Analysis of the technical capacity of fuel cell buses for route between different geographical heights

Final report

30 JUL 2021

Programa de Energías Renovables y Eficiencia Energética en Chile

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Por encargo de:
Ministerio Federal de Medio Ambiente, Protección de la Naturaleza y Seguridad Nuclear
de la República Federal de Alemania

Ministerio de Energía
Gobierno de Chile

Edition:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Friedrich-Ebert-Allee 40
53113 Bonn • Germany

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn • Germany

Name of the project:
Decarbonization of the Energy Sector in Chile

Marchant Pereira 150
7500654 Providencia
Santiago • Chile
T +56 22 30 68 600
I www.giz.de

Responsible:
Rainer Schröer

In coordination with:
Chilean Ministry of Energy
Alameda 1449, Pisos 13 y 14, Edificio Santiago Downtown II
Santiago de Chile
T +56 22 367 3000
I www.minenergia.cl

Analysis of the technical capacity of fuel cell buses for route between different geographical heights /
Dr. Uwe Albrecht, Hubert Landinger, Prof. Dr. Ralph Pütz, Fernanda Durán Sievers, Reinhold Wurster, GIZ;
edition: Hubert Landinger, Pablo Tello.
Santiago de Chile, Munich, 2021.
51 pages
Energy – Fuel Cell – Buses – Hydrogen – Chile

Clarification:
This publication has been prepared on behalf of the project "Decarbonization of the Energy Sector in Chile" implemented by the Chilean Ministry of Energy and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH within the framework of intergovernmental cooperation between Chile and Germany. The project is funded through the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Protection and Nuclear Safety - BMU. Notwithstanding, the conclusions and opinions of the authors do not necessarily reflect the position of the Government of Chile or GIZ. In addition, any reference to a company, product, brand, manufacturer or other similar in no way constitutes a recommendation by the Government of Chile or GIZ.

The staff of LBST, Belicon and ILF prepared this report.
The views and conclusions expressed in this document are those of the staff of LBST, Belicon and ILF. Neither LBST, Belicon and ILF, nor any of their employees, contractors or subcontractors, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process enclosed, or represents that its use would not infringe on privately owned rights.

CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

ABS	Antilock Braking System
BE	Battery Electric
BEV	Battery Electric Vehicle
CAEX	Camiones de Extracción (high tonnage mining trucks)
GIZ	German Corporation for International Cooperation (GIZ) GmbH (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH)
FC	Fuel Cell
FCE	Fuel Cell Electromobility / Fuel Cell Electric
FCEV	Fuel Cell Electric Vehicles
GPS	Global Positioning System
H_2	Hydrogen
HRS	Hydrogen Refuelling Station
HVAC	Heating / Ventilation / Air conditioning
LBST	Ludwig-Bölkow-Systemtechnik
LoI	Letter of Intent
m.a.s.l.	meters above sea level
M+S	Mud and Snow
NDA	Non-Disclosure Agreement
NDC	Nationally Determined Contributions (intended to achieve the Paris Agreement)
NCh	Norma Chilena
RPM	Rounds per minute
SOC	State of Charge
UAS	Unmanned Aircraft System

Executive Summary

As in many parts of the world, also in Chile the use of green hydrogen is considered as a key element for the decarbonization of the country's energy supply.

As hydrogen is not yet implemented in Chile as an energy carrier, but could play an important role to achieve the NDC targets intended to accomplish the Paris Agreement, stakeholders are searching for suitable early applications. These criteria need to be fulfilled:

- feasibility from a technology availability point of view,
- financial viability in the medium and long term and
- strong and committed actors to safeguard the transition from early non-self-sustaining pilot projects to real business cases.

This analysis provides the basis for the next steps towards the implementation of a pilot project on Chilean mining routes. In order to start the discussions, the 180 km bus route from Antofagasta to Minera Escondida had been chosen as a basis, but can be used as a blueprint for other routes with comparable conditions to be potentially serviced by FC buses. This route offered a good starting point for the discussions with the potential FC bus suppliers in order to overcome challenges such as route length, high altitudes, high gradients, slippery roads, extreme ambient conditions. But it also turned out in the course of the analysis that, due to the limited market size for this specific application scenario, a better knowledge of the various mining routes, the required transport capacities and how they are influencing the vehicle specification is urgently needed in order to evaluate the development and production efforts in comparison to the expected market volume.

In order to proceed with the preparation of a pilot project, contacts have been established to five fuel cell bus manufacturers which all show high interest in getting involved in the further process. In total, 17 potential FC bus manufacturers had been approached but many declined from further involvement due to several reasons such as focus on other world regions or no activities in the requested field of FC buses. It became clear that none of the FC bus manufacturers has a suitable solution for operating the demanding route at hand.

It also turns out that receiving (general) specifications from those companies that already have FC (city) buses in their portfolio is not an issue, but discussing approaches or technical solutions without signing an NDA is understandingly difficult as, of course, the manufacturers want to use their know-how only for their own benefit.

The replies of the potential FC bus manufacturers show that no real-world experience on operation of fuel cell buses at these high altitudes exists and therefore it is still unclear and depending on demand if and when such FC buses will become commercially available. Accordingly, respective pilot projects would be supportive. For the time being and according to the manufacturer's feedback, provision of appropriate FC buses in the short term would be limited to a maximum operation altitude of about 2,500 m.a.s.l. Therefore, a simulation of the mining route operation has been performed.

Based on synthetic data a route simulation could be performed that already gives some insights in the power demand and the hydrogen consumptions on routes of this kind. The simulation results in an average hydrogen consumption of about **14.5 kg H_2/100 km** for **the uphill ride** traction.

Recommended next steps:

(1) Before entering in a pilot project, it is recommended to perform a dedicated market potential analysis as it is required for both the attraction of the fuel cell bus manufacturers and the definition of the fuel cell bus specification. A trade-off needs to be found between overengineered vehicles and too small a market.

(2) It is recommended to establish a consortium which comprises at least one mining company or one mining fleet bus operator as they have to be the main driving force creating the urgently needed pull effects. Most FC bus manufacturers are profiting from the currently high dynamics in the field of hydrogen and fuel cells and therefore this specific field of application is by no means developing by itself but needs real commitment by the stakeholders. For the time being this specific niche seems to be most attractive to start-ups and to global players as they want to cover nearly all potential applications. The objectives of the consortium should not only comprise the smooth implementation of a pilot project, but should focus even more on the successful implementation of FC coach buses in Chile including the required hydrogen infrastructure taking also a fair risk sharing between the partners into account.

Finally, all ingredients required to proceed in this field of fuel cell buses for high altitudes are there – demand for the vehicles, interest of all required stakeholder groups (LoIs submitted) – and the next steps are to be taken. Nevertheless, it is too early to immediately and directly enter into a pilot project as upfront a robust vehicle specification needs to be developed in order to call for reliable and comparable offers. Therefore, it is recommended to enter into a pilot project only after successful finalisation of step (1) and step (2) for this specific type of FC buses capable of servicing those demanding routes.

Nevertheless, in order to gather first real-world experiences especially with regard to hydrogen refuelling infrastructure it might be useful to initiate a pilot project with FC buses already available on the market to service less challenging routes and service conditions, but this was not in the focus of this analysis. This way, stakeholders would get acquainted to the various components of the value chain and ideally a first market for FC buses and the according hydrogen infrastructure could be established.

1 INTRODUCTION, MOTIVATION AND METHODOLOGY

The analysis essentially covers two areas,

- the identification of FC bus manufacturers which are appropriate, capable, and willing to participate in a pilot bus project and to provide FC buses to successively replace the overall vehicle fleet and
- the verification that the FC buses offered are suitable to fulfil the challenging requirements in order to perform well under the harsh conditions applicable when serving the passenger transport on the extraordinarily demanding mining route.

The vehicles required to serve the mining route are preferably not city buses (Class I), but suburban buses (Class II) or coaches (Class III) enabling pleasant travelling including baggage compartments and having the allowance and capability for entering highways. Nevertheless, the wording was kept with “buses”. Furthermore, it should be highlighted already at this point that all FC buses available commercially today are city / suburban buses. Only very few FC coach prototypes exist in Korea (Hyundai) and China (e.g., Hyzon for Australia). Europe started an FC coach development project (CoacHyfied; Ballard and ElringKlinger being partners) in JAN 2021.

