be necessary?

Maintenance Costs:

Maintenance costs are generally lower for BEVs compared to diesel vehicles. This is mostly due to the electric motor's higher reliability, as well as the presence of less moving parts in BEVs. In addition, well-designed electric drive systems include various sensors to detect issues, notify operators of faults, and provide data for predictive maintenance. This reduces the need for maintenance time, effort, and costs.

It's recommended that maintenance workshops consider the space required for chargers and the clearance needed for working on high-voltage systems.

The design of the BEV drivetrain plays a role in determining operational and maintenance savings. Vehicles that have both an electric motor and a full mechanical drivetrain (hybrid vehicles) tend to have more moving parts, potentially leading to higher maintenance expenses compared to fully electric drivetrains. Batteries also require maintenance considerations that factor into maintenance costs, equipment availability, and charging strategies.

Maintenance time and cost of BEVs can be reduced, but also comes with other non-planned operator problems: charging cable damage, receptacle/plug issues. While fixed maintenance costs might decrease for fuel stations, they could rise for charging stations and cranes. Labor cost differences are also a factor to think about.

2.1.4 Health, safety, and environment considerations

Working Environment:

BEVs offer several advantages in terms of the working environment. They produce no emissions, leading to a cleaner atmosphere. Additionally, they generate less noise, and the absence of internal combustion engines reduces vibrations and heat. This reduction in heat is especially beneficial in warm climates and deep mining conditions. It can even potentially eliminate the need for strict work/rest schedules, depending on the ventilation and cooling plan used in the mine. Moreover, the choice of energy source for BEVs can impact external emissions associated with the mine, fostering support from neighbouring communities.

Training:

Transitioning to BEVs requires a shift in skill sets and requires change management, especially related to mine rescue and new risks like battery fires and electric shocks. Those responsible for maintenance will need to acquire different competencies. It's essential to account for the costs involved in training personnel who are currently familiar with diesel equipment to effectively operate and maintain BEVs.

Sustainability and Community Acceptance:

The adoption of BEVs can align mining operations with sustainability goals related to greenhouse gas emissions and improved working conditions. Use of BEVs can help operations meet GHG reductions and work environment related sustainability commitments and improve license to operate credentials and access to certain projects.

2.1.5 Electrochemical energy storage systems

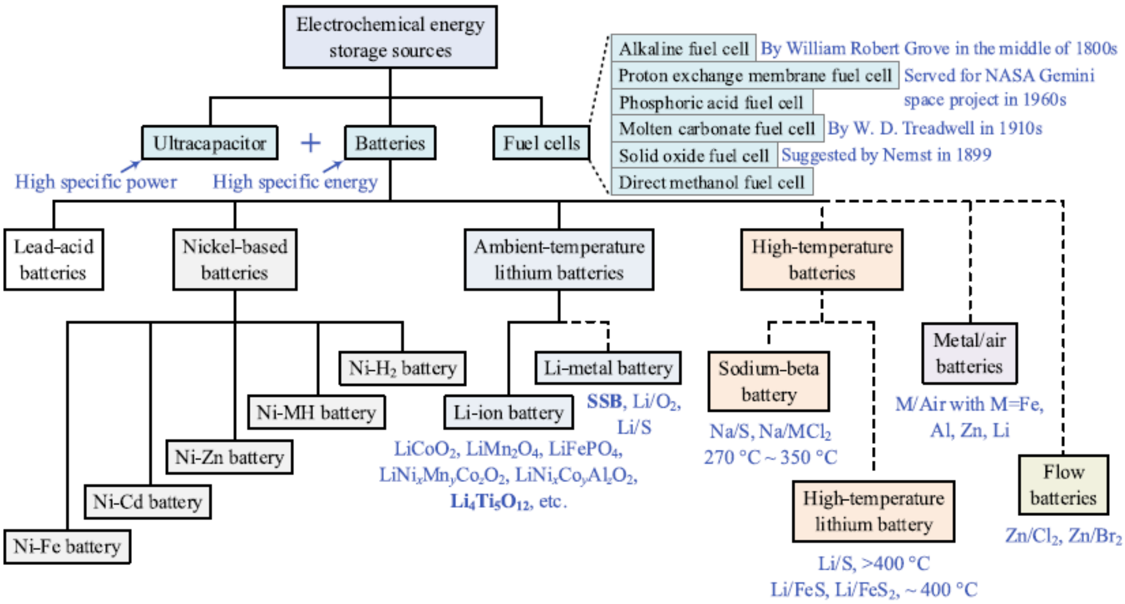


Figure 2.1: classification of electrochemical energy storage sources (Wei Liu et al., 2022)

Electrochemical energy storage systems can be defined as systems that convert chemical energy into electrical energy by process of electrochemical reaction. There are three main electrochemical storage systems: fuel cells, ultracapacitor as and batteries (Wei Liu et al., 2022). This subchapter will focus on batteries. Batteries consist of an anode and a cathode made from varying materials and contains an electrolyte and separator allowing for the movement of ions between the cathode and anode. Most advances done in battery technologies are done regarding these three main parts. BEVs have stacked batteries, or battery packs, as one battery does not suffice. Figure 2.2 shows the simplified schematic of a lithium-ion battery, where one can identify the cathode, anode, and separator with the electrolyte. The ions move between the anode and cathode during charging and discharging.

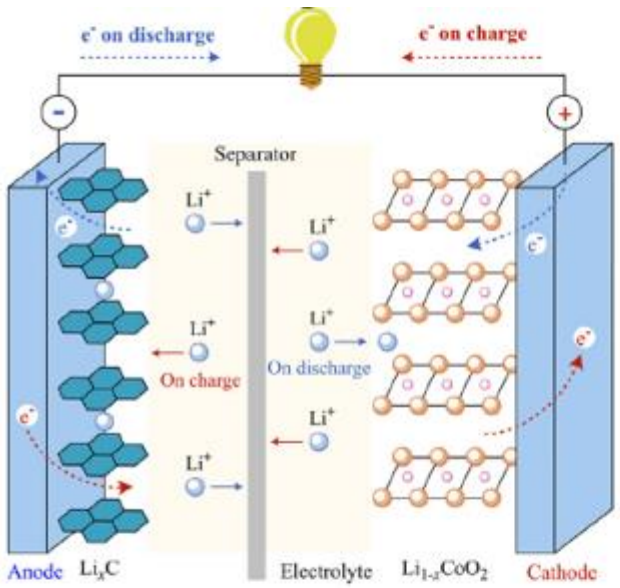


Figure 2.2: Schematic of an exemplified lithium-ion battery cell (Wei Liu et al., 2022)

Currently, lithium-ion batteries (LIBs) are most used in the automotive industry because LIBs have the highest energy density and specific energy compared to other batteries currently available. Batteries have the following KPIs (Wei Liu et al., 2022):

- Energy
  - Specific energy (Wh/kg)
  - Energy density (Wh/L)
- Power
  - Specific Power (W/kg)
  - Power density (W/L)
  - Charge acceptance (= fast charging)
- Lifetime
  - Cycle and calendar life
- Safety
  - Mechanical, electrical, and thermal safety
- Costs
  - Cost per energy content.

LIBs showcase high energy and power, long cycle life and high safety and hence are the most used nowadays.

Batteries can be classified according to three main groups: advanced batteries before lithium (e.g., lead-acid and nickel-based batteries), lithium based batteries (e.g. lithium-metal batteries, lithium-ion batteries), batteries beyond lithium (e.g. metal-air batteries, sodium-beta batteries and alternative batteries). A fourth group can be identified as emerging battery technologies. These include lithium/air and lithium sulphur batteries, solid state batteries and sodium-ion batteries.

2.1.5.1 Batteries before lithium

Lead acid

lead-acid batteries were the first commercially available batteries and dominated the market during the 20th century and have since then acquired significant advances in specific energy, power and charging speed. They are still used in cars for starting, lighting and for ignition. Lead-acid batteries are low in cost and perform well in low and high temperatures but suffer from low-energy efficiency and low specific energy (Fazel et al., 2023).

Nickel-based

nickel based batteries, like nickel-zinc or nickel-iron, were developed after lead-acid batteries. The cathode consists of nickel oxyhydroxides, the anode can cost of varying materials like iron, cadmium, zinc, metal hydroxides and hydrogen. They are low in cost and have high specific power but have low energy efficiency and low specific energy. Ni-Zn is preferred in the market due to highest cell voltage, highest specific energy, and its environmental impact, as it is non-toxic. In addition, Ni-Zn shows good resistance against over-charge and over-discharge, high performance rate and large range of operating temperatures, but has a limited life cycle time due to Zinc's solubility in electrolytes (Wei Liu et al., 2022).

Ni-MH can be found in BEVs due to its nominal cell voltage.

2.1.5.2 Lithium-based batteries

lithium metal

Lithium-metal batteries have high energy density, specific energy, and long cycle life due to their lithium anodes. They have the highest specific capacity and lowest operation potential. However, commercialization is limited since they present a fire hazard and have moderately high cost.

lithium ion

lithium-ion batteries are layered with nickel, cobalt, and manganese oxides. They have increased capacities and smaller production costs compared to other lithium-based batteries. They can be considered the preferred materials for automotive applications.

Table 2.1: Overview of cells and batteries for electric vehicles (Wei Liu et al., 2022)

Battery	Anode	Cathode	Nominal tension (V)	Specific energy (Wh kg^{-1})	Energy density (Wh L^{-1})	Capacity (Ah)	Charge (C)	Discharge (C)	Life cycle	Thermal runaway (°C)	Key features	Manufacturers	EV model	Battery energy (kWh)	Driving range (km)
Li-ion (Cobalt-rich)	C	LCO	3.7~3.9	150~200	-	-	0.7~1	1	500~1000	150	Mature	Sony	-	-	-
Li-ion (Cobalt-medium)	C	NCM	3.65~4.0	130~241	215 393 466	25 56 59	0.7~1	1	1000~2000	210	High energy	Panasonic/Sanyo LG Chem LG Chem	VW e-Golf (2015) Chevrolet Bolt (2016) Renault Zoe 50 (2017) VW ID.3 Pro S (2020) ByD Qin Pro EV NIO ES6 Standard BAIC EU5 R550	24 60 52 82 69.5 84 60.2	135~190 383 390 550 520 490 460
	C, Si or SiO-C, Si-C or SiO_x-C	NCA	3.6~3.65	200~310	673 673 683	3.2 3.4 4.75	0.7	1	500	150	High energy	Panasonic, SAFT, LG Chem	Tesla S (2012) Tesla X (2015) Tesla 3 (2017) Tesla Y (2020)	~100 ~100 ~75 75~100	595 525 500 480~595
	LTO	NCM NCA	2.3~2.5	89 70~85	200	20	1	10	3000~7000	-	Fast charge	Toshiba	Honda Fit EV (2013)	20	130
Li-ion (Cobalt-poor/free)	LTO	LMO													
	C	LNO	3.6~3.7	150~200	-	-	0.7~1	1	>300	150	Bad thermal stability	-	-	-	-
	C	LMO LMO-NCM, LMO-NCA-NCM, LMO-NCA	3.7~4.0 3.7 3.65 3.7 3.7 3.75 3.75	100~150 109 172 185 189 155 167	218 312 357 357 309 375	50 63 37 94 33 40	0.7~1	1	300~700	250	High discharge rate	LG Chem, GS, NEC, Yuasa Li Energy Japan Samsung SDI Samsung SDI AESC	Mitsubishi i-MIEV (2008) Fiat 500e (2013) VW e-Golf SEL (2016) BMW i3 (2017) Nissan Leaf (2015) Nissan Leaf S Plus	16 24 35.8 33~42.2 30 62	100~160 140 201 183~246 172 364
	C	LFP	3.2~3.3	90~130	-	-	1	1	1000~2000	270	Highly stable	A123, Valence Tech, BYD	Chevrolet Spark BAIC EC220	19 -	132 206
Li-metal	Li	O_2; S	-	-	-	-	-	-	-	-	Next generation	-	-	-	-

From table 2.1 one can notice that there are vast differences between lithium batteries. They have varying life cycles from 300-700 cycles for Li-ion cobalt poor/free to 3000-7000 cycles for Li-ion cobalt medium. They also offer different battery energies and driving ranges based on cathode and anode configuration. However, besides lithium-metal based batteries, lithium-ion batteries are used in electric vehicles.

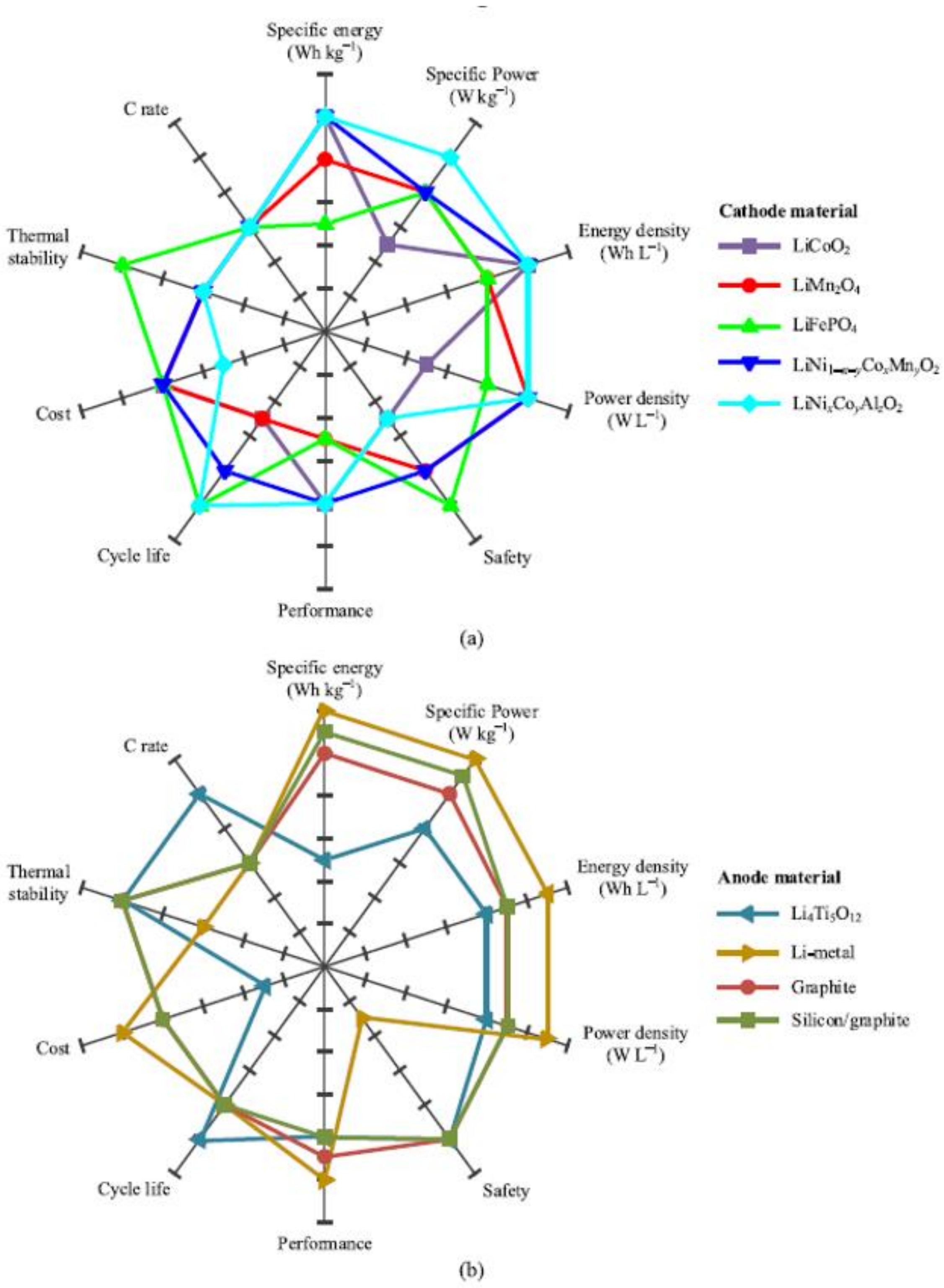


Figure 2.3: Comparison of lithium-ion and lithium-metal battery materials (a) Cathode material, (b) anode material (Wei Liu et al., 2022)

From Figure 2.3, changing the cathode and anode configurations leads to different battery KPIs. For example, while lithium metal cathodes offer the highest specific energy and specific power, they also present the lowest thermal stability and safety, as well as the highest cost.

Table 2.2 and table 2.3 offers a comparison between lead-acid, nickel-metal and different lithium-ion batteries.

Table 2.2: Specific energy of some rechargeable battery types (GMG, 2022)

Type	Specific Energy (Wh/kg)
Lead-acid	30–50
Nickel cadmium	45–80
Nickel metal hydride	60–120
Lithium-ion (cobalt)	150–250
Lithium-ion (manganese)	100–150
Lithium-ion (phosphate)	90–120
Lithium-titanate	30–110

Table 2.3: Comparison between Lead-acid, Nickel Metal hydride, and lithium-ion batteries used for EVs (Fazel et al., 2023)

Specifications	Lead Acid	Nickel Metal Hydride	Lithium-ion		
			Cobalt	Manganese	Phosphate
Main Components	Metallic Lead, Lead Dioxide, Lead Sulfate, and Sulfuric Acid	Hydrogen, Nickel Hydroxide, and Potassium Hydroxide	Lithium, Iron, Aluminium, Copper, Cobalt	Lithium, Manganese, Graphite	Lithium, Iron, Phosphate, Aluminium, Copper, Organic Electrolyte, Graphite
Specific Energy (Wh/kg)	30–50	60–120	150–190	100–135	90–120
Internal Resistance (mΩ)	<100 12 V pack	200–300 6 V pack	150–300 7.2 V pack	25–75 per cell	25–50 per cell
Life Cycle (80% Discharge)	200–300	300–500	500–1000	500–1000	1000–2000
Fast-Charging Time	8–16 h	2–4 h	3–4 h	≤1 h	≤1 h
Overcharge Tolerance	High	Low	Low, Cannot tolerate trickle charge		
Self-Discharge/Month (25 °C)	5%	30%	<10%		
Cell Voltage (Nominal)	2 V	1.2 V	3.6 V	3.8 V	3.3 V
Charge Cut-Off Voltage (V/cell)	2.40	Full Charge Detection by Voltage Signature	4.20		3.60
Charge Cut-Off Voltage (V/cell, 1C)	1.75	1.00	2.50–3.00		2.80
Peak Load Current	5C	5C	>3C	>30C	>30C
Charge Temperature	−20 to 50 °C	0 to 45 °C	0 to 45 °C		
Discharge Temperature	−20 to 50 °C	−20 to 65 °C	−20 to 60 °C		
Maintenance Requirements	3–6 Months	60–90 Days	Not Required		
Safety Requirements	Thermally Stable	Thermally Stable, Fuse Protection Common	Protection Circuit Mandatory		

One can determine that lithium-ion batteries possess the highest specific energy, longest life cycle time, fastest charging time, highest cell voltage and lowest temperature maintenance. Hence why lithium-ion batteries are most preferred.

2.1.5.3 Battery technologies beyond lithium

Lithium based batteries will eventually reach their potential limit, hence other technologies have been researched. Increasing performance of the battery KPIs will become necessary for the popularization of EVs. Energy density, fast charging and safety are the most important KPIs to be improved and are the largest reason for researching battery technologies beyond lithium (Fazel et al., 2023).

metal air

metal/air batteries have for anode a metal and air as the cathode. The anode being the limiting factor for capacity and handling procedures. These batteries could be produced as electrically rechargeable and mechanically rechargeable batteries. However, these options have both low specific power and suffer from the carbonation of their alkaline electrolytes. Zinc/air batteries shows the highest potential (Wei Liu et al., 2022).

sodium batteries

currently, only two sodium batteries have been manufactured thus far, namely sodium metal chloride and sodium sulphur batteries. Sodium batteries are known for high energy densities, good ionic conductivity and can operate at high temperatures (270-350°C)

Sodium metal chloride batteries have been produced with iron and nickel, with iron being more mature. However, nickel chloride batteries have a larger range of operating temperatures, less metallic corrosion, and higher power density.

Sodium sulphur batteries have a decreasing battery performance with increasing internal resistance. Ambient temperature sodium sulphur batteries have been researched and shows high capacity and stable cycling performance.

alternative batteries

alternative batteries have been researched and manufactured, these mainly include sodium-, zinc-, and magnesium-ion batteries. The main benefit of these alternatives to lithium is that sodium, zinc, and magnesium are much more abundant than lithium. Magnesium-ion batteries are low in cost, displays high safety and environmental friendliness. They offer high specific energy and specific power but are still immature in technology.

Zinc-ion batteries are used in energy storage systems and portable electronics, they are safe, cheap, and environmentally friendly, but do not possess high energy density. Sodium-ion batteries shows energy density slightly lower than LIBs and similar chemistry, but cell design and electrode balancing are constraints for further development.

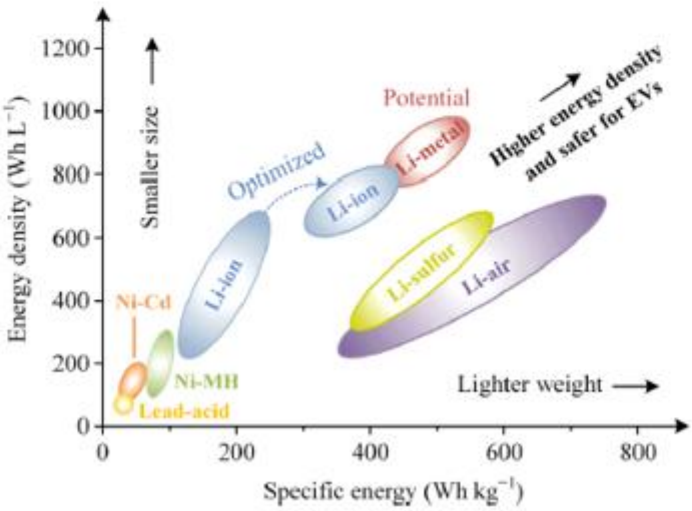


Figure 2.4: Specific energy and energy density of various batteries at cell level (Wei Liu et al., 2022)

Figure 2.4 shows the relation between specific energy and energy density of batteries mentioned.

emerging batteries

emerging battery technologies for EV applications are lithium/air and lithium/sulphur batteries, as well as sodium-ion batteries. Lithium-air batteries have four different classifications based on the electrolyte being used: Nonaqueous, aqueous, hybrid aqueous/nonaqueous and solid state. The latter, solid state batteries, are the most promising because of their high energy density, safety, and stability. Currently they have only a cycle life of 1000 and a low coulombic efficiency, and issues regarding the charge-transfer process, limit their application (Fazel et al., 2023). However, this technology is still immature and needs to be developed further.

In addition to solid state batteries, sodium-ion batteries are a promising emerging technology. It can be charged to 80% in 15 minutes at room temperature. They are lower in energy density, making them unfavourable for long distance applications for EVs, but their cheaper raw material cost and abundance of raw materials make them a favoured alternative. Other promising technologies include dual-ion batteries and dual-carbon batteries for EV applications (Wei Liu et al., 2022).

Looking at the current market and where developments are headed, Libs will remain dominant in the industry for at least the next decade, if not decades. Alternatives like solid state batteries and sodium-ion batteries are the most promising candidates. Technologies replacing batteries like move-and-charge and wireless power drive are also being proposed to remove batteries and their associated issues.

2.1.6 Functional requirements of batteries

Battery management systems

The battery management system (BMS) manages various aspects of BEV batteries in operation, such as energy consumption, battery pack voltage, current, state of charge (SOC), depth of discharge (DOD), temperature, and individual cell voltages. It regulates charging currents and directs energy from regenerative braking from the wheels back to the battery pack. It monitors battery performance, health, and operational status. It is a key component responsible for communication and interaction between the BEV, the battery pack, charging infrastructure and emergency shutdown systems.

Thermal management

Thermal management is a key role of the BMS. For example, the joule effect, which generates heat because of current flow within the battery, necessitates the BMS to monitor not only the overall battery temperature but also the individual battery cells, along with the intake and outtake of coolant. Elevated temperatures can arise from external heat sources or when voltage and/or current deviates from the operational range. Internally, excessive heat can lead to separator failure, fostering short circuits that trigger thermal runaway, subsequently giving rise to the release of hazardous and flammable gases, flame venting, and even battery assembly explosions. The impact of high temperatures extends to the rapid degradation of capacity and power, contributing to imbalances among battery cells. Adhering to testing standards, batteries must demonstrate their resilience by not exhibiting leaking, venting, disassembly, rupture, or fire. Furthermore, their voltage must not drop below 90% of the original voltage threshold.

Batteries have an optimal temperature range for efficient operation. exceeding this range results in decreased capacity, leading to reduced range or the requirement for larger capacity batteries to compensate for the necessity of supplementary systems to regulate temperatures. Due to their sensitivity to temperature fluctuations, batteries can suffer irreversible damage. Managing battery temperatures can prove challenging, especially in extreme heat conditions, often necessitating the implementation of more sophisticated cooling systems.

Cycle performance and battery life

Standards to determine service life cycles of battery packs in BEVs is critical. Repeatable testing conditions ensure comparable data within the same mine. Applicable standards focus on design and testing of battery systems, these standards include but are not limited to: E/ECE/324/Rev.1/Add.82/Rev.5, UL 1642, UL 2580, IEC 62133-2, IEC 62485-6, and IEC 62619.

Automatic shutdown

Based on safety standards, the BMS needs to be designed to monitor and automatically shut down by disconnecting battery contactors if the allowable operating parameters of temperature, current, voltage and state of charge of the battery pack and/or individual cells are exceeded.

Storage

The storing of batteries is regulated by local authorities and applicable standards. There is a maximum number of batteries stored allowed, as batteries can be damaged as a result of long-term storage. To be considered:

- What are the ideal storage temperature and range for batteries?
- What is the life of individual components with and without periodic state of charge/health check?
- What maintenance intervals should be used and how are the procedures documented?
- What equipment is required to maintain components during storage?

End of life

Batteries within EVs have a finite life and will eventually degrade. OEMs need to determine end-of-life options. Disposal should adhere to local regulations and standards. An established disposal plan is necessary as transportation is complex and disposal costs are high.

At the end of their lifecycle, batteries typically have 70-80% of the original storage capacity, allowing for "second life" applications such as power grid stabilization, residential photovoltaic storage, and storing renewable energy from sources like wind and solar. proper handling, disposal, recycling, and transportation methods during battery end-of-life needs to comply to local laws and should be done by consulting with the battery manufacturer.

safety requirements

during storing, charging and discharging, LIBs can lead to safety hazards, including: thermal runaway, venting, combustion of battery cells, rapid disassembly of battery module, venting with flame or ignition of vented gas. Different causes of these hazards can be: (dis-)charging at low temperatures, overvoltage, undervoltage, overloading, overtemperature, short-circuiting, external heating, chemical reactions, mechanical crush, shock, penetration, or rupture of a cell resulting in liquid or gas release.

Thermal runaway can be caused by several factors and can lead to different effects. It occurs when battery temperatures reach a threshold of self-heating where temperature and gasses released increase exponentially. Gases released include H_2, CO and CH_4. Carbon monoxide poisoning is of major concern during fires. Overcharging and overvoltage can lead to short-circuiting due to lithium deposits on the anode. Overdischarge and undervoltage can lead to degradation of the solid electrolyte interface layer on the anode, resulting in high temperature exothermic reaction. Overcurrent and rapid (dis-)charge can cause short-circuiting due to anode copper dissolvement in the electrolyte. Internal short-circuit due to cell defect can lead to overtemperature.

In turn, thermal runaway can lead to various other hazardous conditions. Thermal runaway, as well as an external heat source, can lead to the ignition of flammable gasses created by the breakdown of organic solvents of the electrolyte, resulting in venting. It can also lead to the combustion of battery cells. Battery modules could explode if gases created during thermal runaway are not properly vented. The vented gases in the presence of high heat or a spark can result in ignition.

If not the BMS, then sensors should be able to monitor, prevent and mitigate these hazards. Early detection and effective responsive action can prevent situations from escalating. It is also important to consider containment and cooling of battery fires as LIBs can reignite. Such methods include dry chemical powder, water pressure and water flow, aqueous film-forming foam. Furthermore, packaging, labelling, and storing should be considered carefully when transporting batteries and should be done according to standards and local regulations.

2.2 Hydrogen:

Hydrogen, an abundant chemical element in the universe, serves as a clean energy carrier. When utilized in a fuel cell system through electrochemical oxidation, hydrogen gas produces only pure water as waste and does not emit any CO_2. This research specifically investigates proton-exchange membrane fuel cells, which are widely considered to be suitable for commercial use in automotive applications, particularly for vehicles that require minimal support from hydrogen infrastructure like refuelling stations. These vehicles include fleets of taxis, buses, and logistics vehicles. Furthermore, this chapter will discuss the hydrogen market as well as hydrogen production, storage, transportation.

2.2.1 Introduction to Fuel Cells:

A fuel cell is an energy conversion device with the capacity for perpetual chemical-to-electrical energy transformation if fuel and oxidant resources are made available. The primary advantage for the utilization of hydrogen fuel cells from an environmental perspective includes the production of water as the sole by product of the energy generation process which thereby eliminates carbon dioxide emissions and airborne pollutants responsible for smog formation and health-related issues during operation. These cells show superior operational efficiency compared to internal combustion engines, delivering an electrical energy conversion efficiency that exceeds 60%. This ultimately generates fewer emissions as compared to conventionally used combustion engines. Furthermore, these fuel cells also produce minimal operational noise due to their limited number of movable components making increasing the overall health related safety of this operation.

Although different varieties of fuel cells are available in the market overall, they are all comprised of the same essential operating components. These include the anode, electrolyte, and cathode. The fuel cell functions by oxidizing the hydrogen ($H_2 \rightarrow 2H^+ + 2e^-$) at the anode. This generates cations that migrate through the electrolyte while liberating electrons that flow through an external circuit. Conversely, a reduction reaction occurs at the cathode, where oxygen is reduced to form water through the participation of cations and electrons ($4H^+ + O_2 + 4e^- \rightarrow 4H_2O$) (Ralph et al., 1998).

Since all the fuel cells in the market are predominantly composed of the three major components, based on the specific electrolyte used, the fuel cells can be classified into five main types. These include Proton-Exchange Membrane Fuel Cells (PEMFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs). Although each of these cells has unique characteristics, based on the rapid start-up time, greater range of operating temperature and high specific energy, PEMFCs have widely popularized in their utilization in fuel cell vehicles and stationary applications.

Table 2.4: Characteristics and classification of fuel cells (Lixin fan et al., 2021)

Type	AFCs	PEMFCs	PAFCs	MCFCs	SOFCs
Electrolyte	KOH	Perfluorosulfonic acid ionic exchange membrane	H_3PO_4	$Li_2\ CO_3$–K_2CO_3	$Y_2\ O_3$–ZrO_2
Conductible ions	OH^-	H^+	H^+	CO_3^{2-}	O^{2-}
Fuel	H_2	H_2, CH_3OH	Reformed fuel (CH_4, CO, H_2)	Purified coal gas, natural gas, and reformed fuel (CH_4, CO, H_2)	Purified coal gas and natural gas (CH_4, CO)
Oxidant	O_2	Air	Air	Air	Air
Catalyst	Pt/Ru	Pt/Ru	Pt	NiO	Ni
Operating temperature	65–220 °C	−40–90 °C	150–200 °C	650–700 °C	600–1000 °C
Theoretical voltage	1.18 V	1.18 V	1 V	1.116 V	1.13 V
System efficiency	60%–70%	43%–68%	40%–55%	55%–65%	55%–65%
Application	Special ground and aerospace	Electric vehicle, submarine, and mobile power source	Regional power supply (e.g., power plant)	Power station	Power station
Development	Rapid development at 1–100 kW	Rapid development at 1–300 kW with high cost	Rapid development at 1–200 kW with high cost	Mainly development at 250–2000 kW with short life	Mainly development at 1–200 kW with high preparation technology cost

Given the critical role of PEMFCs in current and future hydrogen technologies, it is important to understand the associated components of the PEMFCs. The typical structure of PEMFCs is illustrated in the figure below and individual components are discussed further on.

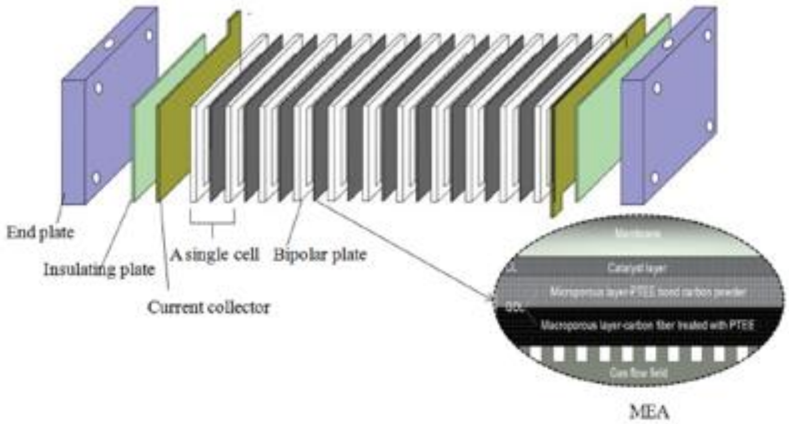


Figure 2.5: Basic structure of PEMFC stack (Lixin fan et al., 2021)

2.2.2 Fuel Cell Assembly:

MEA is a component including three layers, namely, membrane, gas diffusion layer (GDL), and catalyst layer (CL) to provide microchannels for mass transport and electrochemical reactions and influence the performance, durability, and cost of PEMFC (Adamson et al., 2008).

Proton-exchange membrane (PEM)

The proton exchange membrane plays a crucial role in facilitating the conduction of protons, separation of fuel oxidizer, and insulation of protons. The performance of PEMFCs is directly influenced by the properties exhibited by an ideal PEM. These properties include high proton conductivity rate, appropriate water content and gas permeability for molecular diffusion, excellent electrochemical stability, and mechanical durability.

The majority of fuel cells utilize Nafion membranes that typically use perfluorosulfonic acid ionomers. It is crucial to reduce production expenses and enhance the stability of PEMs since membrane production is a complex process that results in relatively high costs (~$2000 per sq.m). Subsequently, in recent years, Ballard has successfully developed a PFSA membrane with comparable properties to Nafion membranes while utilizing a simpler manufacturing process at lower costs (Ballard, 2021). If there is continued growth in market demand, mass production could significantly decrease the cost of these membranes.

While the use of perfluorosulphonic acid membranes is widespread, several alternative membranes have also been created. Notable examples include polybenzimidazole-based membranes, sulfonated aromatic (such as polyphenylsulfone and SPEEK) membranes, phosphonic-based membranes, polyphosphazene-based membranes, and polystyrene sulfonic acid membranes. These alternatives have been explored in research studies by Scofield et al., 2015.

There is a noticeable trend towards developing hybrid membranes by incorporating existing backbones with specific functions for improved efficiency. Several innovative membranes have been developed to enhance performance under different operating conditions. For example, Sutradhar et al. successfully synthesized a promising membrane called sulfonated polyphenylene benzo phenone membrane, using carbon–carbon coupling polymerization technique. This membrane demonstrated high thermal and chemical stability as well as excellent proton conductivity for use in Proton Exchange Membrane Fuel Cells.

