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TECHNICAL AND ECONOMIC FEASIBILITY STUDY FOR LONG-RANGE HYDROGEN FUEL CELL TRUCKS IN THE CHILEAN MINING INDUSTRY

MEMORIA PARA OPTAR AL TÍTULO DE
INGENIERO CIVIL MECÁNICO

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RESUMEN DE LA MEMORIA PARA OPTAR POR EL
TÍTULO DE INGENIERO CIVIL MECANICO
POR: REINALDO VICENTE AYALA MIRA
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ESTUDIO DE FACTIBILIDAD TÉCNICA Y ECONÓMICA PARA CAMIONES DE CELDA DE COMBUSTIBLE DE HIDRÓGENO DE LARGO ALCANCE EN LA INDUSTRIA MINERA CHILENA

La descarbonización es una necesidad, a medida que la economía del país crece, los sectores dentro de la industria también deben crecer para mantenerse al día con el desarrollo, especialmente la industria minera y el sector del transporte, que en conjunto son responsables de alrededor del 30% de las emisiones de CO2 del país, que para 2018 eran de 23,007 kt y han estado creciendo desde la última década, por esto implementar medidas libres de emisiones de CO2 es esencial para evitar el aumento de la temperatura media mundial y hacer el paso a la carbono neutralidad. Por ello, el hidrógeno verde (H2) aparece como un candidato perfecto para diversos usos dentro de la industria que pueden favorecer la transición, concretamente en el sector del transporte debido a sus aplicaciones en electromovilidad y facilitar el primer paso en el mercado del H2 y la carbono neutralidad.

En este trabajo de título, se propone usar un modelo de evaluación técnica basado en modelos dinámicos de consumo de energía para camiones pesados y así estimar perfiles de velocidad de los camiones debido a la ausencia de datos detallados de transporte, sumado a una evaluación económica basada en un análisis de costo total de propiedad, para estudiar la factibilidad de implementar camiones pesados de carretera propulsados por Hidrógeno en un set de rutas de transporte en el norte de Chile, para aplicaciones de la industria minera.

Para evaluar la viabilidad de la implementación, se analizan 3 rutas de estudio y se selecciona el camión Mercedes Benz New Actros como caso base de comparación de vehículos Diesel, mientras que para las tecnologías H2 se seleccionan 2 camiones Hyzon, específicamente el HYMAX-450 y el FCET 8 para evaluar en 2 escenarios de tiempo (2025 y 2035) y así encontrar breakevens e identificar el momento en el que el H2 se vuelve competitivo.

Los resultados muestran que para camiones H2 se necesitan de 2 a 3 estaciones de repostaje por ruta, y al considerar los resultados de cada ruta, las rutas 1 y 3 muestran que es preferible el modelo FCET 8, que es competitivo entre 2032-2033 y 2036 respectivamente, mientras que para la ruta 2 es preferible el HYMAX-450, que es factible alrededor de 2034-2035, esto es considerando el rendimiento de los ciclos anuales frente al caso base Diesel. Por otro lado, el análisis de sensibilidad de estas tecnologías concluye que una variación del 20% en camiones H2 puede acelerar la implementación entre 1 a 2 años, y un impuesto por emisiones de 100 USD/tCO2 puede acelerar en 4 años la viabilidad en todas las rutas.

En conclusión, este estudio estima los costos de implementación y los períodos de competitividad de las tecnologías H2 para el transporte por carretera en base a estimaciones logísticas y ausencia de datos de perfiles reales de velocidad de camiones, mostrando pronósticos similares a otros estudios dentro de la economía H2 en Chile. Y, para lograr mejores resultados en la implementación de camiones H2, se propone el uso de información logística detallada de las rutas y las operaciones de transporte reales, para realizar mejores estimaciones y optimizar los costos de los camiones para la implementación a largo plazo.

ABSTRACT OF THE THESIS TO QUALIFY FOR
MECHANICAL ENGINEERING DEGREE
BY: REINALDO VICENTE AYALA MIRA
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TECHNICAL AND ECONOMIC FEASIBILITY STUDY FOR LONG-RANGE HYDROGEN FUEL CELL TRUCKS IN THE CHILEAN MINING INDUSTRY

Decarbonization is a must, as the country's economy grows, sectors within the industry must also grow to keep pace with development, especially the mining industry and the transport sector, which together are responsible for around 30% of the country's CO_2 emissions, emissions that by 2018 were of 23,007 kt and had been growing since the last decade, that is why the need to implement measures free of CO_2 emissions is essential if we want to avoid the increase in the global average temperature and make the transition to carbon neutrality. Therefore, green hydrogen (H_2) appears as a perfect candidate for various applications within the industry that could favor the transition to carbon neutrality, specifically in the transport sector due to its applications within electromobility and facilitate to give a first step into the carbon neutrality and H_2 market.

In this thesis work, a technical evaluation model based on dynamic power consumption models for heavy trucks is proposed to estimate truck speed profiles due the absence of detail transport data, added to an economic evaluation based on a total cost of ownership analysis, to study the feasibility of implementing heavy road trucks powered by Hydrogen in a set of transport routes in northern Chile, for mining industry applications.

To review the feasibility of implementation, 3 study routes are analyzed and the Mercedes Benz New Actros truck is selected as a Diesel vehicle base case of comparison, while for H_2 technologies 2 Hyzon trucks are selected, specifically the HYMAX-450 and the FCET 8 to evaluate on 2 time scenarios (2025 and 2035) to find breakeven points on a 1-to-1 comparison between technologies, in case H_2 becomes competitive.

The main results show that for H_2 trucks, 2 to 3 refuel stations are needed per route, on the other hand when considering the results of each route, routes 1 and 3 show that the FCET 8 model is preferable, which becomes competitive between 2032-2033 and 2036 respectively, while for route 2 the preferable model is the HYMAX-450, which becomes feasible around 2034-2035, this is considering the performance of annual cycles versus the standard Diesel case. On the other hand, sensibility analysis of these technologies concludes that a variation of 20% in H_2 trucks can accelerate between 1-2 years, and a carbon emission tax up to 100 USD/tCO_2 can accelerate in 4 years the feasibility on all routes.

In conclusion, this study estimates implementation costs and competitiveness periods of H_2 technologies for trucking based on logistics estimations and absence of data of real truck speed profiles, showing forecasts similar other studies within H_2 economy in Chile. And, to achieve better results in H_2 truck implementation, detailed logistic information of routes and transport operations is needed in order to make better estimations and to optimize truck costs for long range implementation.

Dedicado a todas las personas que me han acompañado y soportado, Gracias

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1 Introduction

1.1 Motivation and Basic Backgrounds:

Today, a big part of the Chilean energy matrix is composed of non-renewable sources, such as crude oil, biomass, coal, natural gas, among others, which are mainly used for the industrial and the transport sector, as observed in the Figure 1, which shows a Sankey diagram of Chile's energy consumption at the end of 2019.

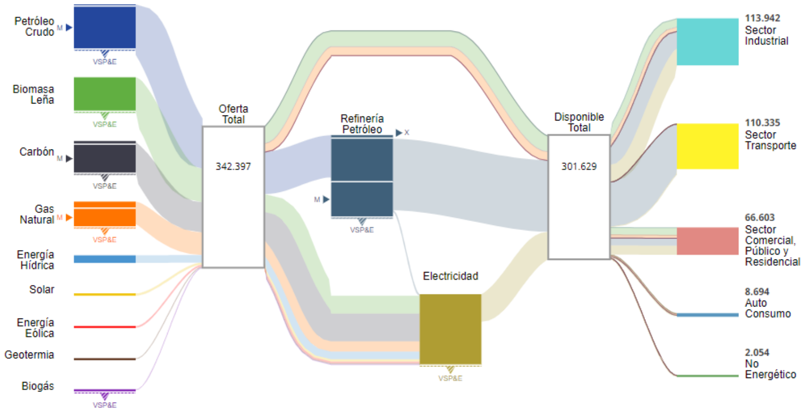


Figure 1. National energy balance of 2019. (Energia Abierta, 2019)

Based on this, the need to implement renewable solutions arises, in order to reduce greenhouse gas (GHG) emissions and align the country with the results of COP21 and its global framework to combat climate change.

Given the country's geography, Chile has a comparative advantage with other countries in terms of its potential in renewable energy development due to the vast northern area with the highest solar radiation rates in the world (Atacama Desert). According to the International Energy Agency (IEA) studies, the cost projection in Chile for high-potential renewable energy sectors estimates costs of less than 1.6 USD/kg H2 by 2050, as seen in the Figure 2

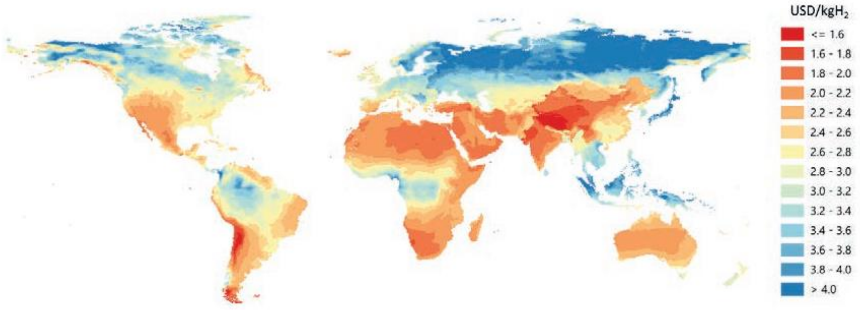


Figure 2. Cost projection based on PV technologies and wind systems in the long term. (IEA, 2019)

One of the sectors with the highest energy consumption, and the most polluting, is the mining sector, due to the fossil fuel consumption of its transport applications. The fossil fuels could be replaced by green hydrogen, allowing to decarbonize the mining sector. Thus, H2 appears as a solution to achieve the decarbonization goals proposed by the country, since it can replace fuels to produce electricity, heat, and various compounds.

This hydrogen can be used inside a fuel cell to generate clean energy, i.e., without $_2$ emissions. A fuel cell (FC), is an electrochemical device that allows to transform H2 into energy, generating an electric current and as a by-product water without requiring direct combustion of this.

This technology can be implemented in mobility, seeking to replace internal combustion engines (ICE) with fuel cell systems and batteries, allowing a transport with zero GHG emissions.

The basic principle of operation of a FC vehicle (FCV) is not very different from a conventional electric vehicle, by the fact that both share a system of batteries and electric motor. The main difference is that the FC system generates the electrical energy that the vehicle will consume during its operation, using the H2 as fuel, while the electric vehicle requires a means of charging, external to the vehicle.

Based on the above mentioned, the main objective of the proposed work, is to identify the feasibility of implementing this technology for mining mobility in the north of Chile.

1.2 Objectives

- General objectives:
  - Carry out a techno-economic feasibility study for the implementation of FCV (Fuel Cell Vehicles) for the transport of concentrates or goods in the mining industry of northern Chile.
- Specific objectives:
  - Perform a mapping of possible truck transport routes from mining companies to port, characterizing operating curves, truck models, elevation profiles, etc.
  - Estimate energy consumption, annual transport parameters and GHG emissions for both technologies based on an estimation model of speed profile calculation.
  - Carry out a techno economic analysis between Diesel and FC trucks
  - Compare implementation costs through a TCO and identify main KPIs
  - Estimate the consumption of H2 necessary for each route and make a first approach to the necessary infrastructure

1.3 Scope

- For this study, part of the contents and some study routes are delivered by the Hydrogen Business Unit of ENGIE (from now on mentioned as “the company”), based on this, some data or clients can’t be mentioned/detailed.
- The study focuses both, on technical implementation and economic implementation for the routes to reach a comparative point between technologies, as for that, technology comparison will be made on a 1-to-1 truck analysis.
- The implementation and costs of hydrogen fueling stations are not considered in this study and will work under the assumption that there is always one available when needed, to

compensate for this, hydrogen consumption is estimated per vehicle and potential zones for refueling station are identified.

- Energy optimization and management will not be considered in the model estimation, thus, being proposed for future studies
- As one of the interests is to reduce CO_2, only green hydrogen is considered in this study as a fuel source.
- Battery swap, Hydrogen tank swaps and hydrogen transports are excluded as factors of implementation.
- CO_2 emissions are calculated based on the stoichiometry of the Diesel combustion reaction.
- Based on the absence of telemetric data, a speed profile is estimated based on a vehicle dynamic model to get power and energy consumptions.
- Costs and efficiencies projections are considered lineal based on reference values for different years.
- In case that the selected Hydrogen FC doesn’t meet the requirements of a certain route, the implementation of a H2 Truck with a bigger FC system configuration at a higher acquisition cost will be evaluated.
- Effect of truck residual value will not be considered.

2 Background

2.1 Chilean Energy Balance and GHG Emissions of Main Sectors

As previously mentioned, the Chilean energy matrix is composed, for the most part, of non-renewable sources that generate greenhouse gas emissions. The mining sector is the largest energy consumer with 38%, followed by the transport sector with 37%, CPR (Commercial, Public and Residential) with 22% and energy with 3%, as shown in Figure 3.

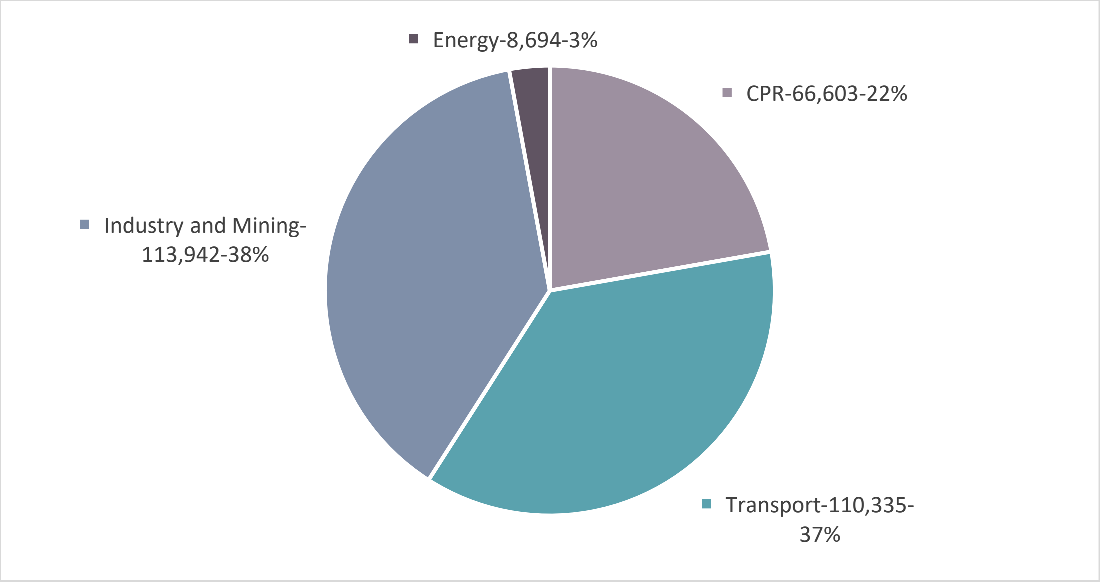


Figure 3. Energetic consumption by sector. (Energía Abierta, 2020)

According to "Energía Abierta" within the transport industry, diesel consumption predominates over the rest of the used fuels, providing about 48.5% of energy consumption for the transport sector in the country. On the other hand, Diesel contributes with the 28% of the energy consumption within the industrial and mining sector.

In the last decade the installed capacity of renewable energies has grown considerably, such as, for example, photovoltaic solar energy, has 3,763 MW and wind energy with 2,492 MW of installed power by 2021. However, most of the electricity generation comes from coal-fired thermoelectric, oil and natural gas combustion, altogether adding 12,854 MW of installed capacity, being able to generate 19,442 GWh versus the 7,747 GWh of Eolic + PV generation to 2021 (Energía Abierta, 2021).

2.2 Transport Sector

While observing the energy balance of some sectors, most of the consumption of the transport sector comes from fossil fuels, as shown in Figure 4, composed of almost a 98.7 %, while the rest is provided by electric and natural gas sources.

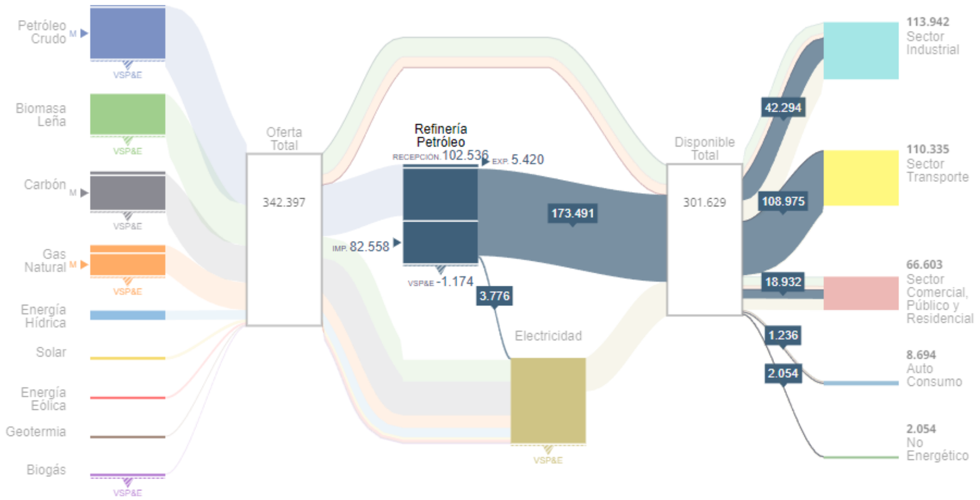


Figure 4. Energy balance for refined oil fuels. (Energia Abierta, 2019)

The transport sector is also responsible for almost a quarter of the total GHG emissions of 2018 according to the Ministry of Energy (Ministerio de Energía, n.d.), reports from the "National Inventory of Chile" of 2020 indicate that, of the total GHG emissions, 77.4% corresponds to emissions from the energy sector, from which 32.9% of this corresponds to emissions from transport, increasing the transport sector emissions to a 25.4% of total GHG emissions of 2018 according to Figure 5

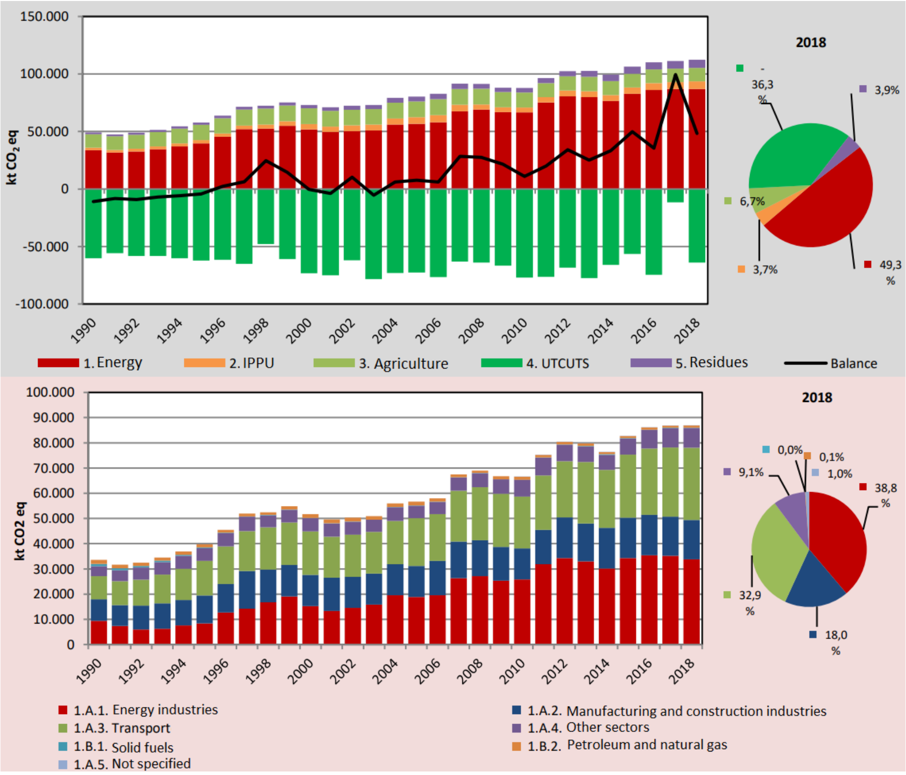


Figure 5. GHG balance per category (up) and subcategory (down, energy subcategories) (Ministerio del Medio Ambiente, 2020)

Considering only the transport sector, 82% of the energy consumption of the year 2018 corresponds to land transport, while 12% air transport, 5% maritime and 1% rail. In terms of CO_2 emissions, 88% of emissions come from land transport, being the equivalent of 23.7 Gton CO_{2e} for the year 2018, while the rest of the emissions are equivalent to 12% with a total of 3.2 Gton CO_{2e}, as shown in Table 1

Table 1. Energy consumption and CO_2 emissions of transport sector (Ministerio de Energía, n.d.)

Method of transport	Energy Consumption [%]	CO_2 Emissions [%]	CO_2 Emissions [Gton CO_{2e}]	Total CO_{2e} Emission of 2018
Land	82	88	23.67	26.9
Aerial	12	12	3.23	
Maritime	5			
Railway	1			

When analyzing in detail the consumption by land transport, 99% of the energy consumption corresponds to fuels derived from petroleum, while the rest corresponds to electricity consumption and natural gas. On the other hand, within CO_2 emissions, 64% of total emissions by land transport corresponds to emissions from buses and trucks, equivalent to 15.15 Gton CO_{2e} (Ministerio de Energía, n.d.)

2.3 Mining Industry

Due to the geological richness in copper ores, the Chilean copper mining industry is one of the most profitable, broad industry and one of the economic pillars of the country, making Chile one of the main producers of copper worldwide.

The main energy sources used by the mining industry can be divided into two groups, as shown in Figure 6. The first corresponds to the electric energy supplied by the National Electric System (SEN), and the second one to the energy supplied by the use of fuels, such as, Gasoline, Diesel, Kerosene, Natural Gas, LNG, etc.

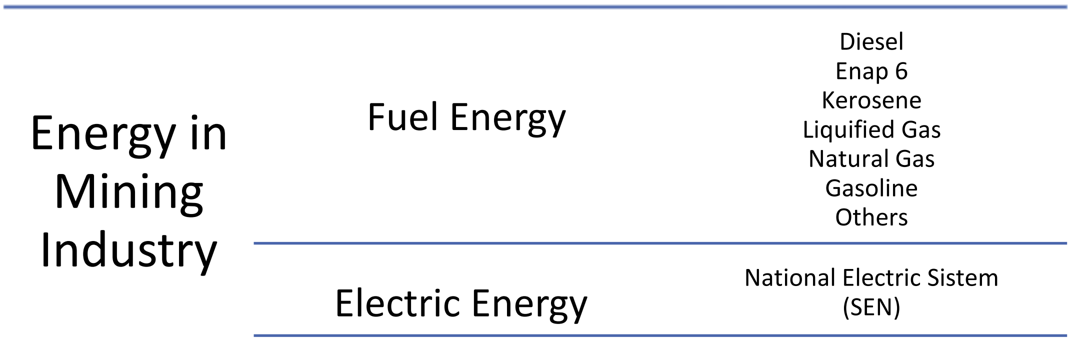


Figure 6. Energy Sources in Mining. (COCHILCO, 2020)

Since 2001, copper mining industry has been steadily increasing with each year, even though the total copper production has remained fairly constant (see Figure 7), growing at an average annual rate of 1.2%. In 2019, copper production decreased a 0.8% compared to 2018 production, reaching a total amount of 5.79 million metric tons (MT), equivalent to a 28% of the total global production.

In the case of total energy consumption, the copper industry since 2001 has more than doubled from around 80,000 TJ to 175,134 TJ in 2019, mainly due to the increase in the size of the mines and the longer journeys needed to transport materials.

In 2019 the copper mining industry alone reached a total energy consumption equivalent to 14% (COCHILCO, 2020) of the total energy consumption of the country with an estimated amount of 175,134 TJ, from which 51.3% or 89,769 TJ were due to electricity consumption and 48.7% or 85,365 TJ due to fuel consumption. Figure 7 presents the total distribution for energy consumptions from 2001 to 2019 in the copper industry.

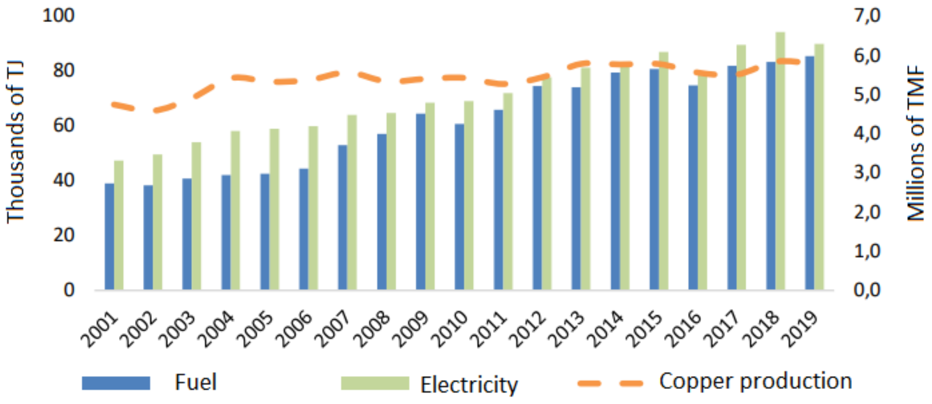


Figure 7. Energy consumption in copper mining industry. (COCHILCO, 2020)

Most of the fuels used in the industry emits GHG emissions, and, since 2001, Diesel has become the most used, reaching a 91% of energy participation or 77.682 TJ, as shown in Figure 8, due to increment in mine production and mine growth over the years.

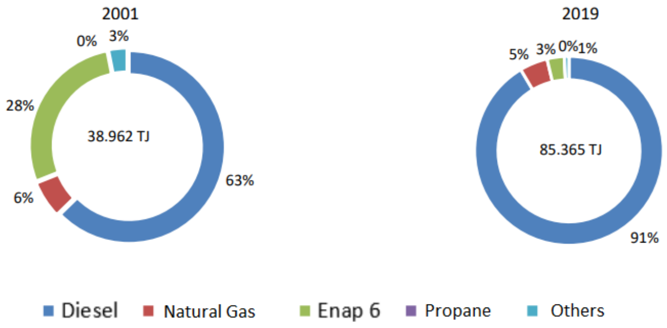


Figure 8. Fuel participation in total fuel consumption.

2.4 Road Trucks

2.4.1 Road Trucks Classification

In the United States, the classifications, and especially for transport vehicles, are typically based on the maximum load that the vehicle can carry.

The classifications are called GVWR or gross vehicle weight rating, and the range of classes 1 to 8 can be identified, where 1-2 corresponds to light duty vehicles, 3-6 medium duty vehicles and 7-8 heavy duty vehicles as shown in Table 2.

Table 2. Vehicle classification by GVWR

Truck Class	Duty Class	Weight Limit [kg]
1	Light truck	0-2,722
2	Light truck	2,772-4,536
3	Medium truck	4,536-6,350
4	Medium truck	6,351-7,257
5	Medium truck	7,258-8,845
6	Medium truck	8,846-11,793
7	Heavy truck	11,794-14,969
8	Heavy truck	14,969 or above

Class 8 vehicles, includes tractor trailers, dump trucks, semi-trailer trucks, among others.

This study uses class 8 vehicles as a basis for comparison, given that these are the main means of transport used by the mining and transport industries for the transport of concentrates, goods or others between collection centers / ports to mining facilities and vice versa.

To carry out this comparison it is important to select a heavy diesel truck that is used within the industry, and based on this select a hydrogen propulsion vehicle that enters the category of class 8 vehicle with properties as similar as possible, that is, considering truck power, GVWR, truck lifetime, etc.

2.4.2 Transport Trucks for Mining

In the case of transport in mining, the Subsecretary of Transport (Subsecretaria de Transporte, 2020) provides specifications regarding the approach of models for the study of transport in mining and a summary of the most used vehicles in this area.

Regarding the above, it is important to highlight:

- Usually, in mining, the transport by cargo truck is carried out by an external company that is responsible for the transport logistics. They usually correspond to large companies.
- The safety measures for transport are much higher. In general, mining loads carry measures like the transport of hazardous substances, which is associated with higher demands for quality, safety and costs.

- The previous point also implies that drivers with more experience and specialization are required.

Finally, the “Update of the economic model of the Subsecretary of Transport” identifies that the main vehicles used are tractors trucks with semi-trailers, which, depending on the transported material is the type of trailer attached to it.

According to what is observed in Table 3, the type of trailers used to transport concentrates and goods is hopper type, while for heavy machinery it is low platform type considering this, the study will compare tractor vehicles that can load with a hopper-type semi-trailer.