The performed activities are structured in the following steps:

- Identification of appropriate FC bus manufacturers
  - Compilation of route specific characteristics for buses
  - Comparison of appropriate FC buses available on the world market
- Evaluation and verification of the FC buses’ technical characteristics
  - Evaluation of technical characteristics under mining route and climate conditions
  - Evaluation of technical characteristics reflecting necessary vehicle modifications
  - Analysis of supply scheme for buses, components, and spare parts
  - Recommendations regarding partners for pilot project and roll-out

2 IDENTIFICATION OF APPROPRIATE FC BUS MANUFACTURERS

2.1 Compilation of route specific characteristics of FC buses

2.1.1 Route characteristics overview

The main route characteristics are shown in Table 1:

Table 1: Main route characteristics

Main route characteristics	
Length Antofagasta Airport to Antofagasta City Center [km]	26
Length Antofagasta City Center to Minera Escondida and Minera Zaldivar [km]	154
Total route length [km]	180
Minimum altitude [m]	10
Maximum altitude [m]	3,200
Maximum gradient (Minera Escondida and Minera Zaldivar / for this analysis (Candelaria))	15 %/ 18%
Average gradient	2.5%
Maximum allowed speed [km/h]	90
Average speed uphill [km/h]	50
Minimum temperature [°C]	-20
Maximum temperature [°C]	40

These characteristics do not only cover the conditions of Minera Escondida but also more extreme conditions in order to enable the FC buses to also service even more challenging routes.

2.1.2 Elevation profiles

Figure 1 depicts the elevation profile from Antofagasta Airport to Antofagasta City Center while Figure 2 shows the elevation profile from Antofagasta City Center to Minera Escondida and Minera Zaldivar.

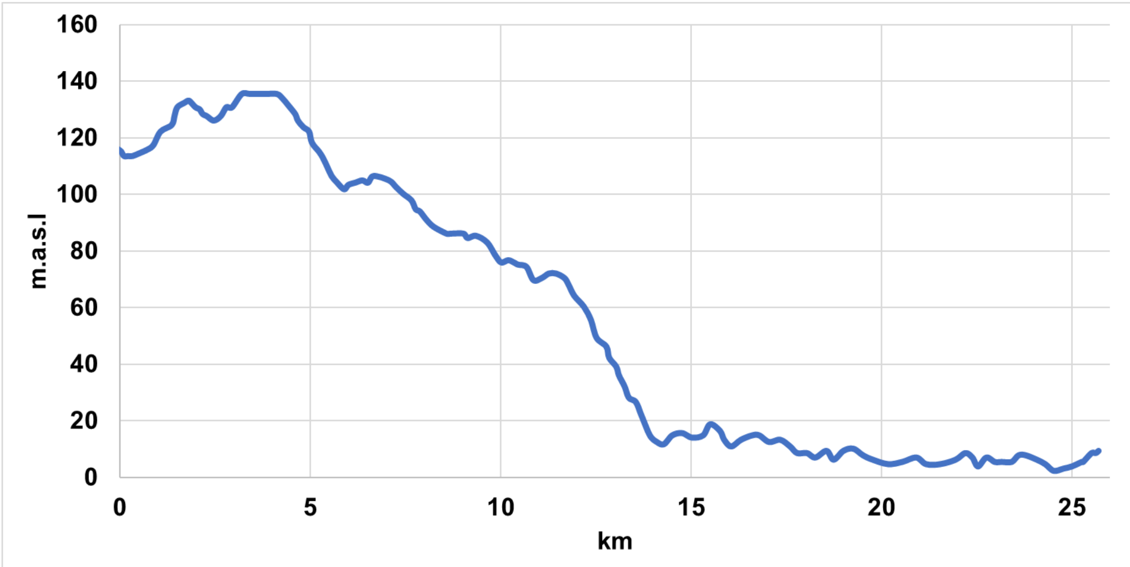

Figure 1: Elevation profile Antofagasta Airport – Antofagasta City Center

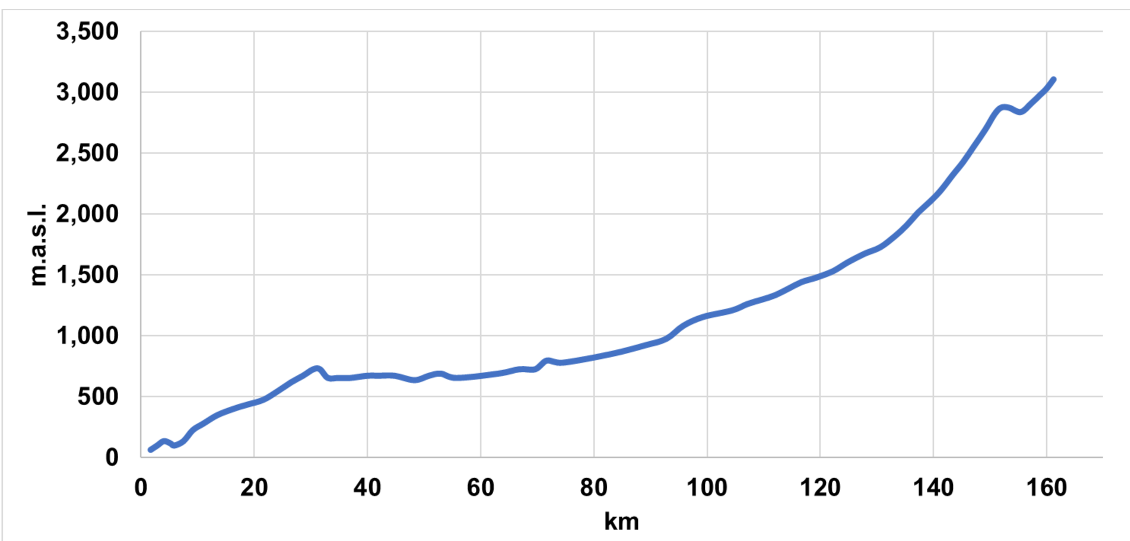

Figure 2: Elevation profile Antofagasta City Center - Minera Escondida and Minera Zaldivar (Antofagasta Minerals)

2.1.3 Speed limits on the route

Figure 3 and Figure 4 show the current speed limits and specialties on the route:

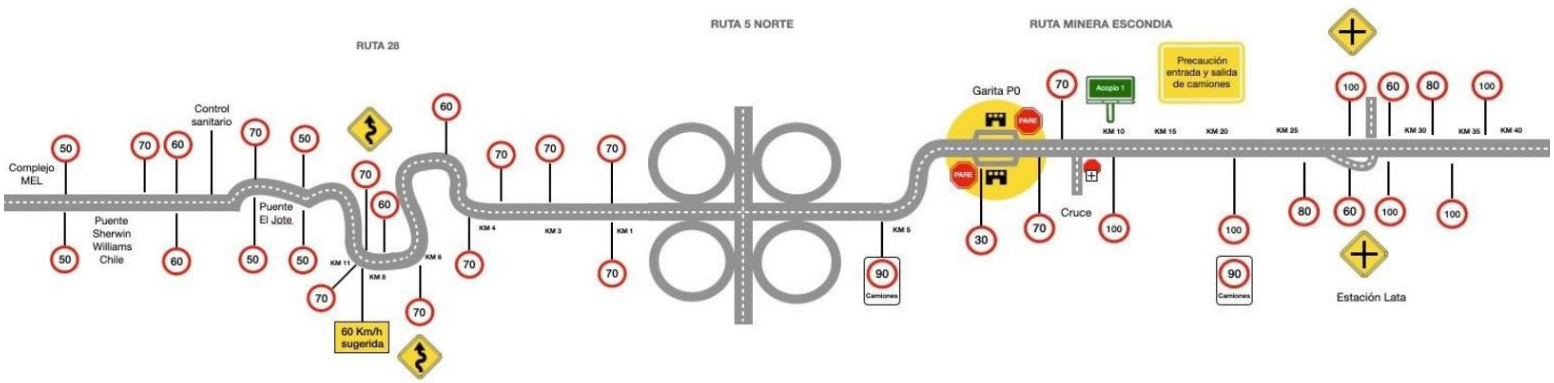

Figure 3: **Route section between Minera Escondida Limitada (MEL) headquarter and km 45 [Source: Tandem]**