Gas Diffusion Layer (GDL)

The Gas Diffusion Layer (GDL) plays a crucial role in the effective distribution of reaction gases on the catalyst surface and the efficient removal of water in Proton Exchange Membrane Fuel Cells. Typically hydrophobic, the GDL serves as a connection between bipolar plates and the Catalyst Layer (Fan et al., 2021). It is essential to maintain properties such as drainage capabilities, gas permeability, and electrical conductivity. The thickness of the GDL directly impacts mass transfer characteristics. Excessive thickness can lead to increased resistance and delayed mass transfer, while thin GDLs pose risks of catalyst leakage and reduced tri-phase reaction area. The impact of hydrophobic materials used in various Gas Diffusion Layers has been extensively studied (Tötzke, 2016; Lee & Huang, 2019). Different configurations for GDL also exist including carbon-polymer mixtures and layers made from carbon cloth. Carbon powders like Vulcan XC-72R and Acetylene Black influence the overall structure within the GDL itself (Sitanggang et al., 2009; Lin & Chang, 2015). However, the exact role of GDLs in facilitating the mass transport of reactants and products remains unclear due to their complex microstructure, multiphase composition, and multicomponent structure.

*Catalyst Layer (*CL)

The catalyst layer is responsible for hosting the electrochemical reactions that convert hydrogen gas and oxygen (air) into water and electricity. It typically has a thickness ranging from 5 to 100 µm, a porosity of 40-70%, and contains particles with sizes between 1 and 10nm. One of the main challenges in fuel cell technology associated with this component is the high cost of utilizing platinum as a catalyst. Platinum is widely used due to its favourable work function and chemical stability, but it accounts for more than half of the catalyst production cost.

Platinum-based catalysts are widely studied for their effectiveness, with research focused on improving both morphology and synthetic protocols. Various factors such as the type of carbon substrate, CL and catalyst properties, surface structures, and placement of CL have been investigated to understand their effects. Furthermore, current studies aim to enhance the catalytic performance of Pt by developing modified carbon-based or non-carbon-based materials as catalyst supports.

Researchers have been working on finding alternative materials that are cheaper and more durable than platinum, although they may not perform at the same level. These alternatives can be categorized into three groups: platinum-based catalysts, modified platinum-based catalysts with other metals like Cr, Cu or Co, and non-platinum-based catalysts including non-noble metal or organometallic catalysts.

Developing platinum group metal (PGM)-free and iron-free electrocatalysts is of crucial importance to break the high cost and short-term durability constraints of PEMFCs due to PGM (Fan et al. 2021). However, currently, nonplatinum-based catalysts and modified platinum-based catalysts are considered promising alternatives. However, their practical application in manufacturing and industrial settings is still a challenge. Various materials have been tested for their suitability in fuel cells with efficient performance, but finding a suitable substitute for platinum as a catalyst remains an unresolved issue that requires further breakthroughs.

Other Components

The bipolar plate serves the purpose of connecting individual cells to form a stack and facilitating the collection and transportation of current generated from one cell to another. Additionally, it ensures an even distribution of fuel gas on the anode surface and oxygen on the cathode surface. Furthermore, it aids in distributing reactant gas across electrodes where electrochemical reactions take place, as well as efficiently removing any unused gas and water.

According to Fan et al., flow channels serve multiple purposes in a fuel cell system. Low channels are responsible for the removal of water and the delivery and distribution of reactants to the membrane electrode assembly. The region between flow channels, on the other hand, is used for collecting current from one cell to another and transferring heat generated within the MEA (2021). It should be noted that only moisture present in the flow channel is removed from the system. Failure to remove moisture in a timely manner can negatively impact gas transmission, increase pressure drop within the system, cause uneven current distribution, diminish performance, and pose safety risks during operation.

The thermal management system involves the generation and transfer of heat within the fuel cell, as well as controlling the distribution of temperature. Different cooling methods can be classified based on the cooling medium used: liquid coolant cooling, phase change cooling, and air cooling. Air cooling techniques include cathode air cooling, reactive air cooling, and airflow separation. These methods are suitable for small-scale fuel cell systems with power outputs below 100 W or between 100-1000 W. In comparison to air-cooled reactors, water-cooled reactors are more commonly employed in practical applications due to their smaller size, compact structure, and higher specific heat capacity. The primary sources of heat in a fuel cell come from Ohmic heat and reaction heat (Fan et al. 2021). There are three primary methods for dissipating the excess heat generated by the fuel cell stack: internal vaporization of water, radiation of heat, and external circulation of cooling water to remove heat. Given that water is present in all essential components, water management systems is crucial to ensure efficient and stable operation of PEMFCs.

2.2.3 Recent developments:

Substantial research has been undertaken on MEA to enhance its performance and lifespan (Mo et al., 2023, Li et al. 2022, Prasanna et al., 2008) Through development in the past decade, three MEA generations called Gas Diffusion Electrode (GDE), Catalyst-Coated Membrane (CCM), and Oriented MEA have evolved to meet the demands of large-scale PEMFC commercialization, enhancing performance, lifespan, and cost-efficiency. It is important to consider that due to differences in expansion systems between gas diffusion layers and proton exchange membranes, there might be isolated areas at the interface that can cause higher internal contact resistance. Consequently, this has limited the widespread adoption of GDEs for commercial manufacturing purposes.

Ultrasonic spray techniques, which involve the combination of spraying and ultrasonic atomization, are utilized to create CCMs. This process involves pressing a gas diffusion layer with catalyst-coated sides and a proton exchange membrane, resulting in an MEA that has evenly distributed catalyst particles. As a result of this method, the prepared MEA exhibits improved performance characterized by low resistance, efficient proton transfer capability, high utilization of platinum catalysts, and cost-effectiveness compared to earlier versions. Consequently, it has found widespread use in large-scale commercial applications.

A more recent advancement in the MEA was introduced by Middelman et al. in 2002, which involved applying a uniform coating of Pt particles followed by a layer of proton conductor on oriented carbon surfaces. A nanostructured thin film, commercialized by 3M which compared to traditional Pt/C electrodes exhibit higher catalyst utilization, activity, and stability with a thickness 5% of that of traditional Pt/C electrodes). They have also shown almost full utilization of Pt resources without compromising performance or efficiency (Debe, 2013).

2.2.4 Hydrogen production:

Hydrogen comes from a variety of different energy sources and can be produced by a range of technologies. Energy sources include unabated fossil fuels such as coal, oil, natural gas, but can also come from biomass, renewable energy, and nuclear energy. The main technologies used to produce hydrogen include Steam Methane Reforming, gasification, electrolysis (IEA, 2022).

Hydrogen can be classified according to different colours based on its production method. There are 4 main colours of hydrogen. Black or brown hydrogen is hydrogen that uses coal or lignite as its feedstock and is produced through coal gasification or lignite gasification. This method inherently emits a significant amount of CO2 emissions. Coal gasification is done by reaction coal with water and steam. The resultant emissions include carbon dioxide, carbon monoxide and methane. This method is relatively cheap, with levelized costs ranging between 2.02$ - 2.47$ per kilogram of hydrogen produced (IEA, 2022). The second colour of hydrogen is grey hydrogen, where hydrogen is produced through a process called Steam Methane Reforming (SMR) or gasification, a process where CO2 as a byproduct is also emitted into the atmosphere. Grey hydrogen is currently the cheapest hydrogen with levelized costs of 1.88$ - 2.30$ per kilo of hydrogen (IEA, 2022). When looking at hydrogen for means of decarbonization, these two options are not good alternatives for fossil fuels as the amount of greenhouse gasses emitted is similar if not more. The third colour that is associated with hydrogen is blue. Blue hydrogen uses the same feedstock and production process with the sole difference that CO2 is captured by means of Carbon Capture Utilisation and Storage (CCUS) technology. Lastly, the favourite colour of hydrogen with respect to decarbonization is green hydrogen, where hydrogen is formed through renewable energy by means of water electrolysis. No carbon emissions are associated with green hydrogen.

Figure 2.6 shows the levelized cost of hydrogen production by the different technologies mentioned in 2021 and their projected levelized costs in the Net Zero Emissions by 2030 and 2050. This graph indicates that producing hydrogen using fossil fuels as feedstock is far less expensive than producing green hydrogen in 2021, making it currently uncompetitive to make green hydrogen, with costs ranging between 4$ to 9$ (IEA, 2022). The levelized cost for green hydrogen production significantly reduce by 2030 but is still not as cheap as black or grey hydrogen. In 2050, producing green hydrogen by onshore/offshore wind or by solar PV can become competitive compared to black, grey, or blue hydrogen. However, due to the recent energy crises as a result of Russia's invasion of Ukraine, fossil fuel prices have risen making the production of green hydrogen or blue hydrogen more favourable, but it is uncertain as to how long this situation will last. In the long term, fossil fuel prices are likely to decline again, having a negative economic impact on the production of green/blue hydrogen.

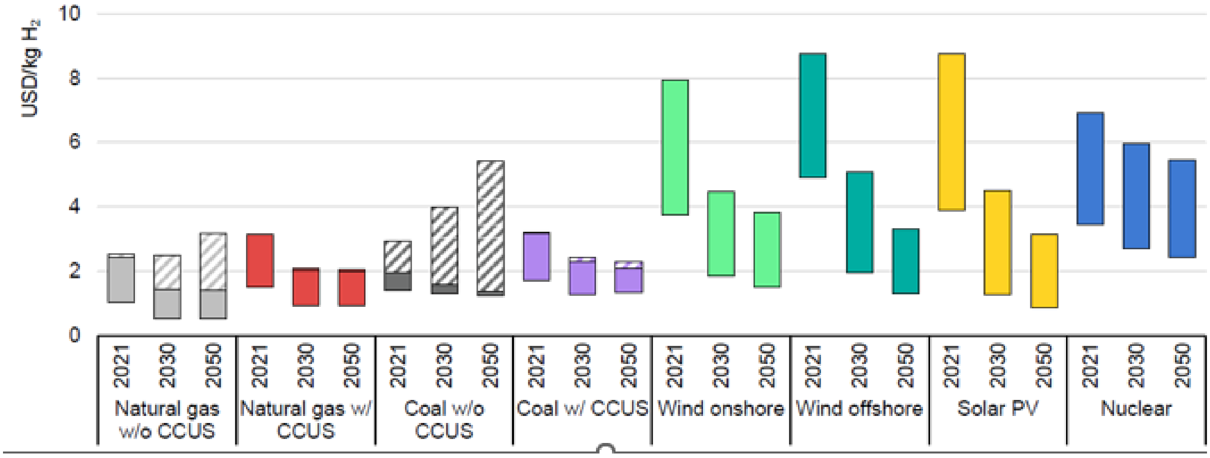


Figure 2.6: Levelized cost of hydrogen production by technology in 2021 and in the Net Zero emissions by 2050 Scenario, 2030 and 2050 (IEA, 2022)

Figure 2.7 shows the evolution of electrolyser capital costs based on project pipeline and in the Net Zero Emissions by 2050 scenario for the year 2025 and 2030. Today, the price per kW of hydrogen produced ranges between 1400$ per kW and 1800$ per kW (IEA, 2022). The price range depends on the type of electrolyser used, i.e. PEM electrolyser or an alkaline electrolyser. The lower range of the cost corresponds to alkaline electrolyser and the upper range for PEM electrolysers. Based on the current pipeline of projects, the capital costs could reduce with 60-64% by 2025 and 68-72% by 2030, with a price range of 440-500 $ per kW in 2030. If the Net Zero Emission scenario is reached by 2030, capital costs would be reduced with 78-82% totalling a price just above 300$ per kW (IEA, 2022). For the prices based on the current project pipeline, it is important to understand that not all projects reach a financial decision stage, meaning that not all projects will happen. This implies that the price range for 2025 could be well above what is projected.

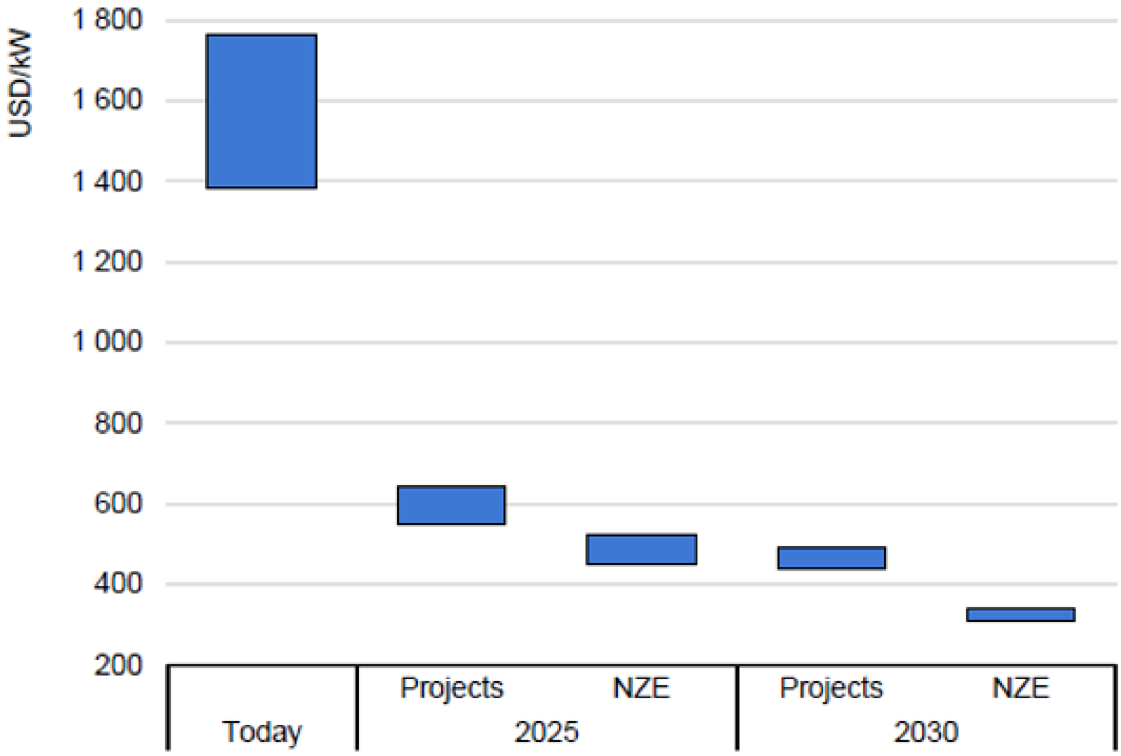


Figure 2.7: Evolution of electrolyser capital costs based on project pipeline and in the Net Zero Emissions by 2050 Scenario, 2025 and 2030 (IEA, 2022)

In 2021, 94 million tonnes of hydrogen were produced, from which 62% was made from natural gas without CCUS, 19% produced by coal, 18% produced as a by-product from the production of naphtha. 0.7% of hydrogen produced has been done by oil as a feedstock and another 0.7% comes from fossil fuels with Carbon Capture Utilisation and Storage. Only 0.04% of global hydrogen production mix comes from renewable sources (IEA, 2022). This means that only 0.74% of global hydrogen produced can be used as a green alternative to fossil fuels. These statistics have been published in 2022 by the International Energy Authority (IEA) and are visualized in figure 2.8. The 94 Mt of hydrogen produced in 2021 was responsible for the emission of 900 MT of CO2eq emissions.

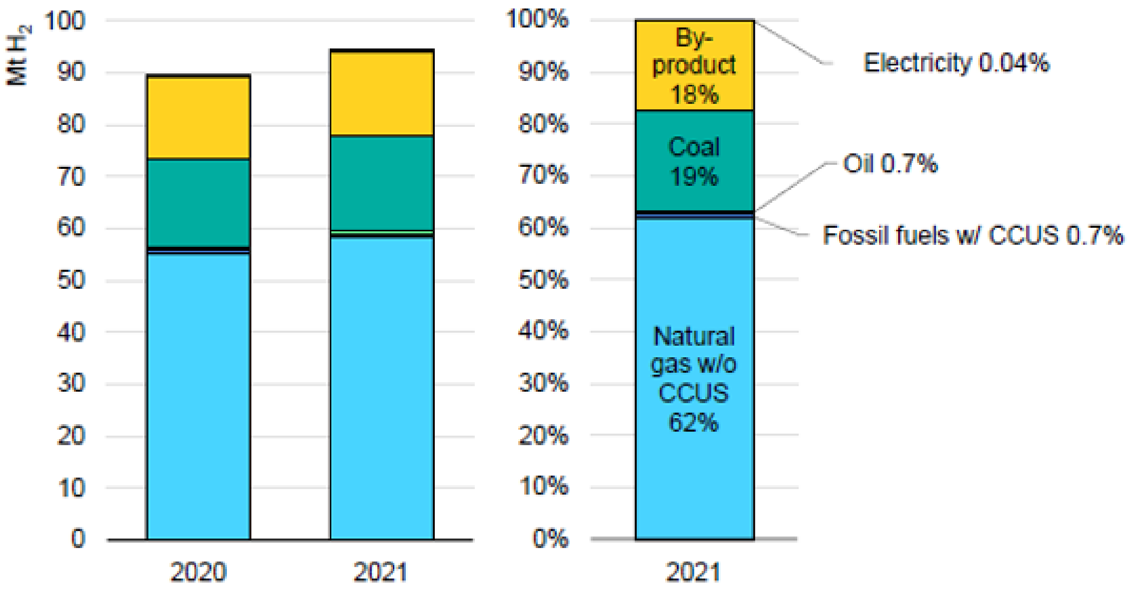


Figure 2.8: Hydrogen production mix, 2020 and 2021 (IEA, 2022)

From Figure 2.9 below, one can see that depending on the price of gas per MBtu, renewable energy as a feedstock to produce hydrogen can become competitive. The largest cost associated with hydrogen production is mainly fuel cost, followed by operational expenditure and capital expenditure.

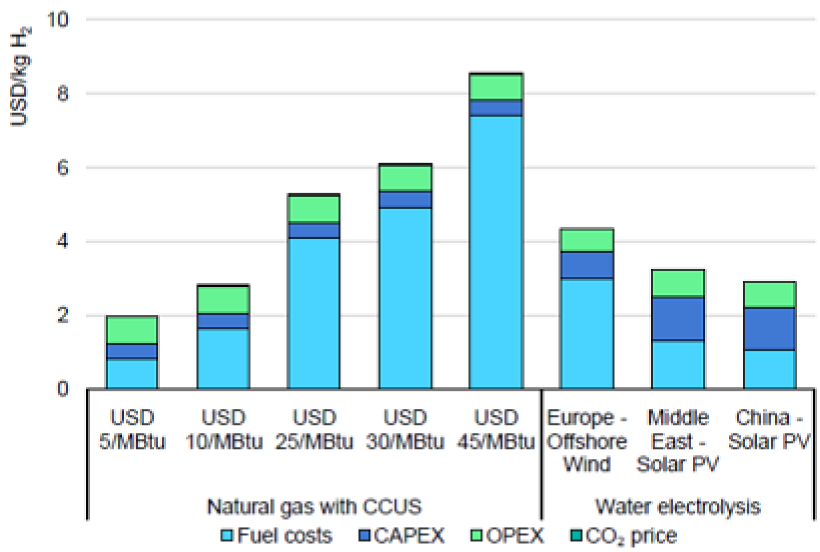


Figure 2.9: Levelized hydrogen production costs from natural gas at various gas prices and from renewable electricity, 2022 (IEA, 2022)

It is also important to note that the price of renewable energy varies from region to region, depending on the availability of wind or solar energy. The following graph shows supply cost curves for different load factors as well as hydrogen production cost for the different regions in the world with different renewable energy availability for solar and wind respectively.

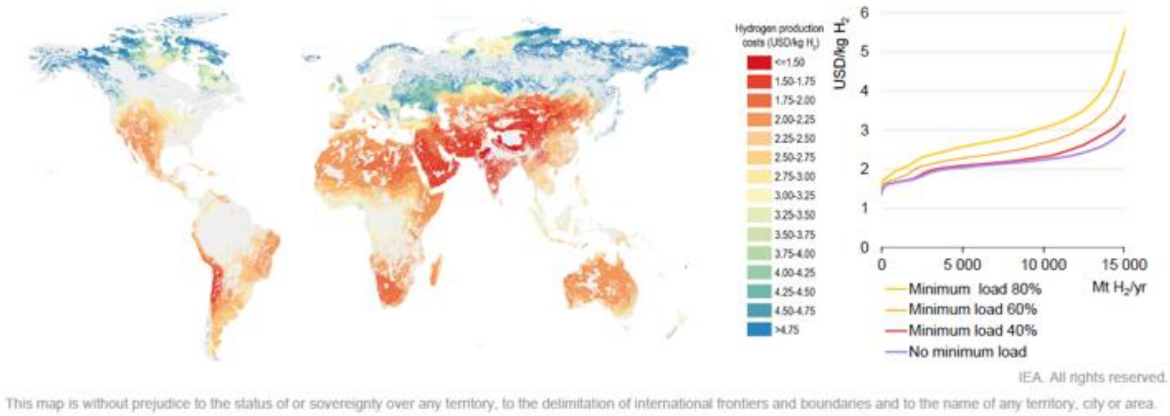


Figure 2.10: Hydrogen production costs from hybrid solar PV and wind systems for a minimum load of 40%, 2030 (left map); global supply cost curves for different minimum load factors (right figure) (IEA, 2022)

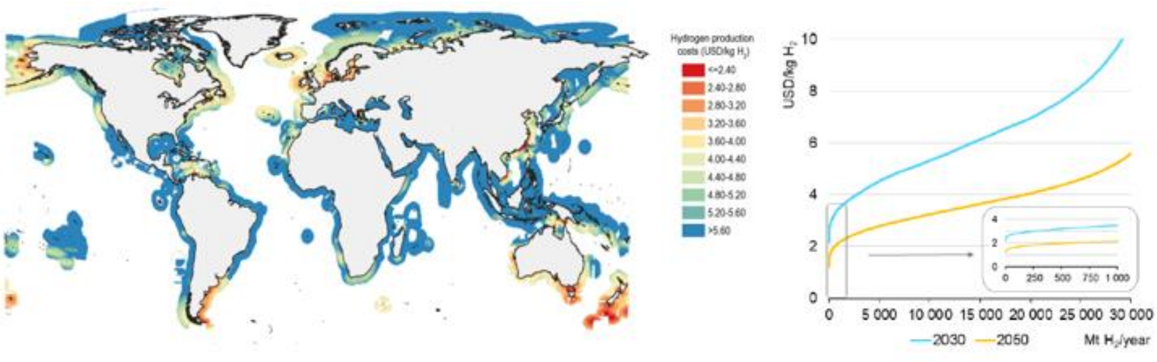


Figure 2.11: Hydrogen production costs from offshore wind in the Net Zero Emissions Scenario, 2030 (left figure); supply cost curves for hydrogen production with offshore wind electricity generation, 2030 and 2050 (right figure) (IEA, 2022)

It is logical to assume that producing hydrogen through solar PV in Siberia will not be as economically favourable as producing hydrogen through solar PV in Australia. The same goes for wind energy.

2.2.5 Hydrogen storage

Different storage methods for hydrogen are available. They can be separated into two main categories: above ground storage and underground storage.

When it comes to above ground storage, hydrogen can be compressed and stored as a gas in pressurized tanks, usually at a pressure of 350 or 525 bars. The capital expenditure required for pressurised storage is between $500 -$1000/kg of hydrogen (IEA, 2022). In addition, hydrogen can also be liquefied and stored as a liquid or implemented into other materials such as metal hydrides by means of adsorption or transformed into hydrogen liquid carriers like ammonia. However, improvements are necessary for storage with respect to safety, durability, and efficiency. If stored as a gas, the main issues are related to storage density and high-pressure conditions, as storing hydrogen needs a significant amount of space as a gaseous form in storage tanks. This can be rather expensive due to the infrastructure needed and issues with leakage are common. Storing hydrogen as a solid in metal hydrides has a greater storage density and safety and can be stored in higher volumes. Storing hydrogen as a liquid can be done by pressurizing and reducing the hydrogen temperature to -253° Celsius so that it becomes a liquid, as hydrogen at standard temperature and pressure is a gas. It can also be stored in liquid hydrogen carriers (LOHCs) like ammonia, which makes it more suitable for the transportation and handling of the hydrogen. However, hydrogen will have to be transformed from its LHOC to its original form by means of dehydrogenization of said LHOC to be used in fuel cells. The same applies to hydrogen in its solid form.

Numerous underground hydrogen storage methods exist. These include storing hydrogen in salt caverns, in depleted gas fields, in aquifers or in lined hard rock caverns. Storing hydrogen in salt caverns requires a medium amount of initial capital expenditure and results in a low levelized cost of storage. There is a limited number of opportunities to store hydrogen in a salt cavern as salt caverns have a limited amount of geographic availability and its capacity is mediocre. 25-35% of the total volume needs to be dedicated to cushion gas to maintain a sufficient pressure with hydrogen withdrawal.
Depleted gas fields require low specific investment but has a higher levelized storage cost compared to salt caverns. They require up to a double amount of cushion gas (45-60%) but has a higher storage capacity with a variable geographic availability. Like gas fields, aquifers also require a low capital expenditure with a similar levelized storage cost but requires a higher amount of cushion gas than depleted gas fields. It also has a similar geographic availability as depleted gas fields. Lastly, storing hydrogen in lined hard rock caverns requires the highest Capex of the 4 methods mentioned with a medium levelized cost of storage. It requires the smallest amount of cushion gas (10-20%) and has an abundant geographic availability.

It is important to note that not all mine sites have underground storage facilities for hydrogen and the most common method will be storing hydrogen above ground.

2.2.6 Hydrogen transportation

If hydrogen is not produce onsite using an electrolyser fed with renewable energy, hydrogen can also be made at a decentralized location or can be imported from abroad and transported to the mine site. The European Union plans on producing 10 Mt of hydrogen itself and importing another 10Mt by 2030 (IEA, 2022). This begs the question of how hydrogen will be transported to the European Union as well as to the operational sites it is required at. There are three methods used to transport hydrogen. Hydrogen can be transported by pipeline, by truck or it can be shipped, but most hydrogen is consumed in the vicinity of where it is produced. But as mine sites can be at very remote locations; transportation of hydrogen becomes an important aspect. Currently, pipelines and trucks are most used for hydrogen transportation and the first shipment of hydrogen has been done in February 2022, from Australia to Japan.

Hydrogen can be compressed and transported by a compressed gas container trucks or tube trailers. The capacity of said truck ranges between 250-460 kg (Fan et al., 2021). This method of transportation is great for large traffic volume, but it is unfit for very long distances. In addition, a tank truck with thermos-insulated cryogenic vessel can be utilised for transportation of hydrogen when it is liquefied at -253° Celsius. The capacity of this truck ranges between 360 – 4300 kg per car depending on the size of the truck (Fan et al., 2021). However, this method requires a high cost for liquefaction and energy requirements, and there is a large demand for these vehicles.

Furthermore, transportation by pipeline is a common method and is favourable for long distance transportation, even if it comes from overseas, as it is most efficient and the least expensive method of transportation for haulage distances larger than 2500 km. This can be done using existing pipeline infrastructure, of which there are millions of kilometres installed already for the transportation of natural gas or other materials. However, using existing pipeline infrastructure requires retrofitting as hydrogen is a very small molecule and can hydrogen embrittlement, where hydrogen penetrates the metal of the pipeline reducing tensile strength and ductility, resulting in possible leakages. Repurposing pipelines is less expensive than building a new network of pipelines and the difference in cost can be 50-80%. However, there is a lack of technical expertise in the retrofitting of pipelines, and retrofitting all pipelines is a multi-billion dollar investment that is not yet justified by the amount of hydrogen used in different industries. However, this can be mitigated by hydrogen blending. Blending is the injection of H2 into the current natural gas network. This is a way to promote hydrogen usage so that the market grows and that investment in pipeline repurposing can be justified. However, there is a threshold value to consider avoiding pipeline degradation and to not alter the quality of natural gas supplied. This threshold value is 2%-3%. If blended, the natural gas stream containing hydrogen will need to be deblended. The associated cost with deblending will depend on H2 concentration, pressure and required purity level of hydrogen and natural gas. The cost can vary between 0.5 – 0.8$ per kilogram of hydrogen to obtain 99.97% H2 purity needed in fuel cell for hydrogen transportation (IEA, 2022). In addition to repurposing natural gas pipeline for blending, LNG terminals will also need to be retrofitted.

This is also an area where there is a lack of technical expertise and is very costly, especially for liquefied hydrogen due its low temperature requirements. Natural gas liquefies at -162° Celsius and hydrogen at -253° Celsius. At an LNG terminal, the LNG tank is 50% of its cost, whereas a hydrogen tank is 50% more expensive than an LNG tank. But due to lack of experience, these estimates are uncertain.

The cost for using pipelines as a method of hydrogen transportation depends on the pipeline diameter as well as whether existing pipelines will be repurposed or retrofitted or if new pipeline networks will be installed. The larger the diameter of the pipeline, the higher the pipeline CAPEX per km as well as the compression costs. Table 2.5 shows the associated costs for new and repurposed hydrogen pipelines.

Table 2.5: Overview of capital costs for various design capacities of repurposed and new hydrogen pipelines (IEA, 2022)

Pipeline diameter (mm/inch)	Type	Design capacity	Pipeline capacity (GW H_2, LHV)	Pipeline CAPEX (million USD/km)	Compression capacity (MW/1000 km)	Compression CAPEX (million USD/km)	Pipeline and compression CAPEX (million USD/km)
1 200/48	New	100%	16.9	3.3	434	1.7	5.0
	Repurposed			0.6			2.3
	New	75%	12.7	3.3	183	0.7	4.0
	Repurposed			0.6			1.3
	New	25%	4.2	3.3	6	0.02	3.3
	Repurposed			0.6			0.6
900/36	New	100%	4.7	2.6	93	0.4	3.0
	Repurposed			0.5			0.8
	New	75%	3.6	2.6	40	0.2	2.8
	Repurposed			0.5			0.6
	New	25%	1.2	2.6	2	0.01	2.6
	Repurposed			0.5			0.5
500/20	New	100%	1.2	1.8	26	0.1	1.9
	Repurposed			0.3			0.4
	New	75%	0.9	1.8	6	0.02	1.8
	Repurposed			0.3			0.3
	New	25%	0.3	1.8	0.6	0.002	1.8
	Repurposed			0.3			0.3

Notes: GW = gigawatt; LHV = lower heating value; km = kilometre; CAPEX = capital expenditure. It is assumed that the investment cost of a compressor station is USD 4 million per megawatt and that 48 inch pipelines would operate at 80 bar, while 36 and 20 inch pipelines would operate at 50 bar.

Transporting hydrogen by ship has been done for the first time in February 2022 from Australia to Japan. Hydrogen can be transported as liquid hydrogen, ammonia or as a liquid organic hydrogen carrier. If transported as liquid hydrogen, hydrogen first needs to be liquified, then transported and finally transformed to a gaseous state by process of regasification. If transported as ammonia, hydrogen goes through a process called Haber-Bosch synthesis, so it is converted into ammonia. After shipping, the ammonia needs to be retransformed to hydrogen through ammonia cracking. Lastly, transporting hydrogen as a liquid organic hydrogen carrier, hydrogen will go through a hydrogenation process together with its organic carrier, and after shipping the LOHC will be dehydrogenated so that the hydrogen can be captured. Transporting hydrogen as liquid hydrogen, ammonia or as an LOHC comes with its challenges. These challenges are related to the conversion and reconversion energy losses and the low maturity of the technologies necessary. These transportation options still require significant improvement to be upscaled at an industrial level. Figure 2.12 below shows the energy losses associated with the three different methods of hydrogen shipping. Liquid hydrogen will have the largest energy availability at the end of the process, but it only has been done for the first time in 2022 and is not at industrial scale yet.

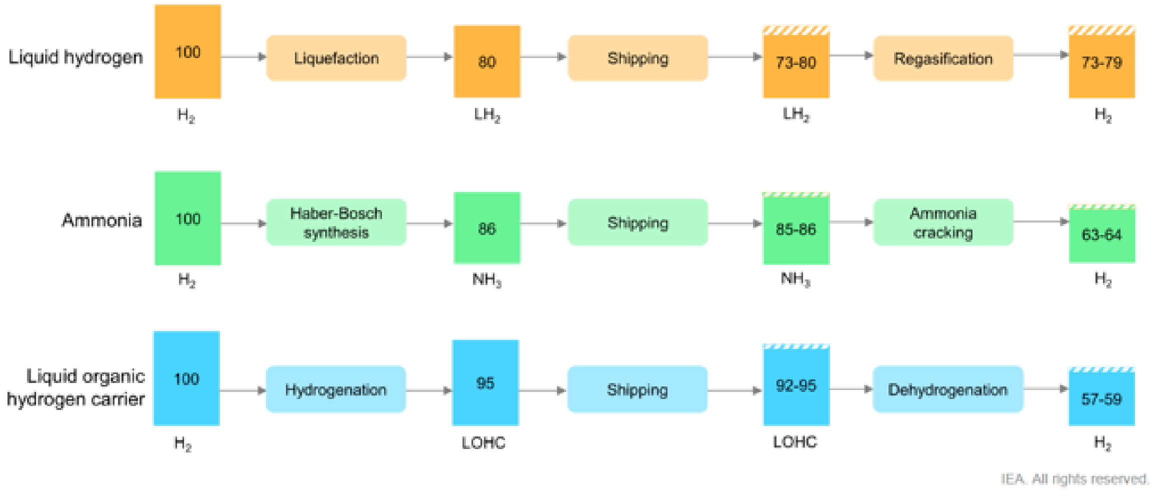


Figure 2.12: Energy available along the conversion and transport chain in hydrogen equivalent terms, 2030 (IEA, 2022)

The cost of hydrogen delivery for various transportation distances by pipeline and by ship as liquid hydrogen, LHOC and ammonia by 2030 are visualized below, indicating what the best mode of transport is for a certain distance. This graph indicates that transporting hydrogen by repurposed 48-inch pipeline will be the cheapest method for all distances, but this does not take into account the capital expenditures associated with the repurposing of said pipelines. The most expensive method for transporting by pipeline is using new 20-inch diameter pipelines. For shipping, ammonia tanker is cheapest whereas liquefied hydrogen tankers are most expensive.