Table 3. Types of vehicles according product importation/exportation (Subsecretaria de Transporte, 2020)

Business unit	Vehicle type
Foreign vegetables and fruits	Refrigerated semi-trailer tractors
Cattle and meats	Refrigerated semi-trailer tractors
Fertilizers	Flatbed semi-trailer tractors
Chemical products	Flatbed semi-trailer tractors
Copper mining (Metallic)	Flatbed semi-trailer tractors
Copper mining (Concentrates)	Hopper semi-trailer tractors
Rest of mining	Hopper semi-trailer tractors
Foods	Flatbed tractor or trucks
	Refrigerated semi-trailer tractors
	Tractors or trucks with specialized bodies
Sea products	Refrigerated semi-trailer tractors
Logs	Tractors with specialized semi-trailers
Forest products	Flatbed tractor or trucks
Cellulose	Flatbed tractor or trucks
Paper and cardboard	Flatbed tractor or trucks
Manufactures	Flatbed tractor or trucks
Machinery and vehicles	Tractors with car transporters
Machinery and heavy equipment	Tractors with low bed semi-trailers
Fuels	Tractors with tank semi-trailers
Chemicals	Tractors with tank semi-trailers
	Tractors or trucks with flat bodies

In addition, reviewing the records of the National Institute of Statistics (INE), for the year 2018 it was recorded that the total population of semi-trailers is 68,347 or 31.5% of the total distribution of vehicles for road transport (Instituto Nacional de Estadísticas, 2018), which allows to obtain a good estimate of the order of magnitude of the vehicles present in the industry.

2.4.3 Gas Emissions by Diesel Consumption

The chemical formula of Diesel is $C_{12}H_{23}$, which means its composed of 86.2% of Carbon in weight. On a fuel combustion 1 molecule of diesel generate 12 molecules of CO_2, if it is considered that one liter of diesel weights 835 grams, and the diesel molecule weights 167.3 grams per mole, one liter of diesel contains 4.99 moles, which means in a complete combustion generates 59.89 moles of CO_2, considering that the CO_2 weight around 44 grams per mole, the combustion of 1 liter of diesel will release around 2635.14 grams of CO_2.

This allows to estimate the emission of CO2 for diesel fuel around 2.64 kg CO_2/l_{Diesel}

2.4.4 Mining routes of transport

As previously mentioned, transport routes for mining companies are mainly focused on the transport of concentrates or the transport of goods for the company.

According to information from the Mining Council of 2019, about 70% of the country's copper production corresponds to concentrate, and within the mining industry in the northern sector Chile, about 29% of the total copper production is transported by truck to ports. (Consejo Minero, 2019).

Table 4 identifies the amount of material transported by truck and by region for 2019 and gives a good estimation if deemed necessary for the study.

Table 4. Annual amount of copper concentrate transported by truck per region. (Consejo Minero, 2019)

Region	Annual Production of concentrate (KTMF)
Tarapacá	23
Antofagasta	266
Atacama	274
Coquimbo	83
Valparaiso	224
RM	438

Then it is necessary to review in detail the mining companies of the northern zone and their operations in order to identify possible study routes for the comparison of trucks, thus, the following set of data is obtained and can be summarized in Table 5 and visualized in Figure 9, by identifying the starting/ending location of the mining operation and the ending/start location with Google Earth

Table 5. Option routes for the study (Self-made, 2021)

Operation	Height [m.a.s.l]	Latitude	Longitude	Place of destination	Latitude destination	Longitude destination	Height destination [m.a.s.l]	Travel Distance [km]	Main product / transport type	Reference
Cerro Colorado	2460	-20.072960	-69.276950	Iquique Port	-20.207	-70.15823	10	118	Copper cathodes / Truck	(Consejo Minero, 2020)
Chuquicamata	2740	-22.316700	-68.933300	Antofagasta Port	-23.6527	-70.40353	10	233	Copper concentrates / Truck and Train	(Nueva Minería y Energía, 2015) (FCAB, 2019)
Collahuasi	4400	-20.980070	-68.640500	Collahuasi Port	-20.8074	-70.19723	30	212	Concentrates / Pipelines	(Collahuasi, n.d.)
Collahuasi	4400	-20.980070	-68.640500	Pozo Almonte	-20.25811	-69.78492	1030	192	Goods / Trucks	(ENGIE information)
El Abra	4020	-21.924630	-68.833510	Antofagasta Port	-23.6527	-70.40353	10	314	Copper cathodes / Train	(El Abra, n.d.)
Escondida	3050	-24.256380	-69.130690	Antofagasta Port	-23.6527	-70.40353	10	159	Copper concentrate / Pipelines	(Consejo Minero, 2020)
Gabriela Mistral	2740	-23.422880	-68.790350	Mejillones Port	-23.0897	-70.41615	10	246	Copper cathodes / Unknown	(CODELCO, 2020)
Lomas Bayas	1530	-23.41696	-69.50046	Antofagasta Port	-23.6527	-70.40353	10	113	Copper cathodes / Truck	(Guia Minera, 2021)
Ministro Hales	2520	-22.346680	-68.888440	Antofagasta Port	-23.6527	-70.40353	10	232	Copper concentrates / Truck	(Nueva Minería y Energía, 2015) (FCAB, 2019)
Radomiro Tomic	2900	-22.199120	-68.867060	Mejillones Port	-23.0897	-70.41615	10	306	Copper Cathode / unknown	-
Spence	1660	-22.805260	-69.274180	Antofagasta Port	-23.6527	-70.40353	10	159	Copper concentrates / Truck and Train	(Nueva Minería y Energía, 2018)
Altonorte	510	-23.824410	-70.31712	Iquique Port	-20.207	-70.15823	10	511	Goods / Truck	(ENGIE information)

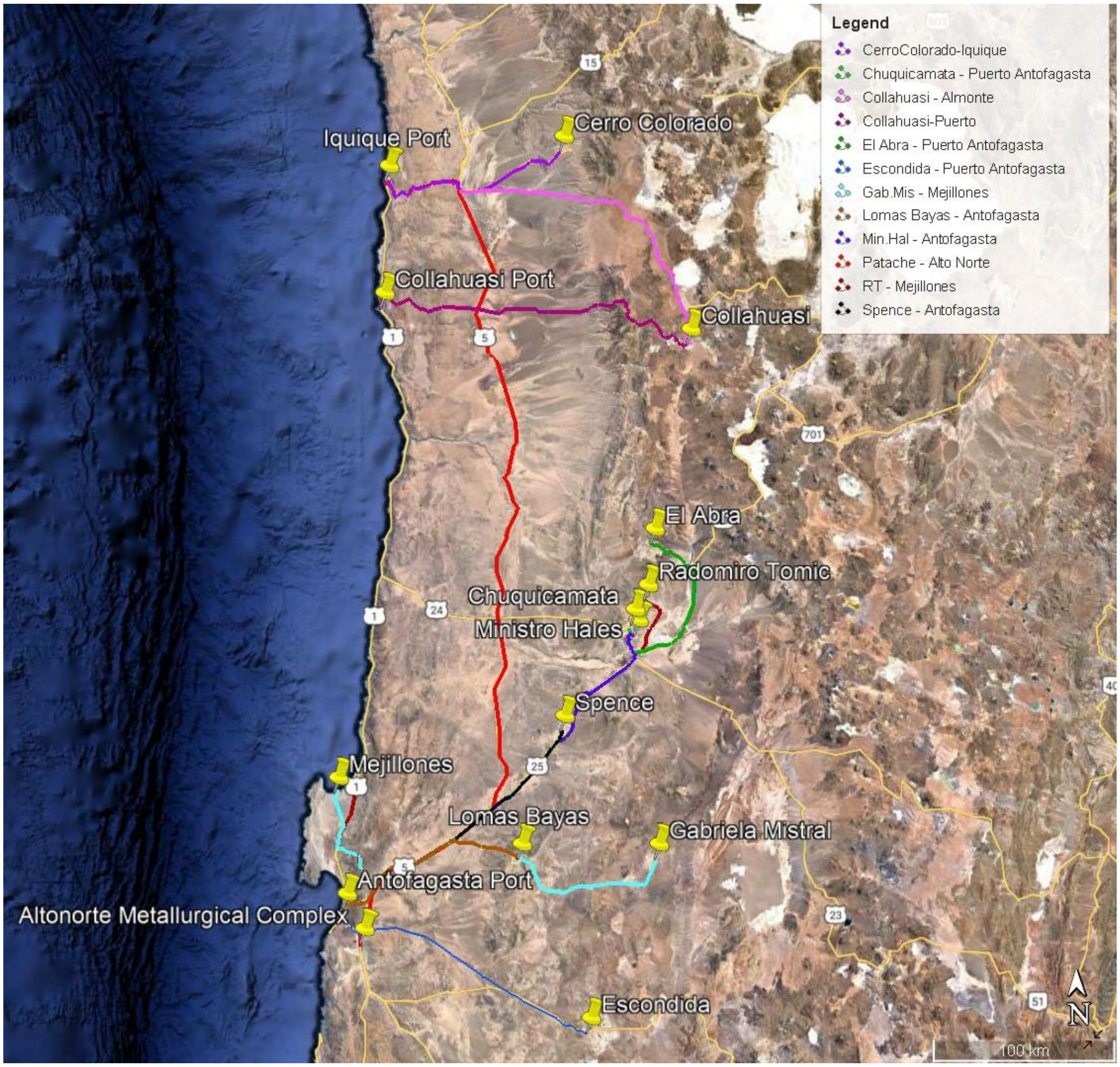


Figure 9. Charted possible routes for the study using Google Earth. (Self-made, 2021)

2.5 Hydrogen and Fuel Cell Trucks

2.5.1 Hydrogen

Hydrogen (H) is the first element of the periodic table, made up of a positively charged nucleus or proton and a negative charge or electron. Compared to other elements, it has the lowest atomic weight of only 1.008 grams per mole [g/mole].

Hydrogen is the simplest and most important and abundant element in the universe, estimating that its mass fraction is within the order of 75%. However, the proportion of Hydrogen on Earth is much lower, only in the Earth's crust is estimated a weight fraction of 0.9% and rarely existing in its pure form, being found mainly in the form of water and water vapor (H_2O).

One of the most important characteristics of hydrogen is its flammability. When it burns its flame is barely visible since it emits radiation in the ultraviolet spectrum. Also, it has a very wide ignition range, wider than other fuels like Diesel, methane or propane, being its lower concentration limit of 4% and the upper 77%, meaning that a mixture of hydrogen in those proportions with oxygen can ignite very easily and only requires an energy of 0.02 MJ, much lower value compared to other fuels.

As for the gas itself, hydrogen has an energy per unit mass or low heat value (LHV) of 120.1 MJ/kg, approximately 3 times more than Diesel. These properties of combustion make hydrogen a good candidate as a fuel and allow its application in different systems, such as internal combustion engines as well as heating systems, Table 6 summarizes the overall properties of hydrogen, comparing it to some other fuels for reference.

Table 6. Hydrogen properties compared with other fuels. (Self-made, 2021) (IEA, 2019)

Properties	Hydrogen	Comparison
Density (gas)	0.089 kg/m3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m3 (-253°C, 1bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C lower than LNG
Energy per unit mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (LHV cond.amb)	0.01 MJ/L	1/3 of natural gas
specific energy (LHV, liquefied)	8.5 MJ/L	1/3 de LNG
Flame speed	346 cm/s	8x methane
Ignition range	4 to 77% volumetric in air	6x wider than methane
Autoignition temperature	585°C	220°C for petrol
Ignition energy	0.02 MJ	1/10 of methane

The use of H2 as an energy carrier allows it to be a storable fuel source. To this date, the most common storage method of hydrogen storage is small-scale in gaseous or liquid form, however as the need and development of technologies that use hydrogen as fuel grows, it will encourage the development and implementation of less common measures, and the most appropriate storage method will depend on the application that will be given to the gas and the volume to be used.

Some of the used storage methods are:

- Mobile or stationary storage (gas)
- Underground caverns (gas)
- Mobile storage tanks (liquid)
- Storage in metal hydrides

2.5.2 Types of Hydrogen

According to what was mentioned in the previous point, hydrogen can be grouped into different classifications based on the method used during its production, allowing to identify its origin, carbon footprint associated with its production and cost. Table 7 summarizes the spectrum of H2 types.

Table 7. Types of Hydrogen by method of production (Self-made, 2021)

Color	Production Method	Energy Source	CO_2 Emissions
Black	Gasification	Coal	High
Gray	Gas Reforming	Natural Gas	Medium
Brown	Gasification	Coal (lignite)	High
Blue	Reforming or Gasification + Carbon Capture	Natural Gas Coal	Low
Turquoise	Pyrolysis	Natural Gas	Solid carbon
Pink	Electrolysis	Nuclear	Minimal
Green	Electrolysis	Renewable energy	Minimal
Yellow	Electrolysis	Mix Renewable and Grid	Medium

2.5.3 Use of Green Hydrogen

As previously mentioned, the classification of "green" for hydrogen serves to identify the origin of its production, characterizing it by being generated from the rupture of the water molecule through the application of an electric current (electrolysis), whose origin is based on renewable energies, such as photovoltaic solar energy, thermal solar energy, wind energy, etc.

The transition from the use of fossil fuels to renewable energies for the generation of H2 allows the manufacture and storage of an energy carrier that does not emit greenhouse gases in its generation, creating a gas / fuel that can be applied in different areas, naming some, is the generation of electric energy, heat generation, manufacture of other chemical products, etc., as shown in Figure 10.

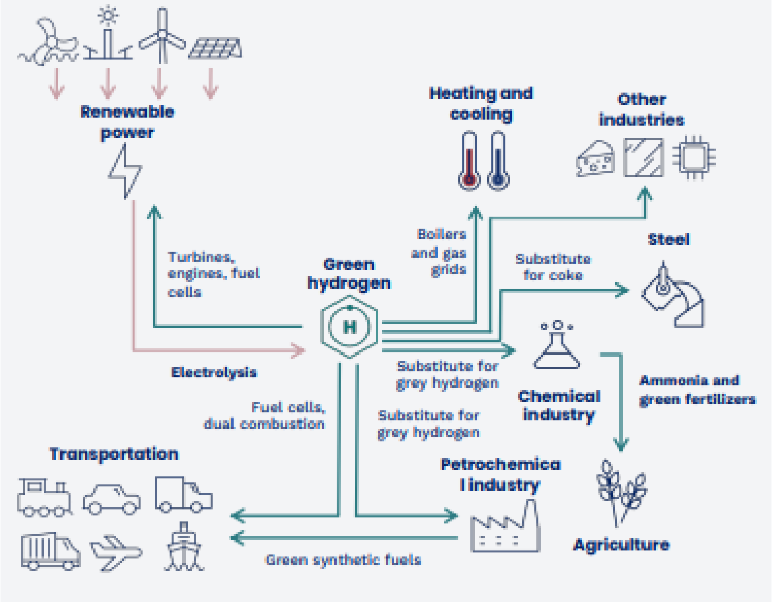


Figure 10. Uses of green H2. (Ministerio de Energía, 2021)

Thus, the production and use of this gas without the emission of GHG can contribute to the decarbonization and reduction in the carbon footprint of broad sectors within various industries.

2.5.4 Levelized Cost of Green Hydrogen

The LCOH is a methodology used to account for all of the capital and operating costs of producing hydrogen, representing the unitary cost of production of one kg of H2 ($/kg), the main factors that affect this parameter depend on the location, size of the generating plant and methods or forms of distribution, but in general, the factors of greater weight are the CAPEX of the electrolyzer and stacks, O&M costs, and the levelized cost of electricity, that is why there is a direct relationship between the price of green hydrogen and renewable energy. The LCOH can be calculated as seen in Equation 1.

$$LCOH = \frac{\mathrm{Capex} + \mathrm{NPV}(\mathrm{C}_{\mathrm{o\&m}} + \mathrm{C}_{\mathrm{el}})}{\mathrm{M}_{H_2}}$$

Equation 1. Levelized cost of Hydrogen formula

Where Capex represents all equipment cost of acquisition, $\mathrm{C}_{\mathrm{o\&m}}$ are the cost of operation and maintenance of each equipment, C_{el} is the cost of electricity necessary to power the Hydrogen plant and M_{H_2} is the total amount of Hydrogen produced of the plant.

Figure 11 shows the projection of reduction of renewable energy costs for the north, center and south of Chile. Given the high renewable potential of the north, mainly by solar photovoltaic energy, and the reduction cost of technologies, the resources allow to estimate lower costs of LCOE or levelized cost of energy, and this being one of the inputs of greater weight in the LCOH, the same behavior can be expected for the projections of levelized cost of Hydrogen production, as seen in Figure 12.

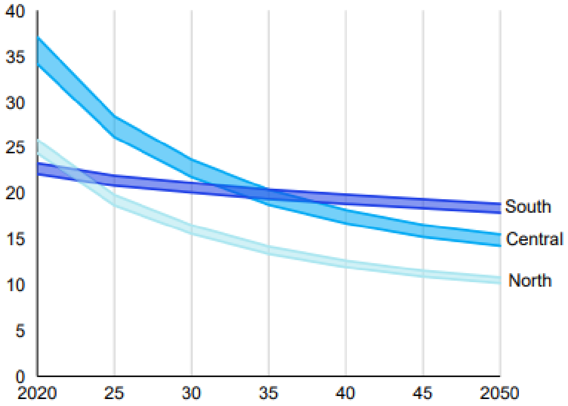


Figure 11. Expected levelized cost of renewable electricity for each sector of Chile [USD/MWh vs year]. (McKinsey & Company, 2020)

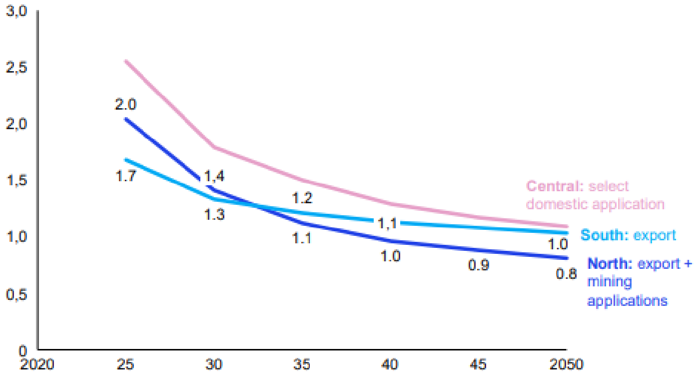


Figure 12. Expected levelized cost of green Hydrogen by sector in Chile [USD/kgH2 vs year] . (McKinsey & Company, 2020)

McKinsey & Company studies present hydrogen costs of 2.0 USD/kgH2 2025, with a considerable reduction of up to 0.8 USD/kgH2 by 2050, making Chile one of the countries with the best cost projection for green hydrogen as indicated in Figure 13, making this highly competitive with gray hydrogen and low carbon hydrogen (blue hydrogen) around 2030.

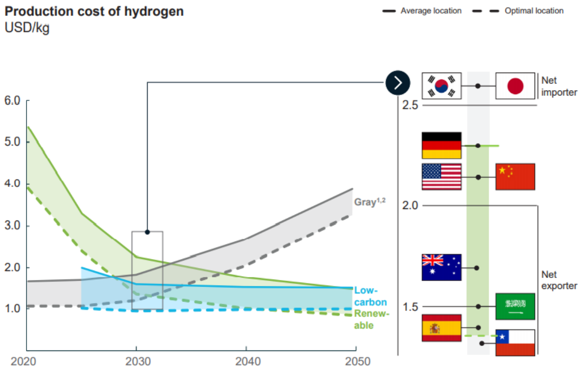


Figure 13. Hydrogen production pathways. (McKinsey & Company, 2021)

2.5.5 Fuel Cell Technology

While the energy contained within the H2 molecule can be harnessed by combusting this gas, the development of fuel cell technologies in recent years has allowed the efficient use of this resource without the need for hot combustion.

Fuel Cell’s (FC) are electrochemical devices that can convert the stored energy of some fuel (e.g., hydrogen) into an electric current and heat, during this process 286 kJ of energy is released per mol of H2, and this type of reaction can reach theoretical efficiencies of 80%.

A fuel cell, unlike a battery that has a finite storage capacity, as long as it is kept fueled, it can supply energy and heat constantly and indefinitely, which allows this technology to be used in combined heat and power processes.

A Fuel cell system consists of a set of individual cells connected in series, forming what is known as a stack. An individual cell is made up of 2 electrodes (anode and cathode), separated from each other by an ionic electrolyte and diffusion layers to facilitate the flow of gases.

As seen in Figure 14, the electrolyte is responsible for separating the gases and is permeable only for some ions, so that, when supplying a fuel through the anode of the cell, it is separated into ions. The flow of these ions through the electrolyte generates a flow of electrical charges on an external circuit to the layers of the cell, which causes the oxygen to ionize near the cathode and rejoin with the hydrogen ions that diffuse through the electrolyte, forming water and heat as a subproduct of the process.

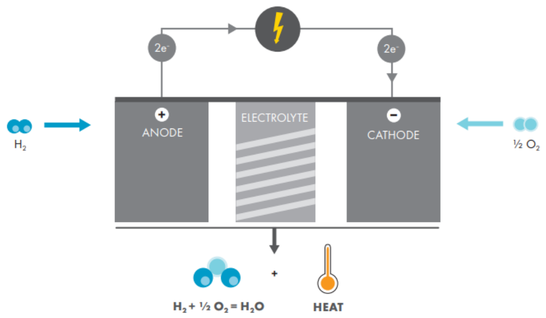


Figure 14. Operation principle for H2 fuel cell. (Shell, 2017)

2.5.6 Fuel Cell Trucks and Diesel comparison

A fuel cell vehicle (FCV) is a type of electric vehicle that uses a fuel cell for the generation of electricity, that can sometimes be combined with a battery system to power the electrics of the vehicle.

A fuel cell vehicle uses hydrogen as an energy source, contrary to internal combustion engine vehicle (ICE) that uses fossil fuels like gasoline, Diesel, or fuel oil, or compared to electric vehicles, that require an external charge by grid connection. The main propulsion system of a fuel cell vehicle comes from an electric motor instead of the standard internal combustion engine and the standard powertrain configuration of a FCV can be seen in Figure 15.

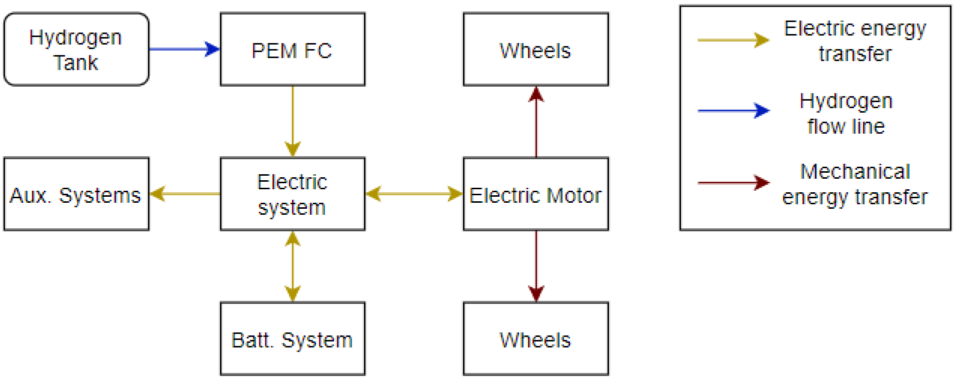


Figure 15. Fuel cell vehicle powertrain. (Self-made, 2021)

Hydrogen is stored in a high-pressure vessel, which serves as a fuel tank for FCV. The fuel cell consumes H2 and generates electricity to send electricity to an electric system. power the electric motor and send power to the wheels or any auxiliary system.

The electric system is composed of converters, inverters, and controllers to supply electricity through a high voltage circuit to the rest of the systems, which include the electric motor for propulsion of the vehicle, the auxiliary systems and the battery system.

The auxiliary system is mostly composed of all the necessary equipment to regulate the FC and other equipment of the car, like cooling systems, vehicle lights, air conditioning, compressors, etc. Meanwhile, the battery systems generally are tasked with supplying electricity to the wheels when necessary if extra power is needed, and this one can be charged either by regenerative breaking of the wheels or by the fuel cell system.

On the other hand, the powertrain of an internal combustion engine is slightly simpler, power at wheels is supplied by a series of mechanical components, considering final drives, transmission, and clutches, while the power is outputted by the engine, which is powered by the combustion of fossil fuels stored in the fuel tank, as shown in Figure 16.

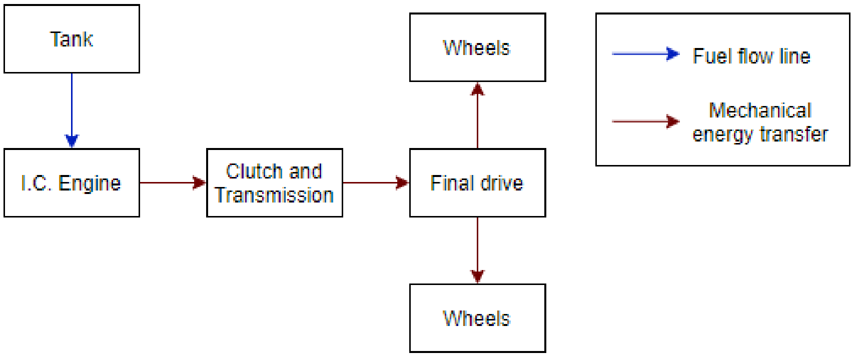


Figure 16. Internal combustion engine powertrain. (Self-made, 2021)

When speaking of heavy-duty vehicles (HDV) the main differences are the power outputs and physical configurations of components. Recent studies show working mechanism, performance metrics and recent developments on HDV powertrains technologies, such as a comparison of Table 8Table 3 based on a review of heavy duty vehicle powertrain technologies (Carlo Cunanan, 2021)

Table 8. Comparison of HDV powertrains. (Carlo Cunanan, 2021)

Parameter	Diesel	Hydrogen Fuel Cell
Tailpipe emissions	Yes	No
Well to tank efficiency	~86[%]	~76[%]
Tank to wheel efficiency	~23[%]	~45[%]
Fuel consumption	6.5 [miles/gallon]	5.5-9.2 [miles/kg H2]
Range	975-1950 [miles]	660-1104 [miles]
Refueling time	6-12 [min]	16.67 [min]
Specific energy (LHV)	42.9 [MJ/kg]	118 [MJ/kg]

When considering the advantages of each technology, FCV help to reduce GHG and air pollution, have higher energy efficiencies than ICE and higher specific energy, but due to being a technology in development, hydrogen fuel cost is relatively high today when compared to diesel. Besides, a heavy infrastructure development is required to be implemented for FCV, without considering that the acquisition cost of FC-HDV is higher than the diesel counterpart.

2.6 Total Cost of Ownership (TCO)

The total cost of ownership is a financial indicator used by many companies and individuals when looking to buy assets and analyzing long term business deals by allowing the comparison of different alternatives and facilitate the selection of the cheapest option.

This type on analysis takes into consideration initial purchase prices as well as direct and indirect expenses along the whole financial period of evaluation. It is especially useful when comparing vehicle implementations and very used in the automotive industry. This indicator can be calculated as:

$$\mathrm{TCO} = \sum_{t=1}^{n} \frac{(I_t + O_t + M_t - R_t)}{(1+r)^t}$$

Equation 2. Total cost of ownership calculation.

Where I_t is the investment cost of period t, O_t is the operational cost of period t, M_t is the manteinance cost of period t, R_t is the residual value, r is the discount rate and n is the length of the financial evaluation.

Figure 17 shows the general framework of factors used to calculate the TCO of truck implementations, showing the main differences of each case of study and allow the comparison of technologies.

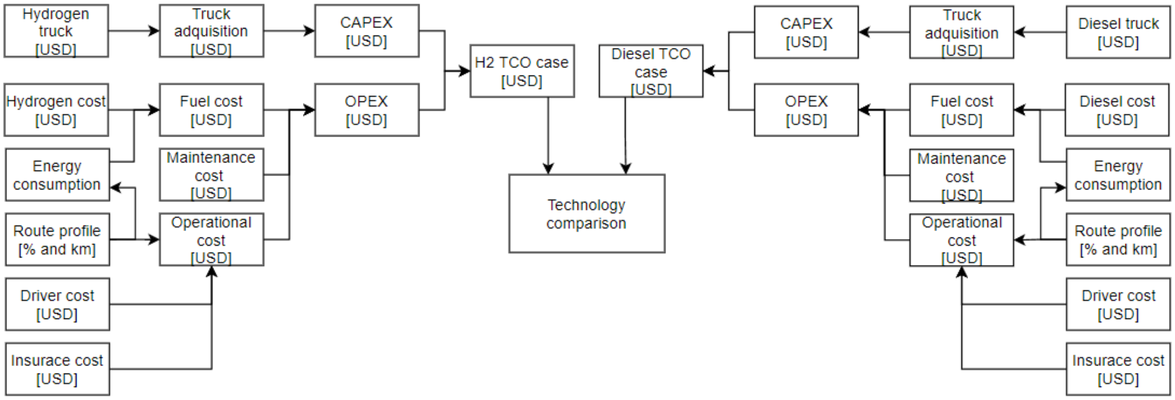


Figure 17. TCO framework diagram for comparison of H2 and Diesel trucks. (Self-made, 2021)

3 Methodology

In order to verify the feasibility of implementing fuel cell technologies for the transport of the mining sector, it is necessary to carry out a series of steps to study each case, establish transport criteria, develop a cycle that adapts to the profile of the routes of interest and thus be able to compare between technologies, based on this, Figure 18 shows the proposed action list for the methodology.