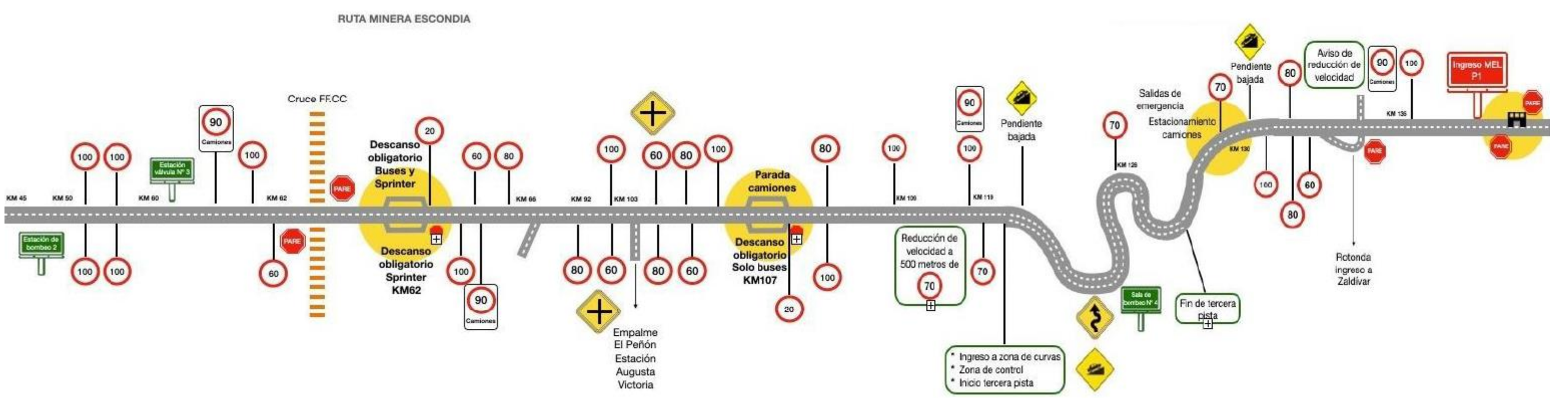

Figure 4: **Route section between KM 45 and gateway Minera Escondida [Source: Tandem]**

2.1.4 Simulation of route and vehicle operation

The parameters required for a simulation (GPS and atmospheric data) of the bus route from Antofagasta City Centre to Minera Escondida were not available in digital format and are only given as diagrams (see Figure 2 to Figure 4). Therefore, as a substitute, the elevation profile from Figure 2 had to be graphically measured and converted into a digital data set. The corresponding atmospheric data are then derived from typical values and allocated to this altitude data set. Since the concrete velocity profile on the route is also unknown and only the respective maximum speeds are available (see Figure 3 and Figure 4), these must be applied and digitised, which corresponds to a speed profile without traffic congestion and applies maximum permissible speeds. The approximated route parameters obtained in that way as a substitute are shown in Figure 5. It has to be noted that the hereby simulated energy consumption for traction is likely to be rather low, as any additional stop-and-go phases are not taken into account. Without traffic congestion, the following overall route characteristics apply:

- Route length [km]: 152
- Total operation time [s]: 8,600
- Average operation speed [km/h]: 63.6

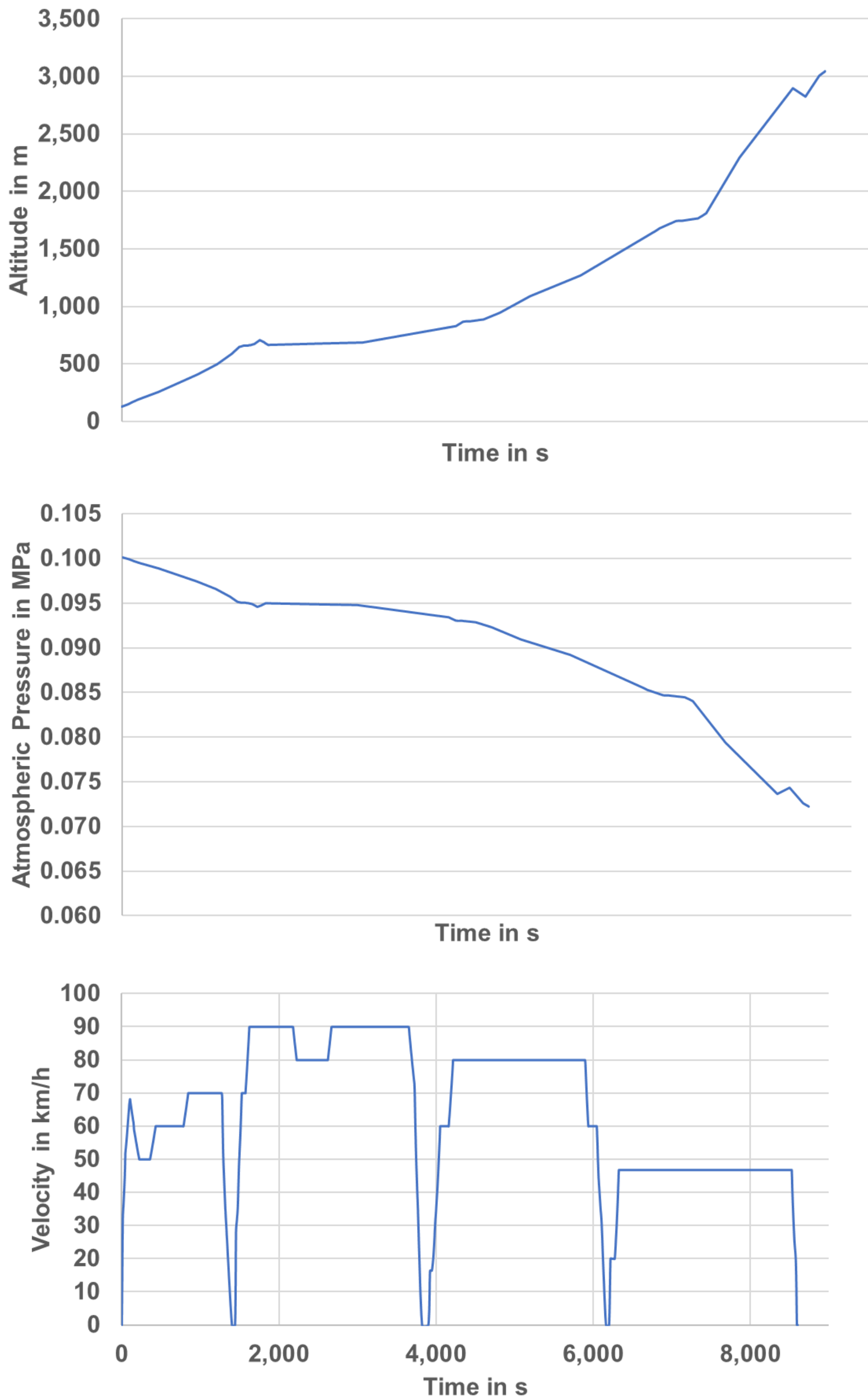

Figure 5: Adopted digitised route profiles from Antofagasta City Centre to Minera Escondida

As already indicated, none of the FC bus manufacturers has a vehicle ready to serve this challenging mining route and in order to keep their potential competitive edge they are not willing to share their concepts and plans without an NDA signed. E.g., Fanalca just shared their view that the FC stack can work up to 3,400 m.a.s.l. with derating that can be compensated by the battery. Further, up to 2,500 m.a.s.l. can be achieved without derating. Therefore, they do not expect general issues with the operation of FC buses at the requested altitudes. Furthermore, Buses4Future claims that their FC system operating at very low pressures is also capable to be operated at these high altitudes as the system is equipped with a patented control software, which adapts automatically for operation at higher altitude. For more details, please see chapter 3.1.

From these statements the conclusion can be drawn that there are no general barriers (showstoppers) for the appropriateness of fuel cell technology for these high altitudes, but both additional developments and trials are necessary and a specific drive train design, at least for some of the FC bus manufacturers, becomes necessary.

As the most appropriate and most complete vehicle data required for the simulation has been provided by Hyzon (Hyzon Coach Bus model) and have been used for the simulation in addition to scientifically proven data in order to take into account potentially required vehicle modifications.