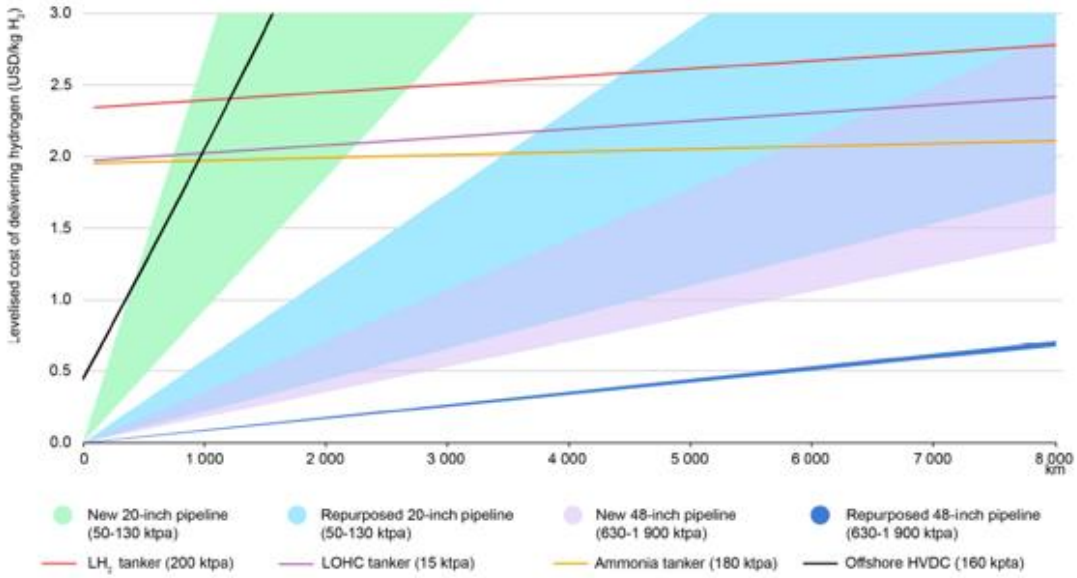


Figure 2.13: Levelized costs of delivering hydrogen by pipeline and by ship as LH2, LOHC, and ammonia carriers, and electricity transmission, 2030 (IEA, 2022)

2.2.7 Green hydrogen market maturity:

When it comes to viable decarbonisation options and alternatives to diesel fuel for LHD equipment in the mining industry, only green or blue hydrogen is an effective and promising alternative. Less than 1% of global hydrogen production comes from renewable energy or from natural gas with CCUS. When investigating the global electrolyser capacity in in 2022, around 1400 MW of electrolyser capacity has been installed of which the largest portion of capacity per electrolyser lies between 10-100 MW. Based on the project pipeline, by 2030, a total capacity of 130 GW from electrolysers are said to be reached, where most electrolyser capacities would by larger than 1000 MW, which as of today does not exist yet. The average current capacity of installed electrolysers lies around 7.0 MW.

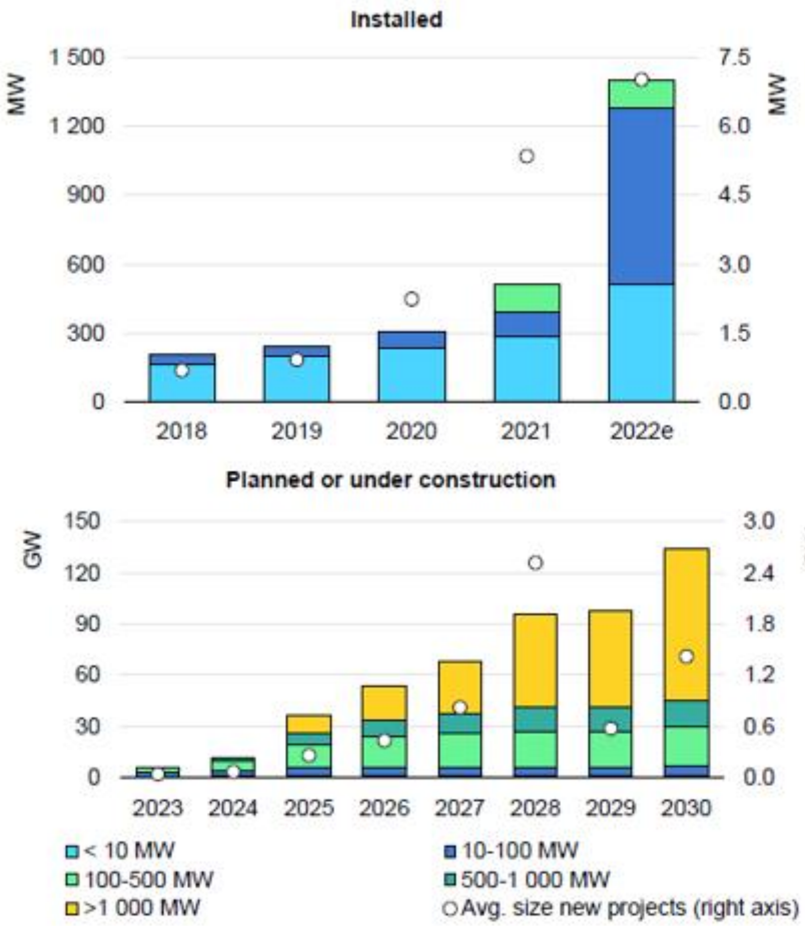


Figure 2.14: Global electrolyser capacity by size based on project pipeline, 2018-2030, (IEA, 2022)

By 2030, the largest capacity by region is planned to come from Africa, Europe, and Australia, where Europe will be the global leader followed by Australia as having the largest capacity to producer hydrogen by electrolyser capacity based on the current project pipeline. The type of electrolyser installed is still unknown, as new technologies are still being developed, but it alkaline electrolyser and PEM electrolysers will be an integral part of the foreseen capacity by 2030.

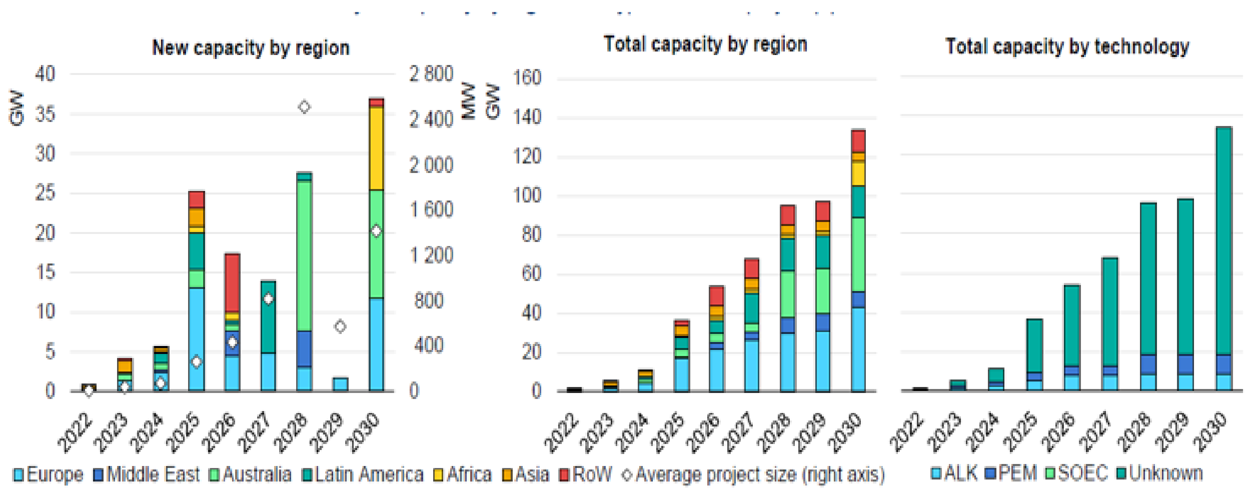


Figure 2.15: Electrolyser capacity by region and type based on project pipeline to 2030, (IEA, 2022)

But even if all projects in the current pipeline are executed, it will still not be enough to attain the Net Zero Emissions scenario by 2050 and neither will it be enough to reach the announced pledges scenario. The global electrolysis capacity from 2021 will be 260 times higher by 2030 if all project in the pipeline is reached, but it will still require twice as much to reach the Announced Pledged Scenarios by 2030. The amount of renewable hydrogen produced in 2021, which is around 0.04%, will be increased by a factor of 19 if all projects in the pipeline are executed, but still a capacity that is 6 times larger than what is in the pipeline currently will need to be reached if governments want to reach the Announced Pledges Scenario by 2030. To reach the Announced Pledges Scenario, average annual investments in low-emission hydrogen (blue or green hydrogen) need to be 21 times larger than what it was 2021. Examples of current investments in projects include a 40 GW electrolyser by the European union which equals an investment of 3.77 billion euros.

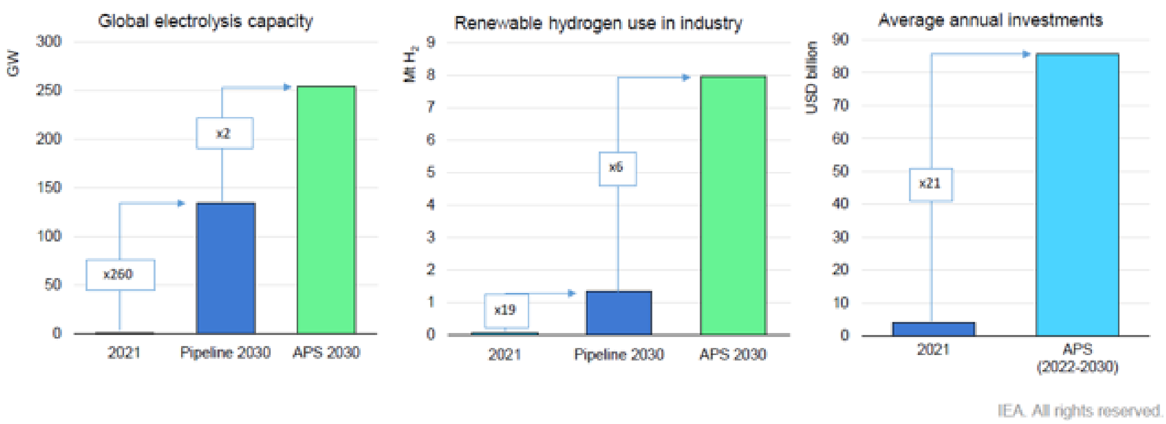


Figure 2.16: Electrolyser capacity, renewable hydrogen uses in industry and average annual investment in low-emission hydrogen in the Announced Pledges Scenario, 2021 and 2030 (IEA, 2022)

Not only is hydrogen used in the transport industry, but it also gets used in industries, refining and heating. As of 2021, the hydrogen consumption in road transport has increased from 2020 to 31 kt, representing less than 0.001% of global hydrogen production. These 31 kt of hydrogen dedicated to the transport industry is divided amongst cars, buses, and commercial vehicles. Commercial vehicles and buses have similar amounts of hydrogen consumption and are both the largest consumers of hydrogen in the transport industry. Circa 4.5 kt of hydrogen produced are for passenger vehicles, circa 12.5 kt are dedicated to buses and the remaining 14 kt of hydrogen go to light-medium and heavy commercial vehicles. These amounts show that hydrogen usage for transport is increasing, but still has a long way to go.

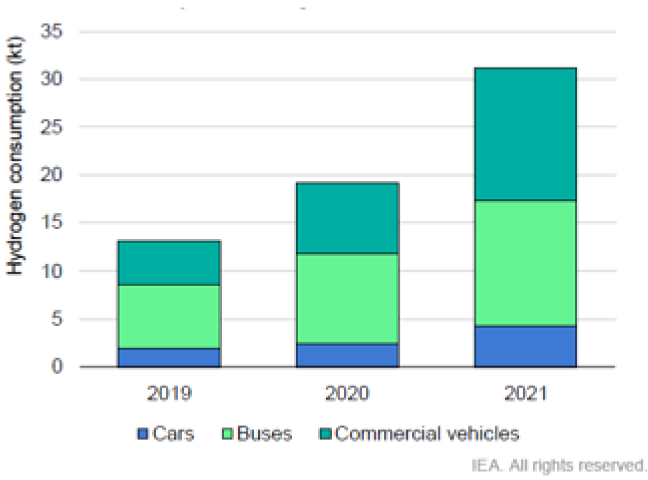


Figure 2.17: Hydrogen consumption in road transport by vehicle segment, 2019-2021 (IEA, 2022)

In June 2021, it was found that around 42 000 fuel cell electric vehicles were in use, the largest portion of which are cars, even though the smallest portion of the hydrogen consumption in the vehicle transport industry is dedicated to cars. The largest players in using hydrogen for vehicles are Korea, the United States of America, China, Japan, and Europe.

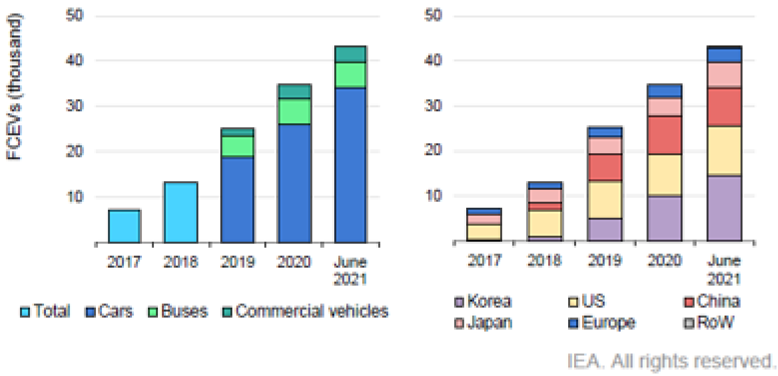


Figure 2.18: Fuel cell electric vehicle stock by segment and region, 2017-june 2021 (IEA, 2022)

Besides the number of FCEVs present in the world, it is also important to consider the amount of hydrogen refuelling stations present. In June 2022, close to a 1000 hydrogen refuelling stations are present globally, where most refuelling stations are in Japan, China, and Korea. The European Union also has a large percentage of refuelling stations. However, there are not as many FCEVs in Europe as in Asia, and hence the ratio of refuelling station to FCEVs in Europe is the lowest globally, with around 10 cars per station. For example, France had 229 FCEVs in operation, with only 44 refuelling stations. The United States currently has the largest ratio of FCEVS relative to hydrogen refuelling station, followed by China and Japan.

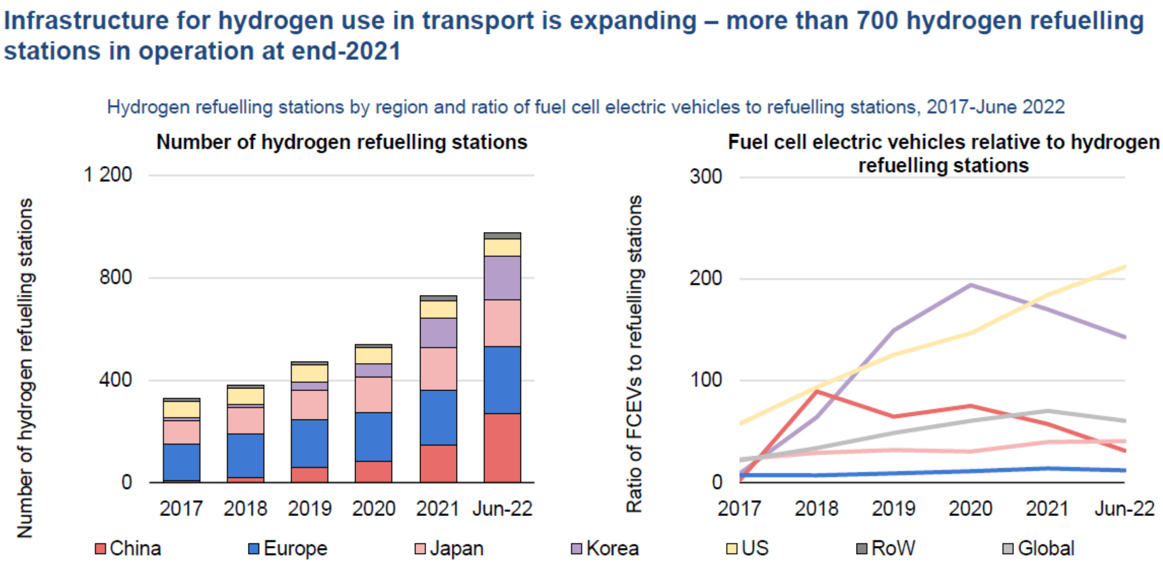


Figure 2.19: Hydrogen refuelling stations by region and ratio of FCEV to refuelling stations, (IEA, 2022)

Since commercial vehicles represent the largest consumers of hydrogen in the vehicle transport industry, the following table gives a list of available heavy-duty FCEV truck models available now and in the near future. Most OEMs that manufactured FCEVs are Asian and American companies. These include Hyundai, Hyzon, Dayun, Feichi, Shaanxi, Nikola, etc.

Table 2.6: Heavy-duty fuel cell electric truck models, 2022, (IEA, 2022)

Make	Model	Range (km)	Year available
Hyundai	XCIENT	400	2019
Hyzon	Hymax	400-680*	2021
Hyzon	FCET 8	800	2021
Dayun	E8	310	2021
Dayun	E9	430	2021
Skywell	TP11	500	2021
FAW	J7	700	2022
Feichi	FSQ4250	500	2022
King Long	KLQ4250FCEV3	510	2022
SAIC	CQ1180FCEVEQ		2022
Shaanxi	X5000		2022
Dongfeng	LZ5180	460	2022
Hyundai	HDC-6	1 280	2023
Kenworth	T680	480	2023
Nikola	Tre	800	2023
Nikola	Two	1 450	2024

The hydrogen market is growing but it is not yet at an industrial mature stage. When it comes to low-carbon hydrogen production, the most mature technologies are PEM electrolysers as well as ALK electrolysers. These methods have passed the demonstration stage and are currently the most promising technologies. However, they are not at an industrial level yet as the amount of green hydrogen produced globally in 2022 has been less than 250 kt out of the 94Mt produced. PEM and ALK are currently in market update scale and will soon be executed at industrial mature stage based on the projects that are currently in the pipeline. SOEC and AEM electrolysers infrastructure is only at a demonstration stage. CCUS technologies are currently at a demonstration stage or at the end of the demonstration stage, but only 0.7 percent of global hydrogen production has been done through CCUS. Hence, they are not at a mature level yet. Other production methods like biomass gasification is at the beginning of demonstration stage and natural hydrogen extraction as well as thermochemical water splitting is only at prototype scale.

Looking at the infrastructure readiness level for storage methods, storage tanks for all carriers currently have the highest maturity level. Other storage methods are at a prototype scale, these depleted gas fields, and aquifers. Infrastructure readiness level with respect to distribution technologies are mature, especially trucks, ammonia tankers and LOHC tankers. New pipelines are at the end of demonstration stage but not yet mature enough for industrial scale. Repurposing pipelines are at the end of the demonstration stage. Liquid hydrogen tankers are in process of being demonstrated. However, liquefying hydrogen is the most mature conversion technology, whereas LOHC conversion infrastructure is still at a demonstration stage. Ammonia cracking infrastructure is only at the end of small prototype scale.

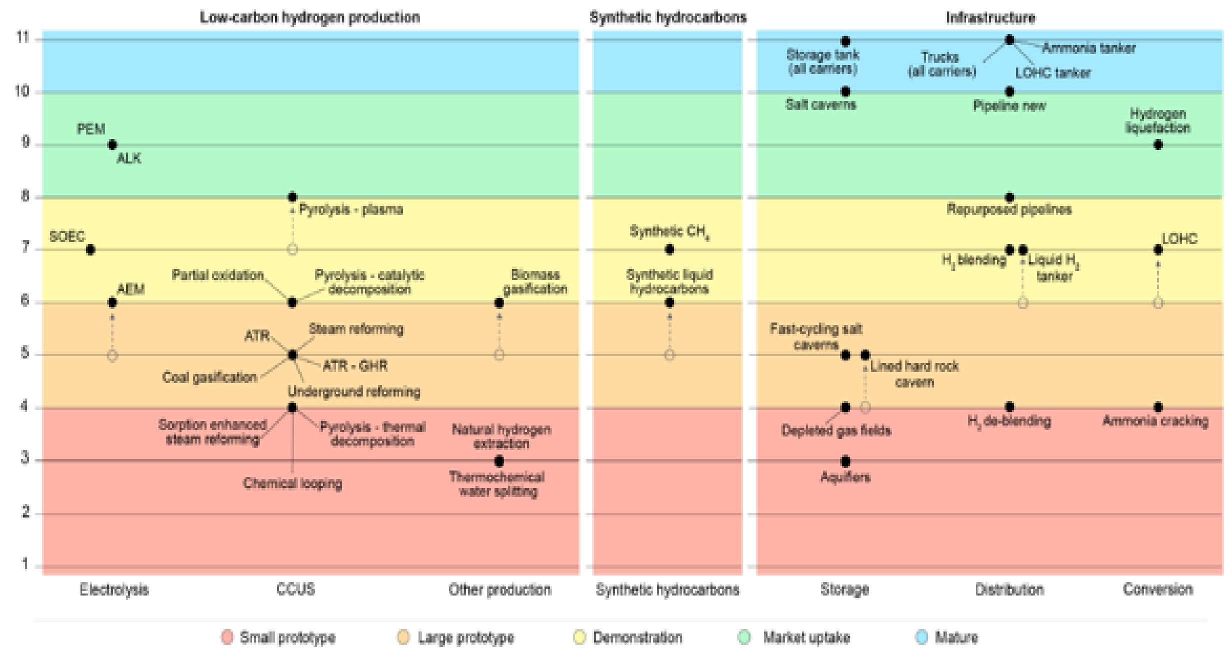


Figure 2.20: Technology readiness levels of production of low-emission hydrogen, synthetic fuels, and infrastructure, (IEA, 2022)

Investigating the technology readiness levels of hydrogen end-uses for the transport sector shows that hydrogen refuelling stations are at a market uptake stage for light duty vehicles. The same applies for hydrogen refuelling stations at 350 bars compression. Hydrogen refuelling stations at 700 bar storage compression for heavy duty road transport has only been done at small prototype scale. Hydrogen used in internal combustion engines for light duty vehicles are at the beginning of the demonstration stage whereas for heavy duty vehicles it is being demonstrated.

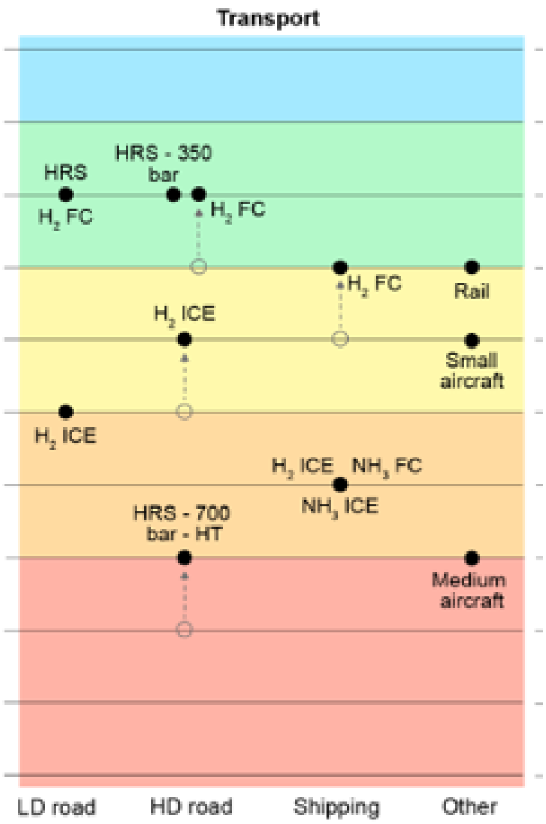


Figure 2.21: Technological readiness levels of hydrogen end users in transport industry, (IEA, 2022)

2.3. Alternative fuels

One of the decarbonization technologies that is considered a viable alternative is alternative fuels or low-carbon fuels. Moving from a current diesel fleet to a zero-emission or lower emissions technology like hydrogen or BEVs can be expensive. Besides the cost of these alternatives, the technological maturity levels are not yet at a commercial level at industrial scale. To bridge this gap, alternative fuels or low-carbon fuels can be used. alternative fuels are promoted by the EU to decarbonize the transportation sector, but they come with its own advantages and disadvantages. They do not require significant infrastructure requirements and can be implemented rather fast at an operational site. However, disadvantages include higher cost of production than fossil fuels, consumer awareness, and lack of supply and distribution. This chapter will consider different alternative fuels and their viability to replace diesel as a decarbonization tool to reduce GHG emissions on a mine site.

2.3.1: Classification of alternative fuels.

Alternative fuels are fuels that are designed to be similar in chemical and physical properties to that of fossil fuels. They are primarily made from renewable feedstocks, such as biomass (sugarcane, rapeseed, olives, waste cooking oil and agricultural waste), water and (captured) CO2 and are chemically converted into fuels that can be used by any type of transportation (aeroplanes, ships, long haul trucks, heavy duty equipment, etc.) Not only in the transportation sector do they prove their value, but also in other sectors like heat and electricity generation. Being made from" carbon-neutral" feedstocks, they can reduce GHG emissions and aid in energy diversification, energy security and energy supply, which is nowadays of critical importance to the EU.

There are four different types (generations) of biofuels to consider. The first generation of biofuels are biofuels that are based on edible food related sources. The feedstocks used for this generation are starch, cereal crops, vegetable oils, sugarcane, and animal fats. Microorganisms ferment the biomass, or the feedstock used and is chemically converted into a synthetic fuel. The second generation of alternative fuels are made from feedstocks that come from non-edible food sources. These types of non-edible foods include wood, straw, waste of edible food sources like animal fats and oil. Non-edible seeds are also used, some seeds (primarily found in India) include mahua, jatropha, Karanja and neem. A third generation of alternative fuels is made specifically from Algae. This generation is still in development/proof of concept stage and has not been used on an industrial scale, but it has promising advantages such as low cost of production. The 4th generation includes the production of alternative fuels made through advanced biochemical techniques but, like the 3rd generation, this is still in very early stages and is still experimental (Ram et al., 2023).

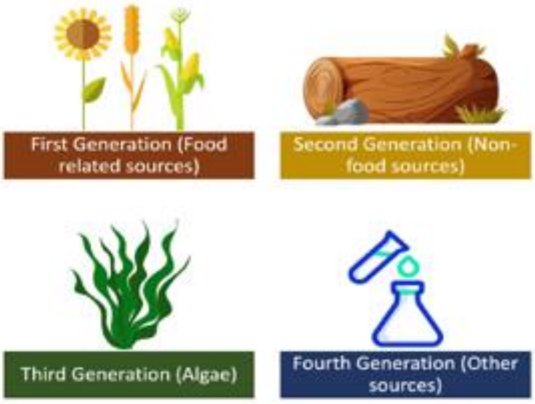


Figure 2.22: Generations of alternative fuels (Ram et al., 2023)

The most promising and widely used biofuels are biodiesel, HVO (hydrotreated vegetable oil), bioethanol and bio-methanol. Fig 5.2 shows the distribution of different alternative fuels in the transportation sector and where they are most used. The aviation industry takes 26% of alternative fuels, the shipping industry 11%. Road transport consist of the remaining 63% where 37% goes to passenger transport and the remainder to freight transport (Müller-langer et al., 2014).

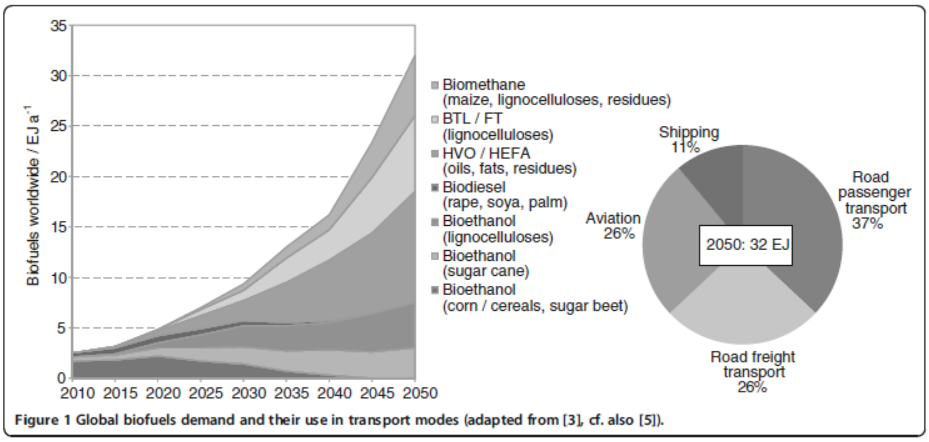


Figure 2.23: Global biofuels demand and their use in transport modes (Müller-Langer et al., 2014)

Biofuels have the advantages of being biodegradable, they are non-inflammable, are usually not toxic, they have a high combustion efficiency and are considered to be safe. However, they suffer from a low calorific value with a poor shelf life and usually result in engine wear and tear. But most importantly, they can represent an increase in nitrous oxide emissions (Ram et al., 2023). It is also important to consider that increasing the supply of 1st and 2nd generation alternative fuels implies increasing food production or non-edible food production. One cannot consider it renewable to grow extra amounts of food just for the production of fuel or paying farmers to convert their food crops to non-edible sources for the increase of alternative fuel production. Animal fats from slaughterhouses are a common source, increasing the consumption of animals is not a renewable method of generating alternative fuels (Ram et al., 2023).

Furthermore, these low-carbon fuels can be used in their pure form or be blended in with fossil fuels. For example, a biodiesel called B40 contains 40% biofuel and 60% fossil fuel. Internal combustion engines (ICE) can support up to 20% (or B20) biofuel blended with fossil fuels without requiring any engine modifications (Ram et al., 2023).

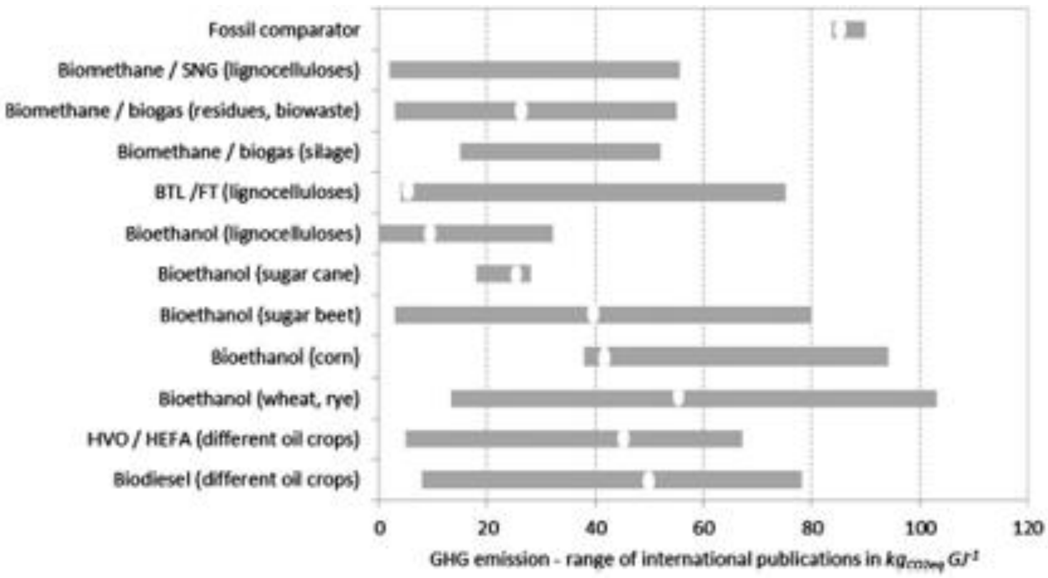


Figure 2.24: Comparison of GHG emissions (Müller-Langer et al., 2014)

Figure 2.24 shows a comparison of GHG emissions based on a variety of literature, showcasing the range of emissions a alternative fuel can have. This range depends on the feedstock used as well as the chemical process behind the production. To compare with fossil fuels, one can see that some fuels like bioethanol from corn or wheat and rye an lead to even more GHG emissions than fossil fuels. One can also determine that the 5 different bioethanols listed have significant different ranges of GHG emissions. So, to accurately determine the emissions associated with alternative fuels, one must have a clear understanding of the feedstock and chemical processes used. There is no clear “Champion” of alternative fuels. However, favourites include biodiesel and HVO fuels.

2.3.2: Biodiesel

Biodiesel is an environmentally friendly and renewable energy alternative fuel synthesized through chemical processes involving different feedstocks like vegetable oils, animal fats or waste cooking oil. Using biodiesel can lead to improved air quality on the operation site (especially in underground environments) and reduced GHG emissions, up to 90% compared to fossil fuels. However, biodiesel are higher in price than fossil fuel diesel and has poor efficiency. In addition, there is a high cost associated with obtaining necessary feedstock and there is a lack of infrastructure present for the distribution of biodiesel from refineries.

Advantages of fuel properties of biodiesel over diesel (Sarıkoç, S, 2022):

- Biodiesel has a high flash point which results in safe storage and transportation.

- When biodiesel is blended with mineral diesel, cetane number of the fuel increases which improves the ignition quality.
- Biodiesel is a sulphur-free fuel and renewable.

Disadvantages of biodiesel over diesel (Sarıkoç, S, 2022):

- Biodiesel possesses high kinematic viscosity which results in poor atomization.
- Biodiesel has a low calorific value due to which a high amount of fuel is required to generate the same power.
- The presence of any impurities like glycerol or catalyst can lead to wear and corrosion in the engine hardware.

Biodiesel is mainly composed of fatty acid alkyl esters (FAAEs) and can be produced through oil blends, micro emulsions, pyrolysis, Fischer-Tropsch method and transesterification (Schemme et al., 2017). The transesterification process is considered the favourite option for producing biodiesel due to the high quality of biodiesel produced. Transesterification involves fatty acids obtained from vegetable oils or animal fats to be converted in the esters. The catalyst used for this process are, for example, sodium hydroxide or potassium hydroxide as well as methanol or ethanol. The most significant property affecting yield during the production process is temperature, time, and pressure. The general reaction of the transesterification process looks as follows (Ram et al., 2023):

Triglyceride + ROH + NaOH → ← Biodiesel + Glycerol (reversible reaction)

This reaction shows that fatty acids react with alcohol and the catalyst (in this case sodium hydroxide) to produce biodiesel and glycerol as a by-product. This process can be done with a variety of feedstock and has been done at industrial scale. However, depending on the feedstock used, the properties of biodiesel can greatly differ. Table 2.7 shows biodiesel parameters made from different feedstocks. Cetane number, viscosity, density, flash point and calorific value are mainly influenced by this as well as the production process. The biodiesel produced must satisfy the fuel properties within the limits of internationally recognized standards American ASTM D6751 and European EN 14214 (Garg et al., 2022).

Table 2.7: Fuel properties of biodiesel from different feedstocks (garg et al., 2022)

Biodiesel	Density (kg/m^3)	Viscosity (mm^2/s)	Cetane number	Flash point (°C)	Calorific value (MJ/kg)
Sunflower	882	4.30	50	178	–
Soyabean	882	4.37	51	170	–
Karanja	882–935.2	3.99–11.82	32	222	35.27–46
Jatropha	919.5–932	4.52	46–55	211.7	37.01–38.73
Corn	878	4.42	56	172	39.5
Cottonseed	883	4.33	56	175	39.5
Rapeseed	880	4.48	54	172	–
Mahua	920	4.23	57	232	36.85
Neem	929	4.38	41	214	39.84
Algae	881	4.55	59	140	41
Waste cooking oil	937	4.67	52	235	38.27

Another production method for creating biodiesel is the Fischer-Tropsch method (Ram et al., 2023). The Fischer-Tropsch method uses Hydrogen and Carbon monoxide, also called syngas (H2 +CO), together with a catalyst, temperature, and pressure to create fuel chemicals, otherwise called hydrocarbons. The syngas feedstock sources can be coal, as well as renewable sources like biomasses. Examples can be found in the table above. More specifically, the Fischer-Tropsch method passes the syngas through a scrubber, neutralising all harmful components, after which it gets purified, compressed, and transferred to a catalytic chamber. This step is followed by a fuel upgrading process and creating the final result, biodiesel. Numerous products can be created with the Fischer-Tropsch method depending on the catalyst used. An example process is depicted below.