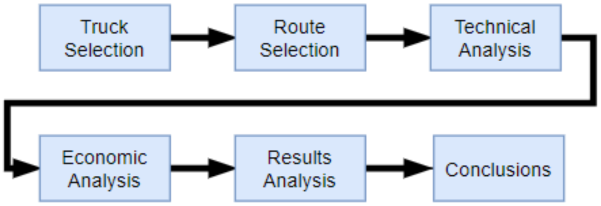


Figure 18. Methodology flow diagram

1. Truck selection: Based on diesel trucks that are used within the mining transport and hydrogen trucks, truck models will be selected for each technology to carry out the comparison between them in a set of routes. For each truck the operational parameters will be obtained by catalog or if necessary, by estimation.
2. Route selection and transport parameters: Based on the research of transport for concentrates and goods within the industry, 3 routes will be selected to study cases for long routes, routes with high variation in height and a route that can represent a case of generic transport within the sector.
3. Technical analysis: In order to represent the behavior of the selected trucks on each route, it is intended to estimate a profile of speeds for trucks on each route, which will depend on specific operational and logistical parameters of the truck and cycle operation. With this, it will be possible to estimate operating times, power consumption, energy consumption, CO_2 emissions, battery load states, among others, and use these results within the economic analysis and compare costs.
4. Economic analysis: For the economic analysis, information on CAPEX and OPEX will be recompiled for each technology based on references and estimates. These parameters will consider factors such as technology acquisition costs, maintenance costs, fuel costs, driver fees, among others. This together with the results of the technical analysis will allow to perform a total cost of ownership (TCO) analysis to compare technologies for different time projections or scenarios
5. Results analysis: Based on the results of the economic analysis, a summary of the main results obtained will be made to evaluate the feasibility of implementing Fuel Cell technologies within mining transport, and, if possible, identificate break evens between these two technologies, or factors than can help in the Fuel Cell Truck implementation.
6. Conclusion and critical analysis: A final review of the results will be synthesized and analyzed according to the initial objectives proposed by this work, together with the problems presented and the approach of solutions for future work

In each section all the data and parameters that will be used will be explained in detail, along with the assumptions used for each calculation and the support of these based on the literature. All the calculations for the technical, economic and results analyses will be made in an Excel spreadsheet, while the routes and elevation profiles of these are obtained from Google Earth.

4 Truck Selection

4.1 Diesel Vehicle

To establish the base case of comparison of the study it is proposed to use the truck of the manufacturer Mercedes Benz, model New Actros 2645. The reason for selecting this model is due to the fact that it is already used within the mining road trucks. Figure 19 shows the selected model and Table 9 details its characteristics by catalog.

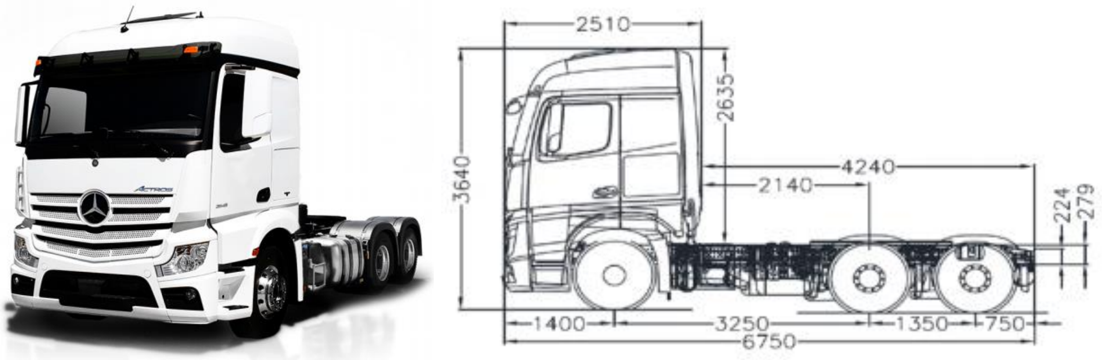


Figure 19. Mercedes Benz New Actros 2645 6X4 EURO 5. (Kaufmann, n.d.)

Table 9. Diesel truck specifications. (Kaufmann, n.d.)

Parameter	Value
OEM	Mercedes Benz
Model	New Actros 2645
Gross Vehicle Weight (GVW)	8.773 [kg]
Gross combines weight rating (GCWR)	45.000 [kg]
Axel configuration	6X4
Engine power	330 [kW] / 449 [HP]
Engine Swept Volume	12.8 [l]
Torque	2.200 Nm
Fuel tank capacity	290 [l] left tank, 370 [l] right tank
Front axle weight capacity	7.500 [kg]
Back axel weight capacity	13.000 [kg]
Fuel Mileage	2-2,5 [km/l]
Maximum payload	70.000 [kg]

4.2 Hydrogen Vehicles for Comparison

To establish the comparative case of H2 implementation it is necessary to look for a manufacturer of class 8 trucks that presents some model of similar characteristics to the selected diesel truck.

Under this methodology, a class 8 PEM (Proton Exchange Membrane) fuel cell electric truck (FCET 8) from the manufacturer Hyzon, is selected, which under the proposed criteria, has similar characteristics in terms of power and loads for transport. Figure 20 shows the truck and Table 10 its specifications.

Considering that this type of technology is found within the market, for the purposes of the study it will not be necessary to estimate costs per retrofit of a standard diesel vehicle to perform the technological comparison, and costs can be estimated directly from the existing technologies, demonstration technologies or by component breakdown.

Figure 20. Hyzon H2 truck (HYZON, 2021)

Table 10. H2 truck specifications (HYZON, 2021)

Parameter	Value
OEM	Hyzon
Model	Not specified
Gross Vehicle Weight (GVW)	N/A
Gross combines weight rating (GCWR)	50,000 [kg]
Electric motor power	320 [kW] / 429 [HP] Continuous 450 [kW] / 603 [HP] Peak
Electric motor Torque	1,180 [lb.-ft] Continuous 1,770 [lb.-ft] Peak
High voltage battery energy	110 [kWh]
Powertrain voltage	700 [V]
Maximum speed	55 [mph] / modifiable to 75 [mph]
Fuel cell power	120 [kW]
Amount of Hydrogen	50-70 [kg]
Storage pressure	350 [bar]
Driving range	375-500 [mi]
CHASSIS Dimensions (l x w x h)	308,19’’ X 97’’ X 200’’

In case the previous truck does not represent a feasible implementation, in terms of total cost or in terms of cycle autonomy, a H2 truck with a higher fuel cell power output will be evaluated.

Thus, in case that the truck has unfavorable results, a new analysis will be made with the proposal of the Hyzon HYMAX-450, which can be seen in Figure 21 and Table 11 shows the truck specifications

Figure 21. Hyzon HYMAX-450 truck (HYZON, 2021)

Table 11. HYMAX-450 truck specifications (HYZON, 2021)

Parameter	Value
OEM	Hyzon
Model	HYMAX-450
Gross Vehicle Weight (GVW)	N/A
Gross combines weight rating (GCWR)	70,000 [kg]
Electric motor power	450 [kW] / 603 [HP] Continuous
High voltage battery energy	140 [kWh]
Powertrain voltage	700 [V]
Fuel cell power	240 [kW]
Amount of Hydrogen	65 [kg]
Storage pressure	350 [bar]
Driving range	650 [km]
CHASSIS Dimensions (l x w x h)	7,320 mm X 2,460 mm X 2,620mm

5 Route for Study and Transport Parameters

In terms of simplicity, only 3 routes will be taken from the previous studied set. For this selection the criteria will consider:

1. The route with the longest distance.
2. The route with the highest variation in height.
3. A mining case that ranges between the 2 previous points and transports concentrates by truck.

Thus, the selected routes are:

1. Route 1: Altonorte to/from Iquique Port with a total distance of 511 km
2. Route 2: Collahuasi to/from Pozo Almonte with a height variation of 3,352 m
3. Route 3: Chuquicamata/M. Hales to/from Antofagasta Port with 233 km with a height variation of 2,640 m

Since Chuquicamata and Ministro Hales are relatively close and transport concentrate by truck to the same port, the same route can be assumed for both operations. Finally, these routes can be seen in the Figure 22, where the red line indicates route 1, pink line indicates route 2 and cyan line indicates route 3.

Figure 22. Chart of the selected routes for the study.

Using Google Earth it is also possible to extract the elevation profiles, allowing to get information about distance, height and elevation of each one of the selected routes to use these as inputs for the calculation of power and energy consumption of each vehicle, the Figure 23, Figure 24 and Figure 25 represent routes 1, 2 and 3 respectively.

Figure 23. Route 1, from Iquique Port to Metallurgic Altonorte complex.

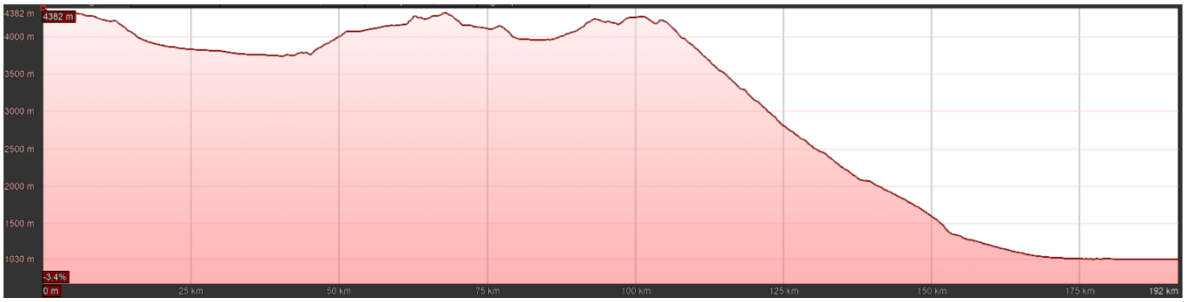


Figure 24. Route 2. from Collahuasi to Pozo Almonte

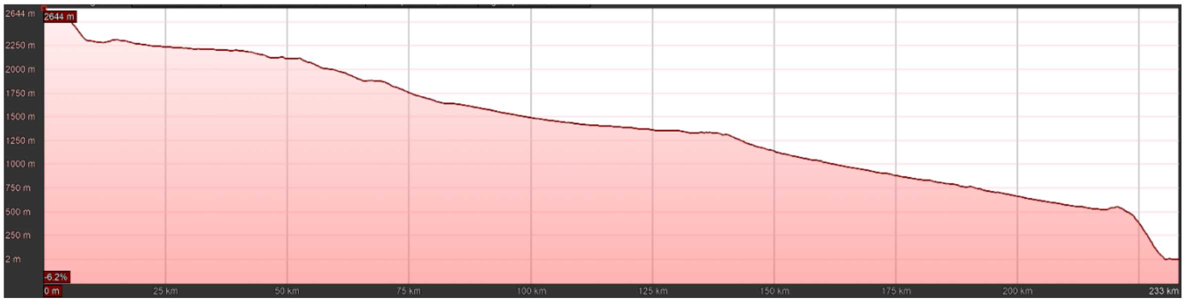


Figure 25. Route 3, from Chuquicamata to Antofagasta Port.

6 Technical Analysis

To evaluate the feasibility to implement new technologies, an economic evaluation is not enough, due to the need to evaluate if deemed technology is capable to meet the basic requirements and/or autonomy of the original technology.

Thus, this section of technical analysis will focus on proposing a methodology to estimate the operation parameters for each technology in each route of study, so that a comparison scenario can be stablished and the autonomy for each technology can be estimated, considering the effects of truck speeds, energy consumptions, required power, cargo effects, among others that will be detailed in each section.

6.1 Estimation for Speed Profiles

Considering the lack of telemetry and consumption information for these specific routes, especially for H2 technologies that have not been implemented or registered in Chile, a calculation method will be proposed for the speed profile of Diesel and H2 vehicles that allows to represent the maximum speeds for transport trucks and truck acceleration/decelerations when there is a variation of slope within the route, for this, the following assumptions are considered within the calculation.

- Route will be divided in segments based on data acquisition from elevation profile (see Figure 26).
- Each segment will have a defined slope, entry velocity and exit velocity (see Figure 26).
- The entry speed of each route (i=1) will be 25 m/s, meaning this study is only on route calculation considering start and end segments negligible.
- For each route, concentrate and goods, transport payload will be of 28 tons of dead weight so that internal forces won’t affect the estimation.
- Maximum speed for class 8 trucks on road is 90 km/h by Chilean regulations (Comisión Nacional de Seguridad de Tránsito).
- Maximum speed can only be reached on a 0% slope segment, any % higher will result in a decrease of speed.
- Due to lack of downslope speed limiting criteria other than the driver safety precaution, for simplicity, the same speed limit as an upward slope will be taken for a downward slope.
- Maximum depth of discharge for battery system will be of 80% in order to avoid battery degradation in the calculation.
- FC systems operate at a constant power output, while excess or lack of power will be reflected by the battery system, either by battery recharge or achieve increased power at wheels.

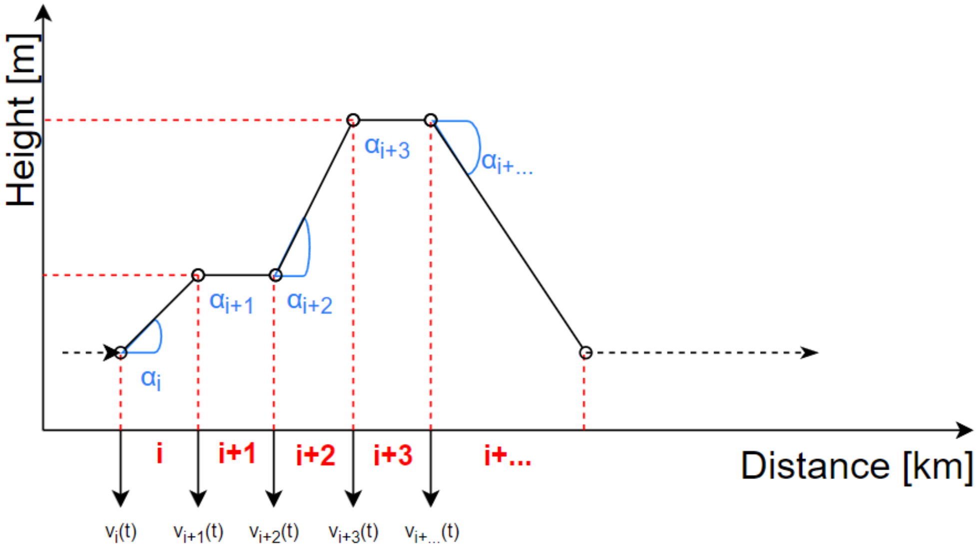


Figure 26. Example of speed profile segmentation for analysis (Self-made, 2021)

The speed profile will be calculated based on the vehicle dynamic model (Hesham Rakha, 2001) and a power based electric vehicle energy consumption model (Chiara Fiori, 2016) which will be later be used again in the estimation of power and energy consumption.

This model allows to calculate maximum vehicle acceleration on a slope based on the vehicle tractive force, aerodynamic, rolling and grade resistance, represented in Figure 27, which follows the Equation 3.

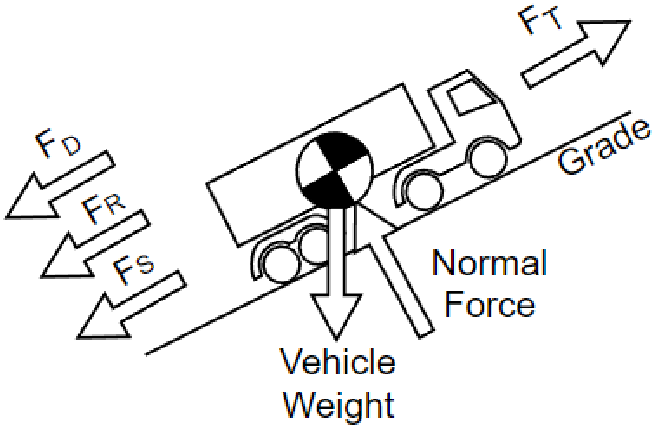


Figure 27. Balance of forces on a moving truck (Self-made, 2021)

$$a(t) = \frac{dv}{dt} = \frac{F_T(t) - R(t)}{m}$$

Equation 3. Balance of forces on a moving truck (Chiara Fiori, 2016) (Hesham Rakha, 2001)

Where $a(t)$ is the acceleration of the vehicle in $[m/s^2]$, $F_T(t)$ is the tractive force of the vehicle provided by the engine or electric motor that depends on the power output and drivetrain configuration, $R(t)$ is the total resistance forces acting on the vehicle and m is the mass of the vehicle in [kg].

On the other hand, the resistive forces are the sum of 3 forces, resistance by aerodynamic friction (F_D), rolling friction (F_R) and road slope (F_S), where each is calculated as seen below

$$F_D(t) = 0.5 * \rho_{air} * A_f * C_D * v(t)^2$$

Equation 4. Aerodynamic friction force formula. (Chiara Fiori, 2016)

$$F_R(t) = m * g * \cos(\alpha) * \frac{C_r}{1000} * (c_1 * v(t) + c_2)$$

Equation 5. Rolling friction force formula (Chiara Fiori, 2016)

$$F_S(t) = m * g * \sin(\alpha)$$

Equation 6. Road slope force formula (Chiara Fiori, 2016)

Where ρ_{air} is the air density, m is the total mass of the vehicle considering truck and payload in [kg], A_f is the frontal area of the vehicle in $[m^2]$, C_D is the drag coefficient of the vehicle, v is the velocity of the vehicle in [m/s], g is the gravitational acceleration in $[m/s^2]$, α is the slope in [radians] and $C_r, c_1\ and\ c_2$ are rolling resistance parameters that depend on the road surface and will be detailed in the power consumption estimation segment later on.

On the other hand, the instantaneous power required by the wheel to make the vehicle move can be expressed as

$$F_T(t) * v = P_w(t)$$

Equation 7. Power at wheels formula.

Where P_w is the power at wheels.

Replacing the Equation 4, Equation 5, Equation 6 in Equation 3 and multiplying by v the power at wheel ecuation is obtain.

$$P_w(t) = \left(m * a(t) + 0.5 * \rho_{air} * A_f * C_D * v(t)^2 + m * g * \cos(\alpha) * \frac{C_r}{1000} * (c_1 * v(t) + c_2) + m * g * \sin(\alpha)\right) * v(t)$$

Equation 8. Power at wheel complete formula. (Chiara Fiori, 2016)

In order to satisfy the speed conditions for the truck, the crawl speed $v_{cr}(t)$ will be calculated for each slope and route configuration, where the crawl speed is defined as the maximum speed a vehicle can reach on a slope depending on the power output of its engine/motor and can be cleared of the Equation 8 when the condition of $a(t) = 0$ is met and all forces are balanced.

Now it is required to meet the condition of maximum speed of 90 km/h or 25 m/s when $\alpha = 0$, by replacing in Equation 8, a maximum value of P_{wmax} can be obtained in order to use this as a power limit for speed estimation on each slope gradient, allowing for each positive value of α clear a value of $v_{cr}(t)$ that solves.

$$P_{wmax}(t) = \left(0.5 * \rho_{air} * A_f * C_D * v_{cr}(t)^2 + m * g * \frac{C_r}{1000} * (c_1 * v_{cr}(t) + c_2)\right) * v_{cr}(t)$$

Equation 9. Maximum power at wheel under maximum truck speed by slope.

Where $m, \rho_{air}, A_f, C_D, C_r, c_1$ and c_2 will depend on the studied route and truck and will be detailed for each configuration in the power consumption segment.

Under this methodology it is ensured that:

- The speed of the vehicle will not exceed the limits established by the Chilean regulations.
- The total power at wheel P_w will not exceed the total power output of the engine/motor by drivetrain configuration.
- The vehicle will decrease or increase its speed when there is a change of slope and that this change of speed is possible under the calculation criteria of the dynamic model of vehicles of (Chiara Fiori, 2016), and, as shown in Figure 26, this speed will be calculated and used for the exit speed of each segment of the elevation profile.

It is also important to mention that the use of this methodology allows to represent the effect of payload on the vehicle fuel consumption when approaching high slopes. For example, a truck with empty payload, when going uphill will require less power output by the engine in order to reach certain velocity, as shown in "case A" of Figure 28, while considering the case "B" on full payload, in order to reach the same speed, the truck will require a higher power output, allowing to represent the different energy consumptions of each case, without affecting the general speed estimation of the studied route.

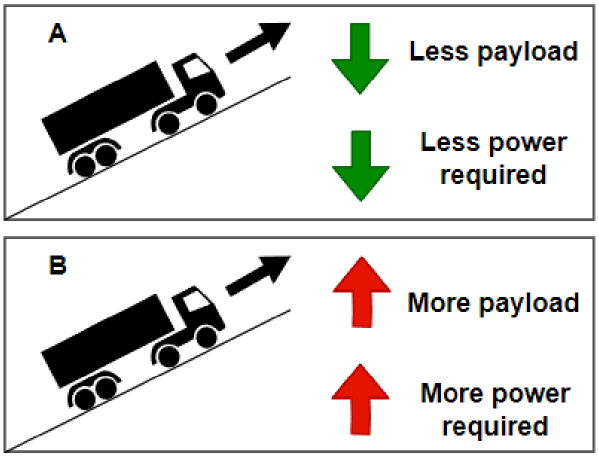


Figure 28. Power comparation by payload (Self-made, 2021)

The last thing to calculate is the time and acceleration of each segment, knowing the entry and exit velocity, the slope, the distance of each segment, and since each segment is considered straight, time and acceleration can be roughly estimated by the equations.

$$d_{i+1} = d_i + v_i(t) * \Delta t_i + 0.5 * a_i(t) * \Delta t_i^2$$

Equation 10. Distance variation for uniformly rectilinear motion per segment.

$$a_i(t) = \frac{v_{i+1}(t) - v_i(t)}{\Delta \mathrm{t_i}}$$

Equation 11. Acceleration for uniformly rectilinear motion per segment

Where d_i is the distance of the segment “i” in [m], $\Delta \mathrm{t_i}$ is the time of the segment “i” in [s] and $a_i(t)$ is the acceleration of the segment “i” in $[m/s^2]$.

6.2 Calculation of Power, and Energy Consumption

Once the speeds, times and accelerations of each segment have been estimated, the power at wheel of Equation 8. Power at wheel complete formula Equation 8 can be used again to get the total power at wheels for each segment of the elevation profile. Due to each technology have a specific powertrain configuration, a detailed description will be given for the power and energy consumption estimation, along with value of each parameter considered. All the same, shared parameters for both technologies are presented on Table 12.

Table 12. Shared parameters for truck power calculation.

Parameter	Symbol	Value	Unit	Reference
Gravitational acceleration	g	9.81	m/s^2	
Pavement coefficient	Cr	1.25	-	(Hesham Rakha, 2001)
Neum coef 1	c1	0.0328	-	(Hesham Rakha, 2001)
Neum coef 2	c2	4.575	-	(Hesham Rakha, 2001)
Air density	ρ_{air}	1.296	kg/m^3	

6.2.1 Diesel power and Energy Consumption

For the diesel truck, a simplified powertrain is considered, where the power at wheel is supplied by the internal combustion engine through a mechanical transmission system, while the auxiliary systems (battery, air conditioning, etc.) will be considered directly as a direct engine consumption disregarding the effects of loss due to energy conversion, Figure 29 show the powertrain configuration, where P_m is the power supplied by the engine, P_t is the power of the transmission after the power loss due to the efficiency of the transmission η_t, P_W is the power at wheel after all the losses and P_a is the power of the auxiliary systems.

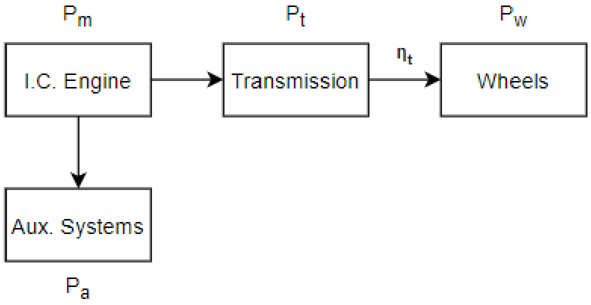


Figure 29. Diesel truck powertrain configuration

$$P_m = P_a + \frac{P_w}{\eta_t}$$

Equation 12. Power distribution for diesel powertrain

The total energy consumption can be calculated using the engine power and time.

$$E_t = \int_0^T P_m dt$$

Equation 13. Energy consumption formula

And since the calculations are being work with wide intervals of time, a simplified estimation can be made as.

$$E_t = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} P_{m_i} * \frac{\Delta t_i}{3600}$$

Equation 14. Discretized energy consumption formula

Where P_{m_i} is the power consumption of the engine for the interval "i" and Δt_i is the time of the interval "i" in seconds.

The last thing to calculate is the total diesel consumption.

$$Q_{diesel} = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} \frac{E_i}{\eta_{ice} * LHV_{diesel} * \rho_{diesel}}$$

Equation 15. Total diesel consumption formula.

Where Q_{diesel} is the total diesel consumption in [l], E_i is the energy consumption in [kWh] of the "i" interval, η_{ice} is the conversion efficiency of internal combustion engines, LHV_{diesel} is the lower heating value of diesel in [kWh/kg] and ρ_{diesel} is the fuel density in [kg/l]

The parameters used for the diesel truck calculation are presented in Table 13.

Table 13. Used parameters for calculation for Diesel truck. (Self-made, 2021)

Parameter	Symbol	Value	Unit	Reference
Vehicle weight	m_v	8773	kg	Vehicle catalog (Kaufmann, n.d.)
Frontal area	A_f	9.14	m^2	Vehicle catalog (Kaufmann, n.d.)
Transmission system efficiency	η_t	0.915	-	Mean value (Hesham Rakha, 2001)
ICE conversion efficiency	η_{ice}	0.3	-	(CDT In Data SpA, 2019)
Engine power	P_m	330	kW	Vehicle catalog (Kaufmann, n.d.)
Auxiliar power	P_a	8.5	kW	(Zhiming Gao, 2017)
Tank capacity	T	660	l	Vehicle catalog (Kaufmann, n.d.)

6.2.2 H2 Power and Energy Consumption

For the H2 power and energy consumption a more complex approach is considered due to the specific powertrain configuration of the truck. In this case the power at wheel is supplied by an electric motor, which can be powered by two different sources depending on the power demand. On one side, if the power at wheels is less than the maximum power that can be supplied by the fuel cell, only the fuel cell will supply energy to the system, and if there is any excess, some of it will be used to charge the battery system, but if the power demand is higher than the maximum power output of the FC, then the excess will be supplied by the battery system, reducing the state of charge of this one.

The Hydrogen powertrain configuration can be seen in Figure 30. H2 Fuel cell powertrain configuration. Figure 30

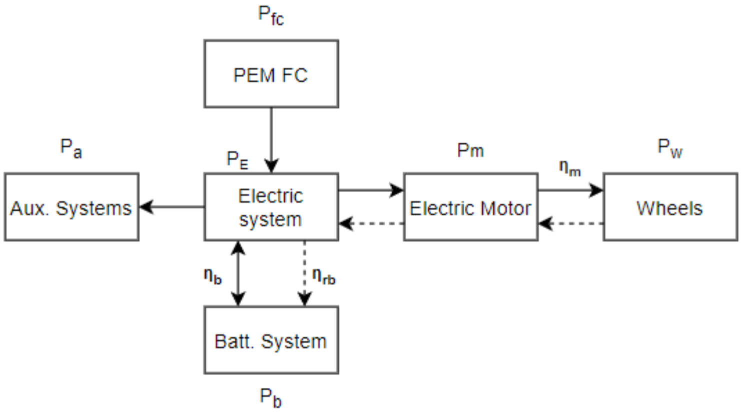


Figure 30. H2 Fuel cell powertrain configuration. (Self-made, 2021) (Alessandro Ferrara, 2021) (Espinoza, 2020)

The power at wheels again is calculated by Equation 8, only that the power distribution is calculated as.

$$P_m = \frac{P_W}{\eta_m}$$

Equation 16. Power at electric motor formula.

Where P_m is the power supplied by the electric motor in [kW] and η_m is the mechanical efficiency of power transmission from the electric motor to the wheels.