For the vehicle simulated on that route, a 12.5 m coach bus with fuel cell (FC) only propulsion system (see Figure 6) and final drive consisting of a central electric motor with conventional portal axle has been selected with the following characteristics:

- Total weight: 19 t (fully occupied)
- Final drive: Central motor with
  - continuous power: 195 kW
  - peak power: 350 kW

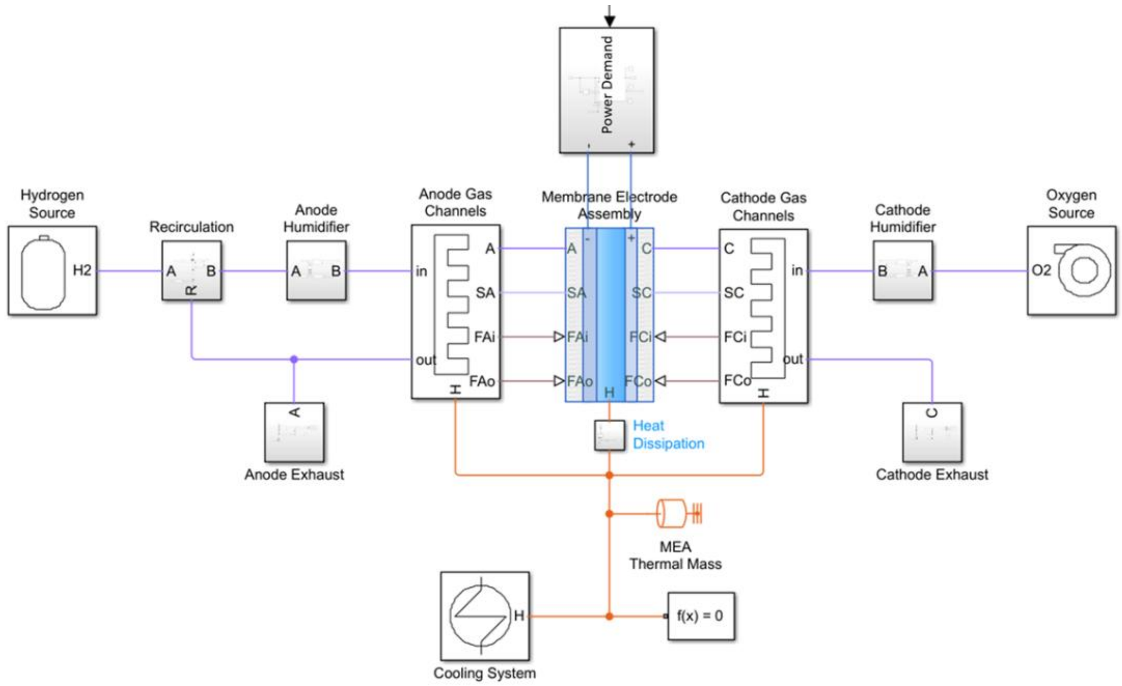

Figure 6: Fuel cell model used for simulation – scheme

The FC operates at a stack target temperature of 60°C. Based on the driving resistances at the drive axle, the route profiles constructed above result in an average hydrogen consumption of about **14.5 kg H_2/100 km** for the uphill ride traction, including cooling pump and air compressor consumptions. At an efficiency of 50%, the FC generates around 365 kWh of electrical energy at the drive axle with this hydrogen consumption, corresponding to **2.4 kWh/km**. This energy consumption may increase significantly with higher stop-and-go shares!

This energy consumption may increase significantly with higher stop-and-go shares! Figure 7 shows the expected development of the energy consumption at lower operational speeds due to higher stop-and-go shares.[1]

[1] 100% is the consumption for the simulation with an average operational speed of about 64 km/h. An average operational speed of only 10 km/h (heavy urban operation) would result in a consumption of 230% (factor 2.3) compared to the consumption at 64 km/h.

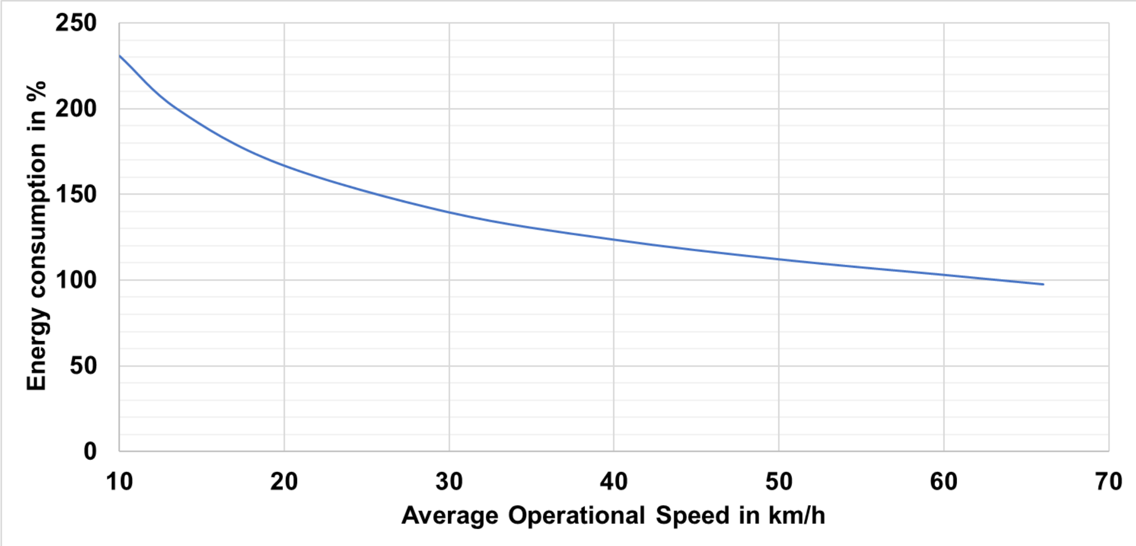

Figure 7: Expected development of the energy consumption at lower operational speeds

In addition to traction consumption, energy consumption for heating/ventilation/air conditioning (HVAC) must be taken into account. Here, heating represents the case with the greatest influence, see Figure 8. At an ambient temperature of around 21°C, the fuel cell and passenger compartment do not need to be cooled or heated. At an ambient temperature of -20°C an average heating power of about 22 kW is necessary to keep an adequate ride comfort for the passengers (at 0°C about 12 kW). In contrast, at about +30°C ambient temperature the cooling power demand merely equals 15 kW.

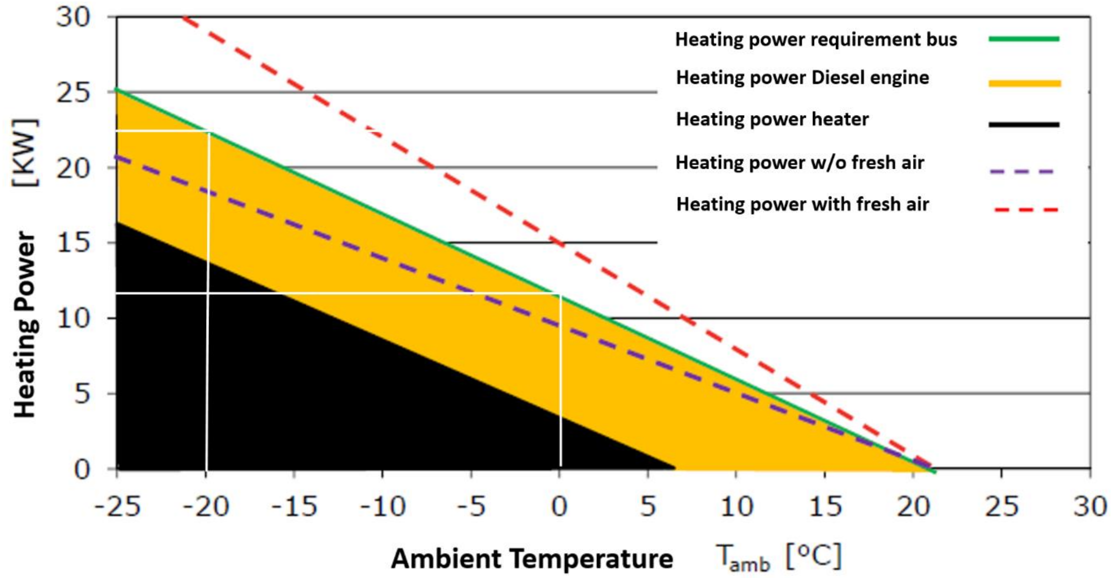

Figure 8: **Heating power demand of a 12 m bus depending on ambient temperature [Source: Spheros]**

The basic rule for the development of temperatures at altitude is: For every 1,000 metres of altitude increase, the temperature decreases by 6.5° C. In extremely dry air, the air can even get colder by 9.8°C per 1,000 metres of altitude. That means if ambient temperature is about 30°C at the start of the bus route the temperature at the final destination may be around 10°C to 0°C. And if ambient temperature is only about 10°C at the start of the bus route in winter, the temperature at the final destination may be around -10°C to -20°C.