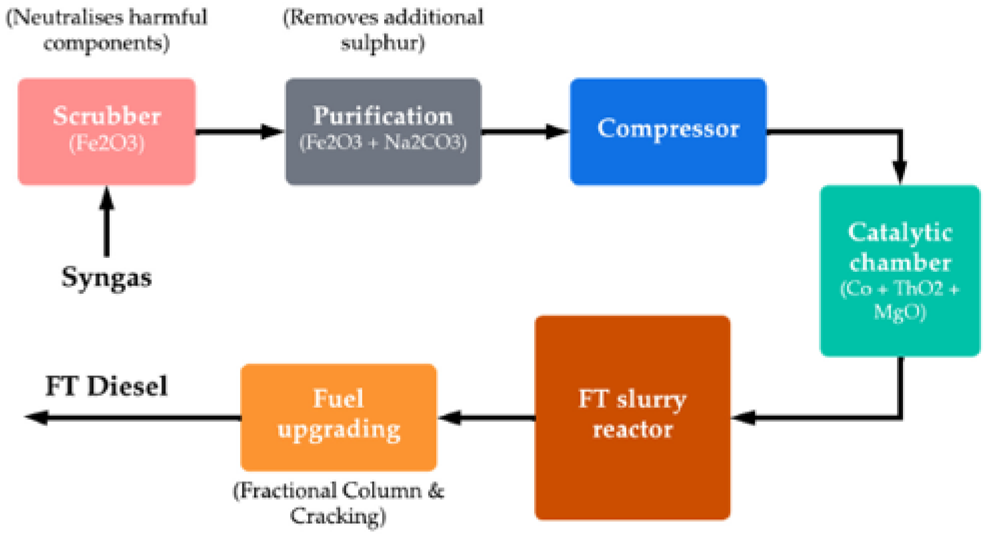


Figure 2.25: Typical Fischer-Tropsch process for FT diesel production from syngas (Ram et al., 2023)

The production and manufacturing of biodiesel has its own difficulties. These involve leftover catalysts from the esterification process that could lead to wear and tear of different components of an internal combustion engine. This is especially the case for acidic catalysts. If alkaline catalysts were used during the esterification process, the combustion of biodiesel can lead to solid ash particles being emitted or left behind within the engine. To ensure high purity of biodiesel, thorough cleaning (washing, drying, filtering) is essential. Factors like the presence of free glycerol, acid, free iodine, viscosity, alcohol, catalyst residues and success of esterification processes can have significant impact on manufacturing quality. Water content and oxidation stability also affect post-production quality. Water can cause corrosion, microbial growth, acidity and sludge development in fuel supply lines and injection systems, resulting in damages to the engine of the vehicle it is used in and the distribution or refuelling systems (Schemme et al., 2017).

Fischer-Tropsch diesel offers advantages such as a high cetane number for improved ignition quality, minimal aromatic compounds to reduce soot formation, lower T90 values for better volatility and mixture formation, and low density, which, while negatively impacting volumetric fuel consumption, increases injection duration, affecting thermal efficiency (Ram et al., 2023).

Biodiesel has experienced a 24% growth in global production for the last decade with the largest producers being Europe, Brazil and Indonesia (Ram et al., 2023).

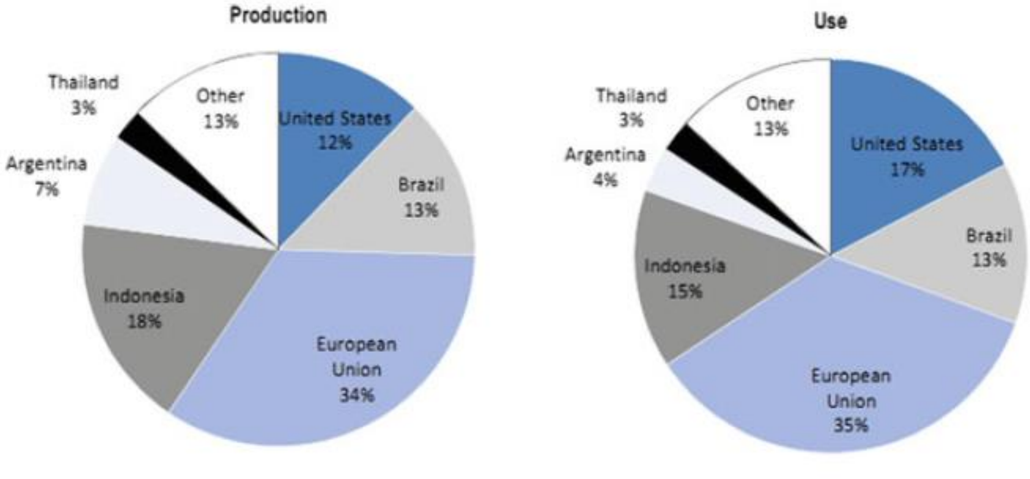


Figure 2.26: Global production and use of biodiesel (Agarwal et al., 2007)

The European union is considered to become the largest producer of biodiesel with Indonesia, Brazil, and Argentina to be the following largest producers. The EU, Indonesia, brazil and the United States are considered the largest consumers of biodiesel.

2.3.3: HVO

Hydrogenated vegetable oil is a low-carbon fuel produced from a range of vegetable oils and fats containing triglycerides and fatty acids. It is made through the process of hydrogenation and hydrocracking of paraffinic hydrocarbon forms of lipids that come from a variety of feedstocks. These include vegetable oils, tallow, and animal fats. The most favourable source of feedstock is rapeseeds, as it produces the highest yield of HVO compared with other sources of feedstock. Although HVO is obtained from similar feedstocks as biodiesel, the main difference comes from its production process. Hydrogenation is used to produce HVO, whereas transesterification or the Fischer-Tropsch method is used to produce biodiesel as explained in chapter 6.2. The process of HVO production is visualized in figure 2.27 below.

Triglycerides obtained from vegetable oils and animal fats are combined with hydrogen and the resultant products can be bio-LPG, HVO and sustainable aviation fuel. The hydrogen and oils and fats go through a hydrogenation process where hydrogen molecules (H2) are splitted apart and attached to a metal catalyst (iron, nickle, etc.) This step is followed by isomerisation, a process where the compound of a molecule is transformed into another molecule that contains the same atoms. This is done in combination with selective hydrocracking, where larger hydrocarbon molecules are splitted or cracked into smaller hydrocarbon molecules. Finally, HVO fuel is produced (Ram et al., 2023).

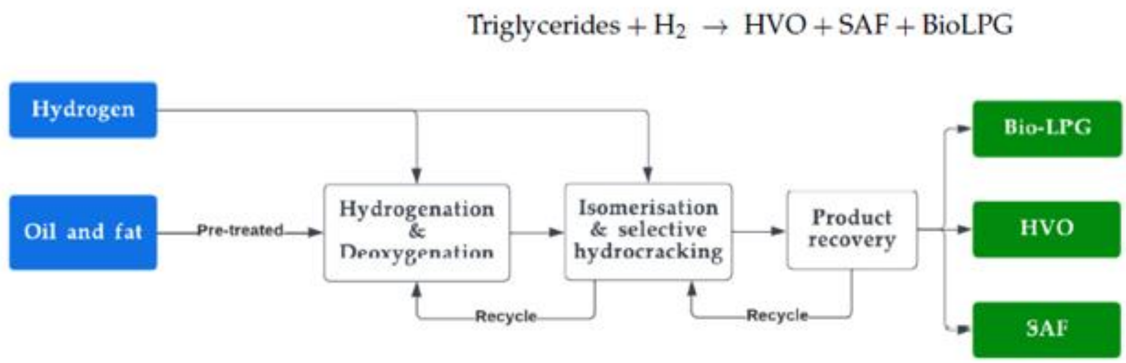


Figure 2.27: HVO production process (Ram et al., 2023)

HVO fuels has its advantages. It has an improved stability, energy density and handling characteristics than biodiesel. It has a better resistance to bacterial growth compared to biodiesel due to a greater oxidation stability. HVO has a higher cetane number and has no presence of sulphur, oxygen, and aromatic hydrocarbons, compared to fossil diesel. The largest advantage of HVO fuels is that it is considered a drop-in fuel, meaning that it can be directly used in an ICE engine without experiencing any major wear and tear of the engine, as opposed to most other alternative fuels. In addition, HVO enjoys the advantages of its portability,

However, the process also has its disadvantages. HVO fuel has a lower energy density than fossil fuel (circa 80% of the energy density of diesel), the production process is complex and requires significant infrastructure, specialised equipment, and expertise. HVO requires a high initial capital expenditure for its production compared with fossil fuels or biodiesel. Furthermore, HVO has a high density, viscosity, and ignition temperature. Any unsaturated fatty acids present can lead to oxidization. In addition, HVO usage in diesel engines can cause narrowing of the spray angle in diesel engines, resulting in reduction of combustion efficiency. This is caused by HVO's higher density and viscosity as well as its boiling points and lower volatility. Carbon accumulation and coking due to precipitation can lead to clogging of injectors, jamming of oil rings, thinning of lubrication oil, and gelling of oil. A reduced performance can also be experienced due to incomplete combustion that is caused by low atomization because of HVO's high viscosity. Short term problems of using HVO fuels in ICE engines is starting up in cold weather, clogging of the fuel filter and the fuel injector. In the long term, coking on engine cover, pistons, and injector as well as wear of engine caused by carbon accumulation.

HVO is increasingly being used as a replacement for petroleum-based diesel in a variety of applications. Although HVO is comparably better than biodiesel and synthetic diesel, requires high capital for production compared to synthetic and biodiesel. Total, Emerald Biofuels, World Energy, Neste, Preem, Petrobras, Nippon Oil and Eni are some of the largest producers of HVO. The figure below shows the global HVO production of HVO from 2019 to 2022. Around 18 million liters of HVO fuel has been produced in 2022, representing 11% (yellow line) of all alternative or low-carbon fuels produced. 18 million litres of HVO sounds like a large amount of fuel but this amount is relatively limited. A CAT 797B dump truck uses around 114 Liters per hour. If this truck operates 8 hours a day for 312 days a year, 18 million Liters of HVO fuel would be enough to replace the fuel consumption of 63 CAT 797B trucks. In addition, the HVO industry is a very competitive market. The Aviation industry is also a big player in the consumption of HVO fuels, making the availability for fuel replacement in the mining sector even more limited.

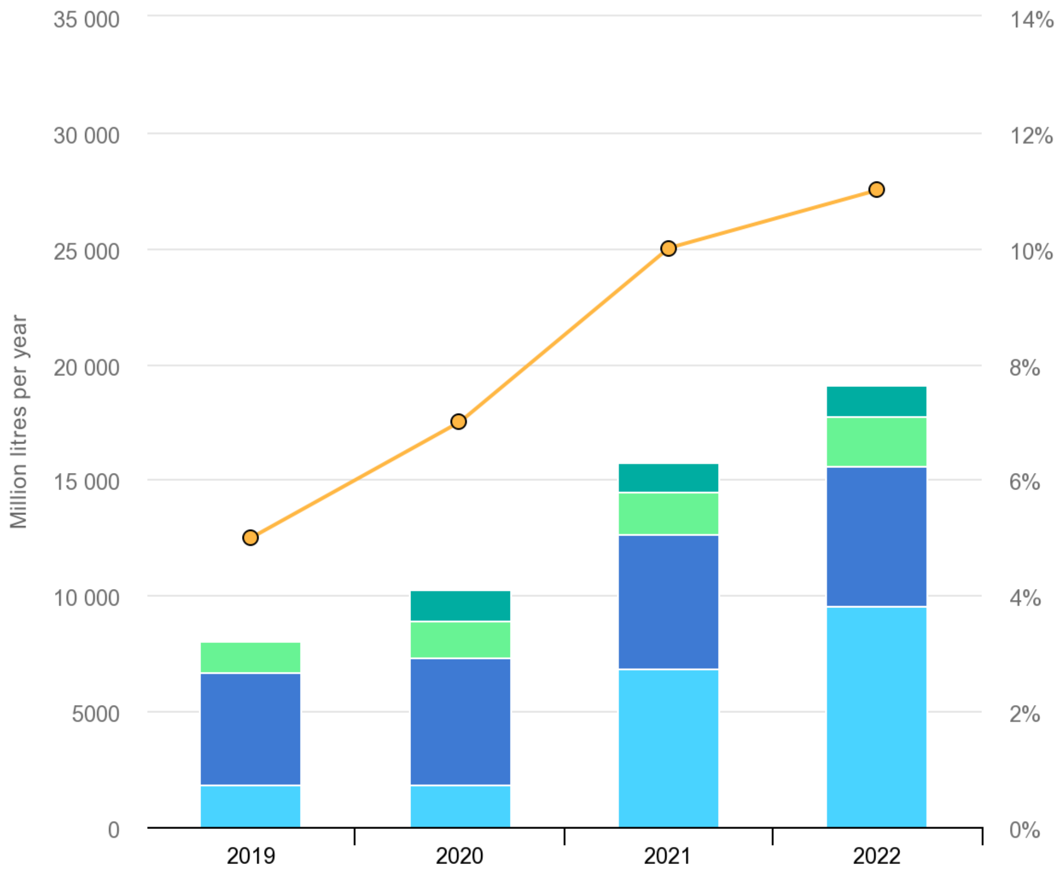


Figure 2.28: Global HVO production and percentage of low-carbon fuels. (IEA, 2022)

2.3.4 Alcohols

Alcohols are considered an alternative to conventional fossil fuel and as a decarbonization method. They are produced globally at industrial scale in large and economic quantities. Alcohols are already widely used in the transportation sector, mainly as a fuel additive that is blended with fossil fuels. They are most commonly produced through the fermentation of biomass or chemically for petroleum products like coal and natural gas.

Alcohols present several advantages when used as fuels in engines. Firstly, their higher octane numbers enable engines to operate at elevated compression ratios, leading to increased thermal efficiencies. Additionally, the rapid combustion of alcohols, combined with a higher mole ratio of products to reactants, enhances the overall efficiency of the engine cycle. Furthermore, alcohols inherently contain extra oxygen in their molecular structure, reducing the air requirement for theoretical combustion and resulting in lower emission levels. This also contributes to lower sulphur content and reduced exhaust gas emissions compared to gasoline. Alcohols, with their high heat of evaporation, possess excellent cooling properties, thereby increasing engine volumetric efficiency. When alcohols are introduced as fuel additives, they lower surface tension and viscosity of the fuel mixture, promoting better atomization. Although alcohols can be used as diesel fuel mixtures, their low calorific value hampers their effectiveness, necessitating research into longer carbon chain butanol with improved properties.

However, alcohols also come with a set of disadvantages. Their energy content is notably lower than gasoline and diesel, requiring approximately twice as much alcohol to generate the same power output. When used in engines, alcohols contribute to the formation of aldehydes and formaldehydes in emissions. Furthermore, they can cause corrosion in engine parts and the fuel supply system, affecting copper, brass, aluminium, rubber, and plastic materials. Over time, the prolonged use of alcohol in engines can lead to the deterioration of fuel lines, fuel tanks, gaskets, and metallic engine components (Mohammad Hossein et al., 2015). The low vapor pressure of alcohols poses a high risk of invisible flame formation and ignition during storage and transportation, especially in fuel pipelines due to rapid evaporation at low temperatures and pressures. Alcohols also have a high affinity for water, which can result in phase separation, decreasing the octane number of gasoline in mixtures and potentially leading to knocking. In cases of phase separation, corrosion may occur in the alcohol-rich water-phase region. Finally, the combination of low volatility, low energy density, miscibility in water, and a tendency towards pre-ignition presents some of the most significant drawbacks of using alcohols as fuels in engines.

2.3.4.1 Ethanol:

bioethanol (C_2H_5OH) is produced through fermentation of different feedstocks including corn or sugarcane in combination with yeast. The main difference between ethanol and bioethanol is the fact the production process of bioethanol is made from biomass. It is primarily used as fuel additive that can be directly injected into internal combustion engines. Examples of blended fuels include E10, which can be commercially found in at fuel stations worldwide. E10 signifies 10% ethanol and 90% conventional diesel. Usage of bioethanol as a fuel additive has the advantages of reduced CO_2eq emissions as well as an improved air quality.

Bioethanol is made through the harvest of biomass that gets turned into a fine powder. This powder in combination with water and yeast results in fermentation, where sugars are turned into alcohol. This alcohol is then extracted from the biomass and purified into bioethanol. The primary source of bioethanol feedstock is classified as the first-generation feedstock, meaning it comes from edible food sources, such as maize, sugar beets, sugar cane, corn, etc. Essentially, glucose reacts with yeast to create ethanol and CO_2 (Ram et al., 2023)

$$C_6H_{12}O_6(\text{biomass containing glucose}) + \text{yeast} \rightarrow C_2H_5OH(\text{ethanol}) + CO_2$$

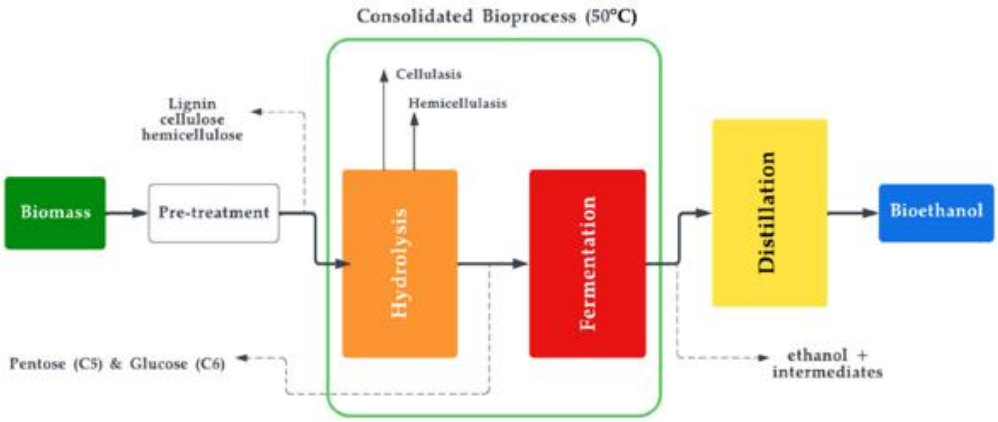


Figure 2.29: Bioethanol production process (Ram et al., 2023)

Advantages of using ethanol as an alternative to diesel includes a reduction in black smoke, nitrous oxide emissions, sulphur, and greenhouse gas emissions in general. In addition, ethanol has good combustion properties. The increase in water content in ethanol leads to lower combustion temperatures and higher thermodynamic efficiency within the engine. The flammability limit of ethanol leads to increased combustion stability at lower loads compared with diesel (Ram et al., 2023).

However, ethanol also has its disadvantages. Ethanol has lower ignition quality and hence using pure ethanol in ICE engines would result in wear and damage of the engine. Fuel mixtures like E85 cannot be used within a conventional ICE engine at a long term as it will result in damages. In addition, using ethanol can lead to corrosion of copper, brass, aluminium, plastic, and rubber components of the engine, specifically the tank coating and injections components in fuel distribution systems. To acquire the same power output by the engine, the volume of ethanol is 70% larger than diesel. Since ethanol is produced from various feedstocks, chemical properties can also differ. These include water content, aldehyde formation, ester, copper and ash content and acidity. The variation in composition can lead to differing corrosion characteristics. There is need for regulation of ethanol production (van Grinsven et al., 2021).

The table below displays the average global warming potential of ethanol, diesel, and gasoline at well to tank and well to wheel perimeters.

Table 2.8: Average Global Warming Potential (GWP) of ethanol and petroleum fuels at well to tank and well to wheel perimeter (Choi B, 2022)

	GWP (g CO_2/MJ)	
	WtT	WtW
Ethanol (commercial)	13	34
Diesel	87.1	91.9
Gasoline	81.0	88.6

2.3.4.2 Methanol:

Methanol (CH3OH) is an alcohol that is also considered as an alternative to diesel. It is a flammable and toxic by nature. Methanol is produced similarly to ethanol; main difference lies within the use of microorganisms instead of yeast. These microorganisms can create methanol from various feedstocks, including 1st generation and 2nd generation sources like wood or agricultural waste. Other feedstocks include captured CO2, natural gas, coal and syngas. The reaction of methanol production using biomass and methanol produced through hydrogenation of carbon monoxide looks as follows:

$$\text{Biomass} + \text{Microorganism} \rightarrow CH_3OH(\text{methanol})$$

$$CO_2 + H_2 \rightarrow CO + H_2O$$

$$CO + 2H_2 \rightarrow CH_3OH\ (\text{methanol})$$

The fermentation process of biomass is similar to the ethanol production process, with the sole difference that yeast is replaced by microorganisms. For the production of methanol through the hydrogenation of carbon monoxide with a catalyst like zinc oxide or copper chromite, the carbon monoxide is obtained from natural gas and. Only with the use of carbon capture is this method sustainable, but this method is expensive due to specialised infrastructure and high-quality catalyst needed. One can also produce methanol by direct methane to methanol conversion, but this method is expensive because of its energy requirements. Fermentation of biomass has the advantage of being able to be done at a smaller scale. The process is economical and sustainable and allows for a reduction in CO2eq emissions and improvement of air quality. The yield of methanol is determined by several factors in the production process. These include carbon source, fermentation time, temperature, pressure, and Ph. Even though not all feedstocks are sustainable (coal and natural gas), majority of methanol production comes from biomass, solid waste, and carbon capture technologies (van Grinsven et al., 2021).

Methanol enjoys the advantage of emitting low levels of CO, particulate matter, and no sulphur dioxide, resulting in a cleaner burning fuel compared to conventional diesel. However, it is toxic to humans and the environment, and displays corrosive qualities to internal combustion engines on its metal components. Methanol, used as a fuel additive, can result in the 500% increase in nitrous oxide emissions and formaldehyde formations, but also in a reduction of carbon monoxide and hydrocarbon emissions. In addition, methanol reacts with water and separates from gasoline leading to heterogeneous mixture. This mixture has variable air-fuel ratios, leading to inconsistent and irregular running of the engine. Methanol is cheaper to produce than ethanol but has worse combustion performance and higher corrosion rates when blended with diesel in comparison to ethanol. Methanol also has a lower specific energy than ethanol (Choi B, 2022). The figure below summarizes the effect of methanol properties on engine performance.

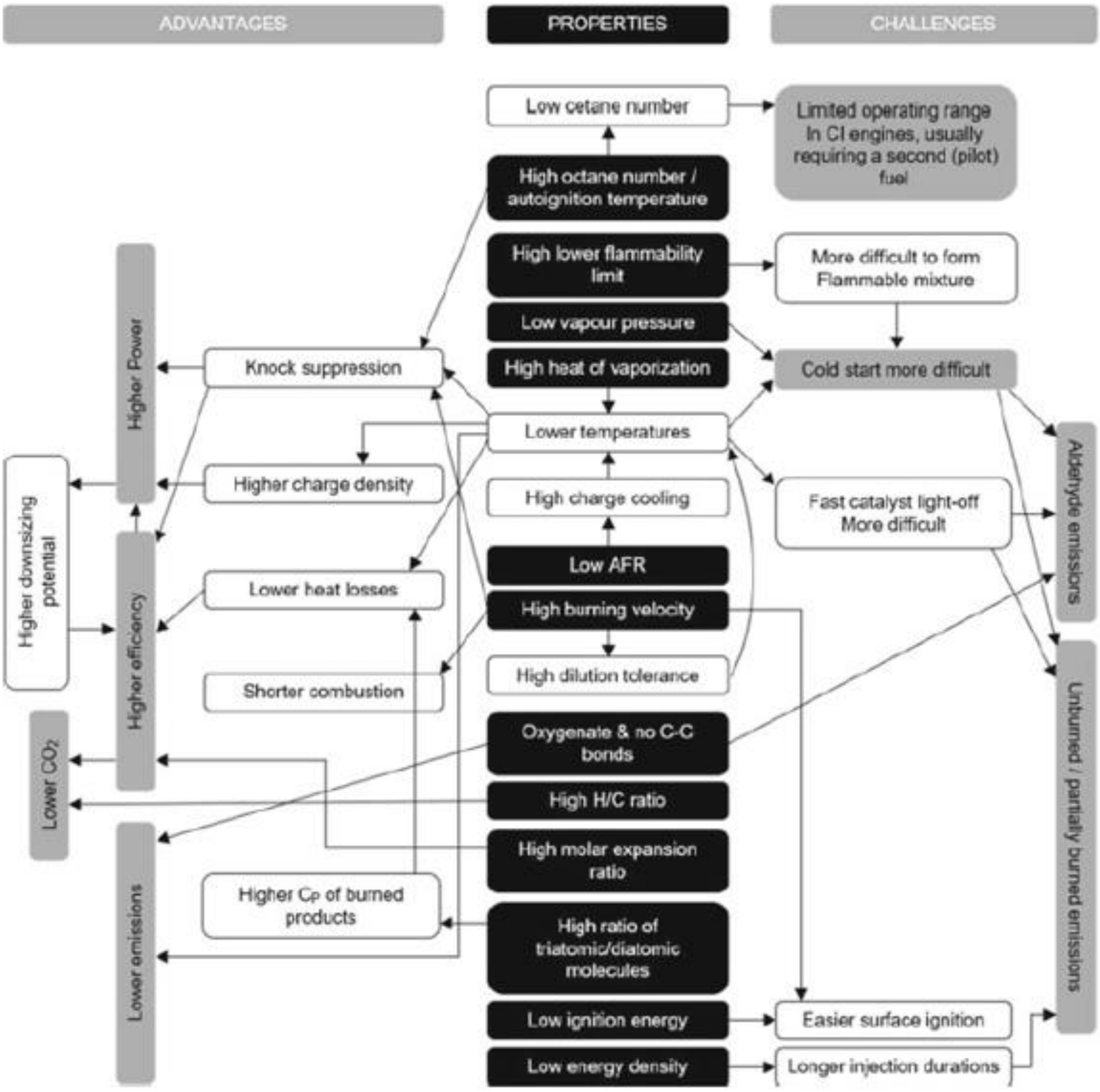


Figure 2.30: Effect of methanol properties on engine performance (Choi B, 2022)

Table 2.9 shows a comparison of combustion properties and evaporation properties of methanol, ethanol and gasoline.

Table 2.9: Combustion properties and evaporation of methanol, ethanol, and gasoline (Agarwal et al., 2007)

Fuel type	Boiling point (°C)	Theretical air/fuel ratio	Enthalpy of evaporation (kJ/kg)	Enthalpy of combustion	
				(MJ/kg fuel)	(MJ/kg theoretical blend)
Methanol	65	6.5	1170	22.2	3.03
Ethanol	78.5	9	850	29.7	2.97
Gasoline	25–175	14.5	310	42	2.71

2.3.4.3 Butanol:

Butanol (C4H9OH) is produced from 2nd generation feedstock (inedible biomass) and is considered to optimal alcohol to use as an alternative transportation fuel. It is produced from the same feedstocks as ethanol and methanol through fermentation but globally, it is mainly produced from fossil fuels, but has the possibility to reduce GHG emissions with almost 50% (Ram et al., 2023).

Advantages of biobutanol include a higher cetane number and it is also less corrosive than ethanol and methanol. It has a longer shelf life as well and can be stored longer in conventional diesel storage tanks. It has a lower ignition temperature than the other alcohols and displays lower vaporization enthalpy than ethanol or methanol. Furthermore, butanol absorbs less moisture from the air and is less miscible. Using butanol as a fuel additive, it experiences no phase separation and is a more stable mixture compared to ethanol or methanol blending mixtures. In addition, it has a better self-ignition resistance and contains a higher calorific value and circa 25% more energy content than methanol. Butanol is less volatile, and its higher flashpoint allows for safer handling, storing and transportation. Its higher energy density, viscosity and miscibility properties make it a more favourable alcohol than ethanol or methanol (Choi B., 2022). Table 2.10 gives an overview and comparison of the chemical properties of ethanol, methanol, butanol, and gasoline.

Disadvantages of butanol include a low global production. Producing butanol through fermentation of biomass also results in a yield that is significantly lower (10-30 times) than bioethanol. Compared with diesel or gasoline, butanol still has a lower heating value. Butanol experiences similar wear and tear on engines as ethanol and methanol and is not compatible (at high rates) with fuel system components as well as engine parts, as it is corrosive (Choi B., 2022).

Table 2.10: Properties of methanol, ethanol, butanol, and gasoline (Agarwal et al., 2007)

Properties	Methanol (CH_3OH)	Ethanol (C_2H_5OH)	n-Butanol (C_4H_9OH)	Gasoline (C_8H_{15})
Density, 15 °C (kg/m^3)	791.3	789.4	809.1	750
Molecular weight (kg/kmol)	32.04	46.07	74.12	114.23
Vapor pressure (mmHg)	127	55	7	562.5
Boiling point (°C)	65	78	117.5	30–190
Research octane number (RON)	110	119	–	97
Motor octane number (MON)	92	92	–	86
Cetane number	5	11	17	8
Stoichiometric air/fuel; (kg air/kg fuel)	6.5	9	–	14.7
Lower heating value (MJ/kg, 15 °C)	19.8	26.4	33.09	41.3
Flash point at closed cup (°C)	12	13	29	−45

3. BEV roadmap to implementation:

The roadmap to implementation is based on the Global Mining Guidelines paper "Recommended practices for Practices for Battery Electric Vehicles in Underground Mining" released in 2022.

3.1 Charging systems and methods

Mine operations will heavily depend on the state of charge and availability of fully charged batteries. Heavy duty vehicles require larger charging time and larger battery capacity. Including charging into mine plan and schedule is of great importance to have an efficiently running mine. This section will talk about charging systems and methods.

Installation of charging methods and systems should be done according to local regulations and safety standards. It should be ergonomic to prevent shock and mechanical hazards to prevent injury. Charging systems have electromagnetic emissions and can lead to exposure of electromagnetic radiation for personnel. Charging systems should also be compatible with batteries used in the electrical equipment and usable under different conditions. In addition, an emergency stop should be installed located outside the charger, shutting down the charge first followed by opening the contactors.

Communication and monitoring of the charging systems becomes vital. A single charging management software should be implemented across the entire mine site, regardless of the manufacturer used for charging infrastructure, especially in a mixed fleet. It should allow for electric load management, notifying operators and personnel of events (e.g., normal operation, fault, charging in progress, remaining charge time, charging complete) when the charger is connected to the BEV. It should also be aware of any charger instructions for the BEV as well as minimum and maximum current and voltage limits.

The power requirements for chargers should be given by the OEMs, however, here are some considerations for the incoming power system:

- Location of distribution equipment within a distance that maintains system strength.
- Incoming short-circuit rating/withstand capability
- Input power requirements: voltage, current, frequency, phases, grounding, isolation.
- Voltage fluctuations and other mine power challenges in mine grid
- Harmonic frequencies produced by chargers and compatibility with other equipment.
- Power study is recommended for overall underground electrical design.
- Chargers usually need to comply with IEEE-519 or other standards.

3.1.1 Types of charging methods

Charging methods have significant impact on the design and infrastructure requirements of the mine. Operations are different for differing charging methods. Charging methods include on-board charging, off-board charging of on-board batteries, off-board charging of off-board batteries, hybrid charging, overhead catenary systems, and tethered electric equipment. The electrical grid in a mine provides AC current. However, a battery is not able to store AC current and needs to convert it to DC current to store.

On-board charging

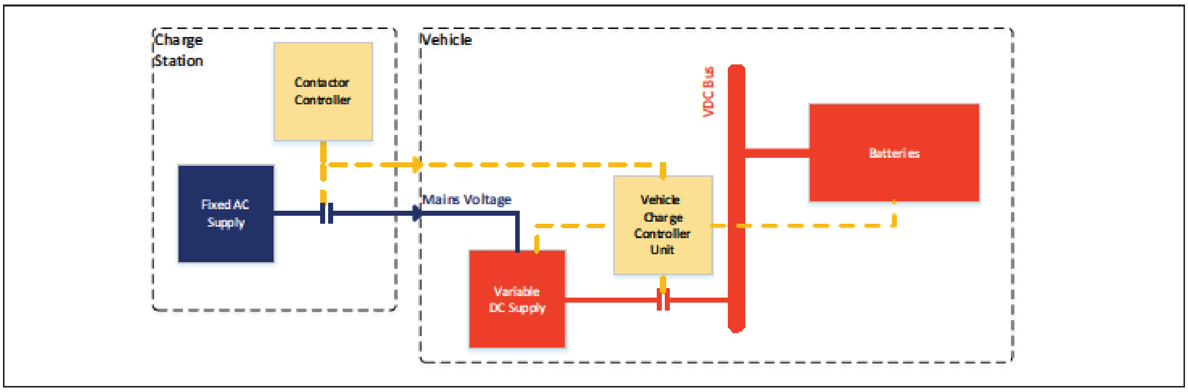


Figure 3.1: Typical On-board Charging arrangement (GMG, 2022)

On-board charging is done by charging through an AC supply, which gets converted by an AC-to-DC converter installed on-board the BEV. Along with the converter, a transform is used to regulate incoming voltage and to help isolate from the fixed power system. This method of charging requires AC connections to be integrated in the mine design where BEVs can park. The BEV design requires an onboard charger with the appropriate charging plug according to the mine specifications or local authorities. Since the charger is located on the BEV, OEMs are responsible for all infrastructure on the BEV and only an AC supply is required from the mine.

Advantages

- Charger is located on the BEV, instalment of the charger in a separate enclosure is not necessary.
- Flexibility of charging location due to elimination of charger instalment in a separate location.
- Reduction of downtime associated with traveling to a specific charger location.
- Charging can take place when vehicle is stationary (loading/unloading), reducing charging downtime.
- “handshaking” or communication between BEV and stationary connections are minimized or eliminated.

Disadvantages

- Maintenance of on-board charger can reduce equipment availability.
- The power of an on-board charger has limitations and might not be the best option for high-capacity (>100 kW) charging.
- Each BEV might have a customized charger, leading to increase in spare part storage, maintenance, and repair difficulty.
- With high-capacity chargers, the power electronics should be cooled while charging.

- The BEV is exposed to dust, vibrations, and harsh operating conditions, potentially impacting its on-board charging equipment.
- Added weight and volume of on-board charging equipment reduced space and range of the BEV.
- Battery and charger size pose difficulties for OEMs to design and integrate along with drivetrain and cooling and protection equipment, especially for larger LHD equipment.

Off-board charging of on-board batteries:

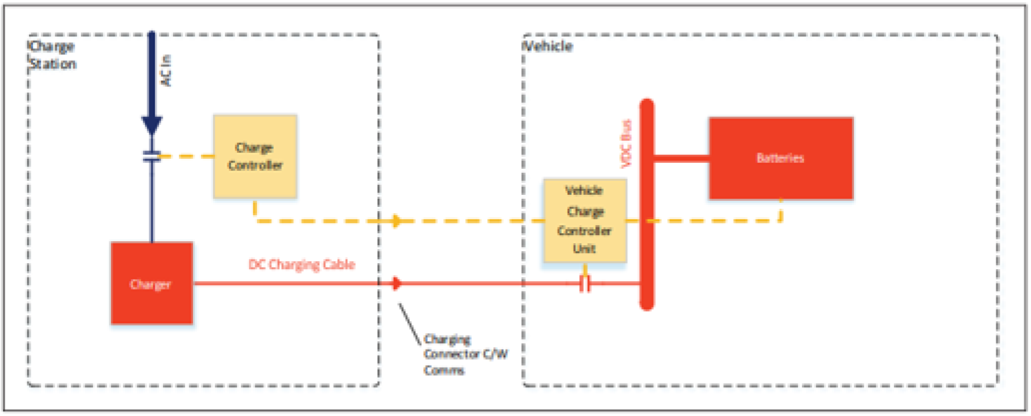


Figure 3.2: Off-board Charging Arrangement (GMG, 2022)

Off-board charging requires the AC-to-DC converter to be located externally from the BEV in a fixed enclosure. The mine design should take into account these fixed charging locations with parking space included. These charging stations should be compatible with the BEVs in the fleet. The charging stations should provide for wayside equipment such as transformers, charging pads, cooling units and rectification equipment as well as ease of access for maintenance and inspection.