While the vehicle demands power, the general formula follows Equation 17

$$P_m + P_a = P_E = P_{fc} + P_b * \eta_b$$

Equation 17. General power distribution for powertrain consumption.

Where P_E is the electric power demand of the vehicle, when this value is higher than $P_{fc,max}$, the maximum power output of the fuel cell, P_b is positive and represents a consumption on behalf of the battery system. When P_E is lower than $P_{fc,max}$, P_b value is negative and represents a charge of the battery system and affects directly in the state of charge (SoC) of the battery.

For electric vehicles, it is also possible to charge the batteries by regenerative breaking, the equation for this can be defined as Equation 18 and its effect is considered in the battery SoC.

$$P_{b,reg} = \begin{cases} P_W * \left[exp\left(\frac{0.0411}{a(t)}\right)\right]^{-1}, & if\ a(t) < 0 \\ 0, & if\ a(t) \geq 0 \end{cases}$$

Equation 18. Regenerative breaking for battery system. (Chiara Fiori, 2016)

The total energy consumption can be calculated similar to Equation 13 and Equation 14, but instead on using the engine power it is calculated with the electric power consumption of each individual interval as shown in Equation 19.

$$E_t = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} P_{E_i} * \Delta t_i$$

Equation 19. Total energy consumption for H2 powertrain.

Hydrogen consumption is calculated similar to diesel consumption as

$$Q_{H2} = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} \frac{P_{fc,i} * \Delta t_i}{3600 * \eta_{fc} * LHV_{H2}}$$

Equation 20. Total Hydrogen consumption

Where Q_{H2} is the total Hydrogen consumption in [kg], E_i is the energy consumption of interval “i”, $P_{fc,i}$ is the power demand of the fuel cell of the interval “i” in [kW], Δt_i is the time of the interval “i” in seconds, η_{fc} is the fuel cell energy conversion efficiency and LHV_{H2} is the lower heating value of Hydrogen in [kWh/kg].

Finally, the battery SoC can be followed as

$$SoC_i = SoC_{i-1} - \frac{(P_{b,i} + P_{b,reg,i}) * \frac{\Delta t_i}{3600}}{E_b}$$

Equation 21. State of Charge of the battery system per segment

Parameters used for the H2 truck calculation are shown in Table 14:

Table 14. Used parameters for calculation for H2 trucks. (Self-made, 2021)

Parameter	Symbol	FCET 8	HYMAX-450	Unit	Reference
Vehicle weight	m_v	9000	10800 (+20% FCET8)	kg	Vehicle catalog (HYZON, 2021) Estimation due to bigger FC, electric motor and battery system
Frontal area	A_f	8.51	10.578	m^2	Vehicle catalog (HYZON, 2021)
FC conversion efficiency	η_{fc}	0.6	0.6	-	(U.S. Department of Energy, 2015)
Electric motor power	P_m	320	450	kW	Vehicle catalog (HYZON, 2021)
Fuel cell power	P_{fc}	120	240	kW	Vehicle catalog (HYZON, 2021)
Auxiliar power	P_a	10	20 (X2 FCET 8)	kW	(Alessandro Ferrara, 2021)
Tank capacity	T	60	65	Kg H2	Vehicle catalog (HYZON, 2021)
Mechanical efficiency of electric motor	η_m	0.9	0.9	-	(Chiara Fiori, 2016)
Battery energy	E_b	110	140	kWh	Vehicle catalog (HYZON, 2021)
Battery efficiency	η_b	1	1	-	Typical eff charge/discharge Li-ion batteries

6.3 Truck Operating Cycles

To estimate the yearly operating cycle some assumptions are taken in consideration for the operational parameters and annual availability of the truck, thus, the methodologies used are as follows

6.3.1 Individual Truck Cycle

The individual truck cycle considers the complete time of one operation cycle of transport, for each route, for each studied truck.

This takes in consideration the start and end of transport at the same point. Using previous data of speed and elevation profiles, total fuel consumption, total traveled distance, the energy consumption and transport time can be obtained, but extra data must be considered, such as load and unload time of cargo, driver resting time per worked hour and refueling times in order to estimate the total amount of cycles per year a truck can achieve. The parameters used per cycle are shown in Table 15.

Table 15. Truck cycle extra parameters. (Self-made, 2021)

Parameter	Symbol	Value	Unit	Reference
Load time (goods and concentrates)	L_t	3.5	h	Engie reference
Unload time (goods and concentrates)	U_t	3.5	h	Engie reference
Driver resting time per driving hour	R_t	0.4	h	(Dirección del Trabajo, 2021)
Diesel refuel time	$Fuel_{diesel}$	113.56	l/min	(Inspection for industry)
Slow H2 refueling time	$Fuel_{H2slow}$	3.6	kg/min	Engie reference
Fast H2 refueling time	$Fuel_{H2fast}$	7.2	kg/min	Engie reference

Thus, the total cycle time of operation is:

$$TC_t = IC_t + L_t + U_t + R_t * IC_t + \frac{Q_f}{60 * Fuel_t} + B_t$$

Equation 22. Total cycle time per truck

Where TC_t is the total cycle time in [h], IC_t is the individual cycle time of driving in [h], calculated as the sum of time of each segment of a route, L_t, U_t and R_t are the load, unload and resting time in [h], Q_f is the fuel consumption of the cycle which depending on the fuel can be in [kg] or [l], $Fuel_t$ is the refuel time, depending on the fuel can be in [l/min] or [kg/min] and B_t wich is the extra time for hydrogen vehicles to fully charge the battery system using only FC in [h] while on stand-by.

6.3.2 Total Year Operation

For simplicity, the total number of yearly cycles a truck can achieve will be estimated as a fraction between the total amount of hours a driver can operate a year over the total cycle time of each truck on each route. By law (Dirección del Trabajo, 2021), the total transport of land cargo for drivers can not exceed 180 hours per month. So, considering 12 months per year a rough amount of 2,160 hours of operation can be considered in order to calculate the amount of cycles of each route for each truck.

The annual number of cycles allows to calculate the annual amount of cargo transported, annual fuel usage, annual distance traveled, annual energy consumption and annual CO_2 emissions. Summarizing all previous points, the working and calculation criteria can be seen in Table 16, Table 17 and Table 18 for each route.

Table 16. Route 1, Altonorte – Iquique.

State of transport	Diesel Truck	H2 truck
Pre-Begin of transport	Goods are loaded to the truck at Iquique	Goods are loaded to the truck at Iquique
Begin of transport	Transport begins towards Altonorte with specified speed profile. Resting times and refueling times are considered if necessary	Transport begins towards Altonorte with specified speed profile. Resting times, battery charges and refueling times are considered if necessary
First Stop at destination	Goods are unloaded at Altonorte, refill if necessary	Goods are unloaded at Altonorte, refill if necessary
Return from transport	Truck returns without payload to Iquique with specified return speed profile. Resting times and refueling times are considered if necessary	Truck returns without payload to Iquique with specified return speed profile. Resting times, battery charges and refueling times are considered if necessary
End of transport	Truck returns to starting point, refill of the tank to full capacity is considered to start next cycle	Truck returns to starting point, refill of the tank to full capacity and battery charge to 100% is considered to start next cycle

Table 17. Route 2. Collahuasi - Pozo Almonte.

State of transport	Diesel Truck	H2 truck
Pre-Begin of transport	Goods are loaded to the truck at Pozo Almonte	Goods are loaded to the truck at Pozo Almonte
Begin of transport	Transport begins towards Collahuasi with specified speed profile. Resting times and refueling times are considered if necessary	Transport begins towards Collahuasi with specified speed profile. Resting times, battery charges and refueling times are considered if necessary
First Stop at destination	Goods are unloaded at Collahuasi, refill if necessary	Goods are unloaded at Collahuasi, refill if necessary
Return from transport	Truck returns without payload to Pozo Almonte with specified return speed profile. Resting times and refueling times are considered if necessary	Truck returns without payload to Pozo Almonte with specified return speed profile. Resting times, battery charges and refueling times are considered if necessary
End of transport	Truck returns to starting point, refill of the tank to full capacity is considered to start next cycle	Truck returns to starting point, refill of the tank to full capacity and battery charge to 100% is considered to start next cycle

Table 18. Route 3. Chuquicamata – Antofagasta.

State of transport	Diesel Truck	H2 truck
Pre-Begin of transport	Trucks does not require load of cargo	Trucks does not require load of cargo
Begin of transport	Transport begins towards Chuquicamata with specified speed profile. Resting times and refueling times are considered if necessary	Transport begins towards Chuquicamata with specified speed profile. Resting times, battery charges and refueling times are considered if necessary
First Stop at destination	Concentrates are loaded to the truck, refill if necessary	Concentrates are loaded to the truck, refill and battery charge if necessary
Return from transport	Truck returns with full payload to Antofagasta with specified return speed profile. Resting times and refueling times are considered if necessary	Truck returns with full payload to Antofagasta with specified return speed profile. Resting times, battery charges and refueling times are considered if necessary
End of transport	Truck returns to starting point, concentrates are unloaded and refill of the tank to full capacity is considered to start next cycle	Truck returns to starting point, concentrates are unloaded and refill of the tank to full capacity and battery charge to 100% is considered to start next cycle

7 Economic Analysis

The economic analysis to compare diesel and hydrogen propulsion systems will be based on a Total Cost of Ownership (TCO) analysis to evaluate all the costs associated with the use of the vehicles throughout the investment scenario, or rather, the period of use of each vehicle and compare scenarios for each of the selected routes.

Considering the above, two different scenarios have been selected as a comparison criteria to evaluate the implementation for each of the routes, being the first scenario with a starting year in 2025 and the second in 2035. Thus, the difference in the starting year will allow to identify the effect of cost projections of both technologies within the total cost of implementation.

7.1 Economic Parameters

In this analysis the main parameters considered in the total cost are from the vehicle acquisition, fuel type and quantity, driver, CO_2 taxes, truck maintenance, insurance, permits and licenses. Common parameters used in the study can be seen in Table 19.

Table 19. Scenarios shared parameters

Parameter	Value	Unit	Reference
Year of reference	2021	Year	Actual year
Start year scenario 1	2025	Year	Assumed
Start year scenario 2	2035	Year	Assumed
Length of truck implementation	7	Years	(Subsecretaria de Transporte, 2020)
Inflation	5.7	%	(Banco Central, 2021)
WACC	6.05	%	(PwC eValuation Data, 2021)

A length of 7 years for the implementation for both scenarios is considered, based on mean truck lifetime for mining operations, and a value of 5.7% inflation is considered based on recent end year forecast of the Central Bank, finally, WACC is considered as the last mean value for the transportation and logistics sector registered from October 2021.

7.1.1 Capital Expenditures

The main capital expenditures of this study are centered in the vehicle acquisition costs and fuel cell stack replacements. For the Diesel scenario a constant Diesel truck cost will be considered based on references and technology stagnation, as for the H2 truck, considering Hydrogen trucks being a technology in development, truck acquisition costs will be estimated based on components cost of the “Techno-economic assessment of a hydrogen fuel-cell tractor semi-trailer” (Oostdam, 2019). The values considered on the study are shown in Table 20.

Table 20. Truck acquisition costs.

Parameter	Value (2019)	Unit	Reference
Fuel Cell system cost	2,530	USD/kW	(Oostdam, 2019)
Hydrogen tank cost	1,150	USD/kg	(Oostdam, 2019)
Battery system cost	322	USD/kWh	(Oostdam, 2019)
Electric motor + inverter	20.7	USD/kW	(Oostdam, 2019)
DC/DC converter	20,000	USD	(Oostdam, 2019)
Tractor	135,000	USD	(Oostdam, 2019)
Heavy duty H2 truck cost reduction to 2030	50	%	(Hydrogen Council, 2020)

To estimate H2 truck costs for 2025 and 2035 scenarios, reference values of Table 20 are used, and for the projections, the reduction cost of heavy duty trucks from “Path to Hydrogen Competitiveness” (Hydrogen Council, 2020) is considered for the year 2030, thus 2025 and 2035 costs are interpolated and extrapolated linearly, up to 2035, from which the H2 truck cost is considered constant. Used parameters for both scenarios are shown in Table 21.

Table 21. Truck values for comparison

Parameter	Scenario 1 (2025)	Scenario 2 (2035)	Unit	Reference
Diesel truck	117,430	117,430	USD	(Statista, 2021)
FCET 8 truck	431,195	161,698	USD	(Oostdam, 2019) (Hydrogen Council, 2020)
HYMAX-450	665,160	249,435	USD	(Oostdam, 2019) (Hydrogen Council, 2020)

As for the FC stack replacement, after a certain amount of transport hours per FC design, a replacement is needed in order to avoid FC degradations higher than 10% in voltage output, for that the stack cost and lifetime considered are shown in Table 22.

Table 22. Fuel Cell Stack replacement cost and lifetime.

Parameter	Value	Unit	Reference
FC PEM Stack cost	395	USD/kW	(Berkeley, University of California, 2014)
PEM FC Design Lifetime target	25,000	h	(Nikola Motor Company, 2020)

7.1.2 Operational Expenditures

The operational expenditures are the sum of the cost necessary to keep an asset, business or system working, and in this case, the transport by truck trailer for mining operations. For this study this cost will be considered, calculated and/or estimated annually, thus , used values can be seen in Table 23

Table 23. Operational parameters for the study

Parameter	Scenario 1 (2025)	Scenario 2 (2035)	Unit	Reference
Diesel fuel costs	0.972	1.103	USD/l	(Ministerio de Energía, 2020)
Green H2 production cost in Chile	2	1.1	USD/kg	(Ministerio de Energía, n.d.)
Extra H2 cost for trucking	157.7	151.1	% Of Production cost	(Hydrogen Council, 2020)
Total H2 cost for trucking	3.14	1.66	USD/kg	-
Driver cost	70,800	70,800	USD/year	(Oostdam, 2019) (Westport Fuel Systems, 2021)
H2 Truck maintenance cost	11,800	11,800	USD/year	(Oostdam, 2019)
Diesel Truck maintenance cost	15,000	15,000	USD/year	(International Used Truck Centers, n.d.)
Insurance, permits, licenses and tolls	6,500	6,500	USD/year	(International Used Truck Centers, n.d.)
CO_2 Taxes	5	5	USD/tonCO_2	(Precio al Carbono Chile, 2017)

Regarding the previous values, Diesel costs and projections up to 2050 are from the “Long-term Energy Planning” (or “PELP” in Spanish) data base from 2020, while for the H2, a base production cost is considered with values from the “National Green Hydrogen Strategy” (Ministerio de Energía, n.d.), while an extra percentual value is considered for H2 conditioning for trucking based on the “Path to Hydrogen Competitiveness” (Hydrogen Council, 2020).

Driver cost will be considered constant and the same for both technologies, truck maintenances costs will also be considered constant throughout both evaluations periods, with lower maintenance cost for the H2 truck because the powertrain has fewer moving parts.

Insurance, permits, licenses and tolls will be considered all together for both technologies throughout both evaluation periods and a 5 USD/tonCO_2 value will be considered for the CO_2 emissions in the Diesel truck case.

8 Results Analysis

8.1 Truck Cycle Results

Based on the cycle analysis, the proposed calculation criteria allow to estimate all truck cycle data from Table 24, allowing to estimate a certain amount of cycles per year for each truck on each route.

Table 24.Calculated results for each route, comparison between truck models New Actros 2645 and Hyzon FCET 8

Route	**1**				**2**				**3**			
From->To	Start	Return	Start	Return	Start	Return	Start	Return	Start	Return	Start	Return
Fuel	Diesel [l]		H2 [kg]		Diesel [l]		H2 [kg]		Diesel [l]		H2 [kg]	
Truck	New Actros 2645		FCET 8		New Actros 2645		FCET 8		New Actros 2645		FCET 8	
On Cycle Total Fuel Consumption	525.6		98.3		298.2		61.9		176.9		49.4	
Cycle Time (IC_t) [h]	13.7		16.4		7.9		10.3		6.7		8.2	
Total Distance [km]	1,022.0		1,022.0		386.0		386.0		466.0		466.0	
Total Transported Material [kg]	28,000.0		28,000.0		28,000.0		28,000.0		28,000.0		28,000.0	
Energy Consumption [kWh]	1,016.9	540.6	944.8	441.8	739.0	144.6	751.4	129.7	221.6	302.7	195.8	260.0
Total Energy Consumption (E_t) [kWh]	1,557.5		1,386.6		883.6		881.1		524.2		455.8	
Fuel tank end state [%]	48%	72%	10%	26%	62%	93%	36%	60%	89%	85%	53%	64%
Batt End of Cycle (SoC) [%]	-	-	95%	100%	-	-	81%	100%	-	-	100%	100%
Tot Load + Unload (L_t+U_t) [h]	7.0		7.0		7.0		7.0		7.0		7.0	
Rest Time (R_t) [h]	2.80	2.40	3.20	2.80	1.60	0.80	2.40	1.20	1.20	0.80	1.60	1.20
Batt recharge time (Operation + End of cycle) B_t [h]	-	-	0.00	0.68	-	-	0.00	0.36	-	-	0.00	0.33
Extra H2 consumption for Batt Charge [kg]	-	-	0.00	4.09	-	-	0.00	2.18	-	-	0.00	1.97
Fuel Consumption per Cycle (Q_{H2} or Q_{Diesel})	525.6		102.4		298.2		64.1		176.9		51.3	
Refuel Time [h]	0.08		0.24		0.04		0.15		0.03		0.12	
Total cycle time (TC_t) [h]	25.9		29.6		17.3		21.1		15.7		18.1	
CO_2 Emissions [kg]	905.91	481.63	0.00	0.00	658.34	128.83	0.00	0.00	197.39	269.63	0.00	0.00
Cycles per year	83.0		72.0		124.0		102.0		137.0		119.0	

For the base case of Diesel truck, routes 1, 2 and 3 estimate a total of 83, 124 and 137 cycles per truck respectively. The main differences on the number of cycles between routes is the distance and height variation.

Due to longer refueling times, general restriction in power output and maximum velocity, the first H2 truck used for comparison (FCET 8) takes longer time to make a complete operating cycle, taking 3.7 and 3.8 hours more for route 1 and 2 due to long distance for route 1 (1,022 km total) and the high-power requirement for route 2 (increased height variation). While for route 3 it only takes 2.4 hours more considering this one as the less demanding route.

FCET 8 truck cycle results are considerably lower, being 72, 102, and 119 cycles for route 1, 2 and 3, respectively, which produces a lower amount of annual total cargo delivered per truck, and the effect of this technical results for truck implementation will only affect if the truck cannot deliver the minimum annual cargo that the company demands for each specific route. Thus, in order to reach same cargo transport as Diesel, a bigger fleet size is required.

Considering the previous data, the same analysis will be done with the second H2 truck to achieve result with higher cycle autonomy and later evaluate the economic feasibility, Table 25 shows the calculated data for HYMAX-450 truck.

Table 25.Calculated results for each route, Hyzon HYMAX-450. (Self-made, 2021)

Route	**1**		**2**		**3**	
From->to	Start	Return	Start	Return	Start	Return
On Cycle Total Fuel Consumption [kgH2]	162.64		92.25		79.76	
Cycle Time (IC_t) [h]	13.54		7.68		6.64	
Total Distance [km]	1,022.00		386.00		466.00	
Total Transported Material [kg]	28,000.00		28,000.00		28,000.00	
Total Energy Consumption (E_t) [kWh]	1879.96		1032.12		667.14	
Fuel tank end state [%]	-35%	-15%	13%	45%	32%	46%
Batt End of Cycle (SoC) [%]	0.99	1.00	0.99	1.00	1.00	1.00
Tot Load + Unload (L_t+U_t) [h]	7.00		7.00		7.00	
Driver Rest Time (R_t) [h]	2.80	2.40	1.60	0.80	1.20	0.80
Batt recharge time (Operation + End of cycle) (B_t) [h]	0.00	0.67	0.00	0.32	0.00	0.32
Extra H2 consumption [kg]	0.00	8.07	0.00	3.86	0.00	3.80
Total Fuel Consumption per Cycle (Q_{H2} or Q_{Diesel})	170.70		96.11		83.56	
Refuel time fast [h]	0.40		0.22		0.19	
Total cycle time (TC_t) [h]	26.13		17.30		15.83	
CO_2 Emissions [kg]	0.00	0.00	0.00	0.00	0.00	0.00
Cycles per year	82.00		124.00		136.00	

For the HYMAX-450 truck, due to a higher battery capacity, double the FC power output, higher H2 storage and a higher maximum speed, the amount of cycles per year are much closer to the base case, being 82, 124 and 136 cycles for route 1, 2 and 3. Making this type of implementation preferably for high demand and/or long haul cycles if the annual transported cargo has high influence in the company income, being the only setback the elevated cost per truck.

It is important to consider that cycle analysis and technical analysis by themselves do not give enough information about the result of economic and logistic implementation. It does serve as a first approach into technical implementation of H2 truck for long range transport in mining sector in terms of cycle autonomy and annual efficiency.

Therefore, without knowing specific detail about minimum annual cargo to haul, it is impossible to discard technologies for each route, and the obtained values serve only as an estimation.

8.2 TCO Results

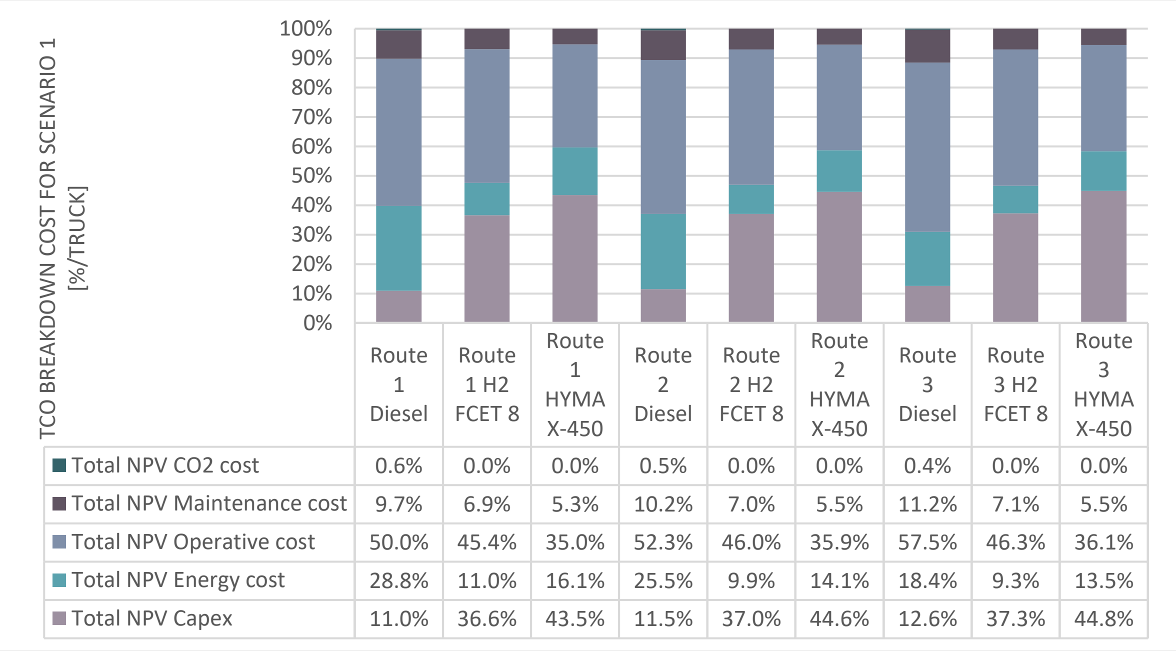
8.2.1 TCO Weight Breakdown

From the TCO calculation, a cost breakdown for both scenarios was performed in order to represent the weight of each category in the total cost of ownership, as seen from Figure 31 and Figure 32, in which the main categories for cost distribution are the CAPEX, Energy cost, Operative cost, Maintenance cost and CO_2 cost due to green taxes.

For the Diesel base case, for both scenario 1 (2025) and scenario 2 (2035), operative costs represent the higher weight in total cost for all routes, being around 50% of total cost, followed by the energy cost of Diesel fuel, truck CAPEX, maintenance costs and CO_2 taxes, being the last category less than 1% for any route on any scenario.

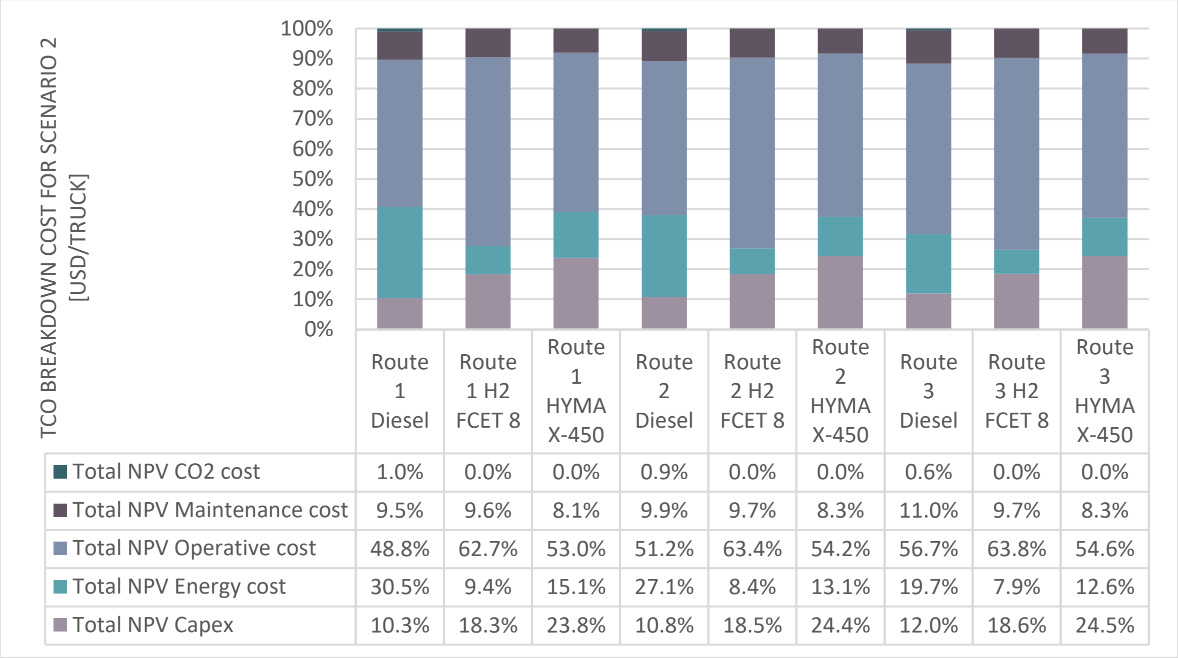
For H2 trucks, a similar behavior can be seen for each model across routes and scenarios. For scenario 1, FCET8 and HYMAX-450 differ slightly in truck CAPEX percentage when considering the total of the 7-year implementation. As expected, CAPEX has more weight for the HYMAX-450, being around 44%, followed by operative costs, energy costs and maintenance, meanwhile for the FCET 8, operative costs have higher effect being around 46% due to lower H2 truck costs, being followed directly by CAPEX, energy cost and maintenance, in that order.

Meanwhile, due to the reduction in acquisition costs of H2 Trucks to more than half the original cost, scenario 2 shows a general reduction in CAPEX for both H2 trucks, thus, the category of higher weight is the operative cost, followed by CAPEX, energy cost and maintenance in that order. As for specific values Figure 31 and Figure 32 show detail data for each category.