For the HVAC system simulation an advanced heat pump with CO_2 (R744) as refrigerant has been applied in accordance with Figure 9.

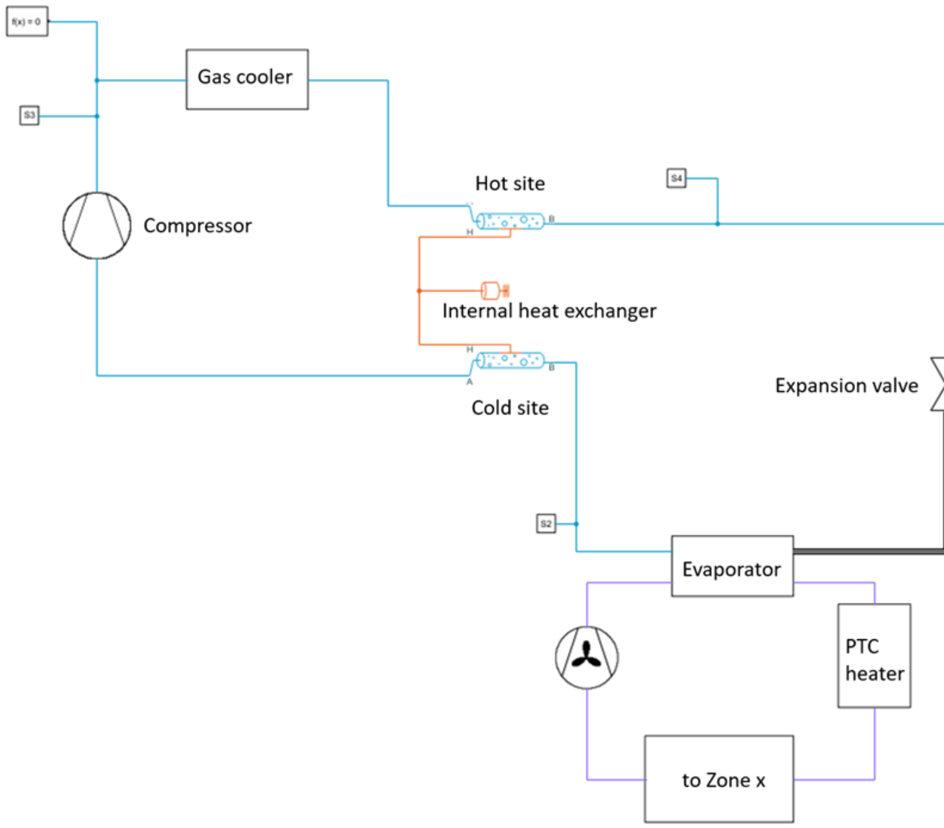

Figure 9: Heat pump model with R744 refrigerant used for simulation

As a result, even with energy management of HVAC to minimize consumption, an **extra consumption** for **HVAC** may rise to an average of **0.2 kWh/km** additional to traction consumption. This equals an increase in overall energy consumption of up to about 10%. The less the operational speed, the higher the relative share of energy for HVAC!

It should be emphasised at this point that in many electric buses today attempts are being made in practice to reduce energy consumption by intermittently switching on/off the heating/air conditioning system, but this is accompanied by a significant loss of comfort for the passengers. On city bus routes with frequent stops and door openings this may be justifiable, but certainly not on intercity bus routes.

2.1.5 Further information

Tandem, one of the operators of the passenger transport services on the mining route, has carried out a comprehensive, proprietary documentation on an inspection of the mining route performed in MAR 2021 ("INSPECCIÓN DE RUTA MINERA ESCONDIDA"). Such documentation exists for many mining routes and can serve as a starting point for preparing a comprehensive route profile.

Furthermore, speed profiles (from bus operators), detailed route (height) profiles and meteorological information regarding the mining route, ideally in digital format, will be required by the potential FC bus manufacturer upfront to the preparation of a pilot project in order to enable the manufacturers to run according simulations which are a prerequisite for starting the layout of the vehicle drive train.

2.1.6 Preliminary vehicle specifications

In the course of the analysis a preliminary vehicle specification has been compiled to give the potential FC bus manufacturers a first rough idea which type of vehicles will be required. The preliminary vehicle specification can be found in Annex I attached to this report.

2.2 Comparison of appropriate FC buses available on the world market

2.2.1 FC bus manufacturers

In a first step, all bus manufactures have been summarized for which fuel cell bus activities are known and a principal chance that these manufacturers might be appropriate, capable, and willing both to participate in a pilot bus project and to provide FC buses to replace the overall bus fleet of the mining route at a later stage can be seen.

In early 2021, the following list of potential FC bus manufacturers could be compiled. All of them have been approached in order to learn about their interest and preparedness in the foreseen pilot project and following fleet roll-out:

- Buses4future
- Fanalca
- Foton
- Hyundai
- Hyzon
- King Long
- Lightning eMotors
- Mercedes / Evobus
- New Flyer ADL / MCI
- Safra
- Solaris
- Toyota / Caetano
- Van Hool
- VDL

- Wrightbus / Bamford Bus Company (BBC)
- Yutong
- Zhongtong

Many of the FC bus manufacturers responded that their current focus is on other world regions and/or other vehicle segments with regard to the implementation of fuel cell technology. Only very few did not answer on the request at all and two, even interested in FC bus activities in Chile, declined to be listed in a public report due to the company's non-disclosure policy. Some of the FC bus manufacturers show very high interest in participating in an according activity and provided the requested information e.g., specification sheets of currently available FC buses. For those, chapter 3 will further elaborate on the information provided in a structured manner, manufacturer by manufacturer.

There is also a number of Chinese manufacturers of inter-urban FC buses which are expected to mainly serve the home market. An overview of the various manufacturers and models is provided in Annex II attached to this report.

2.2.2 Letters of Interest of stakeholders and general Chilean market potential

In order to arrange the approach of the potential fuel cell bus manufacturers as attractive as possible, the client was asked to provide meaningful and convincing Letters of Interest (LoIs) of relevant stakeholders such as mining companies and mining route bus operators. This was an ongoing process throughout the analysis phase and finally LoIs could be received as given in Table 2:

Table 2: Received Letters of Interest (LoIs)

Company	Stakeholder role	Comments
Corporación Nacional del Cobre de Chile (CODELCO)	Mining company	2 mining routes (San Gabriel & El Salvador) hardly to be serviced with BEVs
Big mining company in Central Chile	Mining company	

Furthermore, and also to stimulate the interest of potential fuel cell bus manufacturers, a side exercise to generate a rough estimate on the market potential for fuel cell buses in Chile which have to fulfil these specific mining route conditions (Table 3) has been performed. Even if it is for sure not complete, it enables a rough idea of the potential overall demand.

Table 3: Market potential in Chile and implementation timeline

Mining route bus operator	Total buses / coaches	For servicing mining routes	ZEV targets	Comments
Tandem	~1,700	~850 (60+ for servicing Minera Escondida)	50% in 2025	Mining route operation market share ~40%
Buses Hualpen	~1,200 (~700 in coach buses)	~350	No targets yet	Although they have not yet set targets, they have been evaluating with customers the costs of different technologies to reach a ZEV fleet. They are interested in implementing this type of technology.
Others		~1,000		
Total Chile	**?**	**~2,200**	**-**	**-**

3 EVALUATION AND VERIFICATION OF THE FC BUSES' TECHNICAL CHARACTERISTICS

3.1 Evaluation of technical characteristics under mining route and climate conditions

This chapter documents the information provided by FC bus manufacturers with regard to the products and vehicles currently available or under development as well as the interest of the manufacturers to supply FC buses coping with the extraordinary requirements of the envisaged mining route. The FC bus manufactures are in an alphabetical order and this order does not imply any ranking.

3.1.1 B4F

Buses4Future (B4F) is a German start-up company focused exclusively on hydrogen powered fuel cell buses. They want to present all interested users and customers an attractive, future-oriented offer for fuel cell electric buses. They offer emission-free mobility and see themselves as the company with overall responsibility for the whole customer project. For this they work closely and trustingly with a consortium of medium-sized companies.