Advantages

- Battery capacity and range can be increased due to size and weight reduction as charging equipment is located elsewhere from the BEV.
- Charging equipment is not exposed to harsh conditions but in contaminant-free areas, leading to less monitoring and maintenance.
- Possibility of high-capacity chargers as they are not constrained by size and weight as they are with on-board chargers.
- Multiple BEVs can share one charger, if compatible.
- Multiple chargers can be connected to multiple ports on one vehicle for higher charging rate.
- If chargers are standardized, this charging method would be compatible for mixed fleets and would require less training for equipment operators.

Disadvantage

- No standardization of chargers yet, leading to a range of different chargers and charging infrastructure required.
- Space is required for infrastructure instalment. This can be a limiting factor in flexibility, especially in underground mines.
- Larger mines may need multiple chargers and charging locations.
- Productivity can be affected by BEV movement to charging locations, and downtime will be increased for charging.

Hybrid charging:

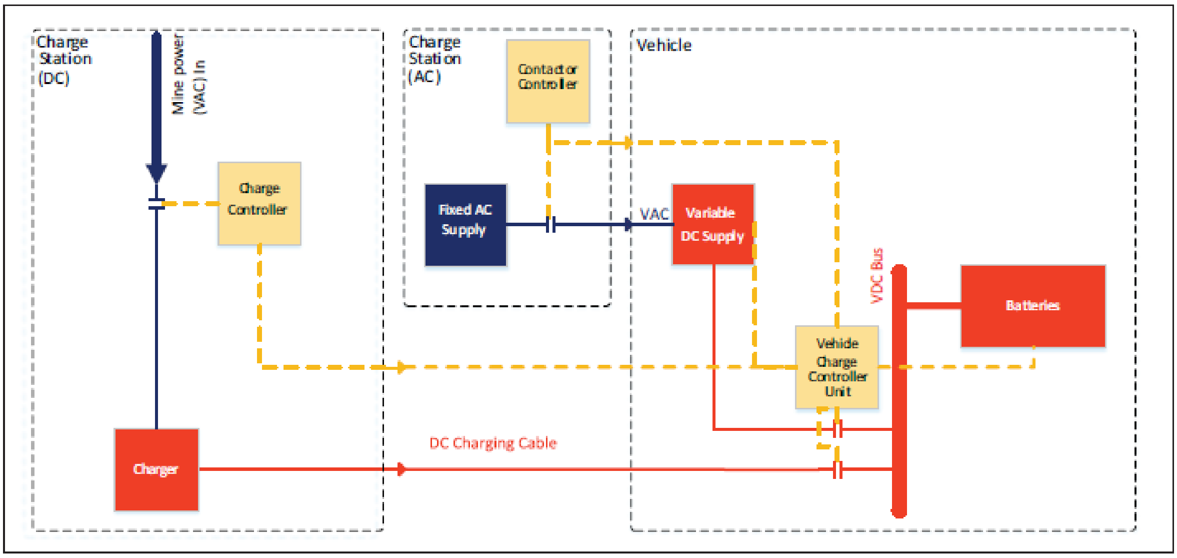


Figure 3.3: Hybrid Charging Arrangement (GMG, 2022)

Hybrid charging is a combination of on-board charging of on-board batteries and off-board charging of on-board batteries. Most (commercial) BEVs have a hybrid charging system. It reaps the benefits and disadvantages of both methods. the on-board charging component is used as a low-capacity charger, for which a full charge would require a longer time span. Fast charging can be achieved with the off-board charger. This would in turn require the installation of required infrastructure.

In a mixed EBV fleet, it is less advantageous to have a specific charger for each type of BEV. Potential charging locations would need an equipment-specific charger installed, resulting in multiple chargers at each charging location. Personnel would require training on each type of interface, and capability to maintain and troubleshoot each specific charger would need to be taught as well. This issue can be made redundant by employing only one OEM to standardize the drivetrain of the BEV in the mine, but this might reduce options.

Off-board charging of off-board batteries:

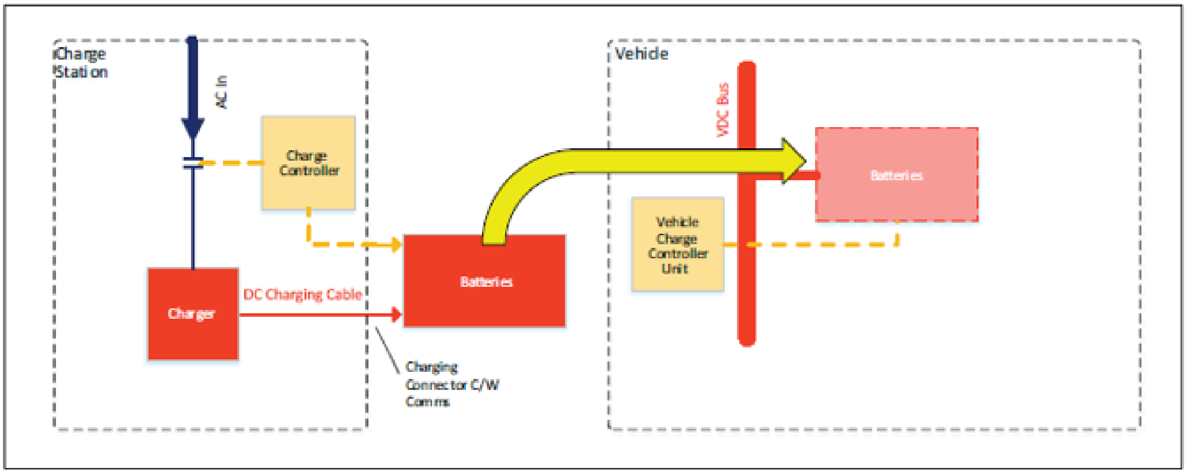


Figure 3.4: Battery Swapping Arrangement (GMG, 2022)

Off-board charging of off-board batteries is also referred to as battery swapping. A BEVs empty battery is replaced with a fully charged battery. Whilst the empty battery is charging, the BEV can continue its operations. Instead of requiring charging stations and parking as seen with the off-board charging of on-board batteries, a swap-and-charge station will be required. Due to energy density limitations of LIB, battery swapping is useful especially when long loaded uphill trips (as is most common in open pit mines) are the only option.

Advantages

- Battery maintenance will have less impact on BEV availability.
- BEVs do not need a designated parking spot to charge at the shift's end, only the batteries need to be charged at the swap-and-charge station.
- Reduction of some charging infrastructure necessary
- On-board battery capacity can be reduced as battery swapping can be done multiple times during a shift. Reducing the size of the on-board battery could lead to a reduction in cost per tonne of ore.

Disadvantages

- Battery swapping infrastructure (such as cranes, battery transportation tools, etc.) can demonstrate logistic and safety issues, especially with a higher rate of battery swapping.
- (autonomous) Battery swapping infrastructure could experience wear due to the mining environment and would require high level of engineering to accommodate a variety of BEVs, especially in mixed fleets.
- BEV design options can be constraint by facilitating battery removal in its design.
- Battery swapping requires fixed swap-and-charge locations. These swapping locations can be large and would require significant amount of space, which can be an issue, especially in underground mines.

- Mining fleet would have to move between work areas and go to the allocated swap-and-charge station, reducing operational time.
- Battery inventory management would be necessary and can be complex. Especially since one needs more batteries than available BEVs (e.g., 2 batteries for 1 BEV)
- Inventory management can be complex especially since there is no standardization for battery types in BEV, posing an issue especially in larger mixed fleets.

Overhead catenary systems:

Figure 3.5: Two pantograph interfaces (GMG, 2022)

Overhead catenary systems, aka trolley assist, are rail-mounted AC or DC power fed cables to help diesel/electric trucks move ore and personnel. They have been widely used in open pit mining industry already. It allows for reduction of diesel consumption on uphill climbs. The truck operator must align the truck with overhead lines, deploying the pantographs manually and turning of the diesel system. This procedure is then reversed at the end of the trolley assist line. Downhill trolley assist usage allows for regenerative braking and taking this energy up back into the grid.

The main issue is that the truck is only not emitting when connected to the overhead catenary system. When the truck disconnects from the trolley assist, it is no longer supplied with electrical energy and consumes diesel. However, the technology is moving towards replacing diesel with electrical energy and automating alignment and pantograph deployment. Good road maintenance is required as bouncing of the pantograph along the wires can result in high-voltage arcing, debilitating transformers and causing vehicle issues.

3.2 Charging and connection interfaces

On-board charging from AC supply interfaces

In the charging process, the BEV connects to the AC connector. Essential power conversion equipment and communication systems are integrated within the BEV itself to regulate the charging rate. This setup reduces the need for extensive communication between mobile and stationary components.

For commercial BEVs, on-board charging is primarily suited for low rate charging, commonly occurring at owners' residences or business locations. In North America, the IEC 62196 Type 1 (SAE J1772) connector is the standardized choice for BEVs. In Europe, the Type 2 connector is used, offering greater voltage capacity yet lower current, thereby allowing for up to 22 kW delivery.

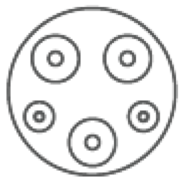
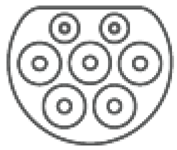
Current type	Connection Type	Description	Image	Region(s)
AC	SAE J1772 (also referred to as IEC 62196 Type 1)	1 phase and 3 phase AC charging		North America, Japan
	IEC 62196 Type 2 Connector (also referred to as Mennekes)	1 phase and 3 phase AC charging		Europe and other markets

Figure 3.6: On-board charging from AC supply interfaces (GMG, 2022)

Communication via the IEC 62196 connectors for AC charging includes detecting the insertion of the plug into the BEV and informing the BEV about the available mains current, preventing the BEV from drawing more current than what the charging station can supply. The AC feed cable and output cable chosen should be easily replaceable when damages occur.

Off-board charging from DC supply interfaces

As previously mentioned, infrastructure requirements for off-board charging includes an AC to DC converter, located in the allocated charging station stationary next to the BEV. A DC connector is used to supply energy to the battery onboard the BEV. To increase the charge after 80%, the BEV will require larger amounts of power and changes in terms of charging rate. This dynamic charging rate to increase the SOC to 100%, the BMS needs to be able to communicate efficiently between the BEV and the charging infrastructure. The BMS will be responsible for monitoring temperature, cell voltage and battery pack voltage.

Currently, various charging connectors exist globally, hence OEMs have mitigated the lack of standardization by including multiple standers on a single charger.

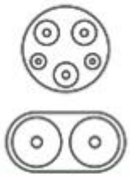
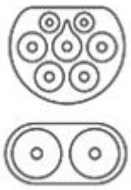
Current type	Connection Type	Description	Image	Region(s)	Cross-reference
DC	CCS Type 1/ Combo-1 (also referred to as CCS1)	High-power DC charging via dedicated pins		North America, South Korea[1]	See Section 8.3.1
	CCS Type 2/Combo 2 (also referred to as CCS2)	High-power DC charging via dedicated pins		Europe, Greenland, South America, South Africa, Saudi Arabia, Australia, and other markets[2]	See Section 8.3.1
	GB/T 20234	DC charging		China	See Section 8.3.1
	ChAdeMO	DC charging		Japan	See Section 8.3.1

Figure 3.7: Off-board charging from DC supply interfaces (GMG, 2022)

The most common types of charging interfaces spread across different markets and regions are CCS type 1/Combo 1, also referred to as CCS1, and CCS type 2/ Combo2, also referred to as CCS2. Both allows for high-power DC charging rate. CCS1 is mainly available in North America and South Korea whereas CCS2 is available in Europe, Greenland, South America, South Africa, Saudi Arabia, Australia, and other regions as well. The main difference between CCS1 and CCS2 is the physical connection interface. CharIN recommends adopting CCS Type 2 Combo 2 in global markets that do not yet have recommended regulations supporting a specific CCS connector type yet (CharIN, 2020). CCS1 and CCS2 allow for charging current up to 500 A and charging power up to 350 kW.

Other DC charging interfaces currently available are the GB/T 20234 and chAdeMO, available in China and Japan respectively. The chAdeMO has also been used in Europe and North America but is currently constrained by a current charging rate of 125A. The GB/t 203234 allows for up to 250 A charging rate.

The CCS1, CCS2 and CHAdeMO have been widely proven in the commercial automotive industry due to several reasons. The charger interfaces are easily maintained and manageable with readily available spare parts. They are lightweight and come with a locking connector. However, the main downside is that the connectors are made of plastic and the CHAdeMO connection type has limited voltage.

Not only can these connecting types be manually applied, but they also come as automated connection devices. They main advantages that come with their automated counterparts is time savings (due to high-power fast charging rates), greater comfort (operator can remain in vehicle), reliability (reduction of human interaction and hence human error). However, they come at a higher initial cost, greater weight and are harder to maintain due to an increased number of components.

Pantograph charging interfaces

Referring to figure 3.5, there are two main pantographs available and standardize in SAE J3105, namely the top-down pantograph and bottom-up pantograph.

The main benefit of the top-down pantograph is that the pantograph is not located on top of the vehicle, reducing its weight. It also allows for less reduced time whenever the pantograph requires maintenance, as the vehicle can remain in operation. Replacing parts for the top-down pantograph is easier and cheaper than replacing parts necessary on the vehicle. The bottom-up pantograph implies that the pantograph is located on the BEV, increasing its weight. When maintenance of the pantograph is required, the vehicle will be in downtime and out of operational service. However, in general both pantograph systems come with its advantages. They are safe automated connection systems with no need for human interaction with power elements. They allow for very high-voltage ratings and very high-power DC charging capabilities (up to 600 kW at 1000 VDC), and they allow for interoperability among different types of BEV.

A recently developed technology, the underbody charging method, is another version of the bottom-up pantograph, allowing to charge BEVs from below. The pantograph is built on the ground, the connection interface located on the chassis/axles of the BEV. Whilst in operation, the BEV drives over the pantograph and stopping at a certain location where the pantograph will move from the ground up to the BEVs chassis or axle and connection to the BEV, allowing for high power charging. Useful on BEVs especially when there is limited available space to build roof connection interfaces.

Figure 3.8: Underbody charging method interface (GMG, 2022)

In addition to underbody charging method, inductive charging is a new technology allowing for automated and wireless charging. It gets rid of any physical contact between the charger and the BEV. It uses a form of resonant charging where one coil is inductively charged, and the secondary coil oscillated at an equal frequency. The created oscillating electromagnetic field on allows for moving energy between the primary and secondary coil. The main advantages of this charging interface is the removal of all cables, pantographs, making installing of infrastructure clean and efficient, with a significant decrease in hazards like electric shocks. There is no need for corrosion protection and there is no risk of damage to components (cables, plugs, etc.). There are no moving parts or any human interaction, allowing for a fully automated charging process. This charging method comes in a stationary and dynamic form. Stationary installation has its primary coil underground and the secondary coil at the bottom of the BEV. In its dynamic version, the primary coil is placed along a certain route, allowing for the BEV to charge while moving. As of today, the stationary technology is at a more mature stage, whereas dynamic inductive charging interfaces are only used experimentally.

Battery swapping interfaces

Battery detachment from the BEV involves methods such as crane, forklift, or an on-board lifting mechanism. Following detachment, the battery is connected to a charger, and upon completion of charging, reconnected to the BEV's on-board battery. The interface utilized between the charger and the BEV's battery is of great significance, as it experiences the most wear within this system.

The wear on the connection interface requires the consideration of a high and reliable mating cycle connector. This connector should be able to withstand multiple charging cycles without performance reduction or the need for substantial maintenance. Additionally, the connector should minimize battery swapping time while optimizing overall system efficiency.

Charging at a swapping station needs to facilitate swift replacement of batteries into other vehicles, minimizing delays and reducing the requirement for additional batteries and space. The connector must effectively manage high power for rapid charging rates, along with the capacity to handle elevated continuous current and occurrences of high short-circuit events. The capability to accommodate high continuous current ensures maximum performance and minimal power loss due to heat.

The absence of uniformity in shapes, sizes, and the overall configuration of swappable battery packs and their integration into BEVs presents a key challenge in adopting battery swapping. Utilizing a standardized infrastructure across diverse vehicle types proves difficult due to these variations, especially in mixed fleets.

3.3. Performance standards

Performance standards for equipment, batteries and chargers are of paramount importance for mine operators to specify performance to achieve their goals and for OEMS to describe performance to communicate with mining companies to see if BEV or other relevant equipment comply to operational requirements and goals. Once performance standards have been established, mine managers and operators will be able to recognise possible improvements and potential to change diesel equipment to BEVs on the mine site. One consideration to take into mind: if diesel equipment performs better, should we change to BEVs? This consideration also counts for other decarbonization methods.

3.3.1 Duty cycle

Performance evaluation should not be limited to the time between process initiation to completion. Instead, the duty cycle comprises the process time along with any delays, taking into account how equipment acquires energy and behaves in various activities like charging and transportation to charging stations. This duty cycle complexity surpasses that of diesel counterparts due to the inclusion of charging and transportation.

To fully understand the duty cycle, one must understand the main difference between availability and utilization. Availability is the ability to perform over a given period for time. For BEVs specifically, charging and battery swapping is considered as downtime and not available time, unless said BEV can charge while operating. Utilization is the time an equipment/BEV is being used. It considers the available time and the downtime of the BEV. The time required for on-board battery charging or battery swapping procedures can result in significant downtime. Available time is measured by hour meter data from the traction drive, hydraulic power packs, etc. When these components are shut off during charging, they are not measured and do not account for operational time. It is key to record these charging hours to see their potential impact on availability of the BEV. When an operator charges a BEV for longer than necessary to finish their shift, this is considered downtime. Hence, recording charging time and charging situations should be considered in equipment performance data.

Example considerations for LHDs:

1) Swapping batteries, and charging the batteries off-board with off-board chargers:
    a. How long does it take to swap a battery from start to finish?
    b. How long does it take to drive to swapping station?
    c. Any risk of queueing for swap station?
    d. How many trips can be completed before a battery needs to be swapped?
    e. What amount of regeneration can be expected under different payload scenarios?
    f. Typically, higher top speed and increased acceleration to compensate for charging time.
2) Fast charging batteries on-board the equipment with off-board chargers:
    a. How long does it take to charge?
    b. How much additional time does it take to drive to the fast charger?
    c. Any risk of queueing?
    d. How many trips can be completed before battery needs to be charged?
    e. What amount of regeneration can be expected under different payload scenarios?
    f. Typically, higher top speeds and increased acceleration to compensate for charging times.

3.3.2 Equipment performance

Equipment performance allows for one to understand various requirements that need to be considered if implementing BEVs. Firstly, are BEVs able to achieve the same performance standards or better performance standards for a given duty cycle as diesel equipment. Secondly, how much time is required to charge or swap batteries and how does this downtime compare to diesel equipment downtime? Lastly, what are the energy requirements for BEV for a certain duty cycle and how many times can the BEV perform this duty cycle by on-board stored energy before charging is required?

To standardize and implement procedures to understand performance standards of BEVs, one must consider environmental and operational variables of the operation or duty cycle in question. The performance standards should be mentioned by OEMs for certain environmental/operation variables so that operators or other relevant personnel can compare, and contrast results obtained in practice.

The environmental variables in question are road conditions, rolling resistance, ambient temperature, humidity, corrosion ratings, ingress, salt resistance and rock falls, weather conditions, rainfall, etc.

Operation parameters in question can relate to operator skill, idle periods, distance, payload, time to reach charging/swapping station, road grade, speed limit, auxiliary systems like heating or lighting, other battery loads such as electric drives or radios and tyre type and inflation pressure.

In order to assess performance of traction/pump/auxiliary motors of a diesel engine or a BEV, standardized methods should be in place. Such methods can be either peak rating or continuous rating:

- Peak rating: max torque generated at 0 km/h (e.g., stall condition while mucking). A torque converter should last between 5 to 15 seconds before overheating. This method is used as the same drivetrain could run uphill at full power fully loaded. Results tend to be overestimated.
- Continuous rating: average energy use for an action (e.g., continuous uphill fully loaded haulage).

When looking equipment performance, one needs to include regenerative braking into the duty cycle as it allows for range extension and longer availability of the BEV. Regenerative braking depends on grade and road conditions. The better the road is maintained, the lower the rolling resistance of the BEV on that road, resulting in a decrease in service brake usage and an increase in drivetrain usage to regain energy and transfer it back to the battery. In addition to regenerative braking, a well-maintained ramp will lead to increased speed and allowing for reduced cycle time and better productivity. Grade performance data should be provided by OEMs and should contain data such as power (in kW), maximum speed (in km/h) and grade percentage for loaded and unloaded conditions. Overall performance data for BEV can be reported as in table 3.1.

Table 3.1: Overall Performance Data example (GMG, 2022)

Description	Details from mining company
Equipment type	40 t haul truck
Heading size	5 m x 5 m (helps define box capacity limitations)
Ore density	2.1 t/m^3 broken density (for calculation of actual load)
Profile description	2 km haul, uphill carry, 15% average grade, peak of 17%
Seat time	8 h/shift, 2 shifts/day
Objective	Haul 800 t/day
Description	**Examples of outputs by OEM**
Loads per charge	4
Loads per shift	14
Swaps per shift	3 (8 min each, for 24 min total per shift)
Capacity per load	40 t
Speed (km/h)	10 loaded (up), 12 unloaded (down)
Cycle time (minutes)	32 min (22 min tram with 10 min for load, dump and traffic)
Production capability	560 t/shift, 1,120 t/day
Production objective	met with one truck – 320 t/day margin

3.3.3 Battery and charger performance

Like equipment performance, it is important to also evaluate battery and charger performance. Separating these 3 individual performances leads to better understanding of the individual components, were the bottlenecks lie and how to improve them. Key battery performance parameters include:

1) Voltage and current:
    a. Practical/safety limits that should be enforced?
2) Controllable charger:
    a. One fits all.
    b. Leverage bus standards?
3) Battery cycles:
    a. How to represent lifetime battery cycles?
    b. End of life definitions (70%? 80%? Secondary use?)
    c. Rebuild, replace, repair?
4) Capacity:
    a. kWh capacity rating from data sheet – does not represent "usable" energy.
    b. beginning vs. end-of-life
    c. Warrantied kWh delivered?
    d. Number of cycles?
    e. Ah throughput?
    f. Electric brake reserve – how much battery energy needs to be reserved for downhill navigation?

By evaluating energy consumed during a shift and battery capacity, one can estimate the number of charges or battery swaps required per shift per equipment. It will also help to better estimate charging station's location, amount of charging station as well as the dimension of charging stations based on duty cycles of different BEVs in the operation. This will in turn help determine the mine infrastructure design as well as necessary logistics. OEMs should be able to provide battery performance data sheets for mine operators, which should include: Cell chemistry, specific energy, energy density, nominal voltage, amperage, operating voltage cell monitoring system, battery capacity, battery power, optimal (dis)charge rate, maximum charge current, operating temperature range, lifespan cycles, cooling time and method, battery monitoring system, battery pack weight, battery pack dimensions, charging time, kW of heat output per kWh of charging, possibility of battery swapping and opportunity charging.

To better understand and evaluate charger performance, one needs to have a clear idea of time needed to charge, location of charging stations and mine power availability. This in turn will help determining the layout of a charging station and the vehicle operating schedule. OEMs should be able to provide battery charger requirements and provide details about the charging station, such as excavation size (mainly for underground operations) and charging infrastructure needed, including crane to lift batteries and capacity requirements. Battery charger specifications provided by OEMs should include but not be limited to dimensions, weight, operating temperature range, operating humidity range, input/output range, charger efficiency, enclosure specifications, derating of charger capacity, and charger current range.

3.4 Mine design and operations

To implement a new mine design based on BEVs, one needs to consider the charging methods, mine planning and scheduling, duty cycles, maintenance, and operational requirements of the BEV as well as any associated risks. BEVs compared to diesel equipment have limited range and require charging time, hence it is important to implement this in the mine design to increase productivity and vehicle availability. The mine should be tailored to the specific needs and best practices of the BEV fleet.

The handling of ore and waste will be influencing the operations the most as they require the most attention from the BEV fleet. To optimize usage of the BEV fleet, the mine could be designed in such a way that ore and waste is moved downhill instead of uphill, allowing for regenerative braking to recuperate energy and letting gravity aid in reducing rolling resistance. The latter would depend on multiple factors like grade and road conditions. It's important to keep in mind that underground greenfield operations are more easily tailored to accommodate electrification than surface operations.

The typical optimized underground BEV duty cycle would involve the BEV leaving the charging station fully charged at the beginning of the shift. The BEV would travel unloaded uphill to an excavation point where it gets loaded and experience a decrease in battery charge. After being loaded, it travels to a dumping destination downhill fully loaded where the BMS balances braking between actual and regenerative braking, further reducing its battery state of charge. This cycle is repeated until charging of the BEV is required. If downhill material transport is not possible, this can be mitigated by uphill haulage by conveyor belt, but the mine design can easily be constraint by orebody geometry or other factors. Hence, it is not always economical to optimize the mine fully to BEV operations.

Regenerative braking

Hauling ore and waste downwards allows for regenerative braking, which allows for the motor to convert kinetic energy into electric energy and transfer it back to the BEVs battery. The amount of regenerative braking and electric energy recuperated depends on several factors, including grade, gross operating weight, speed, ramp conditions and the operator. The advantage of regenerative braking is an increase in BEV range, a lower energy consumption which allows for smaller batteries and less heat transfer to the mine environment. In addition, because the motor is braking and the service brakes of the vehicle are being used less, the BEV will require less maintenance, allowing for operation savings. These benefits show that the mine should fully optimize the mine for the use of regenerative braking. A BEV moving loaded uphill and empty downhill will need different energy requirements than hauling loaded downhill and unloaded uphill. The differences can be seen in table 3.2, where the power required at maximum speed fully loaded uphill at +20% and +15% grade is 200 kW and unloaded at +20% and +15% grade is 174 and 138 kW, respectively. For regenerative braking downhill at-20% grade loaded will result in 226 kW at maximum speed and 129 kW for unloaded downhill haulage.

Table 3.2: Performance data for loaded and unloaded haulage (GMG, 2022)

Performance Data Power required at maximum speed capable (kW at km/hr)				
	Grade (%)	Estimated or Tested?	Power (kW)	Speed (km/h)
Loaded				
+20% Grade	20%	estimated	200	13.0
+15% Grade	15%	estimated	200	15.5
+10% Grade	10%	estimated	174	17
+5% Grade	5%	estimated	109	20
0% Grade (flat)	0%	estimated	44	20
-5% Grade	-5%	estimated	-28	20
-10% Grade	-10%	estimated	-95	20
-15% Grade	-15%	estimated	-160	20
-20% Grade	-20%	estimated	-226	20
Unloaded				
+20% Grade	20%	estimated	174	20
+15% Grade	15%	estimated	138	20
+10% Grade	10%	estimated	101	20
+5% Grade	5%	estimated	64	20
0% Grade (flat)	0%	estimated	25	20
-5% Grade	-5%	estimated	-16	20
-10% Grade	-10%	estimated	-56	20
-15% Grade	-15%	estimated	-92	20
-20% Grade	-20%	estimated	-129	20
Power required at zero speed with all auxiliary drives operating at max. power		estimated	<10	

These differences in energy profiles will also influence battery capacity and state of charge, as well as any charging requirements. Furthermore, one needs to take into consideration that hauling down ramp fully charged will require the BEV to dissipate energy created during regenerative braking differently by releasing heat through braking resistors or having to use its service breaks, because one cannot charge a fully charged battery. It is important to mitigate this by strategically selecting charging station locations and to charge only to pre-specified states of charge. Limiting the charge will allow for utilizing energy created during regenerative braking.

Trolley assist

If uphill haulage is unavoidable, one can choose to implement trolley assist systems in their mine design. Trolley assist systems are for diesel engines that are fitted with overhead catenary systems so when disconnected they can still do horizontal movements. It allows for opportunistic charging in specific zones with permanent roads, eliminating charging requirements or downtime associated with charging. A combination of BEV and trolley assist would fully eliminate any exhaust emissions and would allow electrification all over the mine despite fixed infrastructure requirements. The main disadvantage of using trolley assist include a large capital investment due to its infrastructure requirements. In addition, road maintenance is significant and will require large operational costs. Maintenance of roads will increase due to relocation of electrical lines and other infrastructure, especially in a highly dynamic mine.

3.5 Maintenance areas

Even though BEVs contain less components than their alternative diesel equipment's, maintenance of BEVs is still equally important and requires well equipped maintenance areas including repair bays, welding bays, tire handling and lube treatment bays. Components found in diesel trucks that are also present in BEVs and require the same form of maintenance are hydraulic systems, mechanical brakes, moving joints, bucket lips, fire suppression systems, tires, and greasing systems. The service areas should prevent contact with moving parts or voltages, especially for energized BEVs. Conductors with high voltages should be covered with protective gear that only can be removed with tools. High voltage energy is always found withing batteries due to capacitors or chemical batteries not immediately dissipating charges, even when de-energized. Risks of shock and burns can still be present. Hence, batteries should have protocols in place should bring these voltage levels to a safe operational level. This should be provided by OEMs, as well as maintenance schedules and preferred maintenance procedures of components.

A typical BEV maintenance area should also include lifting equipment or a crane for removing battery packs withing BEVs. This could require larger maintenance area heights, especially in underground mines. Extra excavation of underground workshops might be required or increasing the roof height for surface mines. Additional rigging tools might be needed to handle batteries. Lifting points for heavy components should be located strategically so that cables or chains do not interfere with other components. Sufficient clearance for maintaining and inspecting components should be provided. High- and low-voltage components should be separated, and system voltages should be easily identified according to standards like ISO IEC 60204-1.

Furthermore, maintenance workshops should include a charging station for BEVs to charge and be ready for operational service when maintenance is finished. A test load with a DC/DC controller should be available to safely (dis)charge batteries.

To mitigate or prevent any fire hazards associated with batteries, maintenance areas should also be equipped with fire suppression or containment systems and a containment area to store damaged batteries. Besides a containment area for damaged batteries, a regular storage space should be provided to store undamaged batteries. In addition, tools for maintaining and troubleshooting electric motors should be available, as well as the necessary space to do so. Low-capacity portable chargers should be present in the maintenance area to (dis)charge batteries. Lastly, a battery maintenance space should be present if batteries are maintained on site.

Personnel movement and parking

In addition to accommodating maintenance areas for BEVs, it is important to considered movement of personnel as well as any parking for BEVs. These have more specific requirements than diesel vehicles as BEVs need to be charged at the end of the shift. If a BEV is parked at a charging station, one needs to consider the movement of personnel from the charging station to the mine exit or shaft for underground operations. This can be done by either walking or using personnel carriers.

If operators and mine personnel are walking from the parked BEV to the mine shaft/exit, the charging station should be located close to the shaft station/exit. This area needs to have enough parking opportunity for all BEVs on site and sufficient chargers as well as power supply chargers. Longer cables for charging might need to be used in parking areas around the shaft/exit to prevent any damage or wear from traffic or dust.

If using a personnel carrier from the parking area to the shaft or vice versa, one needs to make sure that the personnel carriers are located near the shaft station so it can bring personnel to the parking locations, and vice versa. In addition, the personnel carrier should be able to bring personnel to different mining levels to reach any necessary equipment, based on the location of the parking areas. The carrier should be able to charge near the drop off location as well. In this scenario, group travelling is highly encouraged, especially if long uphill travel is necessary at the end of a shift. This method is also more cost effective.

3.6 Charging infrastructure

General considerations for charging infrastructure include appropriate infrastructure for on-board charging, off-board charging and battery swapping. This includes any necessary excavations or provision of space to accommodate for charging. Furthermore, general considerations after having chosen the charging method include locations for charging, the usage of shared chargers, a one size fits all charger, centralized charging options (one power cabinet at a power station would charge more than one system at a time), specific chargers for specific equipment, available space for parking. Lastly, as one opts to use BEVs to decarbonize their mine site, the source and associated emissions that come from the power source is important to consider. In addition, one needs to consider the mine cycle and schedule for both charging time as well operating time, as charging will affect the operations. Lastly, the cost implications of different charging methods need to be accounted for because cost-effectiveness and economic feasibility are important to assess.

Charging philosophy

The main goal of choosing a charging philosophy is to attain the same ease and safety to charge a BEV fleet as it is to fuel a diesel vehicle. One needs to avoid the risk of having incompatible charging stations throughout the mine site. The operational route vehicles need to take as well as the layout of the mine is the main starting point of choosing an appropriate charging philosophy. The charging method should be based, but not limited to, the following considerations:

- Shift schedule relative to when charging will take place.
- Uphill or downhill haulage
- Available ventilation
- Available battery capacity for a certain type of BEV
- Size and capacity of BEV and working areas.
- Greenfield or brownfield operation
- Fleet mix (fully electric or hybrid)
- Energy consumption model

Large batteries would limit uphill haulage due to capacity and weight constraints. Brownfield projects with large uphill ramps or underground operations at great depths should perhaps consider hybrid vehicles with trolley assist. Greenfield projects could install a shaft at large depth to ensure downhill haulage of BEVs and use regenerative braking to increase available battery capacity, given the trade-off between capital cost and operational expenditure. All these factors could constraint or affect the above-mentioned considerations to determine charging philosophy.

Other charger philosophy considerations include:

- Standardizing operation with one type of charger
- Hybrid charging for BEVs with trailing cable.
- Parking arrangements for stationary charging stations
- For larger mixed BEV fleets, consider multiple capacities for charging BEVs with standardized charging interfaces.
    - For larger BEVs, opt for fast-charging and high-capacity chargers, as low-capacity chargers would take too long to fully charge the BEV.
    - Smaller BEVs could use lower capacity chargers as the higher capacity ones would be limited to what the BEV can accept as incoming power.

- Battery swapping would be preferred if the operation involves large uphill haulage. In addition, opportunity charging stations, or a storage battery could be implemented as well.
- Output voltage range at different nominal voltages should be considered for chargers.
- Charging locations should be located to maximize battery operating range. E.g., if a charging station is located on top of long uphill haulage route, BEV will not be able to use regenerative braking on its way down.
- If battery range is larger than shift length, than shift charging would be preferred.
- If battery range is shorter than shift length, battery swapping, in shift charging or shift change charging with opportunity charging would be preferred.
- Battery range will be reduced in the long term as battery quality degrades the more charging cycles it goes through.
- Need to consider trade-off between battery capacity, cost, and infrastructure requirements for different battery capacities.

Opportunity charging refers to the BEV being charged while stationary during its operation. This would imply no downtime with the charging as compared with other charging methods or refuelling of diesel equipment. For example, charging while operator is on lunch break, charging while loading and unloading equipment, charging while operating using a jumbo cable, etc.

3.7 Charging station layout

The environment where the charging station is located is of significance as BEVs have sensitive electronics. The following environmental factors should be avoided: dust, humidity, high salinity, sulphur fumes, heat, vibration, percussion blasts, falling objects, water leakage, flooding, blasting gasses. In addition to these environmental variables, fire suppression is of key importance as chemical fires are often associated with batteries. The fire suppression or detection methods depend on insurance policies, company standards, local laws and regulations as well as the mine and its mining method.