	Route 1 Diesel	Route 1 H2 FCET 8	Route 1 HYMAX-450	Route 2 Diesel	Route 2 H2 FCET 8	Route 2 HYMAX-450	Route 3 Diesel	Route 3 H2 FCET 8	Route 3 HYMAX-450
■ Total NPV CO2 cost	0.6%	0.0%	0.0%	0.5%	0.0%	0.0%	0.4%	0.0%	0.0%
■ Total NPV Maintenance cost	9.7%	6.9%	5.3%	10.2%	7.0%	5.5%	11.2%	7.1%	5.5%
■ Total NPV Operative cost	50.0%	45.4%	35.0%	52.3%	46.0%	35.9%	57.5%	46.3%	36.1%
■ Total NPV Energy cost	28.8%	11.0%	16.1%	25.5%	9.9%	14.1%	18.4%	9.3%	13.5%
■ Total NPV Capex	11.0%	36.6%	43.5%	11.5%	37.0%	44.6%	12.6%	37.3%	44.8%

Figure 31. TCO breakdown of scenario 1 (2025) by percentage. (Self-made, 2021)

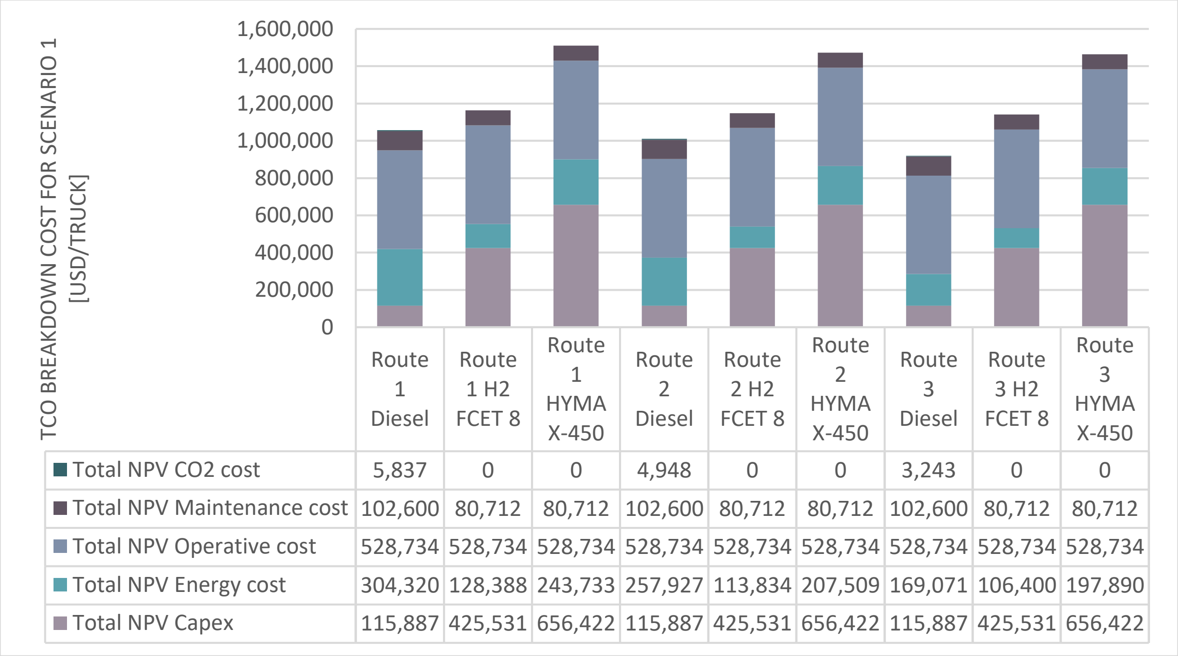


	Route 1 Diesel	Route 1 H2 FCET 8	Route 1 HYMA X-450	Route 2 Diesel	Route 2 H2 FCET 8	Route 2 HYMA X-450	Route 3 Diesel	Route 3 H2 FCET 8	Route 3 HYMA X-450
■ Total NPV CO2 cost	1.0%	0.0%	0.0%	0.9%	0.0%	0.0%	0.6%	0.0%	0.0%
■ Total NPV Maintenance cost	9.5%	9.6%	8.1%	9.9%	9.7%	8.3%	11.0%	9.7%	8.3%
■ Total NPV Operative cost	48.8%	62.7%	53.0%	51.2%	63.4%	54.2%	56.7%	63.8%	54.6%
■ Total NPV Energy cost	30.5%	9.4%	15.1%	27.1%	8.4%	13.1%	19.7%	7.9%	12.6%
■ Total NPV Capex	10.3%	18.3%	23.8%	10.8%	18.5%	24.4%	12.0%	18.6%	24.5%

Figure 32. TCO breakdown of scenario 2 (2035) by percentage. (Self-made, 2021)

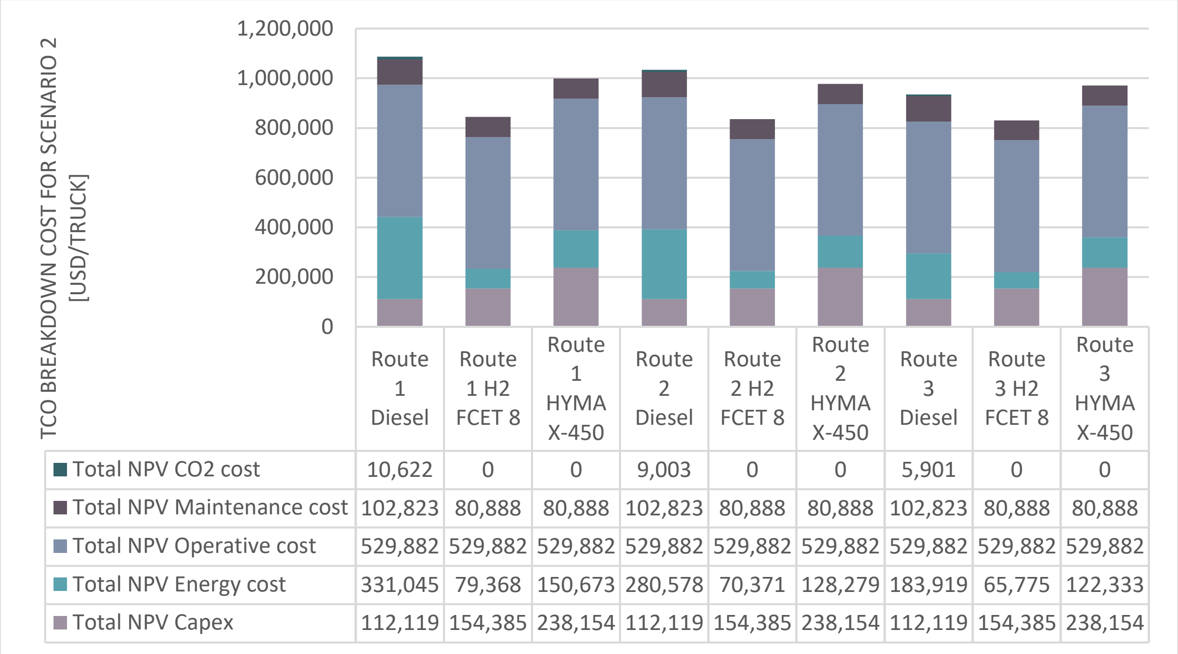
8.2.2 Results for TCO Breakdown, Base KPI [USD]

Figure 33 and Figure 34 show the total cost of ownership for a 7-year truck implementation for each case and scenario. Due to high technology costs and fuel costs, H2 trucks are not feasible on a near future as shown from scenario 1.



	Route 1 Diesel	Route 1 H2 FCET 8	Route 1 HYMA X-450	Route 2 Diesel	Route 2 H2 FCET 8	Route 2 HYMA X-450	Route 3 Diesel	Route 3 H2 FCET 8	Route 3 HYMA X-450
■ Total NPV CO2 cost	5,837	0	0	4,948	0	0	3,243	0	0
■ Total NPV Maintenance cost	102,600	80,712	80,712	102,600	80,712	80,712	102,600	80,712	80,712
■ Total NPV Operative cost	528,734	528,734	528,734	528,734	528,734	528,734	528,734	528,734	528,734
■ Total NPV Energy cost	304,320	128,388	243,733	257,927	113,834	207,509	169,071	106,400	197,890
■ Total NPV Capex	115,887	425,531	656,422	115,887	425,531	656,422	115,887	425,531	656,422

Figure 33. TCO Breakdown in [USD], Scenario 1 (2025) (Self-made, 2021)



	Route 1 Diesel	Route 1 H2 FCET 8	Route 1 HYMA X-450	Route 2 Diesel	Route 2 H2 FCET 8	Route 2 HYMA X-450	Route 3 Diesel	Route 3 H2 FCET 8	Route 3 HYMA X-450
■ Total NPV CO2 cost	10,622	0	0	9,003	0	0	5,901	0	0
■ Total NPV Maintenance cost	102,823	80,888	80,888	102,823	80,888	80,888	102,823	80,888	80,888
■ Total NPV Operative cost	529,882	529,882	529,882	529,882	529,882	529,882	529,882	529,882	529,882
■ Total NPV Energy cost	331,045	79,368	150,673	280,578	70,371	128,279	183,919	65,775	122,333
■ Total NPV Capex	112,119	154,385	238,154	112,119	154,385	238,154	112,119	154,385	238,154

Figure 34.TCO Breakdown in [USD], Scenario 2 (2035) (Self-made, 2021)

On the other hand, due to technology cost projections for H2 trucks of more than a 50% drop in cost for truck acquisition in a 10-year range, and highly competitive prices for green H2, scenario 2 presents a cost competitive situation. Both H2 trucks achieve lower costs compared to the Diesel case, except for route 3 for the HYMAX-450, meaning this truck is still too expensive for a route not as demanding as route 1 and 2, and the slightly effect of a higher CO_2 tax could make this truck a feasible option.

When comparing scenario 1 v/s 2 directly, the FCET 8 truck shows a total implementation cost reduction of around 27% for the 3 routes, the HYMAX-450 shows a total implementation cost reduction of 33.7% for the 3 routes, while Diesel truck has an increase in total cost of 2.8%, 2.4% and 1.6% for routes 1, 2 and 3 respectively due to Diesel fuel projections.

8.2.3 Results for TCO Breakdown, [USD/km] KPI

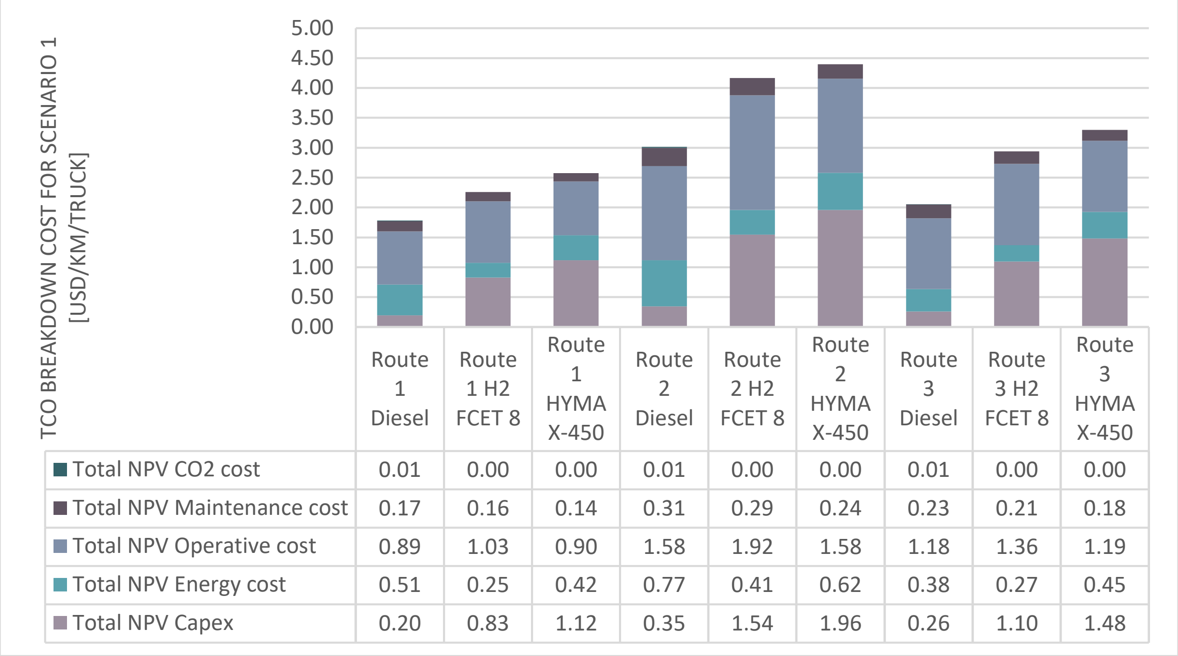
Based on previous data, the main key performance indicators (KPI) used in the transport sector, and of interest for this analysis, is the cost per km of transport [USD/km] for each truck on each route.

If only USD is considered, it is clear that the HYMAX-450, by being more expensive, could not be a feasible option compared to the FCET 8, as seen in from Figure 33 and Figure 34, but, since the range difference between this 2 H2 trucks is broad, lower comparative cost can be achieved by the HYMAX-450 on certain routes where a higher demand is required.

Thus, Figure 35 and Figure 36 show the cost breakdown for each truck, and scenarios. Results from scenario 1 show the same behavior as previous comparisons, being scenario 1 still too close to allow enough cost reduction for H2 technologies to achieve cost competitive prices.

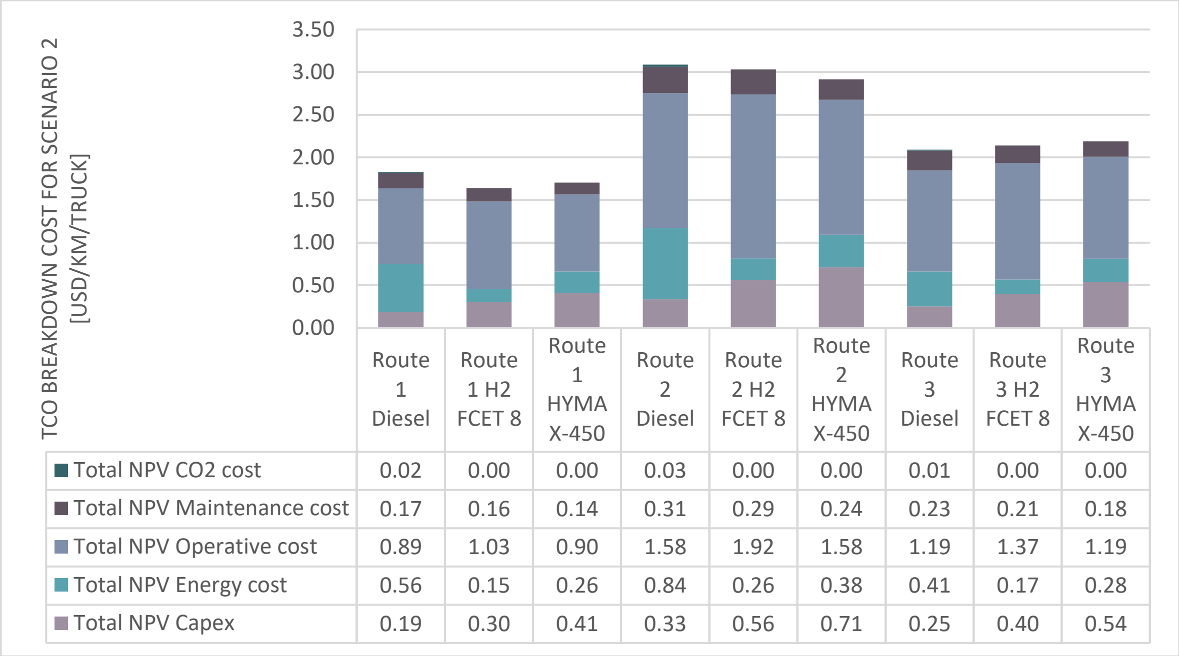
Meanwhile, scenario 2 show different results for each route. For route 1, both H2 trucks show lower cost per km than the Diesel case, being the FCET 8 slightly lower than the HYMAX-450, because this route does not require a high-power demand, but only on a high travel distance demand. As for route 2, HYMAX-450 is much cost competitive against the Diesel and the FCET 8 due to the high requirement of power demands of this route due to elevated road inclination across the route.

Lastly, route 3, even though it showed lower costs for the FCET 8 truck, its cost efficiency per-km is not enough, and Diesel technologies are still a cheaper option for routes not as demanding as route 1 and 2 up to year 2035. As mentioned before, a slight increase in CO_2 taxes or price variation of another factor could be enough to achieve cost competitiveness.



	Route 1 Diesel	Route 1 H2 FCET 8	Route 1 HYMAX-450	Route 2 Diesel	Route 2 H2 FCET 8	Route 2 HYMAX-450	Route 3 Diesel	Route 3 H2 FCET 8	Route 3 HYMAX-450
■ Total NPV CO2 cost	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
■ Total NPV Maintenance cost	0.17	0.16	0.14	0.31	0.29	0.24	0.23	0.21	0.18
■ Total NPV Operative cost	0.89	1.03	0.90	1.58	1.92	1.58	1.18	1.36	1.19
■ Total NPV Energy cost	0.51	0.25	0.42	0.77	0.41	0.62	0.38	0.27	0.45
■ Total NPV Capex	0.20	0.83	1.12	0.35	1.54	1.96	0.26	1.10	1.48

Figure 35. TCO Breakdown in [USD/km] for the 3 routes, for the 3 trucks, Scenario 1 (2025) (Self-made, 2021)



	Route 1 Diesel	Route 1 H2 FCET 8	Route 1 HYMA X-450	Route 2 Diesel	Route 2 H2 FCET 8	Route 2 HYMA X-450	Route 3 Diesel	Route 3 H2 FCET 8	Route 3 HYMA X-450
■ Total NPV CO2 cost	0.02	0.00	0.00	0.03	0.00	0.00	0.01	0.00	0.00
■ Total NPV Maintenance cost	0.17	0.16	0.14	0.31	0.29	0.24	0.23	0.21	0.18
■ Total NPV Operative cost	0.89	1.03	0.90	1.58	1.92	1.58	1.19	1.37	1.19
■ Total NPV Energy cost	0.56	0.15	0.26	0.84	0.26	0.38	0.41	0.17	0.28
■ Total NPV Capex	0.19	0.30	0.41	0.33	0.56	0.71	0.25	0.40	0.54

Figure 36. TCO Breakdown in [USD/km] for the 3 routes, for the 3 trucks, Scenario 2 (2035) (Self-made, 2021)

8.3 Implementation Year of H2 Technologies

The previous results allow to estimate if it is feasible to implement each truck on every scenario. It is also relevant to estimate "when" an implementation is possible, so, using both scenarios it is possible to evaluate and estimate the breakeven between technologies while also applying the effect of sensibility on certain parameters that could affect the implementation or have greater weight in the total cost.

Considering this, a pessimistic (P) and optimistic (O) cases for H2 truck implementation were considered for both scenarios and the variable parameters to study, based on previous results, the selected parameters to study independently are the CAPEX of H2 trucks, with a ± 20% cost and CO_2 green taxes with a variation of 0 to 100 [USD/tCO_2], Table 26 summarizes the proposed cases.

Table 26. Selected parameters and values for the analysis.

Case of study	**Parameter to analyze**	
	CAPEX	CO2 Taxes
Pessimistic	+20 %	0 USD/tCO2
Standard	+0 %	5 USD/tCO2
Optimistic	-20 %	100 USD/tCO2

8.3.1 H2 Truck Cost Variation

As previously stated, a ± 20% CAPEX variation analysis was considered to stablish a year for technology implementation. Based on this, Figure 37, Figure 38, Figure 39, Figure 40, Figure 41 and Figure 42 show the cost projections of the TCO for every case.

Starting with route 1, FOR FCET 8 H2 truck (Figure 37) THE implementation becomes feasible around 2032, setting the optimistic and pessimistic case for half of 2030 and 2033. as for HYMAX-450 (Figure 38) implementation competitiveness comes later half 2033, while the optimistic and pessimistic being half 2022 and half 2034.

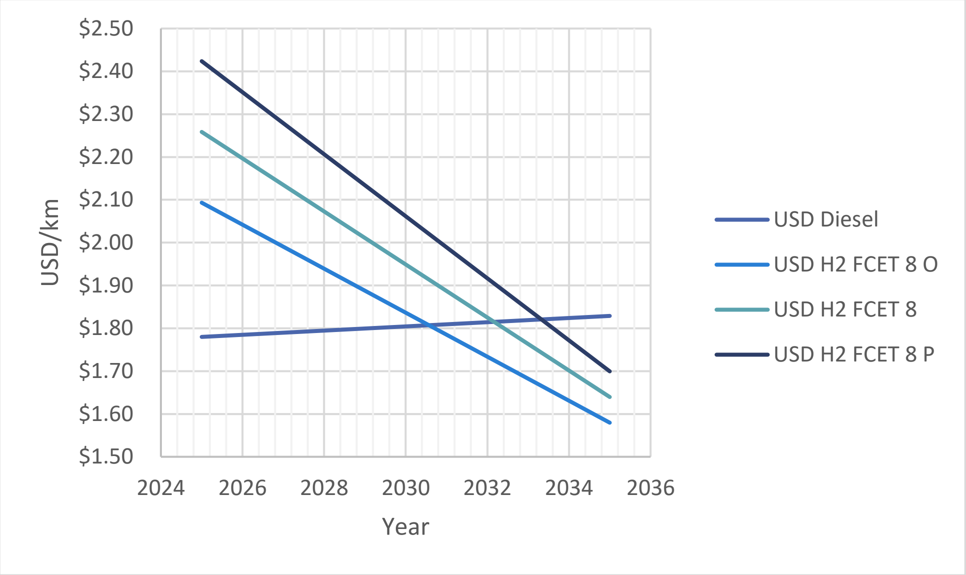


Figure 37.TCO projections for route 1 ,FCET 8 H2 truck CAPEX variation [USD/km] (Self made, 2021)

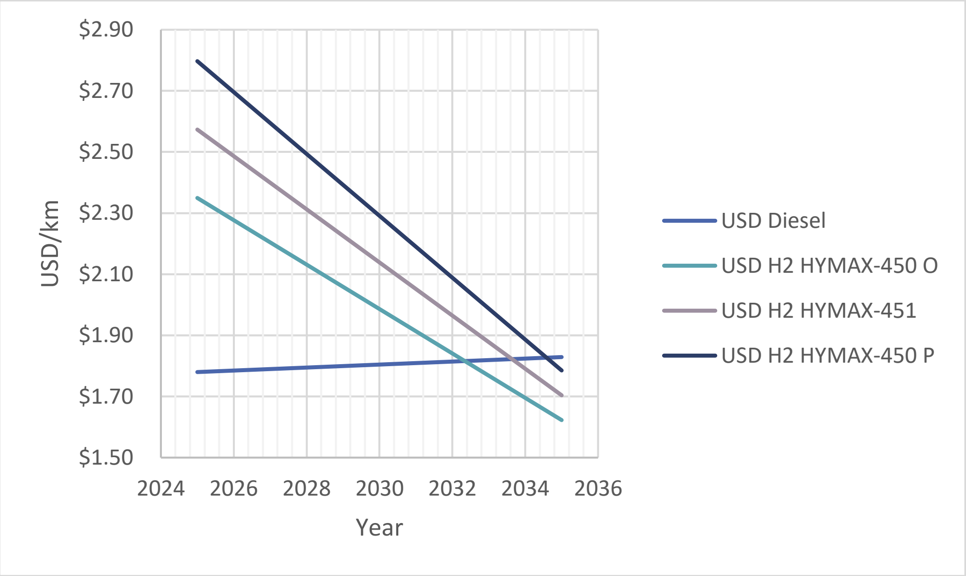


Figure 38. TCO projections for route 1,hymax-450 H2 truck CAPEX variation [USD/km]

For route 2, implementation of FCET 8 truck (Figure 39) becomes feasible in the standard case around half 2034, setting the optimistic and pessimistic cases as 2033 and roughly 2035 respectively. For the HYMAX-450 truck (Figure 40), feasibility comes slightly before than FCET 8 at ends of 2033, being half of 2032 and end of 2034 the optimistic and pessimistic cases.

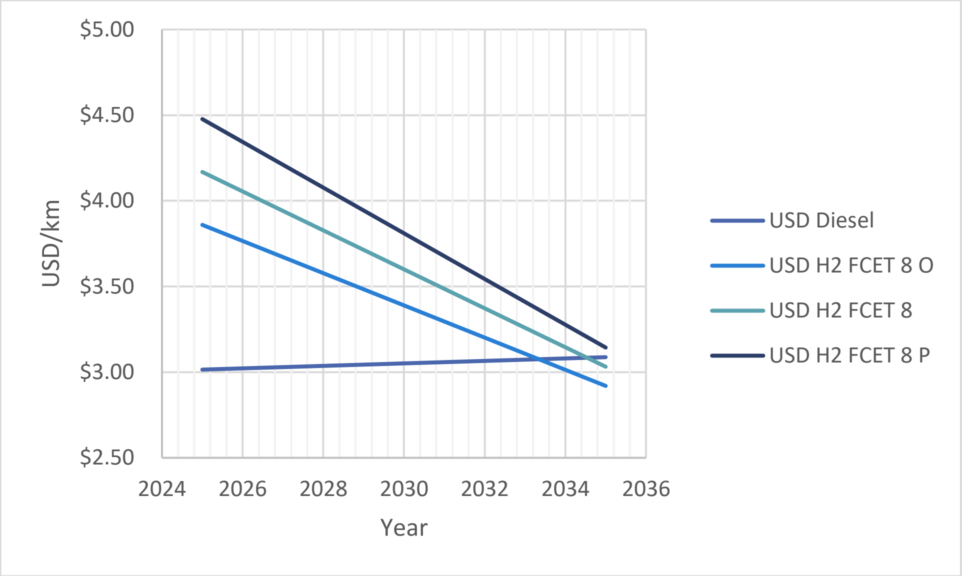


Figure 39. TCO projections for route 2, FCET 8 H2 truck CAPEX variation [USD/km]. (Self-made, 2021)

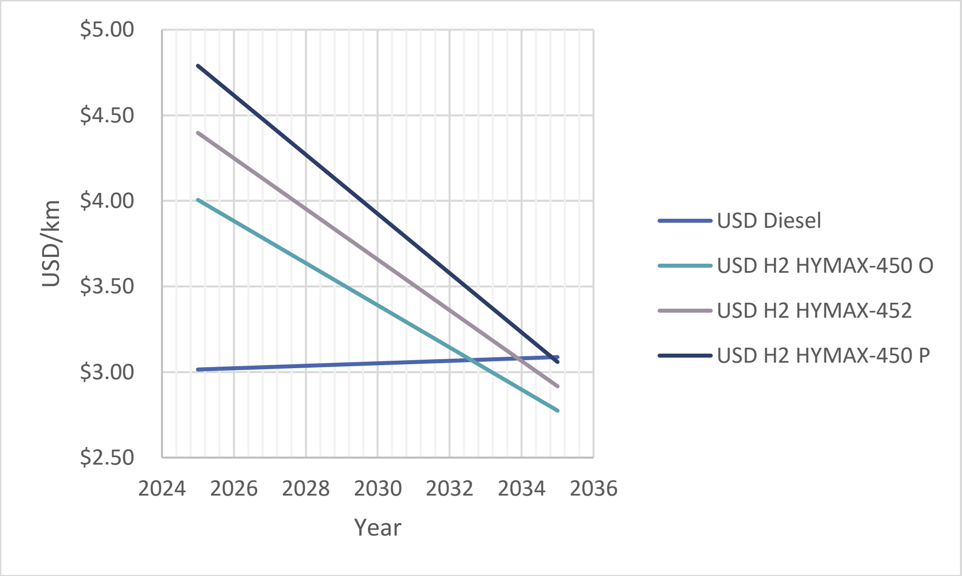


Figure 40.TCO projections for route 2, HYMAX-450 H2 truck CAPEX variation [USD/km] (Self-made, 2021)

For route 3, as previously stated, the H2 trucks do not become feasible for the standard case between 2025 and 2035. Through a lineal extrapolation, FCET 8 truck (Figure 41) becomes feasible around half 2035, while the optimistic and pessimistic cases set a range from half 2034 to half 2036, and for the HYMAX-450 truck (Figure 42), standard implementation comes around 2036, while 2035 and half 2036 are the range limits for optimistic and pessimistic, setting the FCET 8 truck as the cheapest technology between these 2 trucks for this route.