B4F FC bus profile:

General company information	
Company short name	B4F
Company official name	Buses4Future GmbH
Company website	https://buses4future.com/
Contact person 1	Dr. Hans Hermann Schreier
Position	Managing Partner
e-mail	hermann.schreier[at]buses4future[dot]com
Contact person 2	Susanne M. Schreier
Position	Partner
e-mail	susanne.schreier[at]buses4future[dot]com

General FC bus / coach information	
FC bus / coach experience	Prototype operating for 2 years in real world public transport application (see also https://www.kfw.de/stories/economy/start-ups/buses4future/); Q4 2021: delivery of 3 FC buses to the city of Münster / Germany; Production capacity: 40 buses p.a. from 2022
FC bus / coach types available	Type I (12 m LF)
FC bus / coach types under development	Type I (12 m LE, 18 m LF)
Fuel cell partner	HyMove / Netherlands
Specific information	Company fully dedicated to hydrogen powered fuel cell drive trains; video available at https://www.youtube.com/watch?v=Xfsdr5roBGA
Further documentation available	Yes, German presentation

"Off the shelf" specification	
Model	12 m LF
Hydrogen tank technology	Type III / service pressure 35 MPa
Battery technology	NMC
FC system nom. power	45 kW, 60 kW and 90 kW
Battery capacity	63.5 kWh
Bus peak power	180 kW
Torque	2,100 Nm
Driving range (per 1 refuelling)	> 400 km
Hydrogen consumption	< 6.5 kgH_2/100 km
Refuelling time	15 min

Interest & Commitment	
Interest in Chilean activity	Yes
Manufacturer's commitment	B4F claims to be in a position to enable fuel cell bus / coach operations at the requested sea level and gradients

Technical approach to service demanding mining route	
Issue(s) to be solved	The use of hydrogen FC buses at high altitude encounters specific problems. Most FC engines for automotive applications require air supply at pressures between 2,000 and 4,000 mbar absolute pressure. Given that the average atmospheric pressure at an attitude of 3,000 meters is around 700 mbar, the pressure rise factor by the compressor must be between 3 and 6. Conventional compressors for FC engines do not offer this pressure factor and FC engines will not reach their nominal power at 3,000 m altitude.
Proposed solution	HyMove FC engines are equipped with a patented control software, which adapts automatically for operation at higher altitude. HyMove FC engines are uniquely fit for operation at 3,000 m altitude, because they operate at an absolute pressure level below 1,300 mbar. At atmospheric pressure of 700 mbar, the air compressor only needs to reach a pressure factor below 2.

Project approach and next steps	
Proposed approach	1) Coach bus concept development including specification sheet 2) Engineering and prototype manufacturing 3) Short-term testing in Germany / Austria 4) Adapted development and production of 5 - 10 coach buses 5) Accompanied operation in Chile 6) Framework contract for the supply of >> 100 coach buses in cooperation with local partners
Next steps	B4F stands ready for next steps.

3.1.2 Fanalca

Fanalca SA is a Colombian company and its name means "National Factory of Bodyworks". In keeping with its initial company name today, due to its diversification, the name does not really reflect the wide field of activities that the company carries out in the industrial and commercial area. The company originates from the metalworking sector and as a business group it is also manufacturing auto parts, motorcycle parts, pipe bodies, garbage compactor boxes, vehicles for passenger transport and the collection and transport of solid waste (Source: Wikipedia; further company information available at https://fanalca.com/nosotros/).

Fanalca FC bus profile:

General company information	
Company short name	Fanalca
Company official name	Fanalca S.A.
Company website	www.fanalca.com
Contact person 1	Eduardo Cando
Position	Director de Electrificación
e-mail	ercando[at]fanalca[dot]com

General FC bus / coach information	
FC bus / coach experience	Fanalca expects to have a prototype available by JUN/JUL 2022 for performance testing
FC bus / coach types available	-
FC bus / coach types under development	Fanalca prepares to offer Class I, II or III FC vehicles
Fuel cell partner	Toyota
Specific information	Body can be updated according to comfort requirements of the end user
Further documentation available	Yes: Spec sheet FANALCA FC eBUS as well as a Fanalca company presentation

"Off the shelf" specification	
Model	FANALCA FC eBUS
Hydrogen tank technology	Hexagon
Battery technology	NMC high power
FC system nom. power	60 kW
Battery capacity	140 kWh
Bus peak power	230 kW
Torque	1,400 Nm (continuous); 3,000 Nm (peak)
Driving range (per 1 refuelling)	450 km (depending on energy required for HVAC and gradients)
Hydrogen consumption	1.2 g/sec
Refuelling time	12 min

Interest & Commitment	
Interest in Chilean activity	Yes, interested to get to know the terms and conditions about a potential pilot project
Manufacturer's commitment	-

Technical approach to service demanding mining route	
Issue(s) to be solved	-
Proposed solution	There are no issues about altitude as the FC stack can work up to 3,400 m.a.s.l. (with derating) that can be compensated by the battery; up to 2.500 m.a.s.l. can be achieved without derating.

Project approach and next steps	
Proposed approach	Discuss and define potential pilot project
Next steps	Establish relevant contacts

3.1.3 Foton

Beiqi Foton Motor Co., Ltd. is a Chinese company which designs and manufactures trucks, buses, sport utility vehicles and agricultural machinery. It is headquartered in Changping, Beijing, and is a subsidiary of the BAIC Group (Source: Wikipedia).

Foton FC bus profile:

General company information	
Company short name	Foton
Company official name	Beiqi Foton Motor
Company website	www.foton-global.com
Contact person 1	Alvaro Yu
Position	Sales administrator
e-mail	yuchenguang[at]foton.com[dot]cn
Contact person 2	Cristián Contreras (Andes Motor (Kaufmann Group); Foton distributor in Chile)
Position	Electromobility Manager
e-mail	rcontreras[at]kaufmann[dot]cl
Distributor in Chile	Andes Motors / Kaufmann Group

General FC bus / coach information	
FC bus / coach experience	In 2008, Foton successfully developed the first-generation hydrogen fuel cell bus and served the Beijing Olympics; in 2014, it produced the second-generation 12-meter hydrogen fuel cell bus; Foton has shipped several hundred FC buses to Zhangjiakou, alpine events city of the Beijing Winter Olympic Games 2022; then, Foton developed the third-generation 8.5-meter hydrogen fuel cell bus. In 2021, Foton will ship its first 12m 70 MPa fuel cell city bus to Australia.
FC bus / coach types available	Currently Foton has 12 m fuel cell urban bus/inter-urban buses in their portfolio which they plan to export to the Chilean market
FC bus / coach types under development	on demand
Fuel cell partner	SinoHytec (Toyota technology)
Specific information	Until now, Foton has not been operating fuel cell coach buses in Chile, however, they are extremely interested in this market and are preparing to offer their products to Chile
Further documentation available	Yes: Spec sheet for Foton 12m hydrogen fuel cell coach buses (for Beijing 2022 Winter Olympics)

"Off the shelf" specification	
Model	BJ6122FCEVUH, two axles
Hydrogen tank technology	70 MPa, the total volume is to be confirmed
Battery technology	LMO (MGL)
FC system nom. power	2 x 40 kW
Battery capacity	60.26 kWh
Bus nominal power (engine)	120 kW
Bus peak power	n.a.
Torque	n.a.
Driving range (per 1 refuelling)	550 km
Hydrogen consumption	n.a.
Refuelling time	15 - 20 min

Interest & Commitment	
Interest in Chilean activity	Yes
Manufacturer's commitment	-

Technical approach to service demanding mining route	
Issue(s) to be solved	Foton has not yet operated their coach buses on a high altitude. The routes they are operating is the public transport of Zhangjiakou (urban bus) and the coach buses designed for Beijing 2022 Winter Olympics (inter-urban bus) shuttles between Beijing and Zhangjiakou.
Proposed solution	-

Project approach and next steps	
Proposed approach	Foton stands ready for any further discussions
Next steps	-

3.1.4 Hyundai

Hyundai's fuel cell experiences:

Hyundai is a multinational vehicle manufacturer with a presence in 193 countries, employing more than 75,000 people worldwide. Hyundai has been developing fuel cell technology for more than 25 years and is driving the boundaries of zero emission transportation with hydrogen fuel cell technology in heavy-duty, as well as light-duty, transit, off-road and other applications. Globally, Hyundai is the only OEM offering a Class 8 fuel cell truck for commercial operations to fleet operators. Furthermore, Hyundai has a research and development campus dedicated to hydrogen fuel cell technology in the city of Mabuk in South Korea.