The following are pre-installation considerations for the charging station:

- The station should not be located near any dangerous areas like explosive storage or gaseous areas.
- Adequate space needs to be provided for personnel.
- Early detection and monitoring systems for fire
- Remote emergence of a switch near the charger outside of the potentially hazardous area
- Labelled parking spaces for BEVs
- No presence of water/mud to prevent electrical hazards.
- Protection against ingress of dirt and water entering charger connectors.
- Abrasion protection
- Easily maintainable and level floors
- Adequate visibility of charger controls.

- Easy transportation of charging systems to a new location, especially in highly dynamic mines
- Overcurrent protection device.

Spacing and parking suggestions should be provided by OEMs and should be according to regional laws and authorities. Space should be provided for easy manoeuvrability of the charging cable, as well as adequate size and length of the charging cable are important in parking areas.

If considering battery swapping as a charging method, the BEV needs to enter, charge, and exit in a relatively short amount of time. The swapping station should include a crane system compatible with all BEV types in the fleet mix. The crane systems need to be able to remove, move, and install batteries with ease in the charging area. A charger large enough to charge the necessary number of spare batteries present in the operation should in located within distance. If considering a remote battery swapping method, meaning the swapping of batteries wherever the BEV is located within the mine, necessary tools for battery transportation and installation should be provided within the mine. Remote battery swapping can be advantageous if BEVs are located at a large distance away from the swapping station and would result in significant increase in downtime associated with charging. This can prove to be rather complex and expensive to procure, maintain and operate additional tools required.

Training of necessary personnel is important for safely operating the charging system, the charging systems should be operated according to protocols set by OEMS and charger manufacturers. These include:

- charger needs to be turned off for removal of charger connector.
- charger needs to be turned on for injection of charger connector.
- if charger lock is opened during charging, charging should stop to prevent arcing and shocks.
- charger should report any malfunctions or warnings (e.g., exceeding temperature range) and stop charging.

3.8 Risk assessment

When having decided to implement BEVs into a mine operation, it is important to perform a risk assessment and evaluate any possible treatments.

Financial risk

One major risk associated with implementation of BEVs is an increased CAPEX due to infrastructure. This is due to required charging infrastructure, battery handling infrastructure, any service upgrades, battery procurement, electric vehicle premiums and the need for a larger capacity power infrastructure. To reduce this financial risk, one can optimize the mine design for BEVs or optimize the charging philosophy, implement a mine energy management system, lease equipment instead of owning equipment (the same applies to batteries).

However, especially for underground brownfield operations, opting for BEVs will translate in a reduction of ventilations and fuel infrastructure.

In addition, one can experience an increased operational expenditure due to an increase in power supply required and a possible decrease in production rate. This can be mitigated by, again, optimizing the charging philosophy of the BEV fleet. Furthermore, a reduction in power required for ventilation and refrigeration can be enjoyed. BEVs also showcase an increase in performance compared to standard diesel equipment while in use during operations. Other possible solutions include fast charging, battery swapping, opportunity charging and reduced equipment maintenance.

Furthermore, production rate can be impacted, meaning a reduction in availability and utilization of BEVs. This can be due to battery charging time or charger availability. This can be mitigated by, again, optimizing the mine design for BEVs, optimizing charging philosophy and implementing an energy management system. In addition, optimizing charger location and using opportunity charging can mitigate this risk.

Lastly, early battery replacement might pose a financial threat. This can be due to overdischarging, (dis)charging outside of the optimal temperature range or by overcharging. This risk can be mitigated by employing a battery management system or opting for a certain battery chemistry. Battery maintenance procedures should be in place to prevent damaging or degrading batteries. Lastly, a battery lease program could be put in place.

Health, safety, and environmental risks

One of the HSE risks associated with BEVs is discharged vehicle recovery. This can occur due to battery failure, a discharged battery, operator error or a battery nearing the end of its lifecycle. Possible treatments for this risk include towing disable vehicle plans, charging vehicle to vehicle, providing available charging at deeper depths, on-board charging to common equipment plus, reserving capacity for recovery mode, optimizing charging locations, opportunity charging and implementing a battery monitoring system.

In addition, fires or explosion are of major concern when it comes to BEVs. This can be caused due ot battery failure, short-circuiting, overcurrent or overcharging, excessive charge rates, excessive regeneration, thermal runaway or any collision or punctures. This risk can be mitigated by choosing an appropriate battery chemistry, implementing an adequate battery management system, protection against short-circuits or overcurrents. In addition, protection from puncture or arcing faults, firefighting plans, remote machine monitoring, and fire suppression methods can prevent or mitigate this risk.

Furthermore, asphyxiation can occur due to battery fires, which can prove to be life endangering. Asphyxiation can be mitigated by implementing an automatic fire suppression system, optimizing the location of battery storage as well as parking or charging locations and optimizing ventilation design. In addition, fire door at battery storage locations and carrying oxygen generating self-rescue devices help prevent and mitigate this risk.

Electric shocks and arcing faults can be caused by exposed live electrical parts, damaged batteries or wiring or charging cables. A faulty charger/connector or plug or the inability to de-energize a battery can also lead to this risk. To mitigate or prevent, one can isolate batteries and implement safe work methods and wear PPE. In addition, insulated tools or covers, the isolation of chargers and charger control systems as well as earth fault protection and resistance grounding can be put into place. Short-circuit and overcurrent protection as well as any preventative arc faulting detection systems are possible treatments.

Moreover, the lack of noise can present an HSE risk due to the fact there is no diesel motor inside a BEV, making it hard to notice when a BEV is driving by, potentially leading to collisions and accidents. To mitigate this risk, one can use lighting such as marking lights or strobe lights making the BEV very visible. In addition, collision avoidance systems or personnel alert systems and an audible alarm can mitigate this risk.

Lastly, a work battery that can leak toxic waste or electrolytes to the environment can be dangerous for health reasons. This is mainly due to old and damaged batteries but can be mitigated by selecting appropriate battery chemistry, choose for a battery design with secondary containment, implement a recycling program with the manufacturer of the battery or implement an adequate battery maintenance program.

4. Case study and results

This chapter will introduce the operational site chosen for a case study and will show the result regarding electrification, hydrogen, and alternative fuels, with a focus on costs and emissions. Simulations for diesel equipment, battery electric vehicles and trolley assist will be done, as well as a thorough site description of the case study in question, Ipoh.

4.1 Case study introduction

4.1.1 Site description

Imerys Minerals Malaysia operation is located in the town of Keramat Pulai, next to the wider city of Ipoh (Perak State, Malaysia) at latitude 04° 33' 3.47" and longitude 101° 09' 14.48". For convenience it will be referred to in the report as Ipoh only.

This Ipoh site is composed of one quarry with two crushing lines, namely Big Mac (primary) and RACE (secondary) crushing plants, and two GCC processing plants. The extraction is performed at the top of a marble hill, surrounded by karst topography, and settled under tropical climate with dense vegetation surrounding the facilities. Processing was progressively developed starting from 1999 until 2016 where the RACE optical sorters were added into the crushing line.

Blasting is required for hard rock materials (ore and waste) and all materials are extracted by hydraulic excavators to achieve good mining selectivity and hauled by articulated dump trucks. The mine site has all required permits for operation. Overall mining recovery is assumed to be 95% in most of the marble types based on the Competent Person extraction experience per lithology.

In terms of processing, two crushing steps can be described. Firstly, the ore is sent to ROM pads in homogenous, non homogenous, and high brightness stockpiles depending on the marble quality. Then, to create the final products, two crusher systems are run to process the ore from the run of mine. Firstly, <800mm rocks are processed through BMAC primary jaw crusher which produces 13% of fines (-10mm). Then, the remaining 87% will be feeding the secondary crusher at the RACE plant. This latter crusher aims at processing most of the higher-grade quality ore with optical sorters. Quality control sampling is conducted after RACE crushing. Global process recovery from 2017-2021 is average at XX,X%.

4.1.2 Geology and climate

The Gunung Terundum is a mogote hill with its historical highest point less than 440 m above the mean sea level. It is a typical tropical mogote consisting of steep sided walls and rounded top profiles which rise from a flat alluvial plain. The surrounding alluvial plain is from 70 m to about 80 m above the mean sea level. Gunung Terundum is depicted as a smooth, massive hill. However, seen from the lateral view or from the air, it is observed to be dissected by numerous collapsed "wangs" or karsts. These wangs have also been referred to as "sinkholes" locally, but these are the equivalent of dolines and uvalas of the temperate climate karsts. Several large to medium-sized collapsed depressions are seen on the Gunung Teruntum hill and some of them are elongated along the main fractures of the massif. Typically, the topography at the sides of the steep hill is marked by a sharp and jagged surface of the limestone undergoing strong solution. The top of the hill, however, shows rounded surface due to weathering under a thin soil cover. In addition, the topography on top of the hill can be described as undulating with low to moderately steep gradient. This contrasts with the sides of the mogote hill that is jagged, highly uneven and with a lot of small to medium-sized solution cavities and almost vertical in slope angle. The accessibility to the quarry on top of the marble hill is challenging due to the karst topography with steep flanks. Topsoil is encountered when opening new areas and often contaminates the ores. While no major river is found nearby the site, seasonal streams are observed flowing down from the marble hill in the wet season.

Tropical climate in Malaysia indicates dense vegetation, and small-scale plantation areas (mainly oil palm) are observed near the site. The whole of the Gunung Terundum is covered by tropical vegetation which is growing on whatever soil occurs between the rock crevices and on the top of the hill. Bare rock faces are found mainly along the steep sides surrounding the hill at various parts. These represent collapsed marble walls which are geologically very young, probably less than some thousand years old.

The climate of the region is classified as tropical rainforest. The temperature shows little variance throughout the year, with average mean daily minimum and maximum temperatures of 23 °C and 33 °C. High precipitation is observed throughout the year, with average mean monthly rainfall of 202 mm. The region faces two major monsoon seasons, with wet months starting from April - May, and September - December, with highest precipitation in November, while driest month is June. Frequent precipitation of tropical climates potentially shortens the operation times daily. Especially in monsoon seasons, high rainfall will bring road erosion and potential rockfall hazards.

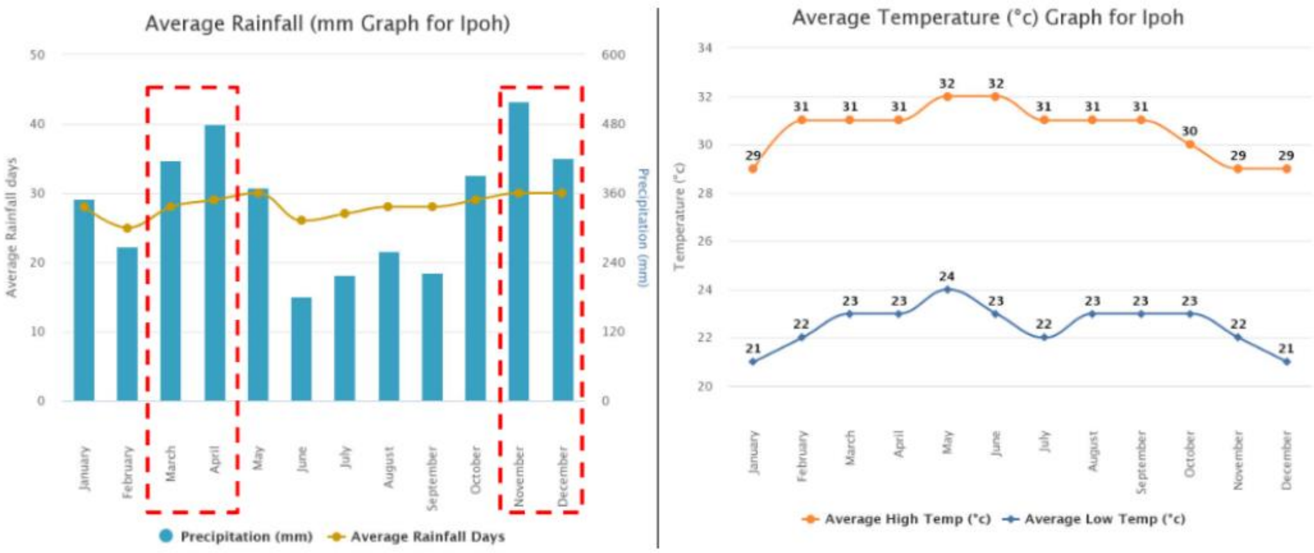


Figure 4.1: Average temperature and rainfall per month in Ipoh

4.1.3 Site infrastructure:

The power supplied to the plants and offices are transmissioned from the national grid, with a 11kV substation placed in the RACE (secondary crushing) plant vicinity. Water supply to the primary and secondary crushing plants is solely depending on the water ponds available at the site. The water recycles in a closed-circuit loop, and replenishment is coming from rainwater.

Several sedimentation ponds are available on site to capture sediments from the quarry, the waste dump and the process (fines reject) before entering freshwater ponds or leaving the site. Internal site access roads are unpaved but generally good condition gravel roads. A short segment of unpaved gravel road to the site entrance from State Route A181 is shared with neighbouring quarries, including a tire washing bay.

4.1.4 Mining method

The Imerys Malaysia quarry is located in Simpang Pulai, Perak. Extraction is performed in an open pit with the longest stretch of approximately 550 metres and the width closes to 280 metres (at present stage). Standard bench height is 10m.

The major ore type is marble that will be processed into the crushing line to create chips products, sorted principally following several brightness levels, namely High Brightness (HB) marble and Regular Brightness (RB) marble. Site supervisor will sample daily on the loading point/ muck pile to check on the ore quality, then mark the wastes onsite and inform the excavator operators for removal. Mining activities in the quarry are fully contracted including blasting / braking / loading / hauling / tipping (described in the next sections). Drill and blast are required for hard rock materials (ore and waste). All rock materials are extracted by excavator and hauled by articulated dump trucks. Ore oversized boulders will be isolated onsite and broken into smaller pieces (< 800 mm) by hydraulic breaker before transport to hopper, while waste will be sent as is to the waste dump. All loaded trucks coming down from the pit will be weighed at the quarry weighbridge before sending to the ROM pad or waste dump. An overview of onsite equipment is given below:

Table 4.1: Equipment available on site

No.	Equipment type	Model	Unit on site
1	Articulated dump truck	Volvo A40F and A40G	11
2	Excavator	Volvo 480	4
3	Breaker	Volvo 480 (with breaker unit)	2
4	Bulldozer	CAT D6R2	1
5	Blasthole drill rig	Atlas Copco T40	3
6	Loader	Volvo L220	4
7	Water/fuel truck	Hino	1
8	Motorgrader	Volvo G930	1
		Total	**27**

Overburden stripping also requires drill and blast - as a mix of soil and subsurface altered marble, and as the pit is deepening in the centre, it is only encountered near to the edge of the pit boundary. The overburden is sent to the waste dump as well or used as cover of the final waste dump slope for rehabilitation (for topsoil only). Selective mining is practised to segregate the ore and waste. While the ore is categorised into several grades essentially based on the brightness, however in the pit it is segregated as homogenous (white - light grey marbles), non-homogeneous (mixture of different colours) and HB (HB, very white marble with brightness >95.5). Internal wastes are referring to the coloured materials (whose chemistry greatly vary as well) such as: calc-silicate bearing marble, black hydrothermal veins, granitic rocks, dolomitic marble, dark grey marble, and fault zone material.

For the Ore, the loaded dump truck is permitted to practise direct tipping under the supervision of the ROM spotter and with a safety berm always maintained at minimum 1m.

The wastes hauled from the pit are sent to the waste dump, which is located ~600 m northeast to the quarry pit. It holds the quarry wastes and plant rejects. The tipping method at the waste dump is different vs. ROM stockpile as no “direct tipping” over the edge is permitted and request short tipping. The loaded dump truck must tip the ore at the waste dump at least a truck length from the edge of the bench, then push by the dozer to the edge. Adequate safety berm (at least 1 m high) shall be maintained at the edge by the dozer all the time.

Figure 4.2: Ore mining activities from drilling to crushing

4.1.5 Deposit geology

Imerys Malaysia quarry is located in Gunung Terendum, Simpang Pulai. It can be further divided into two geological blocks: Honaik block to the west and Zain Liew block to the east, separated by a major N-S trending fault. Honaik block can be subdivided into Honaik top and Honaik bottom by elevation.

Major lithology of the Gunung Terendum deposit is marble, overlying schists and a granitic substratum. In the Zain Liew block, supposed bedding traces are mainly oriented around N100-110ºE with a moderate dip of 20º towards the south. This general orientation is modified close to the North-South fault zones. In the Honaik top block, the structure of bedding traces appears more complicated with many changes related to faulting structures in this area. Measures of bedding traces fluctuate from N70 ºE to 130 ºE and the dip is between 20º and 40º towards the south. In Honaik bottom the bedding direction is oriented around N140 ºE with a dip frequently higher than 40º to the SW

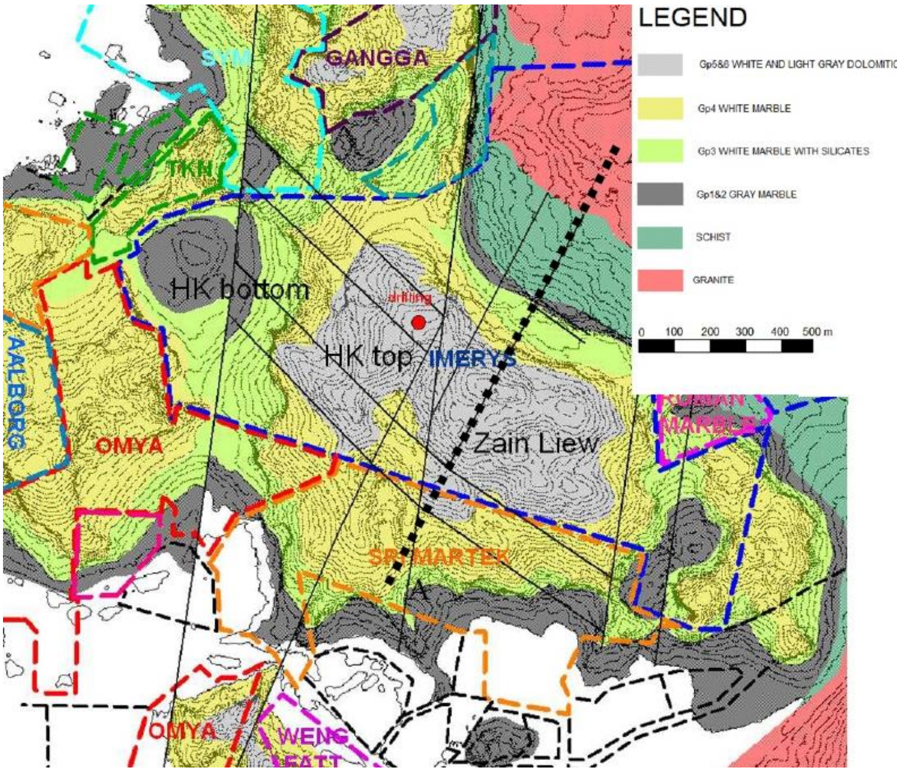


Figure 4.3: Geological map Imerys Malaysia quarry with concession boundaries

The Gunung Terendum marble deposit is part of the Kinta Valley Limestone that overlies on younger granitic intrusion with variable degrees of hydrothermal alteration. Southeast Asia was dominated by carbonate deposition from shallow continental to deeper waters of the Paleo-Tethys in Devonian- Carboniferous, and Kinta Valley limestone is within the region. Similar carbonate deposits are found, among others, in Phuket Thailand, Kampot Cambodia, Vang Vien Laos, Ha Long Bay Vietnam and in the Guangxi province China.

4.2: Software and simulation

To simulate the required haulage network with different fleet options, Quarry Solution 3.2 of RPM global has been used as a software. This subchapter will show how the simulations have been obtained by implementing the necessary parameters.

4.2.1 Waste dump

The waste dump is located south of the orebody. Figure 4.4 shows a plan view and side view of the dump area. The waste dump is located lower in elevation than the orebody, and its volume to put waste is the limiting factor for the life of mine of the orebody. When the dump space is filled, there will be no other area to put the waste. In real life this can be mitigated by acquiring other plots of land or spaces to put the waste material but in these simulations the end of life of the operational site is determined by when the dump space is filled.

Figure 4.4: Plan and side view of the dump space

The first step is to configure the design solids of the dump. This can be done in Quarry solutions by by importing a DTM file to represent the surface topography of the full quarry. This DTM file has been created in Surpac solutions. This step is followed by importing another DTM file created in Surpac representative of the waste dump space, as seen in figure 4.5

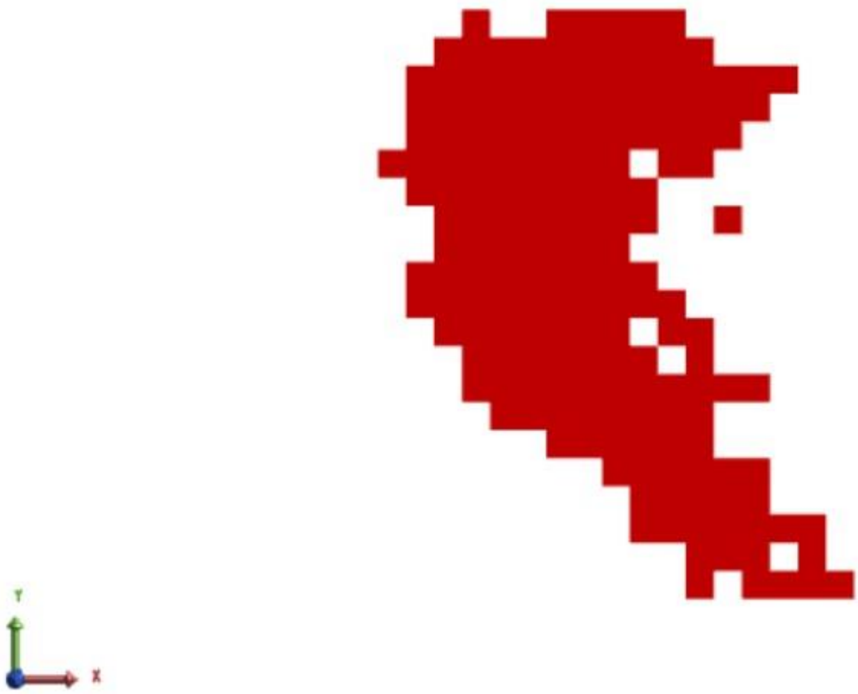


Figure 4.5: Dump space design solid visualisation

After having created and defined material zone properties (volume), dump planning blocks need to be created ("créer des blocs de planification de benne"). This is done by firstly creating the hoisting geometry ("configure la géométrie du monte-charge") and the benches of the dump space. Height of the bench is 10 meters, and the reference height is 130 meters above sea level. The dump space can then be visualized as seen in figure 4.6 and 4.7. The waste dump space is spread out over consecutive benches and totalling around 70 meters in height.

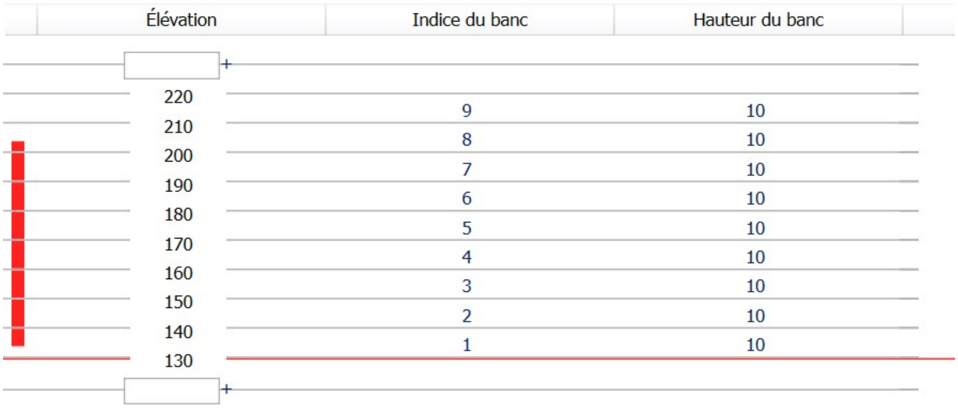


Figure 4.6: Dump space visualisation

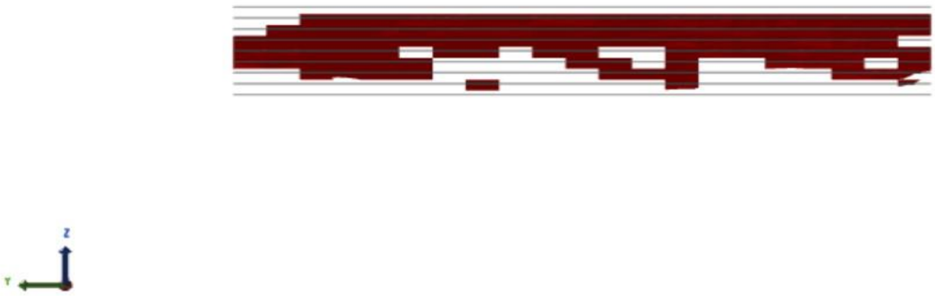


Figure 4.7: Dump space side view

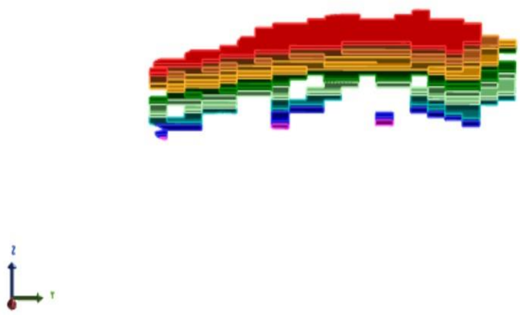


Figure 4.8: Dump space graded by height side view

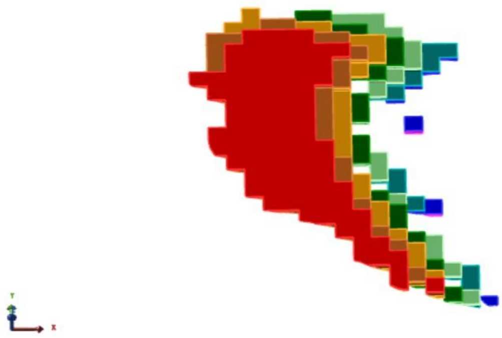


Figure 4.9: Dump space graded by height top view

This step is followed by importing and generating blocks into the dump model, visualized in figure 4.10 and 4.11. The dump space block model is a maximum width 17 blocks and a length of 21 blocks. The height of the dump space block model is 7 blocks high. The blocks are sized

25 meters in both X and Y direction, 10 meters in the Z direction. According to Xpac quarry solutions, the block area is XXX XXX m² and the volume is X XXX XXX m³. XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX.

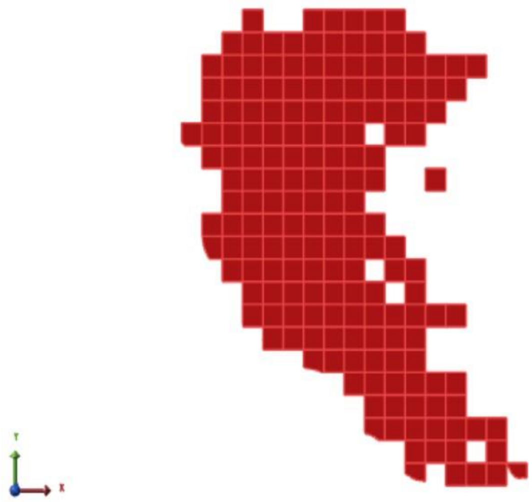


Figure 4.10: Dump space block model

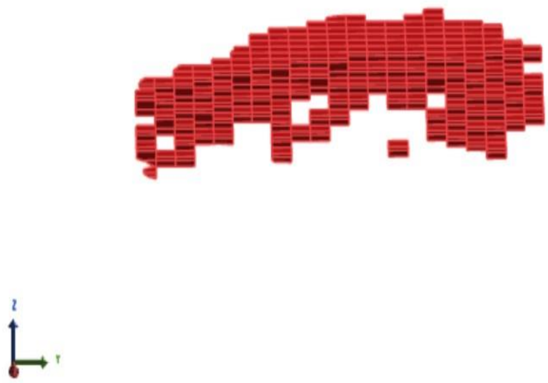


Figure 4.11: Dump space block model side view

Dumping best practices were implemented, with overall slope angle of 30° with 10m bench height and 5m berm width. 2-3% slope angle inward has been foreseen as a drainage scheme, downstream of the dump. Fine material must be spread first and compacted by a dozer in thin layers of 50-70cm for an optimal compaction and waterproofing whereas the rocky material will prevent erosion while allowing water circulation until the bottom of the dump. The dumping best practices have been summarized in figure 4.12.

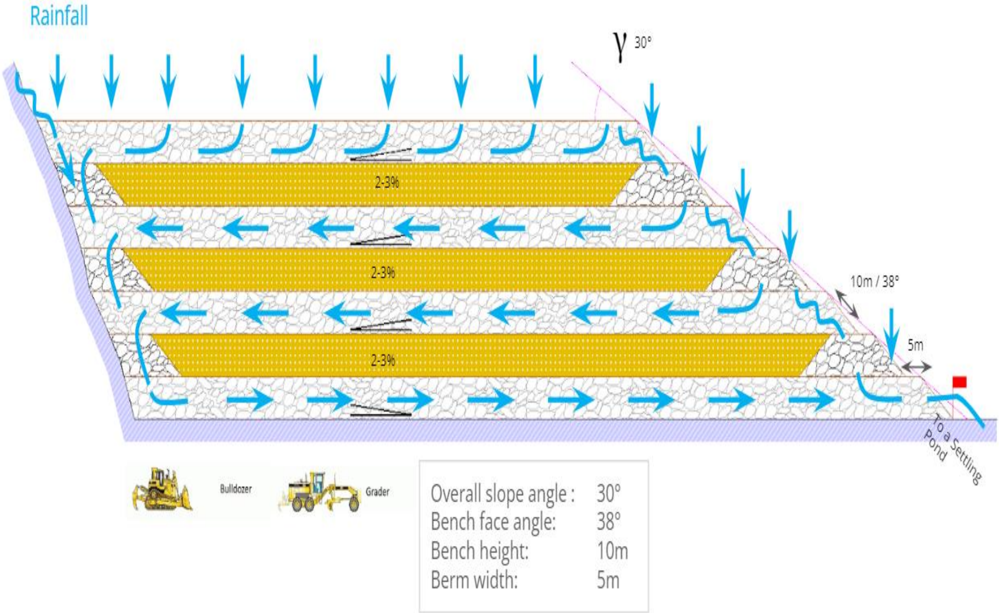


Figure 4.12: Dump concept implemented in Ipoh

Based on the technical report, the dump space looks as follows:

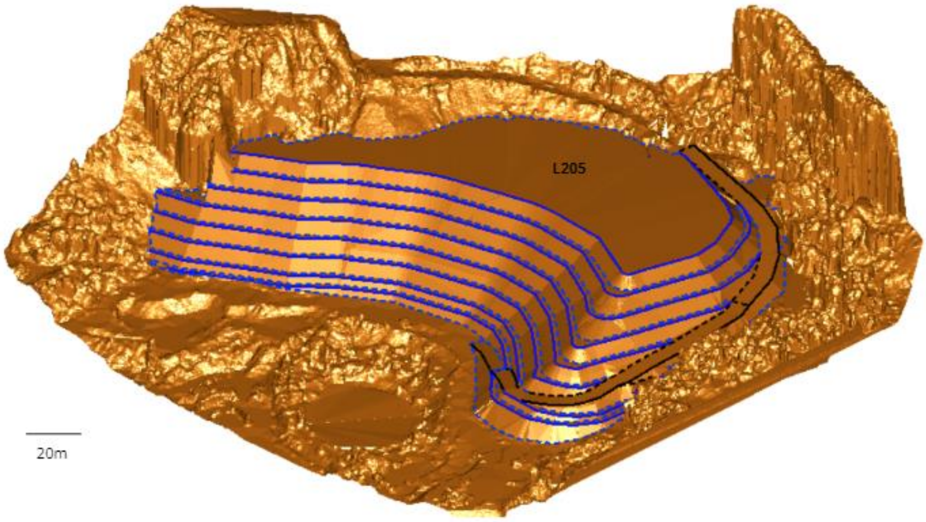


Figure 4.13: Technical report waste dump

One can see that the shape of the simulated waste dump corresponds to the shape and size of the waste dump in the technical report

4.2.2 Reserves

The first to be done to build the reserves of Ipoh in Xpac Quarry solutions 3.2 is to configure block model data. The reserves block model is a complex block model as it contains multiple materials in each block. The imported fields of the reserves are XCenter, YCenter and Zcenter which corresponds to the X, Y, Z coordinated of the centre of the block respectively. In addition, the length of the block in the X, Y and Z direction have been imported as XSize, YSize and ZSize respectively. Furthermore, lithology has been imported, but density, mining recovery and High brightness recovery have been calculated by the software. An mdl (simulation model) file has been used to import all parameters mentioned above. A Surpac dtm file was used for the next step as a solid design file resulting in the following visualization of the reserves:

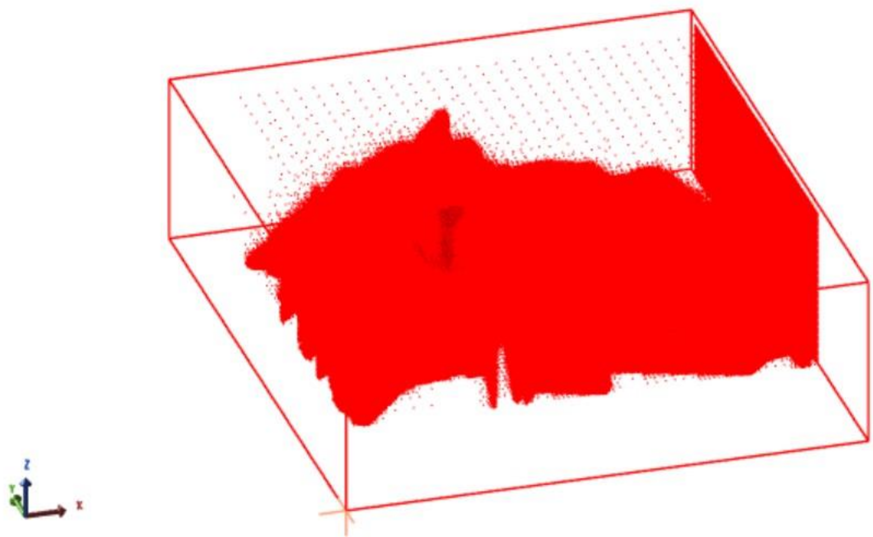


Figure 4.14: Solid reserves design

The next step is to define the materials within the reserves. The materials classified as "ore" are high brightness ore and regular brightness ore. Waste is classified as waste. Based on the definition of materials present in the reserve, two activities have been created: ore and waste. The reserves are then visualized by Quarry solutions software as seen in figure 4.15.