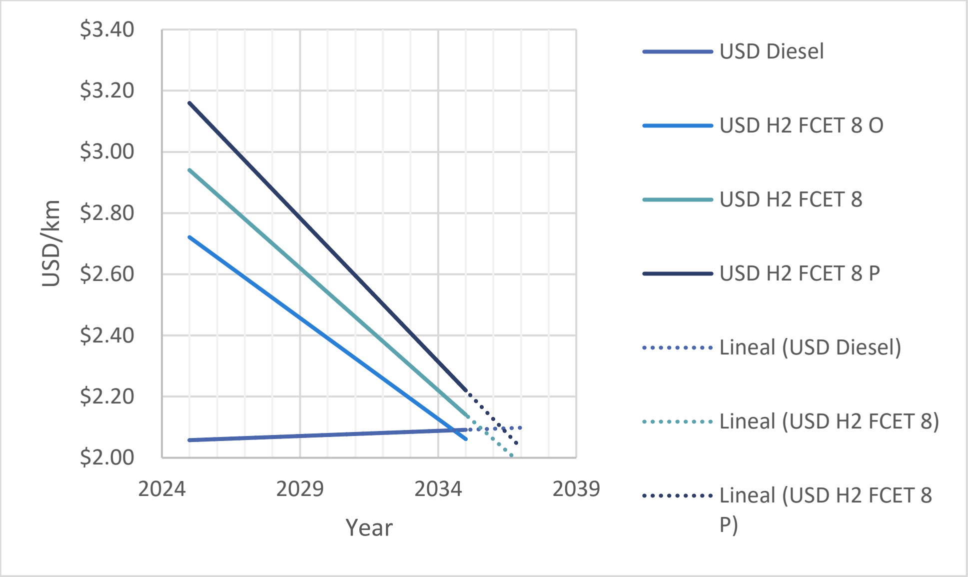


Figure 41. TCO projections for route 3, FCET 8 H2 truck CAPEX variation [USD/km] (Self made, 2021)

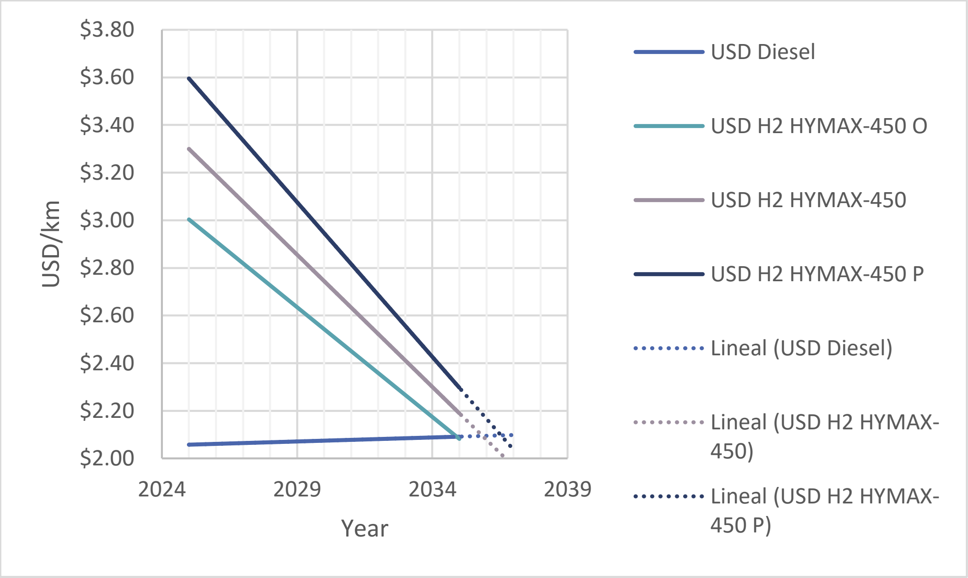


Figure 42.TCO projections for route 3, HYMAX-450 H2 truck CAPEX variation [USD/km] (Self made, 2021)

8.3.2 Green Tax Variation on CO_2 Emissions.

Considering the effect of the green tax on Diesel trucks, an optimistic and pessimistic case of 100 to 0 [USD/tCO_2] is defined to evaluate the effect on the implementation year. Figure 43, Figure 44 and Figure 45 show the calculated results. In this case, the original case of 5 [USD/tCO_2] is not plotted since this graph is slightly above the pessimistic case and is already shown in previous results. For route 1, the effect of a 100 [USD/tCO_2] accelerates de development of H2 market, making the FCET 8 implementation 4 years faster and around 3 years for HYMAX-450, setting the implementation years to half 2028 and half 2031 respectively.

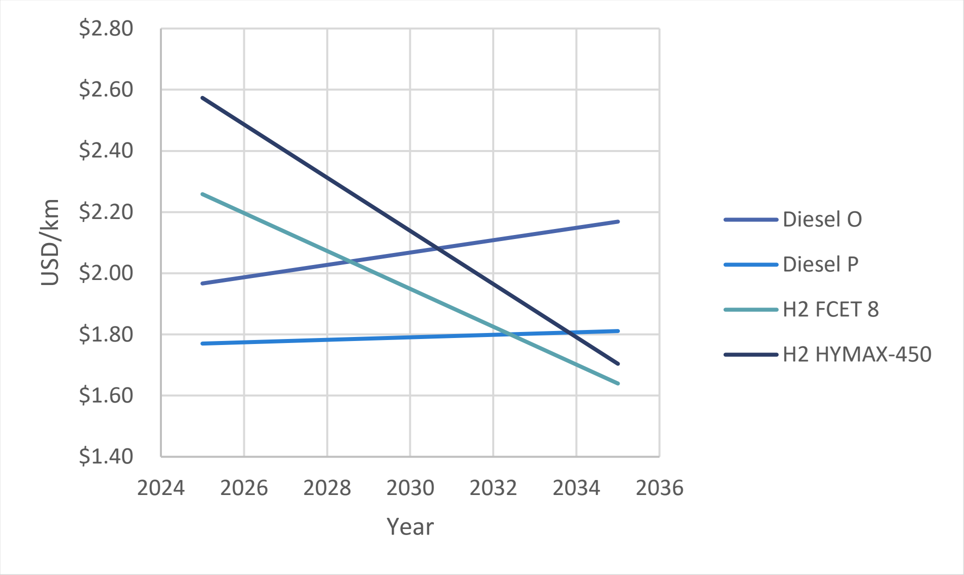


Figure 43. TCO projections for route 1, 0 to 100 variation [USD/tCO$_2$] tax. (Self-made, 2021)

Route 2 results are slightly interesting compared to the other routes, because a breakeven between both H2 trucks occur at mid-2033, previous this year, if Diesel truck cost is higher the FCET 8 truck is preferable than HYMAX-450, while after mid-2033, HYMAX-450 is preferable, mainly due to the cost balance between truck costs and cycle efficiencies.

As for the tax, a similar acceleration of 4 and 3 years can be obtained for the FCET 8 and HYMAX-450 respectively.

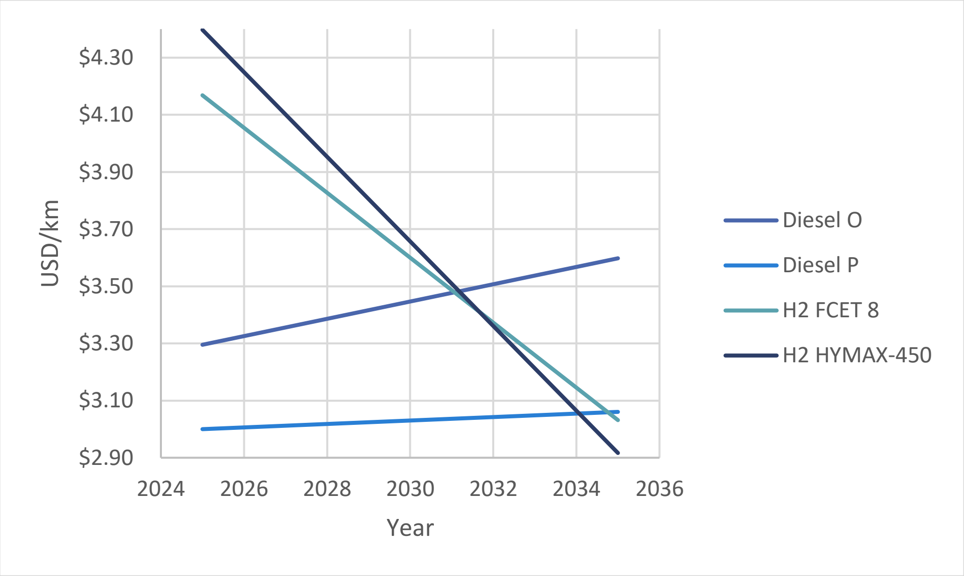


Figure 44. TCO projections for route 2, 0 to 100 variation [USD/tCO$_2$] tax. (Self-made, 2021)

In the case of route 3, implementation year accelerates 3 and 2 years for FCET 8 and HYMAX-450, making the feasibility in this case, in between scenario 1 and scenario 2 as the other routes.

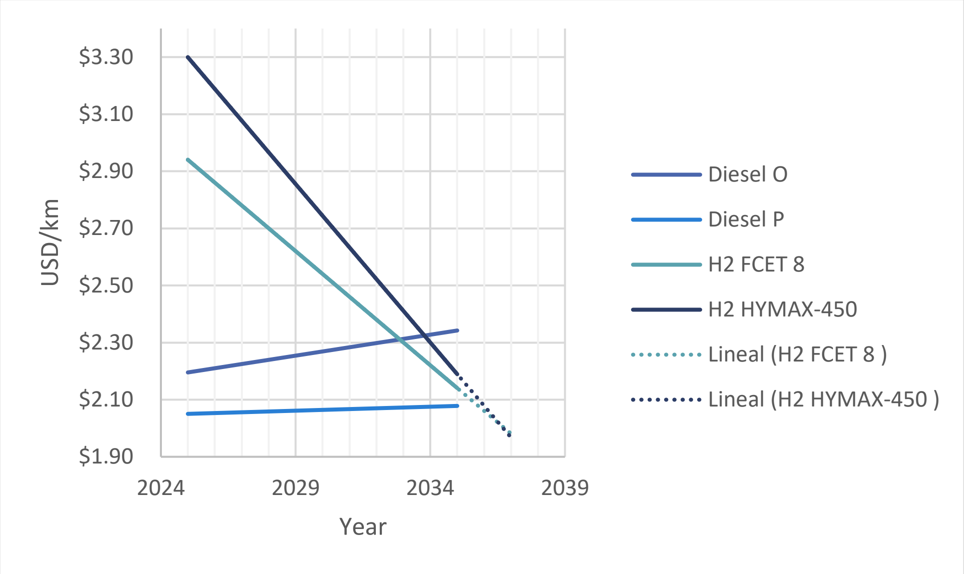


Figure 45. TCO projections for route 3, 0 to 100 variation [USD/tCO$_2$] tax. (Self-made, 2021)

8.4 Energy consumption, Annual Transport Parameters and CO_2 Reduction Potential

Based on the technical analysis results, the energy consumption is calculated for each route and truck, allowing to estimate the annual amount of fuel consumption, and estimate CO_2 emission. It is also possible to obtain the annual transport parameters, based on the amount of cycles a truck can achieve.

Table 27 show the comparison between Diesel base case and FCET 8 for the 3 routes of interest, while Table 28 has the same data for the HYMAX-450.

Table 27. Annual results for transport per truck, comparison between truck models New Actros 2645 and Hyzon FCET 8.

Route	**1**		**2**		**3**	
Fuel	Diesel [l]	H2 [kg]	Diesel [l]	H2 [kg]	Diesel [l]	H2 [kg]
Truck	New Actros 2645	FCET 8	New Actros 2645	FCET 8	New Actros 2645	FCET 8
Total fuel [l/ year] or [kgH2/year]	43,623.36	7,475.69	36,973.08	6,601.54	24,235.84	6,110.53
Total transport [ton/ year]	2,324.00	2,044.00	3,472.00	2,884.00	3,836.00	3,332.00
Total distance [km/year]	84,865.84	74,606.00	47,864.00	39,758.00	63,842.00	55,454.00
Total energy [MWh/ year]	129.27	101.22	109.57	90.75	71.82	54.24
Total CO_2 [tCO_2/ year]	115.17	0.00	97.61	0.00	63.98	0.00

Table 28.. Annual results for transport Hyzon HYMAX-450. (Self-made, 2021)

Route	**1**	**2**	**3**
Total transport [ton/ year]	2296	3472	3808
Total fuel [kgH2/year]	13997.52	11917.14	11364.74
Total distance [km/year]	83804	47864	63376
Total energy [MWh/year]	154.1567	127.9828	90.73156
Total CO_2 [tCO_2/ year]	0	0	0

Considering these results, the total annual energy for each routes show that:

- Route 1 has the higher energy demand per route, considering that this one is more than double the length in [km] of the other 2 routes.
- Route 2 has the higher energy demand per km due to the height variation and power demand.
- Route 3 has the least energy consumption, for every truck because is the less demanding route.

In terms of fuel demand, H2 trucks allow to estimate a reference value for fuel consumption, considering ranges of around 7,500 to 14,000 [kgH2/year/truck] for route 1, 6,600 to 12,000 [kgH2/year/truck] for route 2 and 6,200 to 11,400 [kgH2/year/truck] for route 3.

It is important to mention that this calculation considers ranges of consumption for these estimates, because the energy and power consumption model used does not consider an energy management optimization model, so values should be taken as a reference and not as facts.

As for GHG emissions, Diesel truck emits 115.17 [tCO_2/year/truck], 97.61 [tCO_2/year/truck] and 63.98 [tCO_2/year/truck] for route 1, 2 and 3 respectively, which individually are small number compared to the total CO_2 emission of the land transport sector, but by the replacement of a complete truck fleet for different application, H2 technologies could help considerably in the decarbonization of the transport sector.

8.5 Necessary Infrastructure

As previously calculated, fuel consumption per route was estimated for each H2 truck, thus, giving an approximate value of minimum H2 capacity per truck a refuel station must satisfy.

This, with an addition on the state of charge for each H2 tank across each route, can allow to pinpoint areas of interest where a H2 refuel station is needed to implement H2 long range trucks for mining applications.

Since calculation criteria considers refueling near unloading point and near the starting point, the need of infrastructure is already considered around those points. Now, it is necessary to evaluate size of the refuel station and the need of an additional on-route station. Based on that, Table 29, Table 30 and Table 31 summarizes fuel consumption in detail for route 1, 2 and 3 so that a detailed analysis for H2 technologies can be performed.

For route 1, Table 29 shows that H2 consumption per truck is higher from Iquique to Altonorte due to cargo effect in power consumption, this identifies the need of a higher demand of H2 near Altonorte, of around a 10% higher than Iquique H2 demand. While considering fuel tank state, FCET 8 truck has no need to refuel during transport since the end states are 10% and 26% full at Altonorte and Iquique, On the other hand, HYMAX-450 consumes more H2 leaving negative values of tank state, meaning that a refueling station is needed on route, since the demand is higher than the actual capacity of H2 of the truck.

Considering this, a rough approximation allows to estimate that a H2 refuel station is required at 2/3 of the way from Iquique to Altonorte, thus, refuel on route is possible to reach the metallurgical complex and the needed refuel on the way back.

Table 29. Fuel consumption and fuel tank state summary for route 1. (Self-made, 2021)

Route	**1**					
From->To	Start	Return	Start	Return	Start	Return
Fuel	Diesel [l]		H2 [kg]		H2 [kg]	
Truck	New Actros 2645		FCET 8		HYMAX-450	
Fuel tank end state [%]	48%	72%	10%	26%	-35%	-15 %
Total Fuel Consumption	343.1	182.4	53.8	48.6	87.8	78.7
Total Fuel Consumption per Cycle	525.6 [l]		102.4 [kg]		170.7 [kg]	

Table 30 results for route 2 shows that, even though it is considered the route with higher power demand, due to been relatively short compared to route 1, a refuel station in between start and end point is not required. Fuel tank end state for both H2 trucks are higher than 13% for each case, meaning H2 refuel station near start and drop point is enough to cover this route .

In terms of size, Collahuasi refuel station has a higher demand of H2 due the effect of the positive incline to reach the heigh of the mine site and needs to supply around a 50% more H2 than the Pozo Almonte refuel station.

Table 30. Fuel consumption and fuel tank state summary for route 1. (Self-made, 2021)

Route	**2**					
From->To	Start	Return	Start	Return	Start	Return
Fuel	Diesel [l]		H2 [kg]		H2 [kg]	
Truck	New Actros 2645		FCET 8		HYMAX-450	
Fuel tank end state [%]	62%	93%	36%	60%	13%	45%
Total Fuel Consumption	249.4	48.8	38.1	26.0	56.5	39.6
Total Fuel Consumption per Cycle	298.2 [l]		64.1 [kg]		96.1 [kg]	

For route 3, Table 31 shows a similar behavior to route 2, in terms of refuel needs, H2 demand is the lowest of the3 routes and fuel tank end states are the highest, meaning that H2 infrastructure is only needed near start and drop point.

Meanwhile, sizing of H2 refuel station is the lowest of all 3 routes, and H2 demands are relatively similar for both sides, meaning H2 demands can be considered for both cases similar and the station demands the same.

Table 31. Fuel consumption and fuel tank state summary for route 1. (Self-made, 2021)

Route	**3**					
From->To	Start	Return	Start	Return	Start	Return
Fuel	Diesel [l]		H2 [kg]		H2 [kg]	
Truck	New Actros 2645		FCET 8		HYMAX-450	
Fuel tank end state [%]	89%	85%	53%	64%	32%	46%
Total Fuel Consumption	74.8	102.1	28.0	23.3	44.5	43.3
Total Fuel Consumption per Cycle	176.9 [l]		51.3 [kg]		83.5 [kg]	

As for the previous estimation, a set of locations is presented in Figure 46, where locations from 1 to 5 are marked as possible H2 refuel station location, being more specifically.

- Area 1: Since route 1 must go through, and is near Pozo Almonte, start point of route 2, a shared H2 refuel station could be implemented near this area, estimating around 50 to 80 [kgH2/Truck] depending on the used truck and the fleet size of each route.
- Area 2: Route 2 has the need of a refuel station near Collahuasi since HYMAX-450 is not able to make a full cycle without refuel, and FCET 8 can barely complete a cycle on a fuel tank. Thus, to prevent trucks running out of fuel during operation, a station near Collahuasi is proposed, with a demand of around 40 to 57 [kgH2/Truck] depending on the used truck and the fleet size of each route.
- Area 3: As previously stated, route 1 fuel consumption of HYMAX-450 is higher than its fuel tank capacity, and FCET 8 can barely reach Altonorte without refuel, so a station on route is needed, with a demand of around 65 [kgH2/Truck] to refuel any H2 trucks to full capacity.
- Area 4: Since route 3 is not as demanding, FCET 8 could complete a cycle without refuel at cargo drop point, meanwhile HYMAX-450 higher consumption demands at least 1 refuel apart from the start point. Thus, a station near Chuquicamata serves as a buffer on H2 demand and to prevent trucks running out of fuel, it is estimated a 24 to 44 [kgH2/Truck] depending on the used truck and the fleet size of each route.
- Area 5: Because route 1 and route 3 share a segment of the route, a shared H2 station is proposed to fuel both routes, and based on previous demand data, an amount of 54 to 88 [kgH2/Truck] is estimated to fill the high demand of trucks.

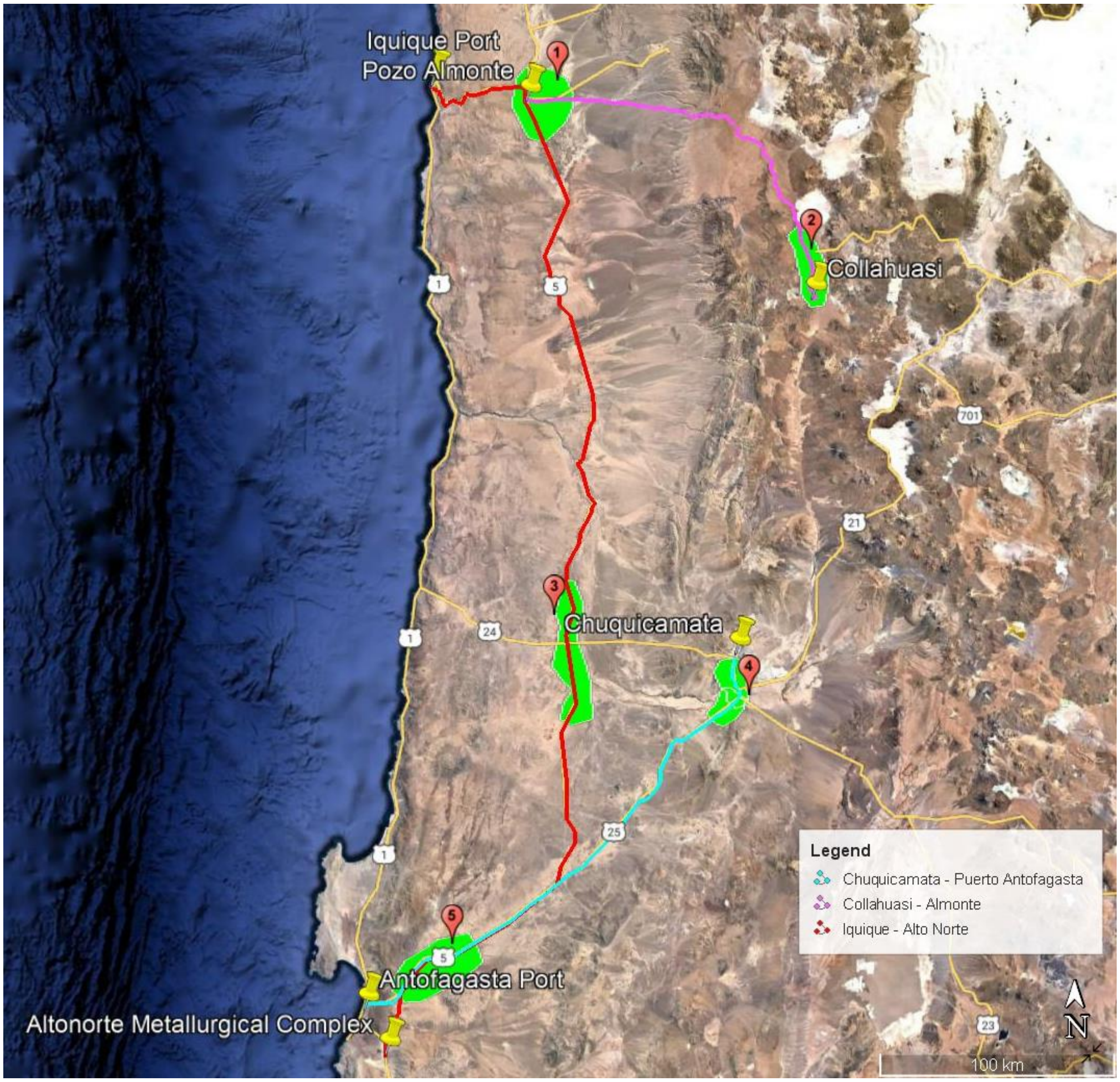


Figure 46. Reference locations for H2 infrastructure to supply H2 trucks for each route using Google Earth. (Self-made, 2021)

9 Conclusions

Based on the result analysis of the previous section the main conclusion that can be performed are as follows.

In terms of truck cycle analysis and results, in the absence of data for specific transport, telemetric data and detail routes, the proposed methodology for speed profile calculation allows to estimate all the necessary data to estimate all transport parameters for each truck and define an operating cycle for each route on each selected truck. It is important to note that these calculated parameters are estimative values, thus it is necessary for future analyses to use real transport data to achieve more precise calculations and use this study as reference for comparison.

Calculation methodology also allowed to estimate energy consumption, fuel consumptions, and estimate direct emissions of GHG, considering that real fleet size and logistic data route is not available, an estimation for this parameter were calculated for unitary values per truck in order to make the scalation of data possible. It is also important to mention that energy optimization models where not considered, meaning the calculated data might show results slightly above real behavior, so it is proposed for futures study the implementation of energy management models in H2 trucks to get better results, reduce energy costs and achieve better scenarios of H2 truck implementations.

General available information allows to estimate and project cost for Diesel and H2 technologies, and the use of a total cost of ownership gives all the necessary tools to compare technology costs for implementation, this, in addition with technical data of cycle operations, allows to evaluate complete scenarios for truck implementation and estimate the optimal type and year of implementation, based on these, the results show that.

1. In general, due to speed and low FC power output limits, the FCET 8 truck achieve less cycles of annual operation compared to Diesel truck, thus, FCET 8 is feasible for route 1 and 3, only if the required demand of transport for each truck is lower than the estimation calculated in this thesis work, for this specific truck.
2. HYMAX-450 on the other hand has higher cycle efficiency, being 1 cycle less at best on some routes, considering that, this truck is feasible for all routes only if a similar amount of cargo is strictly required to haul on each route compared to diesel, on the other hand, this truck has specifically lower costs of implementation for route 2 due to high power demands and comparatively, a better option than the FCET 8 truck.

As for the sensibility analysis, the effects of prices in certain elements can help or impede the acceleration towards carbon free transport, considering the results main observations are.

1. CAPEX for near years is extremely high for H2 trucks compared to Diesel, and even among themselves, being the HYMAX-450 almost 50% higher than the price of a FCET 8, for each route a variation of 20% in cost shows than in the best case, year of implementation could decrease from 1 to 1 and a half year, and in the worst case, delay 1 to 1 and a half years.
2. The effect of CO_2 taxes has greater effect on implementation, showing that on an optimistic scenario on 100 [USD/tCO_2], H2 implementation could accelerate up to 4 to 3 years depending on the route. But it is also important to consider that this analysis is based on an increase in Diesel cost projections, thus market competitiveness is not considered, and the effect of lower green H2 costs and CO_2 taxes could influence in a

lowering of Diesel prices, so estimated values in this thesis work should be consider as reference.

Meanwhile, TCO projections allow to estimate the year of implementation where H2 technologies become competitive against Diesel based on the assumptions proposed by the TCO model, general results show that.

1. For route 1, H2 technologies become competitive around year 2032 and 2033.
2. For route 2, H2 technologies become competitive around year 2034 and 2035.
3. For route 3, H2 technologies become competitive around year 2036.

If all optimistic cases are considered, then acceleration could reduce in up to 5 years, estimating high competitiveness near 2027 at best case considering only the factors mentioned in this thesis work.

Comparing the obtained results against estimations of the "National Green Hydrogen Strategy", estimated data obtained by this thesis work centers in the middle of the estimations made by the strategy for heavy duty trucks break even without additional H2 economy incentives for the H2 chain value, ranging from a start in 2030 to full development in 2040.

Finally, the estimation on fuel consumption and truck fuel tank states for each route allowed to roughly estimate potential zones of H2 refuel station in order to accelerate the decarbonization of the transport sector and estimating rough values for unitary H2 demand per truck.

As for this thesis work, there are a lot of factors to consider in order to make the implementation of H2 truck feasible that where not considered, and thus, proposed as future developments or separate work analyses, such as H2 energy management models, truck size optimization for specific uses, general H2 regulations for transport in Chile, H2 dedicated production plants for transport and the associated chain value, general change of infrastructure for H2 trucking, the effect of the scaling up of technologies and the developing of innovations and solutions to propel the H2 market, among others.

On the other hand, it is also proposed an improvement in acquired/used data for the calculation of speed profile and energy consumption, since this thesis work estimates this information, for future works it is recommended the use of real cycle information of heavy duty vehicles on each specific route using telemetry data, or, if not possible, the use of machine learning in order to create a set of data for the speed profile, representative to the route used and through this method, estimate power and energy consumptions and each respective cycle of operation for each truck.

Therefore, this thesis work presents the complete technical and economical analysis for the feasibility study of H2 truck implementation for long haul, on 3 selected routes for mining operation, with a complete cycle estimation and usage through different scenarios to compare Diesel technologies versus H2 technologies.