Hyundai's FCEV Vision 2030 plan includes $6.7 billion in investments to increase its annual global fuel cell manufacturing capacity to 700,000 fuel cell systems per year. The company is a demonstrated leader in the industry; it is one of the 13 founding members of the Hydrogen Council - a global coalition of leading energy, transport, and industry companies with a united long-term vision to foster the transition to hydrogen.

Nationally, Hyundai has a strong presence in the industry and market in the United States and in California. Hyundai has participated in multiple demonstration projects sponsored by the U.S. Department of Energy to promote the development and use of hydrogen vehicle technologies. Hyundai was the first OEM to introduce light-duty fuel cell vehicles in the California retail market in 2014 with the Hyundai Tucson Fuel Cell (which was the first serial produced fuel cell vehicle worldwide), followed by the second-generation light-duty fuel cell SUV, the Nexo, in 2018. It is important to note that these were the first commercially leased customer operated fuel cell vehicles (prior deployments of other light-duty fuel cell vehicles were part of demonstrations of non-commercially available products). Hyundai is also a founding member of the California Fuel Cell Partnership (CAFCP), and one of the project team members, Jerome Gregeois, is the current chairman of CAFCP.

The European version of the XCIENT fuel cell truck has already been sold commercially in Switzerland with 50 of these trucks deployed in 2020. An additional 140 vehicles will be deployed in 2021, with the goal to put 1,600 trucks into service by 2025. Trucks currently in service are pulling 40 t of gross vehicle weight over Swiss mountain passes, with excellent performance results, as evidenced by driver satisfaction and expanded orders from transport companies. As of 02 JUL 2021, XCIENT fuel cell trucks logged over 1,600,000 km in commercial service, avoiding an accumulated 630 tons of CO_2 emissions.

Hyundai's interest in participating in a potential pilot project:

Hyundai is highly interested in participating in a pilot project. Hyundai has participated in multiple demonstration projects and is still participating in several on-going projects at initial stage working with countries who have both the needs and the investment plans for energy transition including green hydrogen. Hyundai asks for understanding that due to the company's non-disclosure strategy no vehicle specifications or other more detailed information can be shared. Hyundai already has a sales representative in Chile (Indumotora)

Hyundai's capabilities and ideas to provide solutions which are capable to fulfil the challenging requirements (e.g., high altitude, long distance, high gradients) of the specific mining route under discussion):

To answer this question at the current state, Hyundai can only share the following rough estimation of their R&D department:

It is possible to operate the fuel cell system at high altitudes, but limited performance has to be expected due to a limited current of the fuel cell. After the kick-off of a project, Hyundai would look into all the details of the various conditions and would evaluate in-depth in order to find a solution considering the overall performance of a commercial vehicle operation.

3.1.5 Hyzon

Hyzon Motors Inc. (NASDAQ: HYZN) was established as a new business of Horizon Fuel Cell. Hyzon is a global supplier of zero emission hydrogen fuel cell powered commercial vehicles, including heavy duty trucks, buses and coaches. It was known as the Heavy Vehicle Business Unit (HVBU) of Horizon and was responsible for the development of fuel cell systems and the delivery of about 500 fuel cell powered commercial vehicles during 2019 and 2020, leveraging the deep and extensive experience bolstered within the group (Source: Hyzon Motors website).

Hyzon FC bus profile:

General company information	
Company short name	Hyzon
Company official name	Hyzon Motors Inc.
Company website	https://hyzonmotors.com/
Contact person 1	Cory Shumaker
Position	Business Development - Americas
e-mail	cory.shumaker[at]hyzonmotors[dot]com
Contact person 2	André Lagendijk
Position	Sales Manager Europe
e-mail	andre.lagendijk[at]hyzonmotors[dot]com

General FC bus / coach information	
FC bus / coach experience	Hyzon (through the Horizon HVBU) has deployed ten 12 m city buses accumulating over 250,000 km to date (JUL 2021). Hyzon has developed a 50-seat coach bus (the first of 10 for Fortescue Metals Group in Australia) and completed 64 days of testing, consisting of 15,300 km loaded to ~19 t (42,000 lb), at the National Automotive Test Centre in China. The fuel cell coach bus consumed 1,350 kg of hydrogen. Testing included high speed running, fuel economy tests, air conditioning tests, static running (recharging with fuel cell), incline, decline, park brake, corrugations, salt water, etc. HYZON maintained a test-log showing all maintenance and repair actions. The test-log has been shared with the customer. (Source: Automotive World, Hyzon)
FC bus / coach types available	Hyzon currently offers 40’ and 60’ (12 m and 18 m) low-floor city bus models and 50-seat coach buses available for several global markets. Zero emission with fast refuelling, enabling cities to replace diesel bus fleets with zero emission equivalents, without any impact on operating routes and depot facilities. Clean, quiet, efficient and available now. Based on extensive experience from Hyzon Motors and their high-quality international bus partners, they are able to deliver high quality vehicles with best-in-class safety to international standards.
FC bus / coach types under development	Fortescue Metals Group has contracted for up to 10 of Hyzon’s custom-built coach buses in the Christmas Creek mining hub, where summer temperatures commonly exceed 43°C (110°F).
Fuel cell partner	Horizon Fuel Cells (Parent company of Hyzon Motors)
Specific information	While most “fuel cell bus” deployments around the world have been centred around city bus operations, the Hyzon fuel cells designed for trucking are a perfect fit for coach bus operations, where higher sustained speeds and longer driving routes are typical. Many customers are looking for at least 400 km driving range in coach buses, and only hydrogen fuel cells can ensure, this can be achieved with zero emissions. Hyzon coach buses offer superior performance compared to diesel coach buses, and provide improved passenger amenity through zero emission and quieter operations. To the operators, Hyzon fuel cell coach buses offer a compelling alternative to the traditional vehicles, with significant savings in maintenance to be expected, and competitive total cost of ownership based on hydrogen supplied through the Hyzon partner network. Hyzon is setting up coach bus assemblies in USA and Europe, to complement the existing assembly capabilities in Asia.
Further documentation available	Hyzon Coach Bus Brochure & Hyzon City Bus Brochure

"Off the shelf" specification	
Model	HYZON Coach
Hydrogen tank technology	26 kg / 35 MPa
Battery technology	Lithium-ion
FC system nom. power	80 kW continuous
Battery capacity	141 kWh
Bus peak power	350 kW
Torque	n.a.
Driving range (per 1 refuelling)	300 km
Hydrogen consumption	8.7 kg/100km
Refuelling time	n.a.

Interest & Commitment	
Interest in Chilean activity	Interested probably from summer 2022 onwards
Manufacturer's commitment	"What you are looking for is a development of a special fuel cell coach bus that can handle steep inclines, long distances and high altitude. That is not something we are able to spend time developing at this moment. We would like to eventually offer this product and see great demand for it in Chile, however at this time there are other higher priority products we're spending our resources on."

Technical approach to service demanding mining route	
Issue(s) to be solved	n.a.
Proposed solution	n.a.

Project approach and next steps	
Proposed approach	n.a.
Next steps	Check-in with Hyzon towards the end of this year

3.2 Evaluation of technical characteristics reflecting necessary vehicle modifications

It became clear throughout the course of the analysis that none of the FC bus manufacturers has a suitable solution for operating the demanding route at hand. Furthermore, also the discussions on necessary vehicle modifications remained at a very general level. That is well understood as on one hand manufacturers have not yet started any design and/or development activities in this regard and on the other hand this is proprietary knowledge and therefore critical to be shared publicly. Therefore, a comparison respectively an evaluation of the specific FC buses was not possible in the course of this project. As already mentioned above, the potential FC manufacturers do not have this information at hand, and if so, they would not be willing to share them without having an NDA signed.

At least a few of the FC bus manufacturers shared their first ideas concerning challenges they do expect and which approach they would adopt to overcome them.

B4F for example expects that the FC system (HyMove) they are using would not face any issues due to the low ambient air pressure at this high altitude as the HyMove FC systems are equipped with a patented control software, which adapts automatically for operation at higher altitude. They state that these FC systems are fit for operation at 3,000 m altitude, because they operate at an absolute pressure level below 1,300 mbar. At atmospheric pressure of 700 mbar, the air compressor only needs to reach a pressure factor below 2.

Fanalca as a further example concedes that the operation of a FC system at those heights would go along with a derating of the system. 2,500 m.a.s.l. can be achieved without derating. With derating the FC system can be operated up to 3,400 m.a.s.l. Fanalca's first level approach foresees the integration of a battery system that can compensate the performance reduction of the derated FC system.