Figure 4.15: Reserves Ipoh design

After having validated block model data, the mining recovery, density, and ore recovery are calculated as seen below:

Figure redacted

Figure 4.16: Density

Figure redacted

Figure 4.17: Ore recovery

Figure redacted

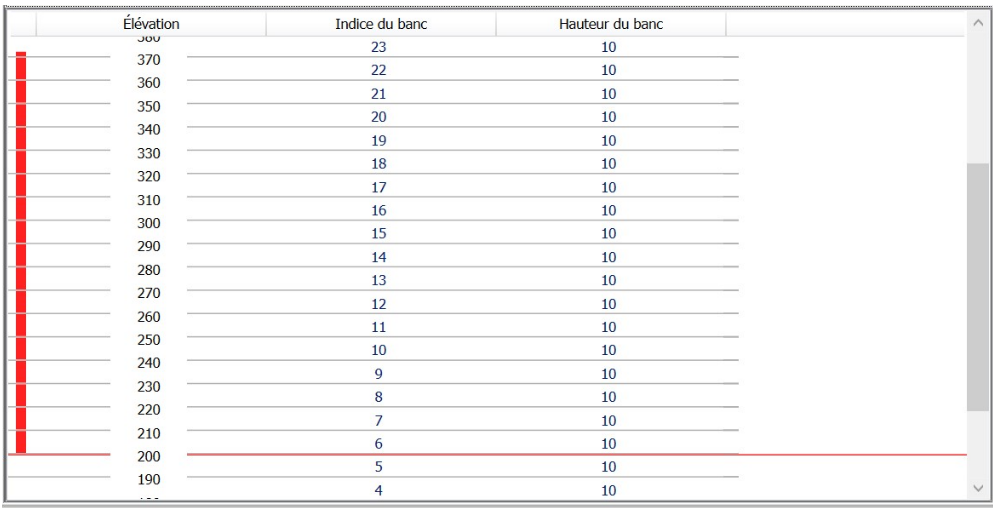
Figure 4.18: Mining recovery

After having validated the reserves block model data, the next step is to establish the reported fields, in this case tonnage and volume for each lithology. The volume and tonnage is calculated as follows:

Volume = solid volume * calculated mining recovery * calculated ore recovery.

Tonnage = solid volume * calculated mining recovery * calculated ore recovery * calculated density.

When the volume and tonnage have been defined, the configuration of bench geometry can be implemented. Bench height is 10 meters with a reference height of 200 meters. In figure 4.19, one can see a graphical representation of Ipoh's reserves as well as a side view of the bench design in figure 4.20.



Élévation	Indice du banc	Hauteur du banc
370	23	10
360	22	10
350	21	10
340	20	10
330	19	10
320	18	10
310	17	10
300	16	10
290	15	10
280	14	10
270	13	10
260	12	10
250	11	10
240	10	10
230	9	10
220	8	10
210	7	10
200	6	10
190	5	10
	4	10

Figure 4.19: Graphical reserves representation

From figure 4.19 we can see that the reserves span over an elevation of 370 meters and 17 benches.

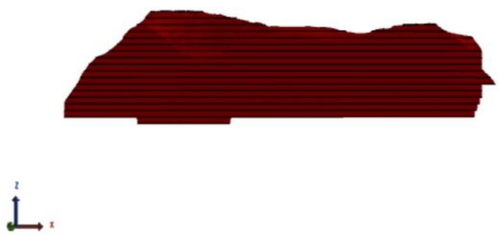


Figure 4.20: Reserves side view

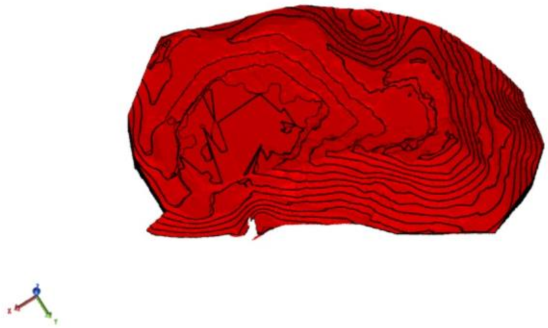


Figure 4.21: Reserves top view

The next step is to generate the blocks into the block model, resulting in a simulation reserves block model as seen in 6.22.

Figure 4.22: Reserves block model

According to the simulation results, the high brightness ore has a volume of XXXXXXXXXX m³ and a tonnage of XXXXXXXXX tons. The regular brightness ore has a volume of XXXXXXXX m³ and a tonnage of XXXXXXX tons. In total there is XXXXXXXX m³ and XXXXXXX tons of ore. In total, there is XXXXXXXX m³ of waste volume and XXXXXXX tons of waste. Tonnage and volume per ore type has been graphically represented in figure 4.23 and 4.24.

Figure redacted

Figure 4.23: Reserves tonnage per material

Figure redacted

Figure 4.24: Reserves volume per material

4.2.3 Haulage network

The simulated haulage network has been created in Haulnet, part of the Xpac Quarry solutions software.

The first step is to construct the haulage network buy creating different annotations on the haulage network: pit 380, pit 200 and pit 190, switchback, dump 200, dump 190, dump 180, dump 170, dump 160, dump 150, dump 140, dump 130 and dump 120. These annotations serve as different destinations on the haulage network. Pit 380 and pit 200 are the top and bottom of the reserves, whereas dump 200 – dump 120 are different destinations on the waste dump representing each bench level. The haulage network looks as seen in figure 4.25:

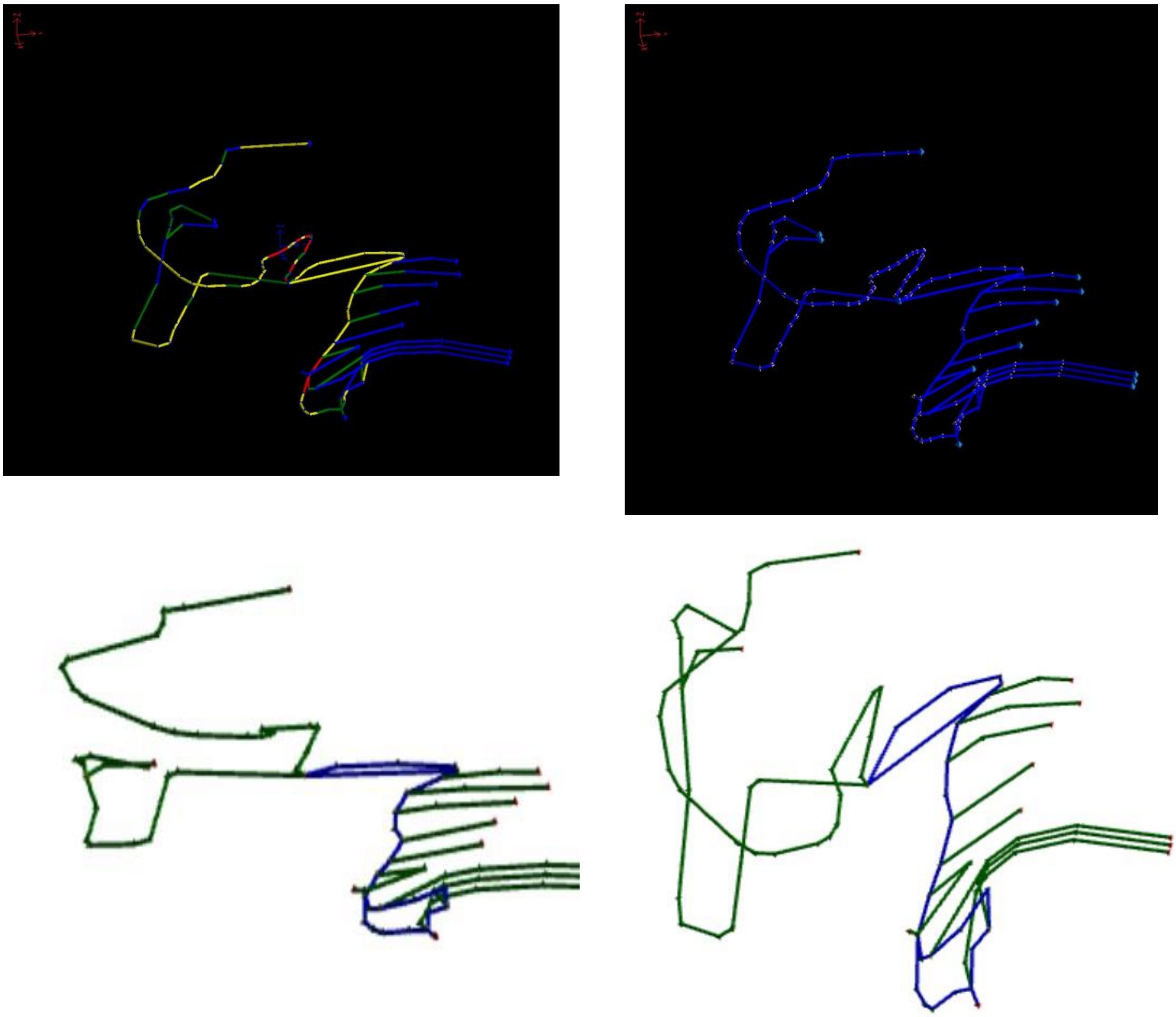


Figure 4.25: Haulage network Ipoh

Different personalised fields have been created. These include pit to denote the pit area; pushback to denote different pushback areas; dump to denote the dump area; Roadtype to denote the type of road (ramp, access road, etc.); trolley to denote if a certain segment can be used with trolley assist and trucktype, as not all trucks can use the trolley assist on the trolley assist segment. Figure 4.26 shows the trolley assist road as well as the length and grade of the different segments. Total length of the trolley assist road is 344.73 meters and the average grade is 10.21 degrees. The reason the trolley assist segment is relatively small is due to the fact that the mine is very dynamic and only this portion of the haulage network is a permanent road.

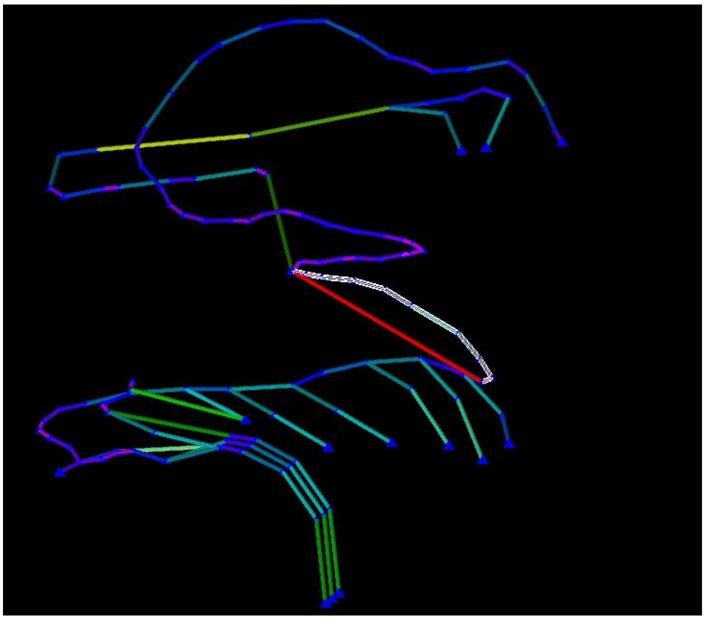


Figure 4.26: Trolley assist road segment

Table 4.2: Length and grade of trolley assist road segments

Longueur	Qualité (%)
13,70	14,76
35,58	8,46
51,46	9,76
75,70	9,29
44,12	11,41
41,85	9,60
42,66	11,80
20,68	14,66
19,17	5,22

The creating of the haulage network allows us to import it back into the Quarry solutions software in the following section.

4.2.4 Planning and scheduling

The first step in creating a schedule for the Ipoh site is to configure the planning reserves by importing the dump and reserves created in the previous sections of this chapter. Furthermore, one needs to define the reference data, define custom database fields and to define the activities. The main activities created is the extraction of ore, more specifically, the extraction of regular brightness and high brightness ore. The second activity defined is the extraction of waste. These steps can then be visualized as follows.

Figure 4.27: Visualization of reference data for planning and scheduling

Furthermore, the material needs to be configured. This implies setting the quantity in terms of tons and volumes in terms of m^3 for both the reserves and the dump. In addition, a swelling factor of 1.2 has been assigned to both ore types as well as the waste. Finally, the last step is to validate the planning reserves, done by the software.

The second step is to configure the haulage network. This implies importing the haulage network and to assign the right fields to the deposit level (pit), the dump level (dump). Road types need to be assigned, these consist of surface roads and ramps. Furthermore, haulage network properties need to be defined. This implies setting speed limits for both low grade and higher-grade surface roads and ramps:

- Flat/ low-grade surface roads and ramps:
  - Fully loaded: 30 km/h
  - Fully unloaded: 30km/h
  - Uphill loaded haulage: 30 km/h
  - Uphill unloaded haulage: 30 km/h
  - Downhill loaded haulage: 15 km/h
  - Downhill unloaded haulage: 20 km/h

- Higher-grade surface roads and ramps:
    - Max grade: 15°
    - Uphill loaded haulage: 15 km/h
    - Uphill unloaded haulage: 15 km/h
    - downhill loaded haulage: 15 km/h
    - downhill unloaded haulage: 15 km/h
- bench roads and lifting roads (route de levage):
    - max speed on bench roads: 20 km/h
    - max speed on lifting roads: 20 km/h
    - rolling resistance: 4
    - traction coefficient: 0.36

After configuring haulage network properties, the planning and scheduling need to be configured. This includes defining the life of mine and weekly working schedule, defining the mining equipment, defining the material flow, and lastly defining the planning resources.

The life of mine has 117 periods of each one month long and runs from May 2023 until January 2033, totalling about 9.5 years, as seen in the tables below.:

Table 4.3: Start calendar time

	Description	Unités	2023						
			Qtr2		Qtr3			Qtr4	
			mai	juin	juil.	août	sept.	oct.	nov.
			1	2	3	4	5	6	7
			01/05/2023	01/06/2023	01/07/2023	01/08/2023	01/09/2023	01/10/2023	01/11/2023
1	Année	Année	2023	2023	2023	2023	2023	2023	2023
2	Trimestre	Trimestre	Qtr2	Qtr2	Qtr3	Qtr3	Qtr3	Qtr4	Qtr4
3	Mois	Mois	mai	juin	juil.	août	sept.	oct.	nov.
4	Numéro de la période	#	1	2	3	4	5	6	7
5	Date de début de la période	DateHeure	01/05/2023	01/06/2023	01/07/2023	01/08/2023	01/09/2023	01/10/2023	01/11/2023
6	Durée	Jours	31	30	31	31	30	31	30
7	Heures Calendrier	Heures	744	720	744	744	720	744	720

Table 4.4: End calendar time

2032							2033
		Qtr3			Qtr4		Qtr1
juin	juil.	août	sept.	oct.	nov.	déc.	janv.
110	111	112	113	114	115	116	117
01/06/2032	01/07/2032	01/08/2032	01/09/2032	01/10/2032	01/11/2032	01/12/2032	01/01/2033
2032	2032	2032	2032	2032	2032	2032	2033
Qtr2	Qtr3	Qtr3	Qtr3	Qtr4	Qtr4	Qtr4	Qtr1
juin	juil.	août	sept.	oct.	nov.	déc.	janv.
110	111	112	113	114	115	116	117
01/06/2032	01/07/2032	01/08/2032	01/09/2032	01/10/2032	01/11/2032	01/12/2032	01/01/2033
30	31	31	30	31	30	31	0
720	744	744	720	744	720	744	0

Ipoh is in operation during the week from Monday to Saturday. Work starts at 5h00 and finishes at 18h00, totalling 13 hours per day 5 times a week. Saturdays the mine site is only in operation until 12h00. In total, Ipoh runs its operations for 72 hours a week. Of the 744 hours in a 31-day month, Ipoh has 417 non-working hours and 327 working hours. For 30-day months this translates to 720 hours of which 406 are non-working hours and 314 working hours.

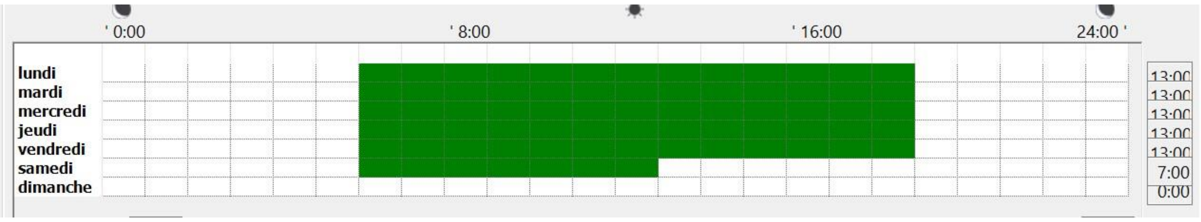


Figure 4.28: Weekly schedule

The following step involves defining mining equipment, in particular trucks and loaders. The loaders used at the mine site and configured in the simulations are Volvo CE – L 220 H. The trucks in question are Volvo CE – A 40 F stage IV.

For the trucks, Fleet size, availability, utilization, and efficiency factor needed to be defined. Fleet size used in the simulation are 9 trucks with an availability of 90%, utilization of 83% and an efficiency of 85%.

	Description	Unités	Valeur par défaut	Qtr2 May 1 01/05/2023	Qtr2 Jun 2 01/06/2023
1	VolvoCEA40FIV				
2	Fleet Size	#	9,00	9,00	9,00
3	Availablility	%	0,90	0,90	0,90
4	Utilisation	%	0,83	0,83	0,83
5	Efficency	%	0,85	0,85	0,85
6	Hours	hrs		1 875	1 801
7	Equivalency Factor		1,00	1,00	1,00

Figure 4.29: Truck parameters

For the loaders, a fleet size of 2 with 90% availability, 83% utilization and 100% efficiency were used. In addition, a dig rate of 450 tons per hour was set. This translates to a monthly capacity of 219 842 tons for a 31-day month.

	Description	Unités	Valeur par défaut	Qtr2 May 1 01/05/2023	Qtr2 Jun 2 01/06/2023
1	VolvoCEL220H				
2	Fleet Size	#	2,00	2,00	2,00
3	Availablility	%	0,90	0,90	0,90
4	Utilisation	%	0,83	0,83	0,83
5	Efficency	%	1,00	1,00	1,00
6	Hours	hrs		489	469
7	Dig Rate	t/hr	450	450	450
8	Capacity	t		219 842	211 102

Figure 4.30: Loader parameters.

Parameters such as drive train, fuel consumption, etc are discussed in section 7.3.

Following truck and loader parameters, flow of material is defined. The starting point is the deposit itself, where the reserves are located. Waste is transported to the waste dump and ore is transported to the crusher. From the crusher, regular brightness marble is transported to the RB stockpile and high brightness marble goes to the HB stockpile. From there it is further processed into their respective products, but this transportation is not accounted for in the haulage network. The flow of material is visualized in the following figure:

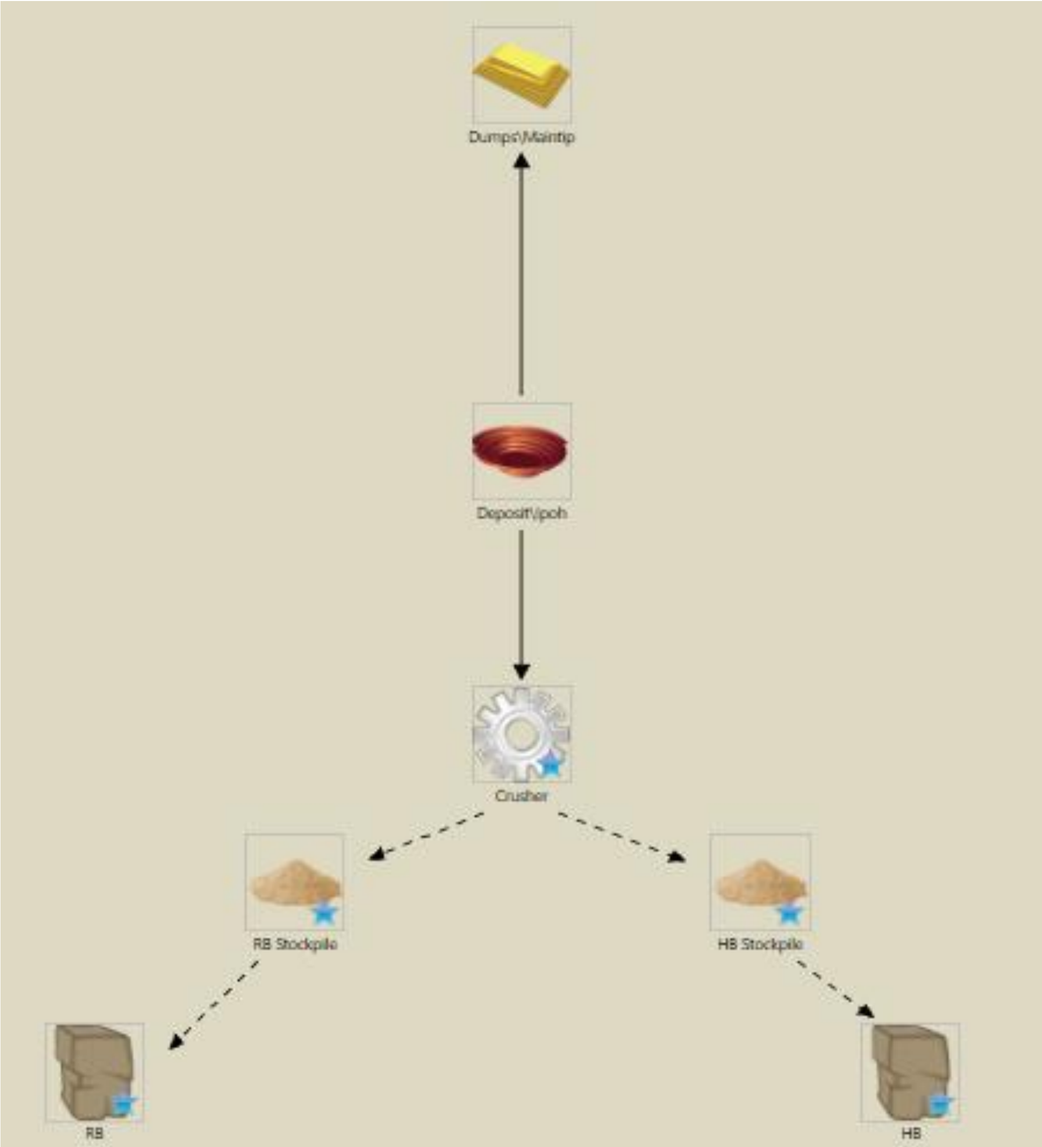


Figure 4.31: Material flow

When the material flow has been defined, one needs to add surface topography as a Surpac DTM file for both the reserves and the waste dump and to define the mining extraction rules. The vertical mining extraction rule states that there are a maximum number of 2 benches active at a time, with a vertical dependence set in place. Entire blocks are mined, and the minimum bench height is set as 10 meters. No horizontal mining extraction rule has been implemented. Furthermore, constraints need to be put in place. The only constraints put in place are extraction constraints. Based on real life extraction results, the maximum quantity of high brightness marble has been set to XXXXXX tons per months. The same limit has been set for waste. The regular brightness ore has been set to XXXXXX tons per month. In the simulation, the extraction limit for high brightness ore has been given priority over the waste and RB ore. This concludes the set-up for the simulations done for diesel equipment, BEVs and trolley assist, which are discussed in 6.3, 6.4 and 6.5 respectively.

4.3 Diesel simulation results

Before simulating the haulage network with diesel LHD equipment (trucks and loaders), the equipment configuration needs to be specified. For the diesel equipment, Xpac Quarry solutions database has been used to import existing vehicle properties of the loaders (Volvo CE L 220H) and the trucks (Volvo CE – A 40 F IV).

For the Volvo CE – A 40 F IV rear dump truck, the following parameters were implemented:

- Engine: Volvo D16
- Gross power: 350 kW
- Net power: 346 kW
- Tray heaped capacity: 24 m^3
- Tray struck capacity: 18.40 m^3
- Drivetrain: mechanical, PT 2519
- Empty operating weight: 30 200 kg,
- Full operating weight: 69 200 kg
- Rated payload: 39 000 kg
- Energy source type: fuel

The fuel consumption of the rear dump truck depends on the load factor of the truck and its corresponding consumption in Liters per hour. The following figure displays the fuel consumption of the truck:

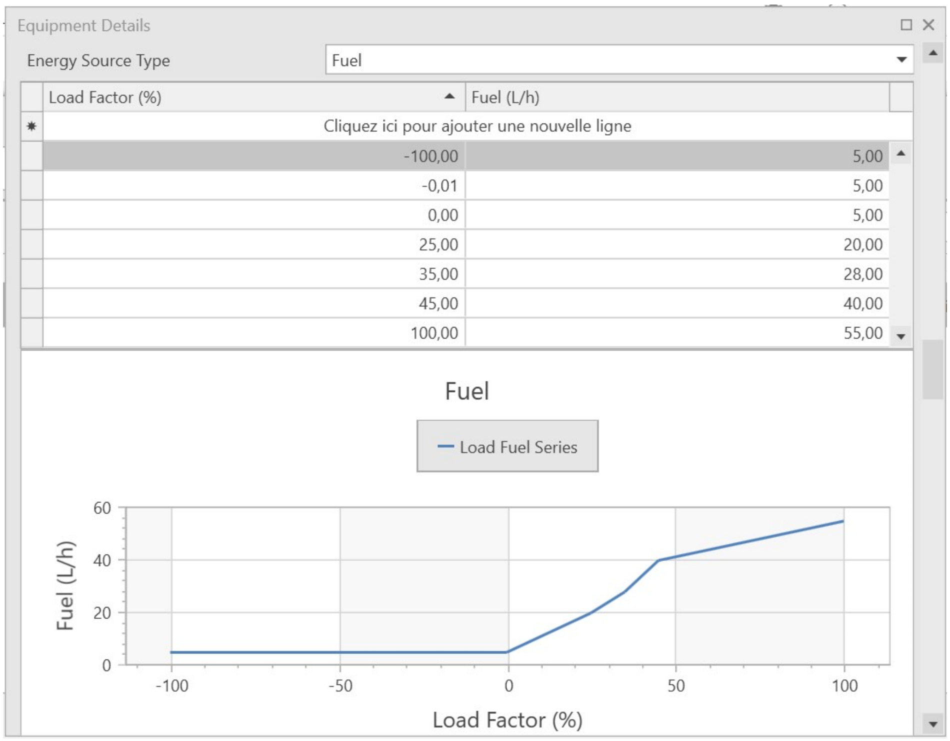


Figure 4.32: Truck load factor and fuel consumption

At this stage, the simulation can be run. The amount of material moved per period can be visualized in the life of mine schedule below:

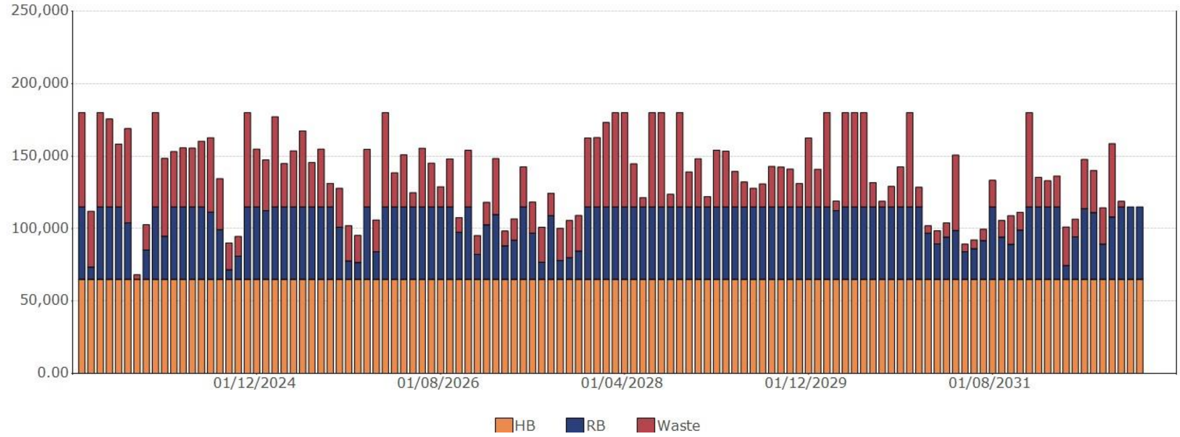


Figure 4.33: Life of mine schedule with amount of material excavated for diesel simulation.

In total, over XXXXXX tonnes of high brightness marble and XXXXX tonnes of regular brightness marble has been excavated, with waste tonnage totalling over XXXX tonnes. In total, over the life of mine, close to 16 million tonnes of material has been moved. As seen in figure 4.34, the waste dump space has been fully filled and hence denotes the end of the life of mine.

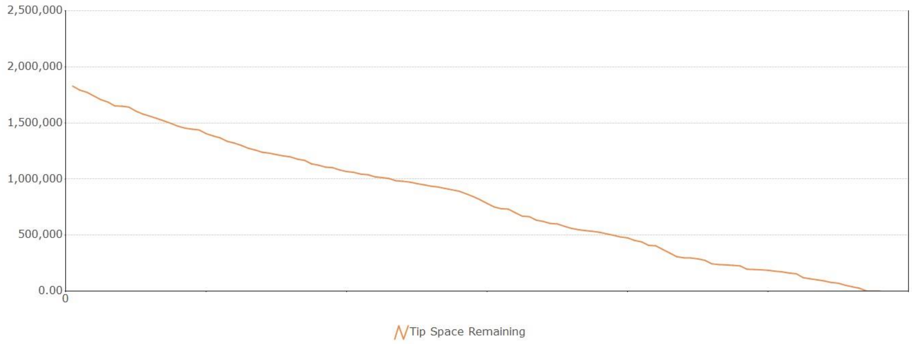


Figure 4.34: Waste dump space over the life of mine

The average haulage distance for the trucks over the life of mine is close to 4 km with an average cycle time of 18.5 minutes. In total, 2.48 million Liters of fuel were used, resulting in close to 7 million kilograms of CO2eq emissions (Well to wheel). This translates to close to 7000 tonnes of emissions. In Malaysia, the price of fuel is 0.42 euros per litre, resulting in a little over 1 million euros in fuel price over the life of mine. This results in a cost of almost 250 000 euros in CO2 taxes, as the price per ton of CO2 in Malaysia costs 35.7 euros. If one were to eliminate all fuel consumption on the mine site with respect to the rear dump trucks used over the life of mine of Ipoh, the total value saved would result in 1.308 million euros. However, it is important to understand the energy mix of Malaysia consists of >99% unabated fossil fuels. The Malaysian government also heavily subsides fuel usage. Hence, it is very cheap in Malaysia to buy and use fuel, as most citizens rely on diesel generators for energy or other usage. Malaysia does not incentive its citizens or companies like Imerys to decarbonize their operations. To compare the potential of savings to a more developed country of which the energy mix does not consist of almost exclusively fossil fuels, let us imagine Ipoh is located in France and apply French prices to fuel consumption and CO2 taxes. The price per litre of fuel in France cost 1.87 euros and price per ton of CO2eq emitted is 80 euros per ton of CO2eq. This would result in a total fuel price over the life of mine of 4.7 million euros and CO2 tax of 555 000 euros. Eliminating all fuel consumption relating to the rear dump trucks used over the life of mine with French prices implemented would result in over 5.2 million euros in savings. Table 4.5 summarizes the above-mentioned values for the diesel equipment simulation.

Table 4.5: Diesel simulation results

	unit	value
HB brightness tonnes	t	XXXX
regular brightness tonnes	t	XXXX
waste tonnes	t	XXXX
total tonnes moved		XXXX
operational hours	hrs	3,64E+04
loader scheduled hours	hrs	3,55E+04
truck scheduled hours	hrs	1,26E+05
truck average total haul	m	4,08E+03
truck average cycle time	min	18,5
fuel used	l	2,48E+06
total CO2eq emissions	kg	6,94E+06
total tonnes of CO2eq emissions	t	6,94E+03
fuel price Malaysia	euros	1,06E+06
CO2eq tax Malaysia	euros	2,48E+05
total cost Malaysia	euros	1,31E+06
fuel price France	euros	4,66E+06
CO2eq tax France	euros	5,55E+05
total cost France	euros	5,21E+06

4.4 BEV results

Before simulating the haulage network with battery electric vehicles (trucks and loaders), the equipment configuration for BEVs needs to be specified. In this case, there is no BEV in the Xpac Quarry solutions equipment database that can represent the loader and truck used in at Ipoh, hence the parameters need to be imported manually.

For the rear dump truck, the following parameters were used:

- Engine: Volvo D16
- Gross power: 350 kW
- Net power: 346 kW
- Tray heaped capacity: 24 m^3
- Tray struck capacity: 18.40 m^3
- Drivetrain: electrical, PT 2519
- Empty operating weight: 30 200 kg,
- Full operating weight: 69 200 kg
- Rated payload: 39 000 kg
- Energy source type: electricity
- Efficiency factor: 65%

The electrical consumption of the rear dump truck depends on the load factor of the truck and its corresponding consumption in kWh. The following figure displays the fuel consumption of the truck:

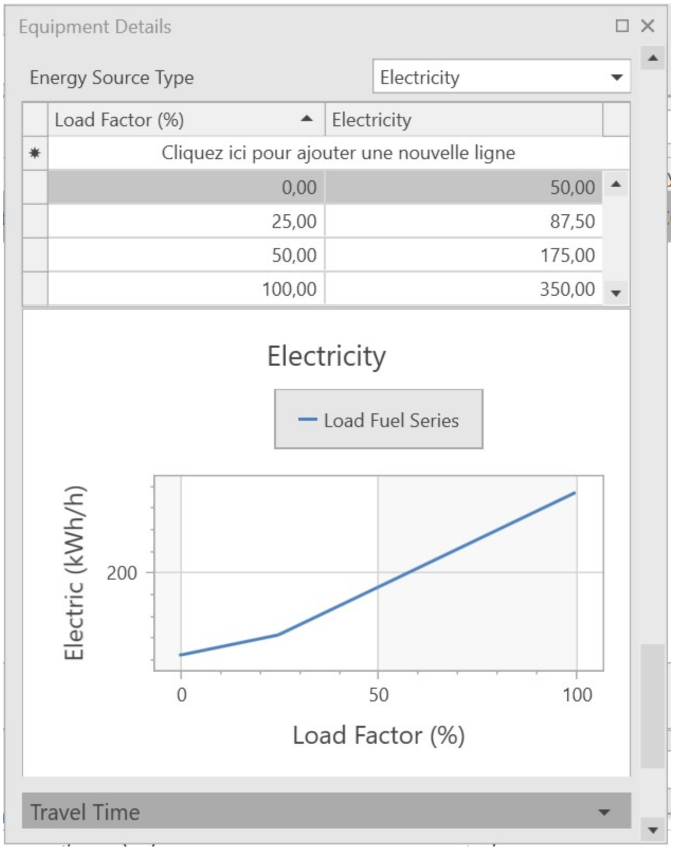


Figure 4.35: Truck electrical consumption and load factor

At this stage the haulage network can be simulated using BEVs. As with the diesel equipment simulation, a total of XXXXX tonnes of high brightness marble has been excavated over the life of mine, together with XXXXX tonnes of regular brightness marble and 3.6 million tonnes of waste, totalling XXXXX tonnes of material moved. The amount of material moved per period can be visualized in the life of mine schedule below:

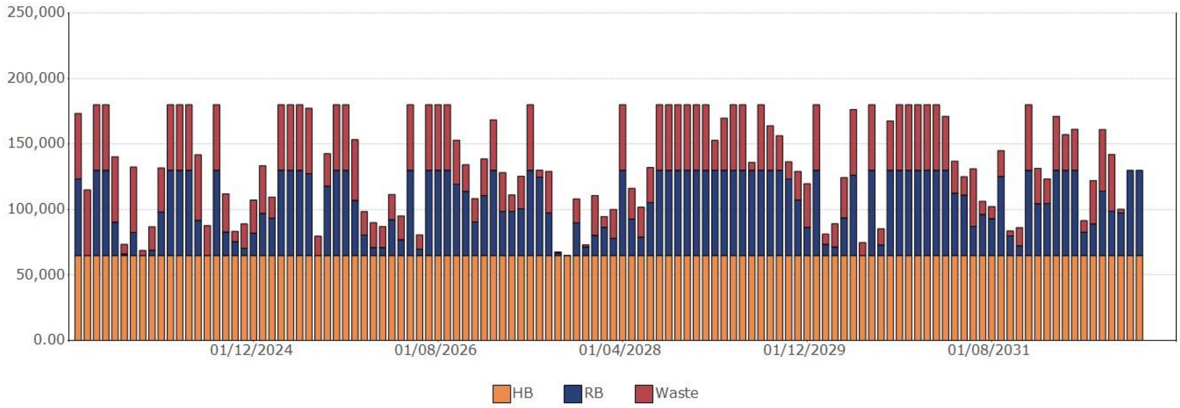


Figure 4.36: Life of mine schedule with amount of material excavated for BEV simulation

The life of mine schedule ends in 2033, similar to the simulation in chapter 7.3 as the waste dump space is fully filled in period 117 (January 2033). This is visualized in the figure below.