Glossary

- a: Truck Acceleration
- A_f: Frontal Area of the Truck
- B_t: Extra Time for Battery Recharge
- CAPEX: Capital Expenditures
- Cd: Truck Aerodynamic Drag Coefficient
- COP21: 21st Conference of the Parties
- CO_2: Carbon Dioxide
- CPR: Commercial, Public and Residential
- Cr: Road Surface Coefficient
- $c1$: First Rolling Resistance Constant
- $c2$: Second Rolling Resistance Constant
- E_b: Battery Capacity
- E_t: Total Energy Consumption
- FC: Fuel Cell
- FCV: Fuel Cell Vehicle
- F_D : Air Drag Force
- F_R: Rolling Friction Force
- F_S: Road Slope Resistance
- F_T: Tractive Force of the Truck
- g: Gravitational Constant
- GHG: Greenhouse Gas
- Gton: Giga ton
- GVW: Gross Vehicle Weight
- GVWR: Gross Vehicle Weight Rating
- GCWR: Gross Combined Weight Rating
- GWh: Gigawatt-hour
- h: Hours
- H_2: Hydrogen
- HDV: Heavy Duty Truck
- ICE: Internal Combustion Engine
- IC_t: Individual Cycle Time
- INE: National Institute of Statistics
- KPI: Key Performance Indicator
- kg: Kilograms
- $kgH2$: Kilograms of Hydrogen
- kJ: Kilojoule
- km: Kilometers
- kt: Kilo tons
- l: liters
- LCOH: Levelized Cost of Hydrogen
- $l_{Diesel:}$ Liters of Diesel
- LHV: Lower Heating Value
- LNG: Liquified Natural Gas

- L_t: Load Time
- m: Truck total Mass
- MJ: Megajoule
- MW: Megawatt
- m.a.s.l: Meters Above Sea Level
- NPV: Net Present Value
- OPEX: Operational Expenditures
- PELP: Long-Term Energy Planning
- PEM: Proton Exchange Membrane
- PV: Photovoltaic
- P_a: Auxiliar Power Consumption
- P_b: Battery Power
- $P_{b,reg}$: Battery System Regenerative Breaking Power
- P_{fc}: Fuel Cell Power Output
- P_m: Engine/Electric Motor Power Output
- $P_{m,max}$: Engine/Electric Motor Maximum Power Output
- P_W: Power at Truck Wheels
- P_{Wmax}: Maximum Power at Truck Wheels Restriction
- Q_{diesel}: Liters of Diesel Consumption
- Q_{H2}: Kilograms of Hydrogen Consumption
- R: Resistance Forces
- R_t: Resting Time
- s: Seconds
- SEN: National Electric System
- SoC: State of Charge
- t: Ton
- T: Fuel Tank Capacity
- TCO: Total Cost of Ownership
- TC_t: Total Cycle Time
- TJ: Terajoules
- U_t: Unload Time
- USD: United States Dollar
- v: Truck Speed
- v_{cr}: Truck Crawl Speed
- W: Watt
- WACC: Weighted Average Cost of Capital
- α: Road Inclination
- η_b: Battery System Efficiency
- η_{ice}: Internal Combustion Engine Energy Conversion Efficiency
- η_{fc}: Fuel Cell Energy Conversion Efficiency
- η_m: Electric Motor Mechanical Efficiency
- η_t: Transmission System Efficiency
- ρ_{air}: Air Density

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Annexes

A- Route 1 TCO Results: Altonorte – Iquique

Table 32. Sensibility on CAPEX, FCET 8 H2 Truck and HYMAX-450 (Self-made, 2021)

Year	KPI	Diesel	FCET 8 O	FCET 8	FCET 8 P	HYMAX-450 O	HYMAX-450	HYMAX-450 P
2025	USD	$ 1,057,379	$ 1,078,260	$ 1,163,366	$ 1,248,472	$ 1,378,317	$ 1,509,602	$ 1,640,886
2035		$ 1,086,492	$ 813,646	$ 844,523	$ 875,400	$ 951,965	$ 999,596	$ 1,047,227
2025	USD/km	$ 1.78	$ 2.09	$ 2.26	$ 2.42	$ 2.35	$ 2.57	$ 2.80
2035		$ 1.83	$ 1.58	$ 1.64	$ 1.70	$ 1.62	$ 1.70	$ 1.79

Table 33. Sensibility on CO2 taxes, FCET8 H2 Truck and HYMAX-450 (Self-made, 2021)

Year	KPI	Diesel	Diesel O	Diesel P	H2 FCET 8	H2 HYMAX-450
2025	USD	$ 1,057,379	$ 1,168,291	$ 1,051,542	$ 1,163,366	$ 1,509,602
2035		$ 1,086,492	$ 1,288,310	$ 1,075,870	$ 844,523	$ 999,596
2025	USD/km	$ 1.78	$ 1.97	$ 1.77	$ 2.26	$ 2.57
2035		$ 1.83	$ 2.17	$ 1.81	$ 1.64	$ 1.70

B- Route 2 TCO Results: Collahuasi – Pozo Almonte

Table 34. Sensibility on CAPEX, FCET 8 H2 Truck and HYMAX-450 (Self-made, 2021)

Year	KPI	Diesel	FCET 8 O	FCET 8	FCET 8 P	HYMAX-450 O	HYMAX-450	HYMAX-450 P
2025	USD	$ 1,010,096	$ 1,063,706	$ 1,148,812	$ 1,233,918	$ 1,342,093	$ 1,473,377	$ 1,604,662
2035		$ 1,034,405	$ 804,649	$ 835,526	$ 866,403	$ 929,572	$ 977,203	$ 1,024,833
2025	USD/km	$ 3.01	$ 3.86	$ 4.17	$ 4.48	$ 4.01	$ 4.40	$ 4.79
2035		$ 3.09	$ 2.92	$ 3.03	$ 3.14	$ 2.77	$ 2.92	$ 3.06

Table 35.Sensibility on CO2 taxes, FCET8 H2 Truck and HYMAX-450 (Self-made, 2021)

Year	KPI	Diesel	Diesel O	Diesel P	H2 FCET 8	H2 HYMAX-450
2025	USD	$ 1,010,096	$ 1,104,100	$ 1,005,149	$ 1,148,812	$ 1,473,377
2035		$ 1,034,405	$ 1,205,457	$ 1,025,403	$ 835,526	$ 977,203
2025	USD/km	$ 3.01	$ 3.30	$ 3.00	$ 4.17	$ 4.40
2035		$ 3.09	$ 3.60	$ 3.06	$ 3.03	$ 2.92

C- Route 3 TCO Results: Chuquicamata – Antofagasta

Table 36. Sensibility on CAPEX, FCET 8 H2 Truck and HYMAX-450 (Self-made, 2021)

Year	KPI	Diesel	FCET 8 O	FCET 8	FCET 8 P	HYMAX-450 O	HYMAX-450	HYMAX-450 P
2025	USD	$ 919,536	$ 1,056,272	$ 1,141,378	$ 1,226,484	$ 1,332,474	$ 1,463,758	$ 1,595,043
2035		$ 934,645	$ 800,053	$ 830,930	$ 861,807	$ 923,626	$ 971,256	$ 1,018,887
2025	USD/km	$ 2.06	$ 2.72	$ 2.94	$ 3.16	$ 3.00	$ 3.30	$ 3.60
2035		$ 2.09	$ 2.06	$ 2.14	$ 2.22	$ 2.08	$ 2.19	$ 2.30

Table 37. Sensibility on CO2 taxes, FCET8 H2 Truck and HYMAX-450 (Self-made, 2021)

Year	KPI	Diesel	Diesel O	Diesel P	H2 FCET 8	H2 HYMAX-450
2025	USD	$ 919,536	$ 981,155	$ 916,293	$ 1,141,378	$ 1,463,758
2035		$ 934,645	$ 1,046,769	$ 928,743	$ 830,930	$ 971,256
2025	USD/km	$ 2.06	$ 2.20	$ 2.05	$ 2.94	$ 3.30
2035		$ 2.09	$ 2.34	$ 2.08	$ 2.14	$ 2.19

D- H2 Cost Projection

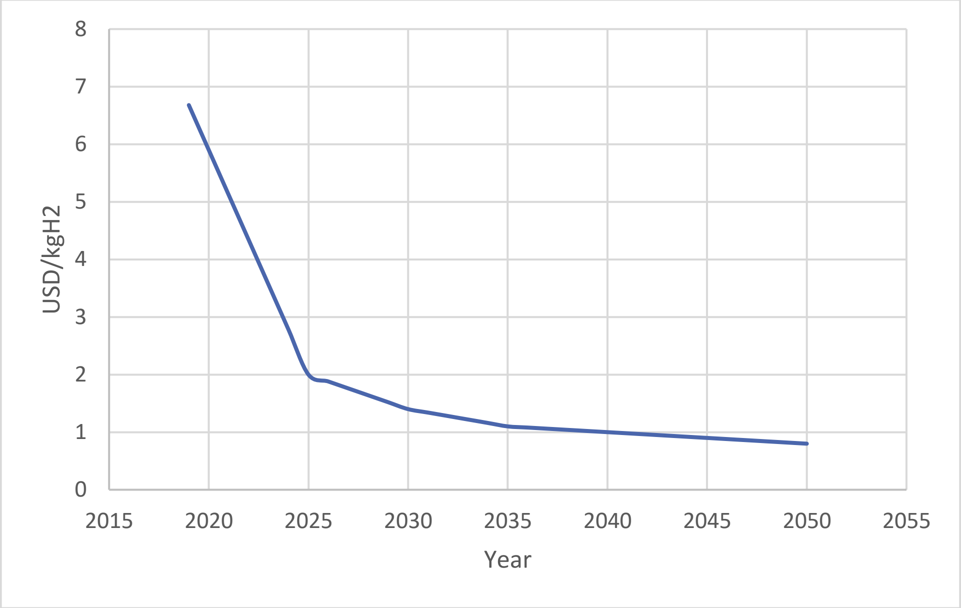

Figure 47. Levelized Cost of Hydrogen Projection Curve (Ministerio de Energía, n.d.) (Self-made, 2021)

E- Diesel Cost Projection

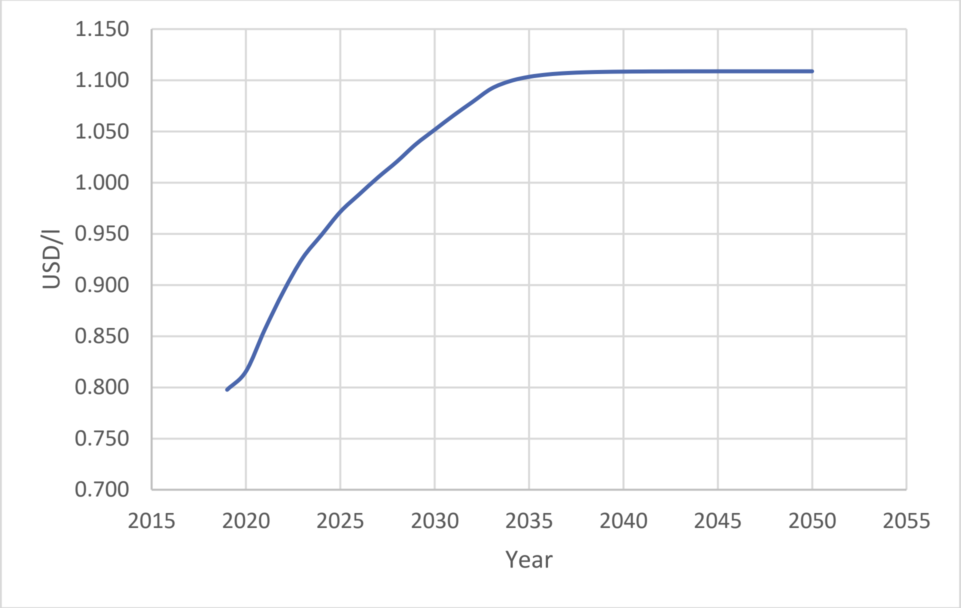

Figure 48. Diesel Fuel Cost Projection Curve (Ministerio de Energía, 2020) (Self-made, 2021)

F- H2 Truck Cost Projection

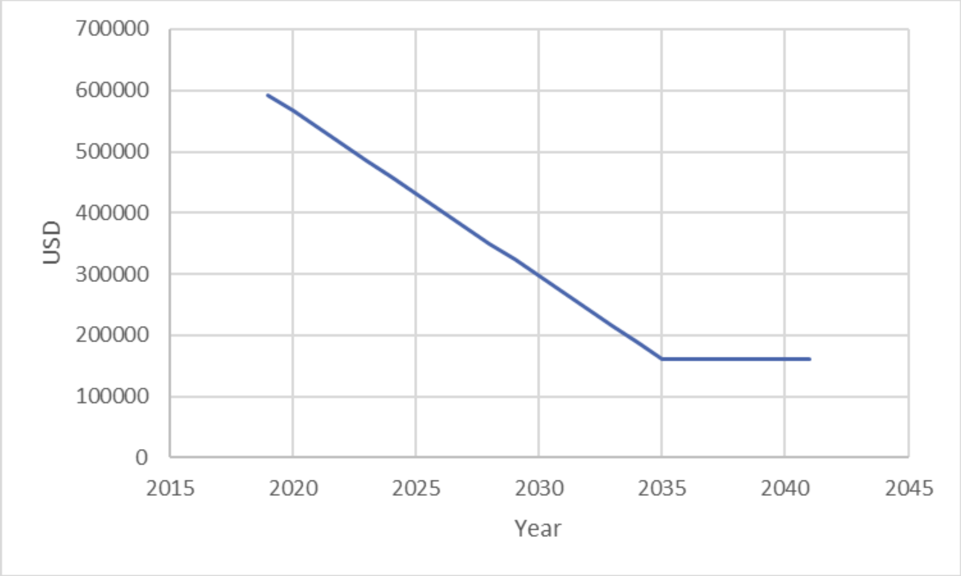

Figure 49. FCET 8 Truck Cost Projection Curve (Oostdam, 2019) (Hydrogen Council, 2020) (Self-made, 2021)

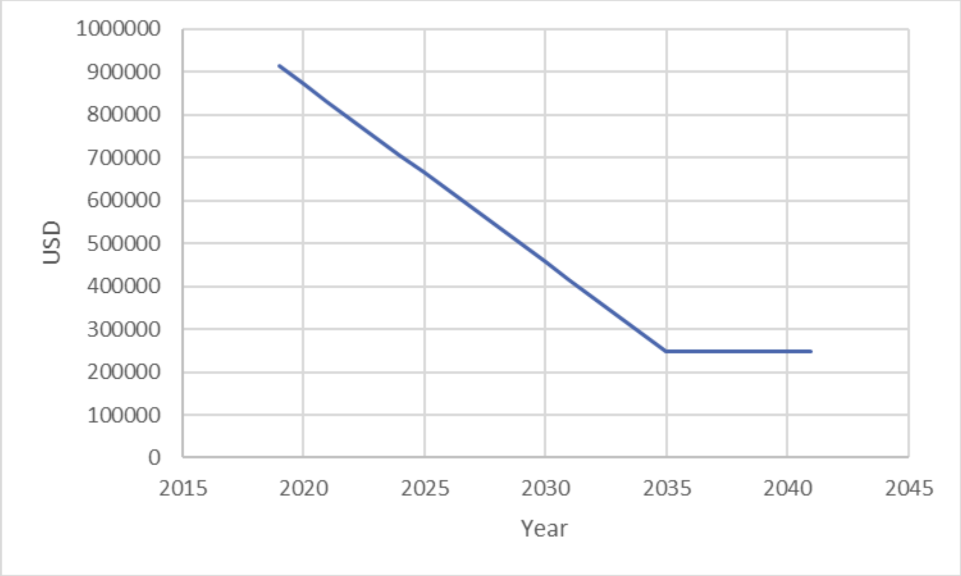

Figure 50. HYMAX-450 Truck Cost Projection Curve (Oostdam, 2019) (Hydrogen Council, 2020) (Self-made, 2021)

G- Speed Profiles Route 1 Altonorte – Iquique

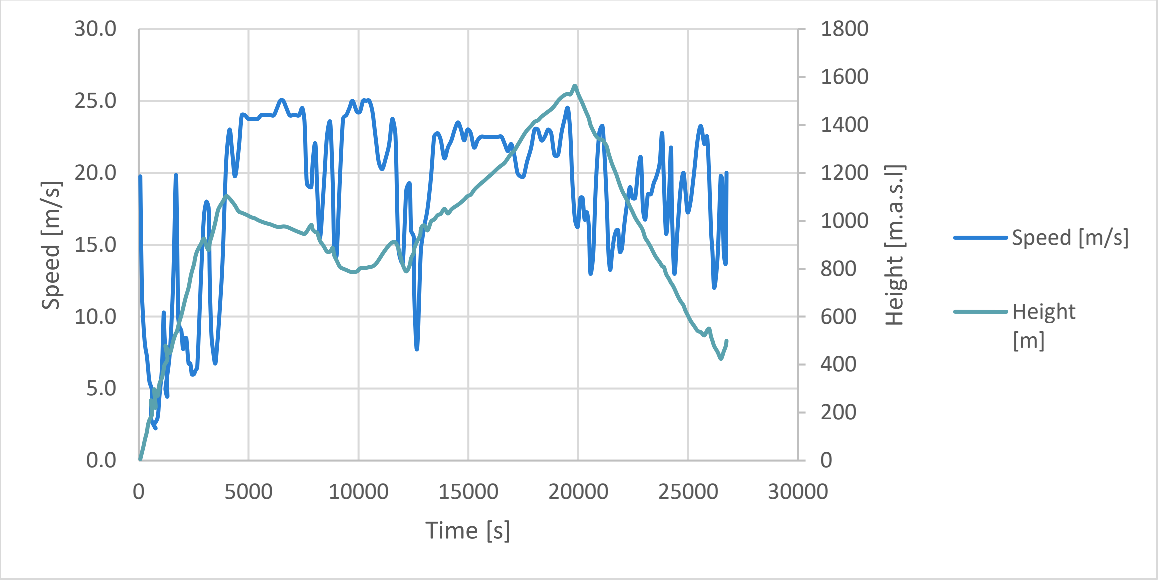

Figure 51. Speed profile for Diesel truck from Iquique to Altonorte (Self-made, 2021)

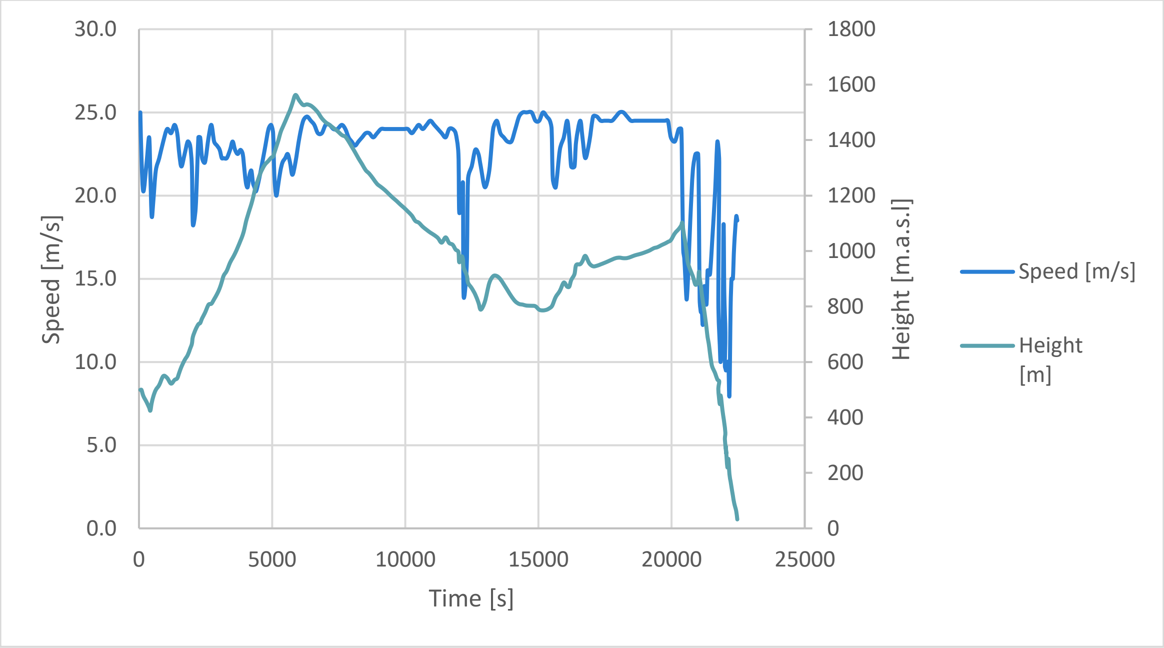

Figure 52. Speed profile for Diesel truck from Altonorte to Iquique (Self-made, 2021)

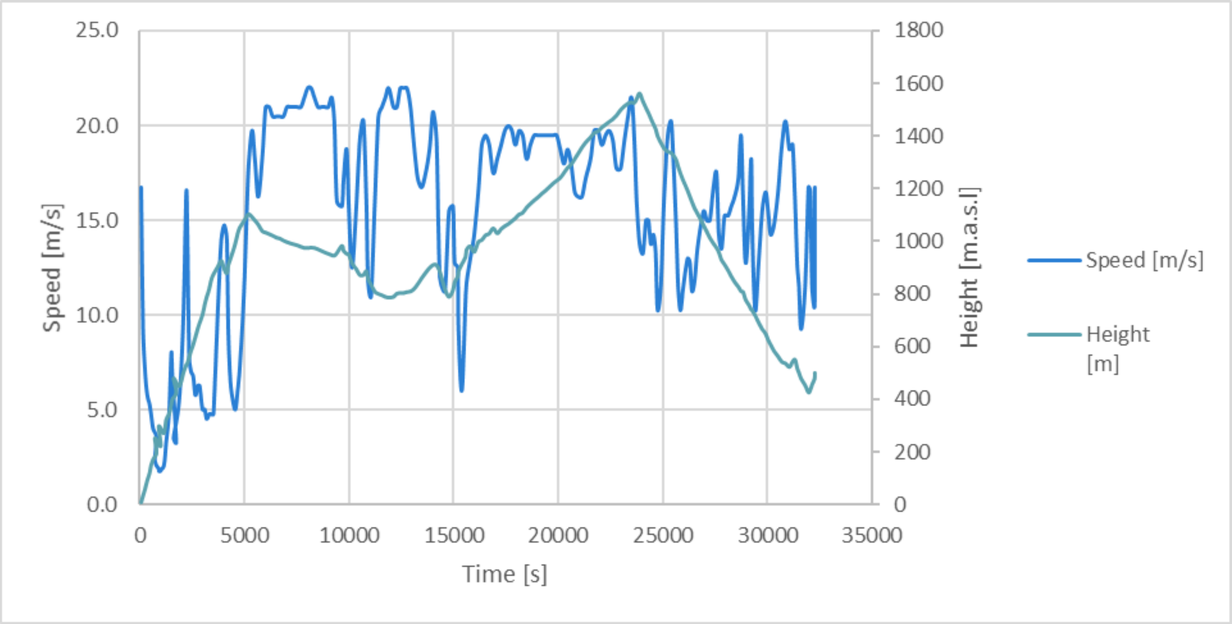

Figure 53. Speed profile for FCET 8 truck from Iquique to Altonorte (Self-made, 2021)

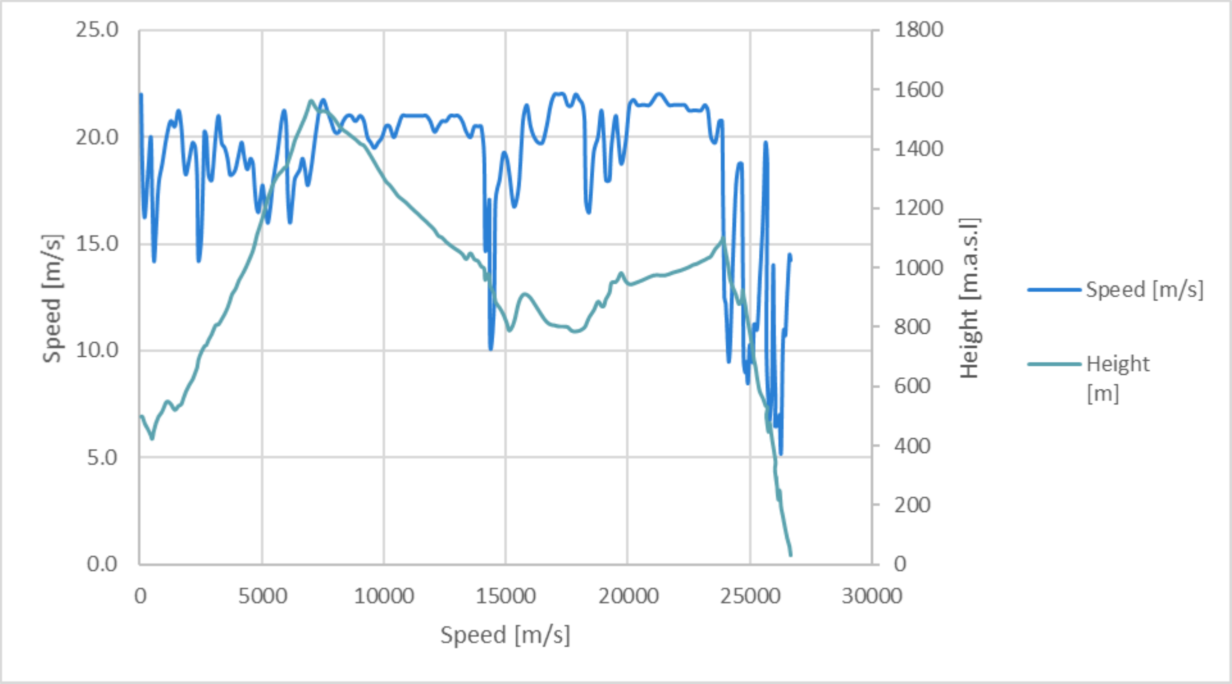

Figure 54. Speed profile for FCET 8 truck from Altonorte to Iquique (Self-made, 2021)

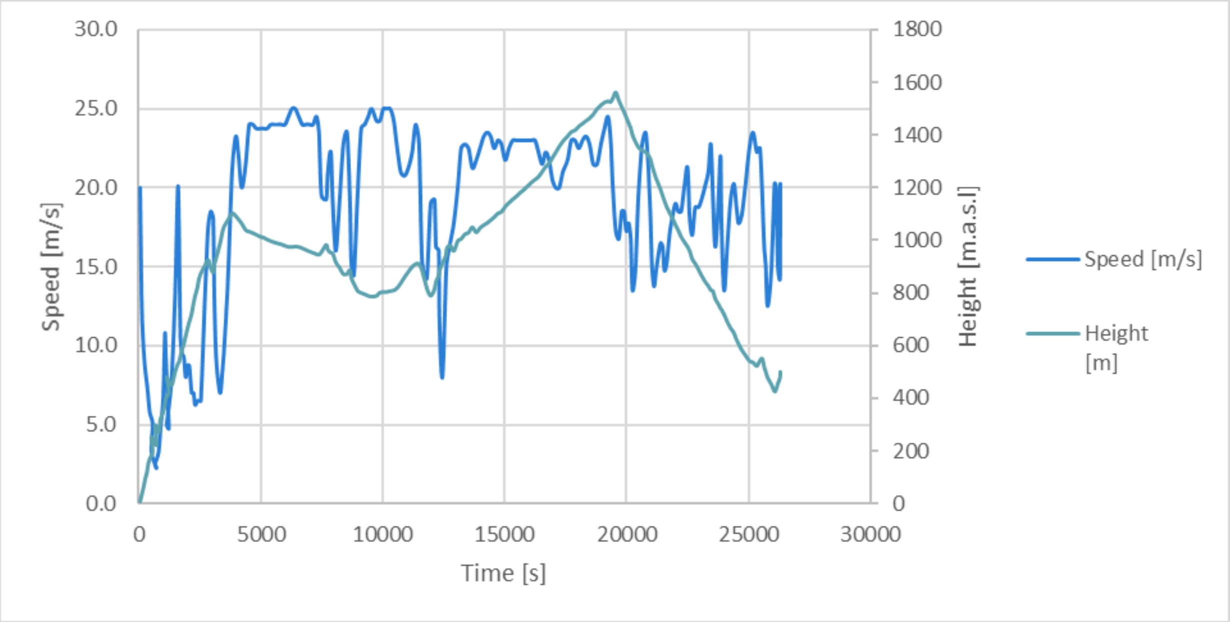

Figure 55. Speed profile for HYMAX-450 truck from Iquique to Altonorte (Self-made, 2021)

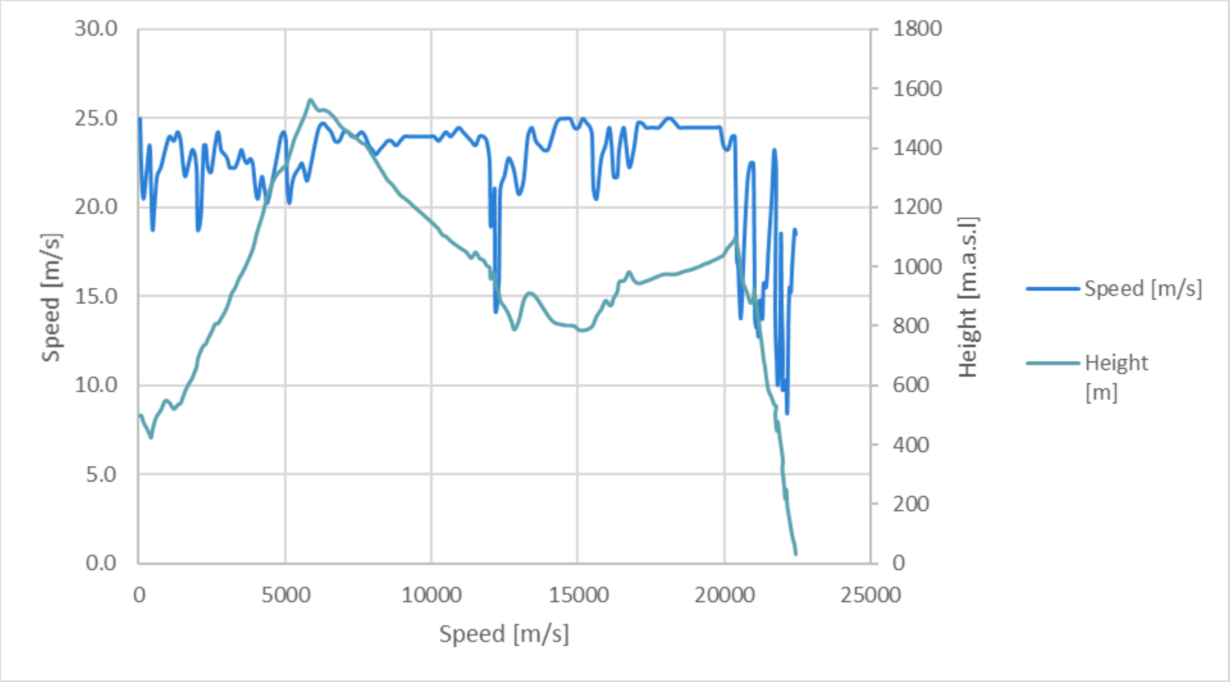

Figure 56. Speed profile for HYMAX-450 truck from Altonorte to Iquique (Self-made, 2021)