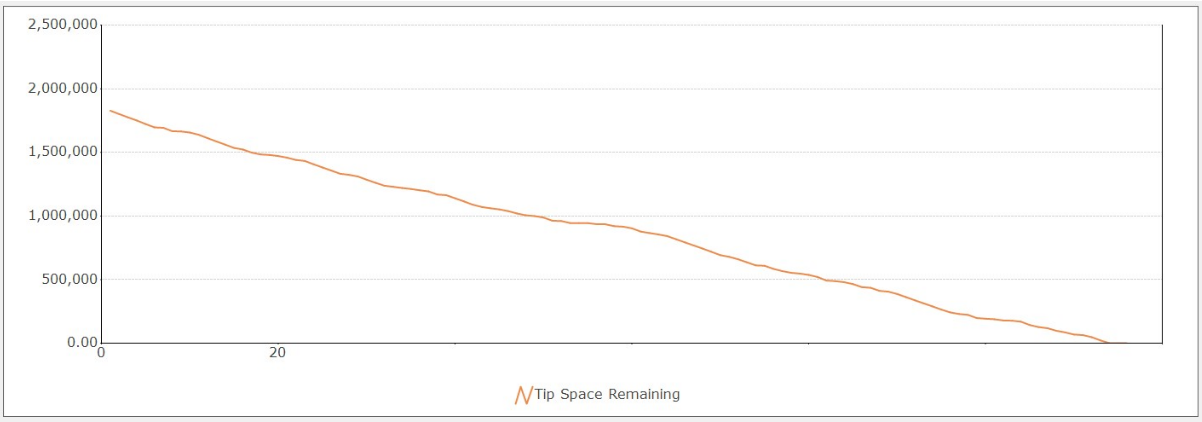


Figure 4.37: BEV tip space

The average truck haulage distance is 4.08 kilometres with an average truck cycle time of 18.28 minutes. The average electrical consumption of the BEV is 153 kWh. Its electricity regenerative potential total to circa 11.6 million kWh over the life of mine, translating to 7.54 million kWh recuperated from regenerative braking and transmitted from the wheels back into the battery. The total electricity consumed by the battery electric vehicle is around 11.4 million kWh. Hence, the gross electrical consumption of the BEV is 18.9 million kWh, of which 7.54 million kWh has been generated by the BEV itself and 11.4 has been used from the grid present at the mine site.

Table 4.6: BEV result

	unit	value
high brightness tonnes	t	XXXX
regular brightness tonnes	t	XXXX
waste tonnes	t	XXXX
total tonnes of material moved	t	XXXX
operational hours	hrs	3,64E+04
schedule loader hours	hrs	3,55E+04
schedule truck hours	hrs	1,24E+05
average truck cycle time	min	18
average total haul	m	4,08E+03
average electricity consumption	kWh	153
electricity regenerative potential	kWh	1,16E+07
electricity used	kWh	9,32E+06
electricity consumed from battery	kWh	1,55E+07
electricity generated	kWh	7,54E+06
total electricity consumed	kWh	1,14E+07
gross electricity consumed	kWh	1,89E+07

At a cost of 0.089 euro per kWh in Malaysia for businesses, the cost of using 11.4 million kWh is **1.01 million euros**. To compare with the hypothetical situation that Ipoh is located in France and using French prices for electricity (0.341 euros per kWh), the electrical consumption would cost 3.871 million euros in France **(3.87 million euros**)

In addition, the associated CO2eq emissions are calculated. Given that the energy mix in Malaysia is mainly comprised of unabated fossil fuels, one kWh emits 630 grams of CO2eq per kWh. In France, of which 80% of the energy mix comes from nuclear energy, generating one kWh of electricity translates to 100 grams of CO2eq, more than 6 times lower than in Malaysia. In Malaysia, this would result in 7150 tons of CO2eq over the life of mine of the operation. In France, this would be 1135 tons of CO2eq, a significant difference.

Table 4.7: BEV emissions Ipoh France and Ipoh Malaysia

kWh	1,14E+07	Malaysia	0,63	kg of CO2 per kWh	7,15E+06	equals	7150,98	tons of CO2eq
		France	0,1	kg of CO2 per kWh	1,14E+06	equals	1135,076	tons of CO2eq

In order to calculate NPV of BEV simulations, one takes the savings from the diesel simulation and subtract the cost of using BEVs. However, the costs associated with the BEV simulation does not include the acquisition of electric vehicles. As there are no current battery electric heavy-duty vehicles commercially available, one can assume a cost of 0.5 million euros per vehicle, but this can be subject to a larger price.

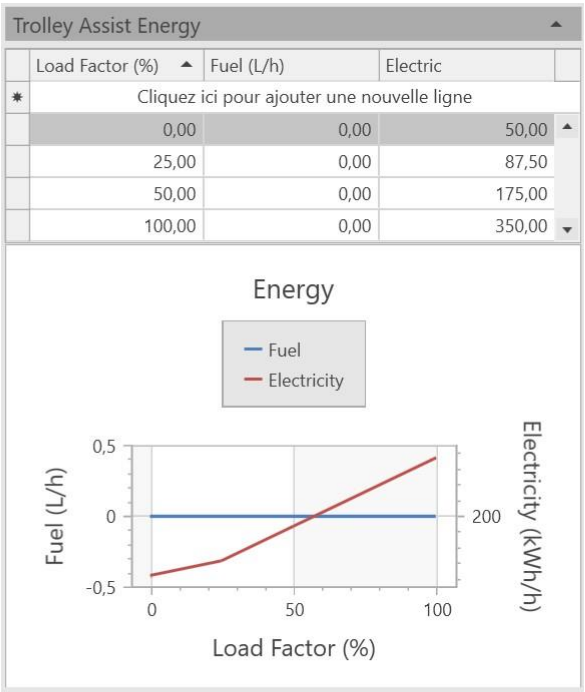
1 310 000 – 1 010 000 – 9* 500 000 **= - 4 200 000 euros NPV** for BEV simulation in Malaysia

5 215 000 – 3 870 000 – 9* 500 000 = **- 3 160 000 euros NPV** for BEV simulation in France

4.5 Trolley Assist results

In order to simulate a trolley assist haulage network with diesel equipment, equipment configuration needs to be specified. In Xpac quarry solutions Haulnet software, a trolley assist segment has been created where diesel trucks can transition to electrical consumption along the segment, resulting in no fuel consumption along that segment. The trolley assist road can be seen in chapter 6.2.3.

For the truck equipment configuration, a combination of the diesel configuration and the BEV configuration has been used such that when the truck is not using trolley assist, it consumes fuel to the same extent as seen in 6.3 and when it is using trolley assist, the electrical consumption is the same as seen in 6.4. The trolley assist consumption is displayed in the figure below:


Trolley Assist Energy

Load Factor (%)	Fuel (L/h)	Electric
Cliquez ici pour ajouter une nouvelle ligne		
0,00	0,00	50,00
25,00	0,00	87,50
50,00	0,00	175,00
100,00	0,00	350,00

Figure 4.38: Trolley assist electric consumption and load factors.

The simulation results in a life of mine schedule as seen in the figure below, with XXXX tonnes of high brightness ore and XXXX tonnes of regular brightness ore and XXXX tonnes of waste material, totalling XXXX tonnes of material excavated over the life of mine. Even though there remains ore to be mined, the waste dump has been completely filled as seen in figure 4.40.

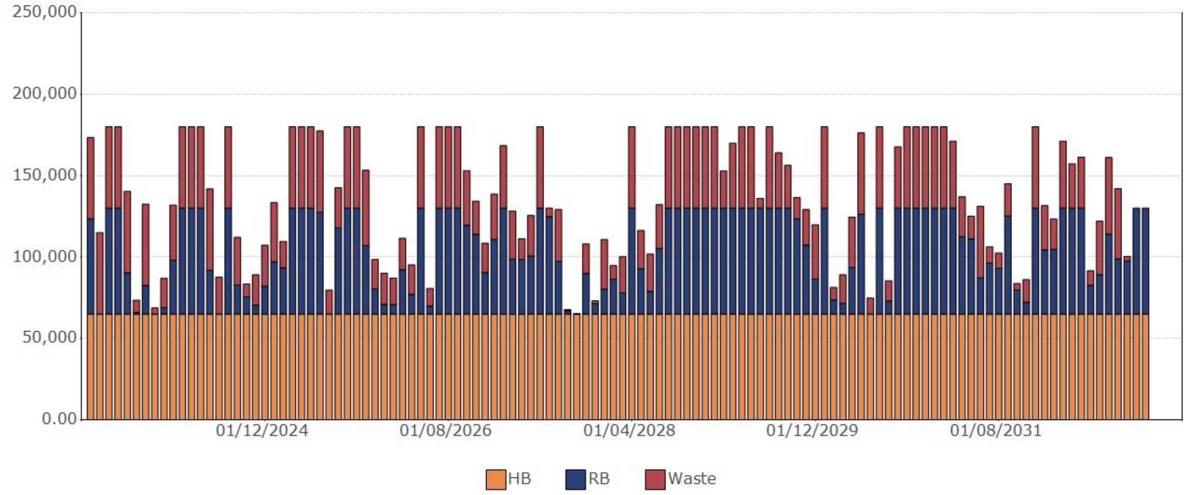


Figure 4.39: Life of mine schedule with amount of material excavated for TA simulation

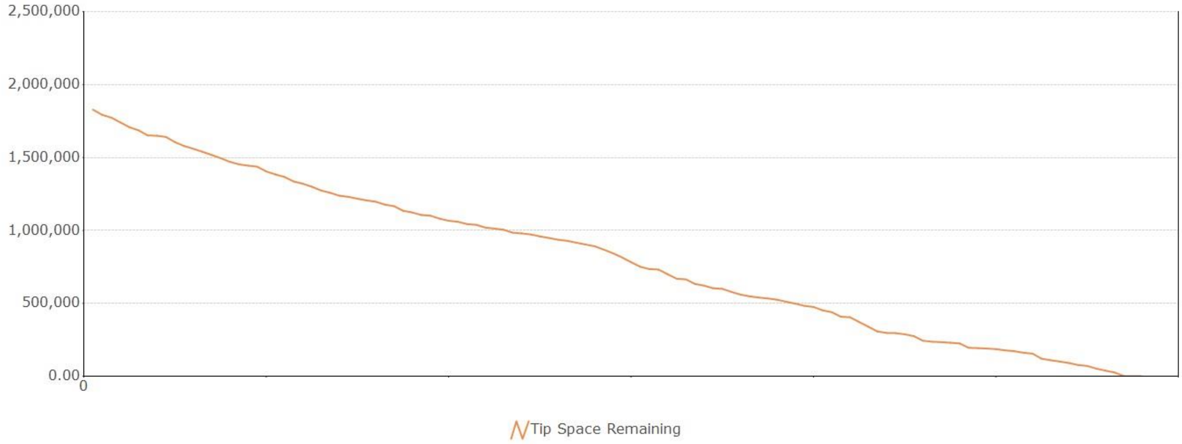


Figure 4.40: TA tip space

The average truck cycle time is 18.51 minutes with an average haulage distance of 4.08 kilometres and an average electric consumption of 130 kWh on the trolley assist segment. Over the life of mine, the total trolley hours are 5070 hours resulting in 720 000 kWh over the life of mine.

the trolley-assist kWh generated results in the following CO2eq emissions for Ipoh Malaysia and the hypothetical Ipoh France case:

Table 4.8: CO2 emissions BEV simulation Ipoh France and Ipoh Malaysia

kwH	7,2E+05	Malaysia	0,63	kg of CO2 per kWh	4,5E+05	equals	4,5E+02	tons of CO2eq
		France	0,1	kg of CO2 per kWh	7,2E+04	equals	7,2E+01	tons of CO2eq

Assuming that the amount of fuel used in the diesel simulation described in chapter 7.3 equates to the amount of kWh used in the BEV simulation described in chapter 7.4, one litre of diesel would be equal to 7.26 kWh. Hence, the 720 000 kWh from the trolley assist trolley assist would translate to **99 400 litres of fuel saved** over the life of mine. Multiplied by 2.68 kilograms of CO2 emitted this would result in 266 tons of CO2 saved over the lifetime.

(6 940 – 267 + 455.) tons of CO_2eq = **6 940 tons of CO2eq** over LOM Malaysia

(6 940– 267 + 72) tons of CO_2eq = **6 745 tons of CO2eq** over LOM France

The cost of the project excluding the installation of trolley assist on the segment mentioned above is calculated as follows:

Diesel consumed * price per L + kwh consumed * price + tonnes of CO2 emissions*CO2 price = cost

(2 480 000 – 99 300) * 0.42 + 0.089 * 720 000 + 450 * 35.7 euros = **1 080 000 total cost Malaysia**

(2 480 000 – 99 300) * 1.87 + 0.341 * 720 000 + 72 * 80 euros = **4 700 000 total cost France**

Assuming an installation price of 2 million and 250 000 for retrofitting the diesel equipment to be compatible with trolley assist, the NPV of the trolley assist project is then:

1 080 000 + 2 000 000 + 250 000*9 = **- 4 020 000 euros NPV Malaysia**

4 700 000 + 2 000 000 + 250 000*9 **= - 5 330 000 euros NPV France**

4.6 Hydrogen

Xpac Quarry Solutions software does not allow for simulating hydrogen equipment simply because there are no commercially available heavy-duty mining vehicles that are commercially available. Hence, using the fuel consumption found in the diesel simulation result, the amount of hydrogen can be found. One kilogram of H_2 is equivalent to 3.78 litres of fuel. Hence, Ipoh will require in total over the life of mine 2 480 000/3.78 = **656 000 kg of H2.** Depending on the hydrogen production method described in the Hydrogen technology chapter, this would result in the following emissions per method:

Table 4.9: H2 emissions per production method over life of mine

Technology for H2 production	parameter	unit	value
natural gas reforming	emission factor	kgCO2/kgH2	8,9
	total emissions for H2 needed at Ipoh	ton CO2eq	5,83E+03
natural gas reforming with carbon capture	emission factor	kgCO2/kgH2	1
	CO2 capture rate	%	90%
	total emissions for H2 needed at Ipoh	ton CO2	6,56E+02
	CO2 capture rate	%	90%
coal gasification	emission factor	kgCO2/kgH2	20,2
			1,32E+04
coal gasification with carbon capture	emission factor	kgCO2/kgH2	2,1
	CO2 capture rate	%	90
	total emissions for H2 needed at Ipoh	ton CO2	1,37E+03
water electrolysis	emission factor	kgCO2/kgH2	0

When considering what production technology to use to decarbonize Ipoh using hydrogen, only water electrolysis is an option. Coal gasification and natural gas reforming emit too much given the installation cost associated. Carbon capture and storage is also not a viable option as only 0.7% total hydrogen production is done with CCS. Hence, this simulation will only consider water electrolysis.

The 656 000 kg of hydrogen needed over the life of mine translates to 208.23 kg per day. It is recommended to have always stored enough hydrogen for 2 days of operation, or 417 kg of hydrogen. The infrastructure requirements and costs are based on Guerra et al's research. A schematic visualization of the infrastructure required can be seen in the following figure:

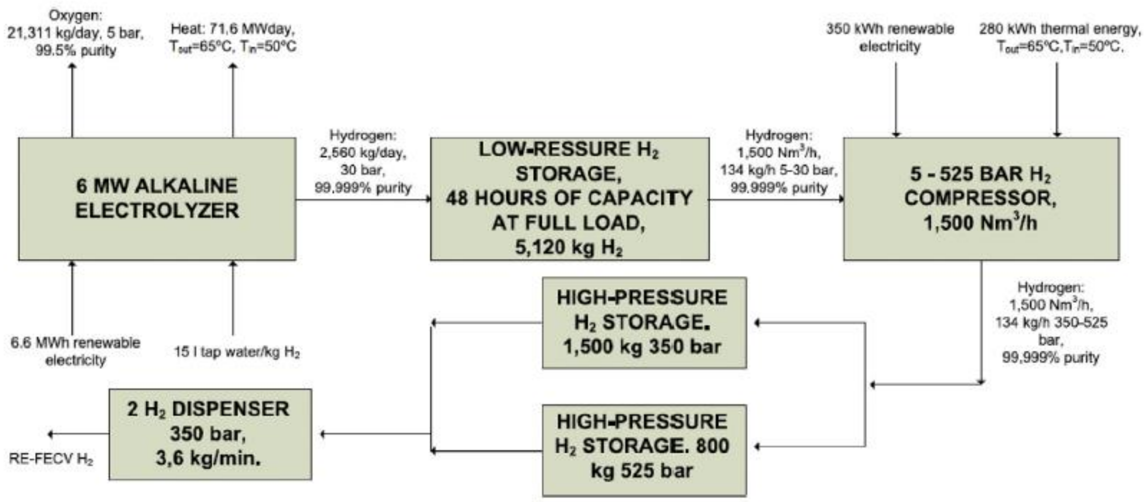


Fig. 2 — Schematic of the hydrogen production plant and the hydrogen refuelling station.

Figure 4.41: Hydrogen infrastructure schematic (Guerra et al, 2020)

The costs associated with producing hydrogen and the required infrastructure can be seen in the table below.

Table 4.10: Hydrogen costs using water electrolysis + solar farm

	capex	opex	opex costs	cost (euros)
h2 storage	220 euros/kg	1,5%	2,75E+03	2,08E+05
h2 compressor	750euro/Nm3	7%	5,33E+04	4,06E+05
350bar storage	400 euro/kg	1%	2,23E+03	3,35E+05
525bar storage	800 euro/kg	1%	2,20E+03	2,24E+05
h2 dispenser	75000 euro/unit	3%	4,50E+03	1,54E+05
total equipment costs in engineering works	20%			2,65E+05
total installation cost + electrolyser				2,78E+06
solar farm	1 million euros/MW	2%		4,42E+06
total cost infrastructure				7,20E+06
payback period				13
H2 trucks/loaders	500 000/vehicle?			4,50E+06
total cost project				1,17E+07
NPV France				-6,49E+06
NPV Ipoh Malaysia				-1,04E+07

included in table 4.10 is the necessary infrastructure required. Given the fact that Malaysia's energy mix is mainly fossil fuels, one needs to install a solar farm or wind farm on site in order to produce green hydrogen. Not using renewable energy to create green hydrogen defeats the point of producing green hydrogen. Given that 50 kWh is needed to produce one kg of H2, this would translate to a solar farm of 3.75 Mw given a load factor of 12 hours a day. For the H2 dispenser, 2 unit have been foreseen as done in Guerra et al, 2020, research.

Hydrogen requires a large amount of storage space. For this reason, the storage has been done for 2/3 in 350 bar storage tanks and 1/3 in 525 bar storage, as seen in Guerra et al, 2019. The total cost of infrastructure would be 2 780 000 euros including the electrolyser. The capital cost of the electrolyser has been assumed to be 1600 euros per kWh necessary and an operational cost of 1.5%. The capacity of the electrolyser needs to be 650 kWh in order to produce 210 kg of hydrogen per day.

Given an assumed value of 500 000 euros per hydrogen vehicle that needs to be bought to replace the current fleet, the NPV of the project is -6.5 million euros for Ipoh in Malaysia and – 10.4 million euros for Ipoh in France.

4.7 Alternative fuels:

Xpac Quarry solutions does not allow for simulating alternative fuels, hence the same method as with hydrogen simulation has been used. Knowing the diesel consumption, one can convert the alternative fuel needed by making sure that there is an equivalent amount of calorific value. As described in chapter five about alternative fuels, the only real option to use is HVO fuel as it is readily available for usage in the current fleet without any consequences of wear and tear on the vehicle.

Table 4.11 shows the cost and emissions associated with implementing HVO fuels at the Ipoh mine site for the life of mine. In this case, it is hard to determine the exact price of HVO fuels in Malaysia and in France, however it has been reported that HVO fuel is about 10% more expensive than diesel fuel. Hence a price of 2.06 euros has been applied (1.87 * 1.1). Usage of HVO fuels, depending on the feedstock used, can lead to 90% reduction of CO2 emissions. The results of the simulation can be found in the table below.

Table 4.11: HVO fuel costs and project NPV

	unit	value
diesel energy	MJ/L	41,00
HVO energy	MJ/L	34,40
fuel consumption Ipoh	Liters	2,48E+06
cost HVO	euros	2,06
total cost	euros	6,12E+06
NPV France	euros	-9,03E+05
NPVIpoh Malaysia	euros	-4,81E+06
CO2eq emissions	ton CO2eq	6,94E+02

For every litre of fuel, about 1.19 litres of HVO fuel is required to get the same calorific value. Knowing the amount of diesel fuel consumed, multiplied by 1.19 and the price of one HVO per litre, the total project cost comes to 6.1 million euros, associated emissions result in almost 700 tons of CO2eq emitted.

5. Discussion

Taking diesel as a base case and comparing the cost effectiveness, environmental benefits, and technological feasibility with the diesel simulation, an answer to the "best" decarbonization method can be found.

Using diesel at Ipoh results in **6 940 tonnes** of CO2eq emissions. Replacing diesel with battery electric vehicles where the electricity required comes from Malaysia's energy grid results in **7150 tonnes** of CO2eq emissions, which implies that using BEVs in Malaysia is less environmentally friendly than diesel. The reason for this is that Malaysia's energy mix primarily consists of (>99%) of unabated fossil fuels, meaning that one kWh produced results in 630 grams of CO2 emissions, which is more than what a litre of diesel emits. However, if renewable energy would have been used to supply the electricity needed to the Ipoh mine site, no emissions would be associated with the usage of BEVs, and it would result in being environmentally very beneficial. However, in the simulations done for BEVs, it was assumed that energy was supplied from the electricity grid. Using renewable energy would imply using solar PV or wind energy but the costs of this would be tremendous and the payback period would be longer than the life of mine, resulting in a guaranteed financial loss. If we were to assume that Ipoh was in France, then the equivalent emissions would reduce to only **1140 tonnes** of CO2eq, resulting in a decrease of 83.6% emissions compared to the diesel base case and 84.1% less emissions compared to using BEVs in Malaysia. But the fact remains, using BEVs instead of diesel at Ipoh in Malaysia is more polluting, hence it is not a viable option for decarbonisation of LHD equipment for this case study. When looking at using green hydrogen as an alternative to only green hydrogen is a viable alternative. If using hydrogen from natural gas reforming or coal gasification, the resultant emissions are **5840 tonnes** of CO2eq emissions and **13200 tonnes** of CO2eq emissions respectively. Natural gas reforming leads to a 15.9% reduction in emissions but does not justify the investment necessary to replace diesel with hydrogen. Coal gasification produced hydrogen leads to a 90.6% increase in emissions, so it is eliminated as an alternative for fuel regarding decarbonization at Ipoh's mine site. However, transforming these black/grey hydrogens into blue hydrogen by implementing CCUS would reduce these emissions by approximately 90%, resulting in 655.6 tonnes of CO2eq emissions for natural gas reforming with CCUs and 1375 tonnes of CO2eq emissions for coal gasification with CCUS. This would mean 90.4% reduction in emissions for natural gas reforming with CCUS compared to the diesel base case and 80.2% reduction for coal gasification with CCUS. However, only 0.7% of global hydrogen production is done with CCUS and none of it is produced in Malaysia, begging the question of transportation of hydrogen to the mine site. Hence, the only viable option in terms of hydrogen is green hydrogen produced by water electrolysis and renewable energy on the mine site, resulting in 0 tonnes of emissions. Lastly, using alternative fuels as an alternative for diesel at Ipoh would be, specifically HVO fuels as it has the least amount of degradation or damage in the long term on current LHD equipment, could result in a 90% reduction in emissions whilst not requiring any significant CAPEX or change in infrastructure, resulting in **694 tonnes** of CO2 emissions. However, to attain the same calorific output as diesel, nearly 3 million litres would be required over the life of mine or 306 000 litres per year, representing 1.6% of global yearly production of HVO, which is quite significant number. The HVO market is also a very competitive market due to its relatively small supply and a large number of customers, like the aviation industry or other heavy-, and light-duty vehicles. Increasing the supply of HVO, especially if the feedstock is 1st or 2nd generation (edible and non-edible food sources) would require an increase in biomass availability. Essentially asking farmers to change their crops to suitable HVO feedstocks, limiting other food supplies, especially if these crops are transformed to non-edible food sources.

Looking at cost effectiveness, all decarbonization methods analysed would result in a negative NPV, especially in Malaysia as the government subsidises fossil fuel usage. Implementing BEVs at Ipoh would result in an NPV of **- 4 200 000 euros** or when assuming Ipoh is located in France and using French prices, the resulting NPV would equal **- 3 160 000 euros.** These NPVs correspond with getting electricity from the national energy mix of Malaysia and France, not using renewable energy from solar or wind farms built in the vicinity of the mine site. In contrast, green hydrogen is assumed to be made from renewable energy, specifically solar energy, produced at the mine sight. In addition to the solar farm, significant infrastructure requirements are necessary, and would result in an NPV of **-6 500 000 euros** in France, based on French diesel prices and costs per ton of CO2eq emissions, and **-10 400 000 euros** in Malaysia. The payback period for implementing green hydrogen at Ipoh would result in almost 13 years, which is longer than the life of mine. Hydrogen is significantly more expensive to implement than BEVs due to the renewable energy infrastructure requirements. However, these can be mitigated by the fact that large energy companies, like Total Energies or Shell, will build solar or wind farms on their costs, eliminating the need for high capital expenditures. But they will require a certain price per kWh produced, significantly increasing the operational expenditures. Hydrogen can also be made at a decentralised location, where the hydrogen produced is transported to different costumers. This would eliminate the need of building renewable energy infrastructure at Ipoh's mine site but will require transportation of the hydrogen to the mine site. To the author's knowledge, there is no green hydrogen being produced currently in Malaysia, so this is not an option. In France this is an alternative that is more possible but since only 0.74% of global hydrogen production is blue or green hydrogen, this production is most likely not all located in France and would need transportation by pipeline or by truck (if made within Europe). In addition, the NPV for hydrogen does not include any extra land acquisition required for building the necessary infrastructure. Lastly, looking at HVO fuels at Ipoh, and assuming similar prices for France and Malaysia, the NPV would result in – **900 000 euros** in France and **– 4 800 000** euros in Malaysia. Malaysia does not produce the amount of HVO fuel required at Ipoh's mine site, hence import and transportation to the mine site needs to be taken into account.

Finally, besides cost effectiveness and environmental benefits, the technological feasibility needs to be discussed. Implementing BEVs at mine sites has been done before and is a big part of OEM's future decarbonization plans. There are not a lot of available BEVs commercially available to replace the LHD equipment at Ipoh's site. Most electric rear dump trucks are being demonstrated and will only become available around 2027, making it technologically not feasible to implement, but in the near future there is a lot of potential. The same applies to hydrogen vehicles that can replace current LHD equipment at Ipoh. The technology surrounding the production of green hydrogen has also not yet been done at an industrial scale, hence implementing this technique would make Imerys a global front-runner when it comes to using hydrogen at a mine site.

Decarbonization techniques are not always favourable to implement at a quarry site. Considering operational sites that are at a remote location and employ a diesel generator for their electricity demands, using BEV's has no advantages as the production of electricity produced still comes from an unsustainable source. The same applies for countries that have a strong fossil fuel-based energy mix like Malaysia. The availability of green energy or low-carbon methods of producing electricity is essential to the usage of BEVs. Hydrogen as a decarbonization principle employs the same principle. Hydrogen produced from unabated fossil fuels as a feedstock is more polluting than the production of diesel. Hence, the feedstock used for hydrogen production needs to be sustainable and environmentally beneficial. Green hydrogen and blue hydrogen are hence the only colours of hydrogen that are viable as a decarbonization method for load and haul equipment at a mine site. As reported by the IEA in 2022, less than 0.7% of total global hydrogen production comes from carbon capture, utilisation, and storage, also known as blue hydrogen. Hence, the only real viable option for decarbonization using hydrogen is green hydrogen. Especially in developing countries or countries that have no access to blue hydrogen. One also needs to take into account the method of transporting a constant supply of hydrogen to a country. If it comes from overseas, the additional emissions of naval transport also need to be taken into account. Brownfield projects that do have a good supply of green or blue hydrogen, or even hydrogen made from nuclear energy, have a decision to make between cost effectiveness and environmental benefit. Often, the payback period for using hydrogen or BEVs can outlast the life of mine. Hence, decarbonizing an operational site is possible, but not always economical. This does not apply to greenfield projects. Decarbonizing a mine that has been specifically designed for a diesel equipment fleet will essentially require twice the capex over the total life of mine if they decide to change their fleet with a hydrogen or battery electric vehicle fleet. A greenfield project can be tailored to a more environmentally friendly fleet without having to spend as much CAPEX. This is mainly true for surface mines, but underground mines have the benefit of being able to reduce the ventilation costs significantly for a decarbonized fleet, increasing savings when it comes to power demand and a reduction in emissions associated with the reduction in electricity demand. Alternatively, low-carbon fuels offer a suitable replacement for BEVs and hydrogen when it comes to reducing the required CAPEX for installation of necessary infrastructure and replacement of the fleet. However, as the alternative fuels market is limited and competitive, not every operational site will be able to fully replace their fossil fuels with alternative fuels. Most alternative fuels also have a severe impact on the life of equipment as they are often associated with detrimental effects on equipment, leading to the need for replacing vehicles, which also requires costs. Not all countries have a good supply of alternative fuels and should consider the associated emissions related to the transport and production of alternative fuels.

6. Conclusion

In conclusion, the need for decarbonization within various industries, particularly concerning Load and Haul (LHD) equipment in the minerals and metals sector, is growing rapidly. The utilization of conventional diesel-powered LHD equipment in quarrying operations leads to the emissions of hydrocarbons and greenhouse gases. These emissions must be mitigated to align with the Net Zero Emissions objective. Potential decarbonization alternatives to replace diesel equipment that are currently or in the near-future available are battery electric vehicles, green hydrogen, and alternative fuels. This research has aimed to provide an in-depth assessment of currently available and near future decarbonization methods, considering their environmental impact, cost-effectiveness, and technological feasibility when applied as substitutes for diesel equipment.

The study focused on a mountaintop marble quarry situated in Ipoh, Malaysia, and compared it to a hypothetical scenario in France to show the potential of decarbonization. Malaysia's current energy mix predominantly relies on unabated fossil fuels and does not incentivize reducing emissions due to fossil fuel subsidies. The research methodology consists of an extensive review of existing and emerging decarbonization technologies that could replace current diesel LHD equipment. A haulage network was created using block model data via Xpac Quarry solutions and its Haulnet package, incorporating diesel equipment as the base case for comparison with Battery Electric Vehicles (BEVs) and trolley assist simulations. Hydrogen and Hydrotreated Vegetable Oil (HVO) fuel consumption were manually calculated to determine Net Present Values (NPVs) and associated emissions. An investigation of the infrastructure necessary and energy requirements was performed to establish accurate cost estimates and total CO2eq emissions.

The findings reveal that substituting diesel equipment with any of the decarbonization methods in Ipoh leads to negative NPVs, primarily due to extensive capital investments required for infrastructure development, exceeding Ipoh's life of mine. Among the alternatives, HVO fuels are the most cost-effective, followed by BEVs and green hydrogen. Additionally, it was observed that using BEVs at Ipoh results in higher environmental impact, primarily because the electricity production for BEVs is more polluting than the production of an equivalent energy amount of diesel. Green hydrogen stands out as the least environmentally polluting option, with no associated greenhouse gas emissions, followed by alternative fuels. However, in terms of technological feasibility, hydrogen presents the greatest challenges at present, with industrial-scale green hydrogen production via water electrolysis yet to be achieved and limited expertise and infrastructure in distribution, transportation, and storage. Commercially available hydrogen-based LHD equipment is also scarce, as is the case with BEVs for replacing the current equipment in use at Ipoh. Given these factors, alternative fuels emerge as the most practical bridge between the current state of the industry and a more sustainable future. This research provides a comprehensive overview of the existing decarbonization possibilities, shedding light on the current landscape of decarbonization options and the industry's readiness in terms of infrastructure and equipment.

To answer the question of which decarbonization option would be most environmentally friendly, using green hydrogen would be the best option as no emissions would be associated with it. The same would apply to BEVs if the electricity required would come from renewable energy, which is not available in Malaysia. Followed by green hydrogen, using HVO fuels would be the second-best option to reduce emissions. In Malaysia, the worst option when it comes to the environment would be to use BEVs with electricity coming from the national energy mix.

To answer the question of which decarbonisation option would be most cost effective in Malaysia, diesel would remain the cheapest option. Changing the diesel fleet to a BEV fleet or a hydrogen fleet would require significant investments. The least expensive option to implement is HVO fuel, this is followed by BEV and then by green hydrogen produced at the mine site.

To answer the question of which decarbonization option is the most technologically feasible, HVO fuels take the lead, followed by BEV and then hydrogen. BEVs are less technologically feasible due to the lack of commercially available LHD vehicles. Hydrogen is currently the least technologically feasible as the technologies used have not been done at an industrial scale and no hydrogen LHD equipment is currently available.

Recommendations for future studies regarding decarbonization of load and haul equipment in the quarrying industry include simulation and calculations done with commercially available equipment for hydrogen and battery electric vehicles in order to accurately estimate the NPV of projects as prices for equipment in this study were guesstimated. In addition, supply and transport of alternative fuels to an operational site done with diesel equipment should be taken into account to accurately assess the negative impacts of alternative fuel implementation. Furthermore, more extensive research into the electric demand of load and haul equipment with varying load factors should be done and included in the calculations to give a more accurate result in terms of electric demand and hence the associated emissions of generating electricity at a mine site. This more exact power demand could be used to determine more accurately the emissions associated with BEV usage as well as the power demand required. Installation of solar farms or wind farms for using BEV could be included as well into the NPV calculations, as not all countries have a green energy mix. Furthermore, the hydrogen demand for load and haul equipment with respect to load factors could be assessed in more detail to give a better understanding of the hydrogen production requirements of the fleet at an operational site. Lastly, a study in cost effectiveness between surface and underground mines should be made as the reduction in ventilation costs significantly impact the payback period of implementation of decarbonization technologies for load and haul equipment.

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