H- Speed Profiles Route 2 Collahuasi – Pozo Almonte

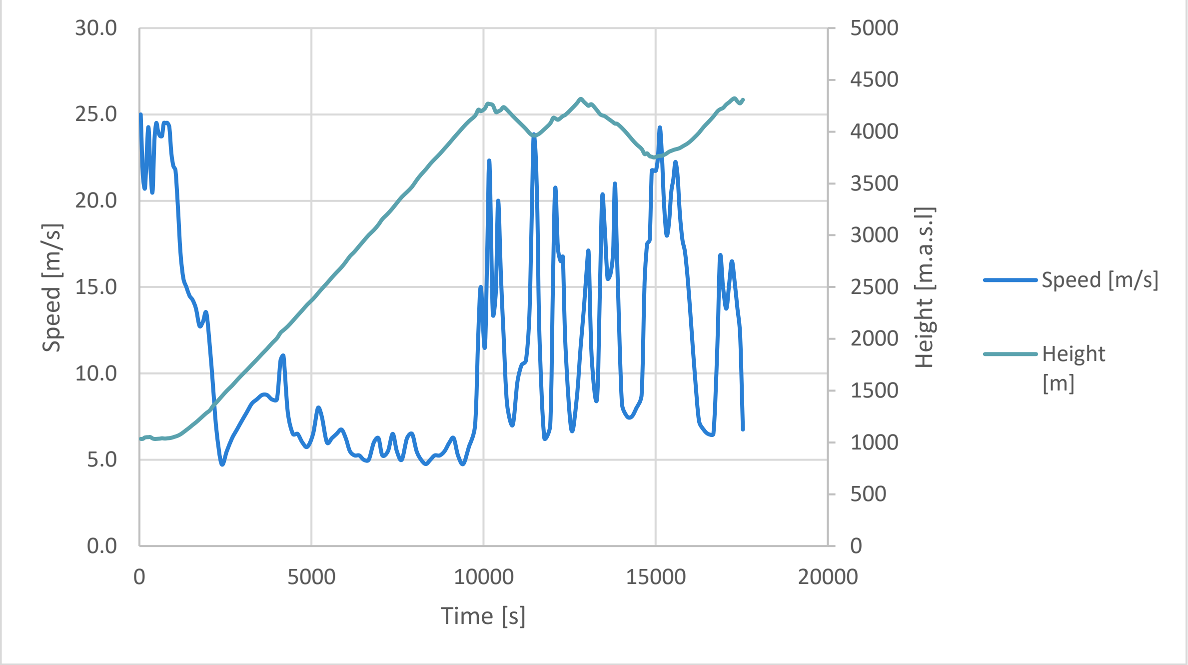

Figure 57. Speed profile for Diesel truck from Pozo Almonte to Collahuasi (Self-made, 2021)

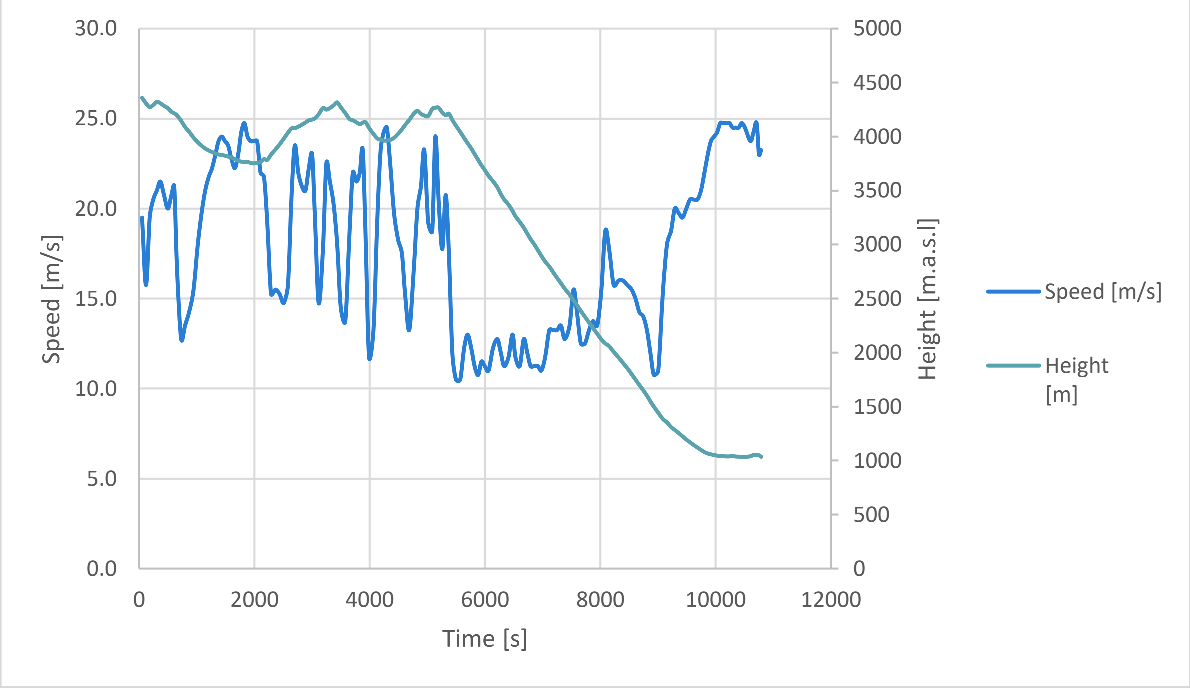

Figure 58. Speed profile for Diesel truck from Pozo Collahuasi to Almonte (Self-made, 2021)

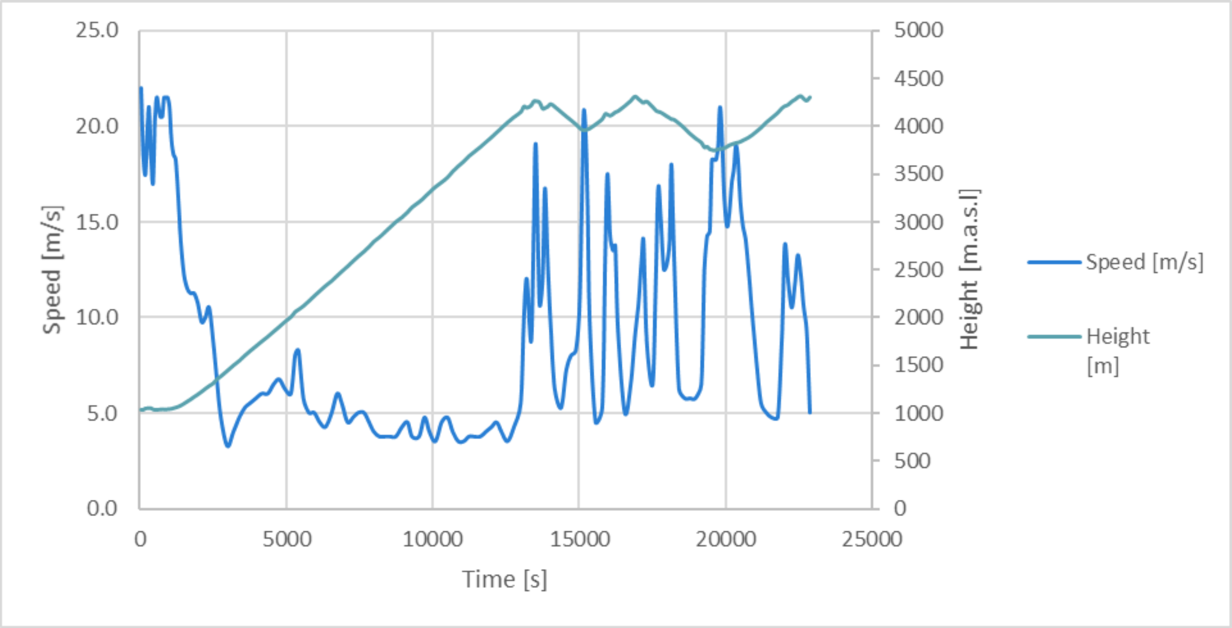

Figure 59. Speed profile for FCET 8 truck from Pozo Almonte to Collahuasi (Self-made, 2021)

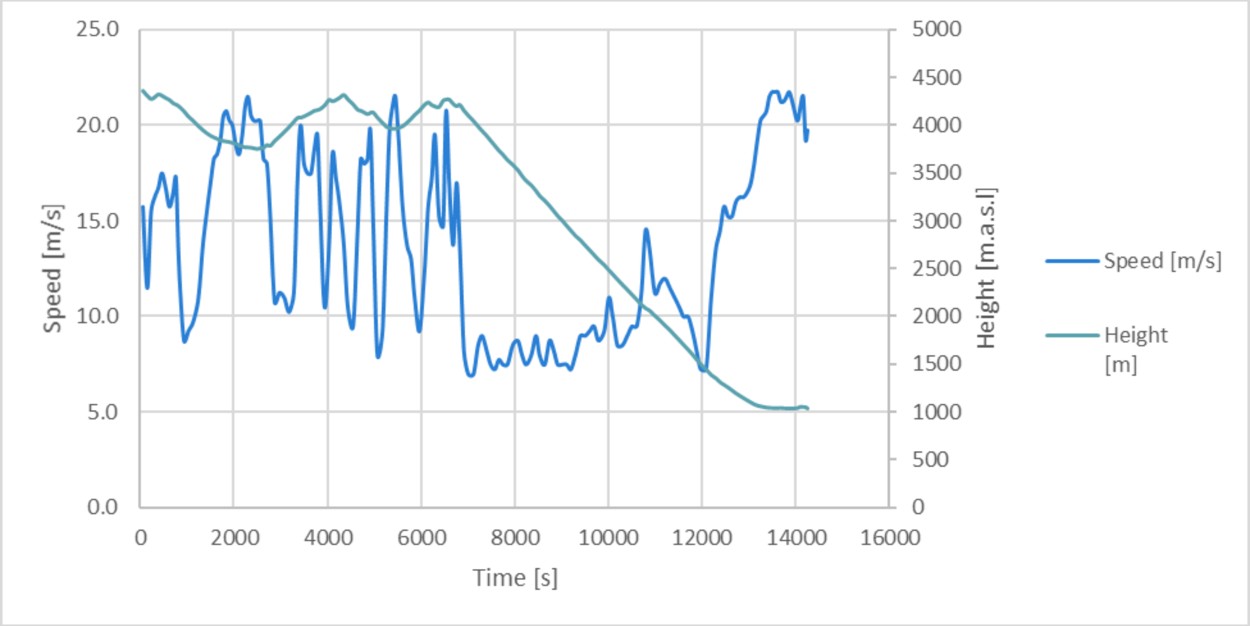

Figure 60. Speed profile for FCET 8 truck from Collahuasi to Pozo Almonte (Self-made, 2021)

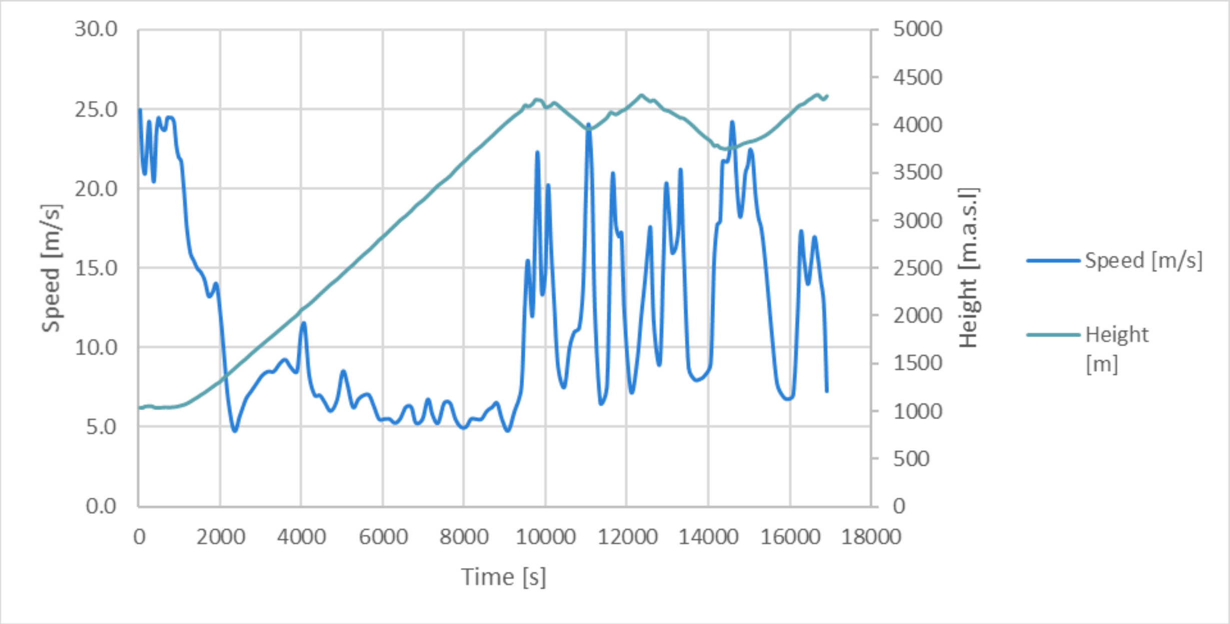

Figure 61. Speed profile for HYMAX-450 truck from Pozo Almonte to Collahuasi (Self-made, 2021)

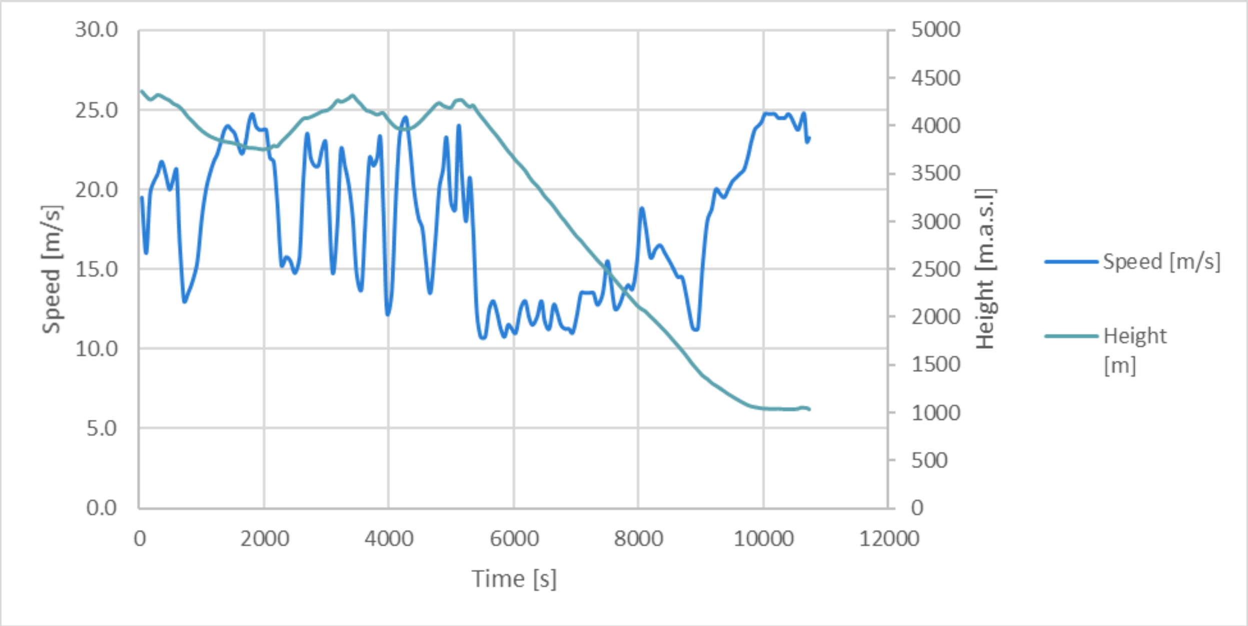

Figure 62. Speed profile for HYMAX-450 truck from Collahuasi to Pozo Almonte (Self-made, 2021)

I- Speed Profiles Route 3 Chuquicamata – Antofagasta

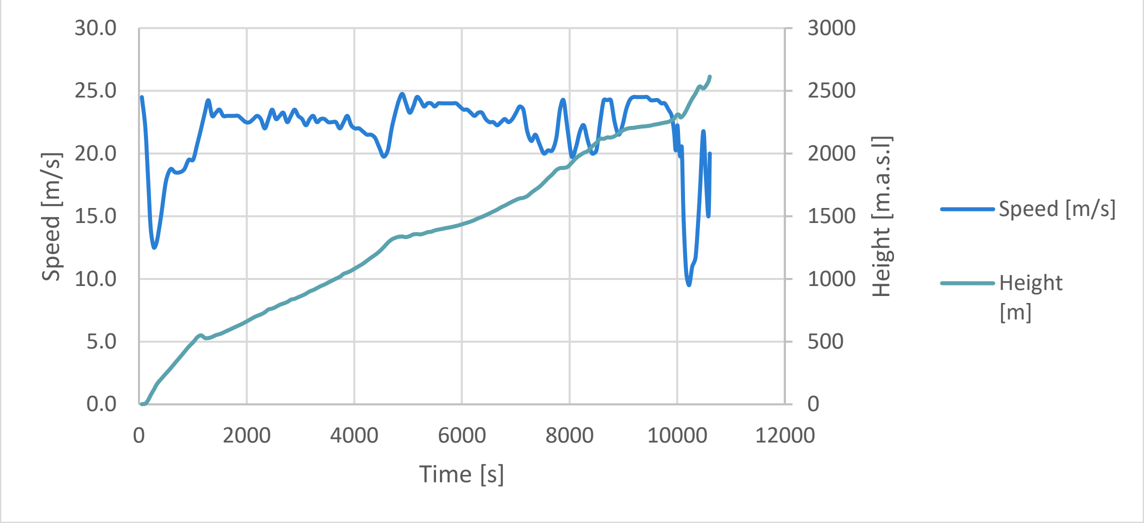

Figure 63. Speed Profile for Diesel Truck from Antofagasta to Chuquicamata (Self-made, 2021)

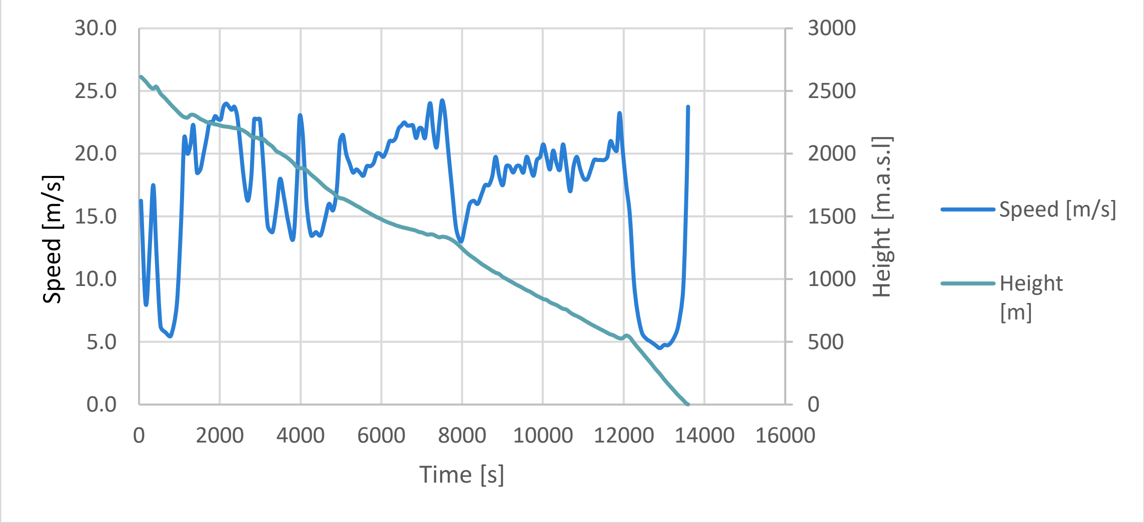

Figure 64. Speed Profile for Diesel Truck from Chuquicamata to Antofagasta (Self-made, 2021)

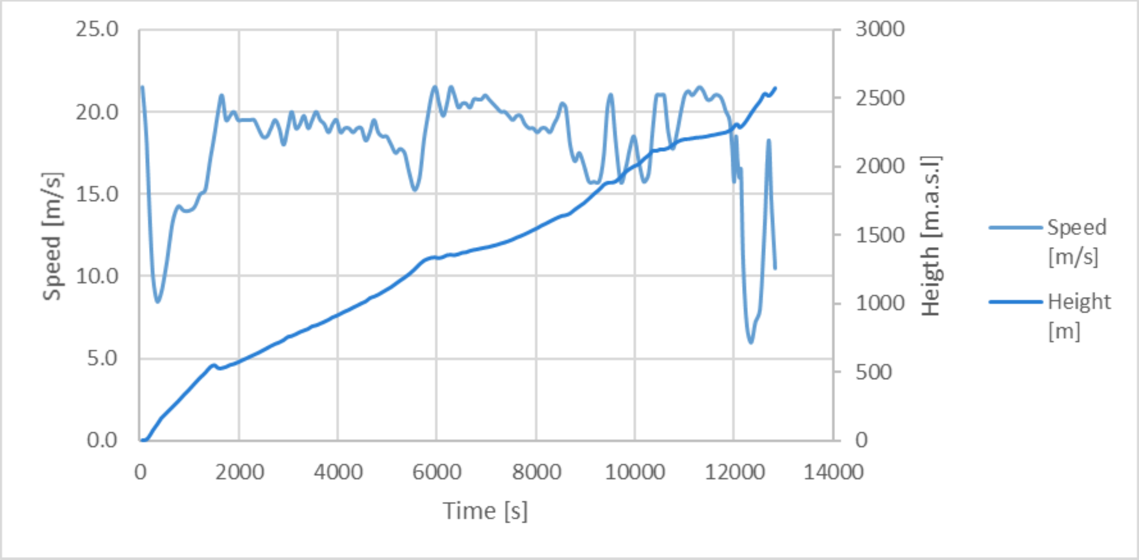

Figure 65. Speed Profile for FCET 8 Truck from Antofagasta to Chuquicamata (Self-made, 2021)

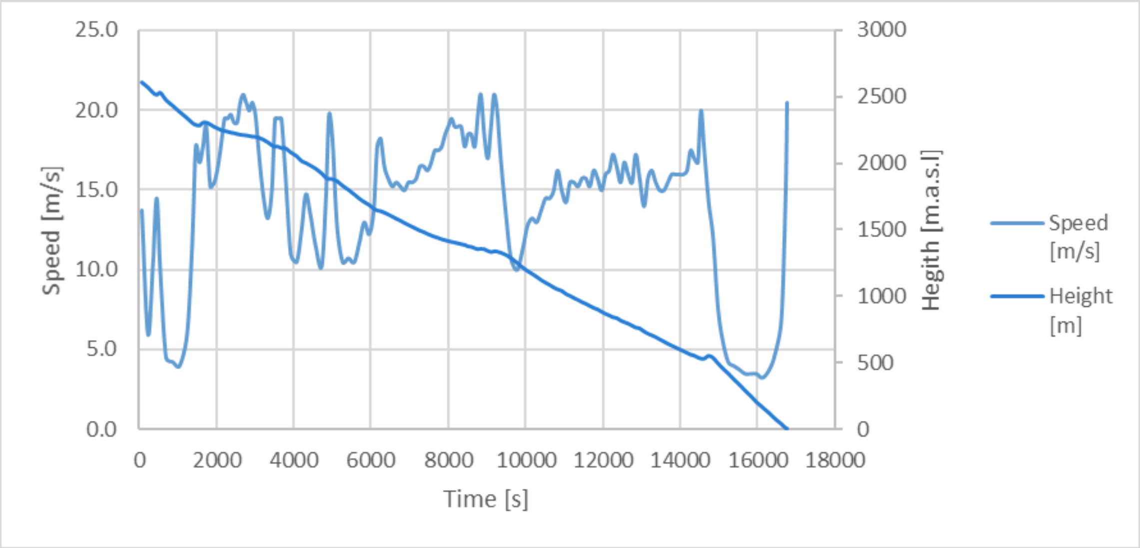

Figure 66. Speed Profile for FCET 8 Truck from Chuquicamata to Antofagasta (Self-made, 2021)

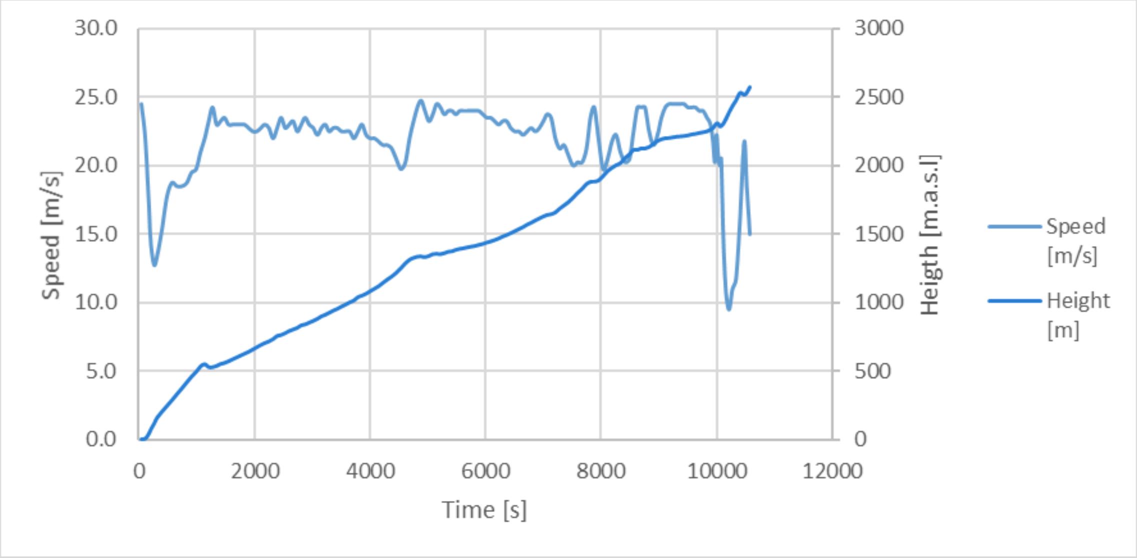

Figure 67. Speed Profile for HYMAX-450 Truck from Antofagasta to Chuquicamata (Self-made, 2021)

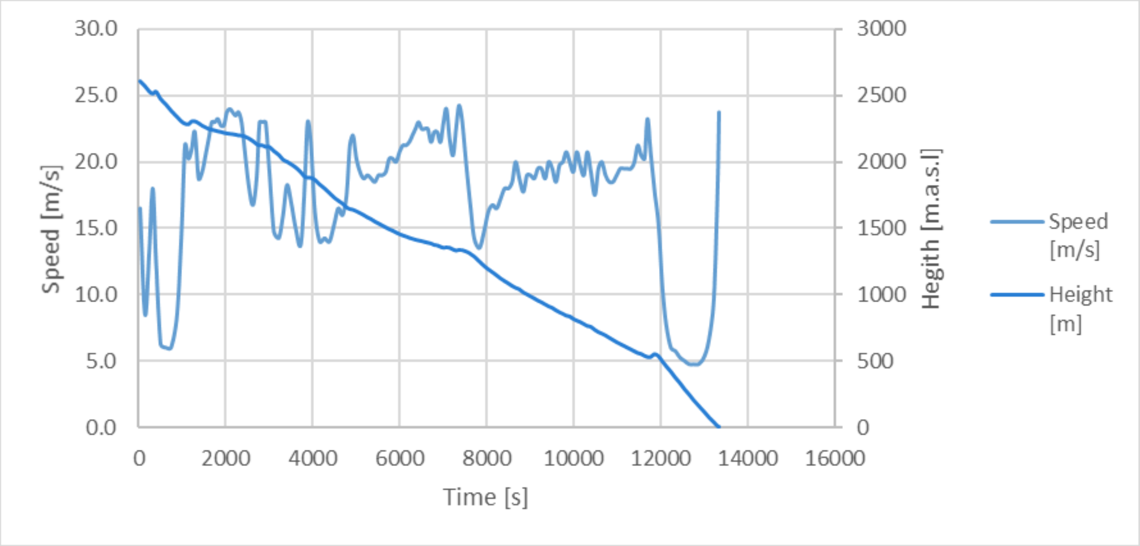

Figure 68. . Speed Profile for HYMAX-450 Truck from Chuquicamata to Antofagasta (Self-made, 2021)