As information to be gathered from FC bus manufacturers was quite limited, a literature research was performed in order to provide information on the challenges to be expected, on solutions that have been proposed and on experiences already gathered. The results of this literature research are presented in the following subchapters.

3.2.1 Environmental Impact of High Altitudes on the Operation of PEM Fuel Cell Based Unmanned Aerial Vehicles (UAS) [Albayati et al. 2018]

In this paper, the impact of directly using extracted air from the atmosphere at high altitudes to feed the stack is investigated, and the governing equations of the supplied air and oxygen to the PEM fuel cell stack are developed. The impact of high altitudes upon the operation and the consumption of air are determined in order to maintain a certain level of delivered power to the load. Also, the implications associated with operating the PEM fuel cell stack at high altitudes and different technical solutions are proposed. Various modes of Integral, Proportional-Integral, and Proportional-Integral-Derivative controller are introduced and examined for different time setting responses in order to determine the most adequate trade-off choice between fast response and reactants consumption which provides the necessary optimization of the air consumption for the developed model of PEM fuel cell used for UAS operation.

3.2.2 Fuel cell bus operation at high altitude [Spiegel et al. 1999]

In an effort both to address air quality problems relating to vehicle emissions in Mexico City and to ascertain the effects of the environment (air pollution and high altitude) on the operating characteristics of fuel cell powered vehicles, a seminar/exposition and a demonstration of clean vehicles were held in Mexico City in June 1997. The seminar and exposition addressed the state of the art of several clean vehicle technologies, including one of the most promising: the proton exchange membrane (PEM) fuel cell engine. The demonstration consisted of the display and operation of the world's first full-size, zero emission, PEM fuel cell powered transit bus, which was built by Ballard Power Systems. The paper describes the bus performance in the atmospheric environment of Mexico City.

Main conclusions of this paper:

The operation of a PEM fuel cell bus in Mexico City (2,240 m) was compared to Vancouver, British Columbia (approximately at sea level):

- Mexico City contains 25% less oxygen than at sea level, which results in performance degradation. The air flowing through the fuel cell provides the oxygen necessary to sustain the electrochemical reaction and also carries the water that is produced by the reaction. If the air flow is inadequate, the output power of the fuel cell is reduced by a too low oxygen concentration in the air stream. The presence of excess water can block air passages within the fuel cell, further aggravating the problem.

- A comparison of the compressor pressure shows that the general characteristics of the compressor outlet pressure are similar for both cities. However, the maximum pressures obtained in Mexico City are lower, especially at higher compressor motor speeds.
- The measurement of the air mass flow versus compressor speed for bus operation reveals that the flow rate is substantially lower for the bus operation in Mexico City, with the gap getting larger as the compressor speed increases.
- The air flow through the air subsystem is also one of the factors that contributes to compressor temperature regulation. It was found that the reduced air flow, particularly at high power levels, caused the compressor temperature to increase to a point where the system instrumentation would go into the alarm mode. For the bus's Vancouver operational data, the temperature rise is well distributed across the entire pressure range. For the Mexico City case the temperature increase is clearly higher.

Overall, the PEM fuel cell powered bus operated as anticipated in Mexico City, given the conditions present at the altitude. The reduction in output power as result of the lower atmospheric pressure was expected. However, the degree of the compressor over-heating problem was underestimated. The system was designed to accomplish this with ambient atmospheric pressures found from sea level up to modest elevations. The solution would be to re-size the air subsystem to provide adequate air flow in an environment of reduced ambient pressure. As a general conclusion of the operating experience in Mexico City, there does not appear to exist any reason for fuel cell buses not to operate successfully in this environment.

3.2.3 Performance of proton exchange membrane fuel cell at high-altitude conditions [Pratt et al. 2007]

The effects of oxygen concentration and ambient pressure on fuel cell performance are explored both in theory and in experiment. For fuel cells in general the effect due to a change in oxygen concentration is shown to be fundamentally different than the effect due to a change in cathode pressure, even if partial pressure is held constant. For a proton exchange membrane fuel cell, a significant reason for this difference comes from the nature of mass diffusion processes in the fuel cell structure, which infers that there is an optimum fuel cell design (macroscale and microscale) for a given operating pressure and oxygen concentration. In the experimental work a proton exchange membrane fuel cell was subjected to varying atmospheric conditions from sea level to 16,307 m with results analysed up to 10,668 m. The results showed that at low current density operation a decrease in either cathode pressure or oxygen concentration led to an increase in irreversible losses associated with reaction kinetics (activation polarization) and confirmed the differing effects of cathode pressure and oxygen concentration.

Consideration of all these effects enables both fuel cell- and system-level optimization of aeronautical fuel cell-based power systems.

3.2.4 Experimental Performance of an Air-Breathing PEM Fuel Cell at High Altitude Conditions [Pratt et al. 2005]

Analysis of the feasibility of using fuel cells in unmanned aerial vehicles (UAVs), auxiliary power for jet-propelled aircraft, and propulsive and/or auxiliary power for long endurance aircraft applications demands accurate predictions of fuel cell behaviour at the conditions encountered in the flight scenarios of each of these applications. This paper presents the final results and conclusions of an experiment whose setup and preliminary results were presented at the 2003 Fuel Cell Seminar in Miami Beach, Florida on 03-06 NOV 2003.

Experimental setup: the fuel cell used in the experiment was an annular-type proton exchange membrane fuel cell (PEMFC) from DCH Enable Fuel Cell Corp. The air side (cathode) of this fuel cell is passive, meaning there is no mechanical fan or blower conveying air to or away from the cathode. The hydrogen side (anode) is dead-ended, meaning all the hydrogen entering the anode compartment is either consumed by the fuel cell reaction, or wasted due to leakage.

Main conclusions of this paper:

It was observed that as ambient pressure was decreased to simulate the pressures at high altitudes, fuel cell performance was degraded. The primary mechanism responsible for this was found to be due to the reaction kinetics (activation losses). Mass transfer effects were found to be minor in comparison, and really only were noticeable in the extreme condition of low pressure and low air flow. An unexpected, but statistically insignificant positive impact of lower pressure was observed for high external resistance (low fuel cell load) conditions. Interesting interactions were observed between the resistance of the external circuit, the flow rate of air across the fuel cell, and ambient cathode pressure. For example, at pressures close to sea level, the air flow did not have a significant impact in the range investigated, but higher air flows at low ambient pressures clearly increased performance.

3.2.5 PEMFC application for aviation: Experimental and numerical study of sensitivity to altitude [Hordé et al. 2012]

The feasibility of PEMFC integration to aircraft raises several difficulties such as the loss of performance due to altitude and ambient pressure decrease. An aerobic PEMFC system is experimentally investigated at three different altitudes representative of aircraft cruise (200 m, 1,200 m and 2,200 m), and at different air stoichiometric factors (from 1.5 to 2.5). The experimental results are employed to perform fitting of PEMFC numerical model parameters and validation of the model. A least square method is implemented in a Matlab code to determine one set of model parameters for all experimental data sets. The model based on literature is modified in order to better represent the effect of ambient pressure on voltage response. Comparisons of experimental and numerical results are presented and show good agreement. Fuel cell performance is found to decrease drastically as altitude increases, as well as air stoichiometric factor decreases. The air pressure in cathode gas channels is measured and analysed. The decline of PEMFC performances in altitude is due to ambient pressure decrease, to air compressor efficiency drop and to flooding in the gas channels. This PEMFC loss of performances is attenuated by high cathode stoichiometric factors.

Main conclusions of these experiments:

These experiments lead to the conclusion that the FC's power decreases as the altitude is increased. A drastic power loss (50% and over) was observed for low air stoichiometric factors, due to a major decline of the maximum operable current. This decline in maximum operable current is most probably due to water management problems. The decline in maximum operable current is triggered by a low single cell voltage (voltage below 0.5 V) observed on the same single cell for every experiments. This effect of low single cell voltage is, according to the author's experience, due to the obstruction of cathode channels by water droplets. The FC's power loss due to altitude can be lowered by increasing the air stoichiometric factor. So, at λ_c = 2.5, the power loss at 2,200 m is only 8%.

The overall system efficiency is also found to decrease with altitude. Even though it is proven that increasing the air stoichiometric factor allows to reduce the power loss due to altitude, it may not be possible to operate the FC system at much higher altitude by increasing even more the air stoichiometric factor (over 2.5). Indeed, by increasing the air stoichiometric factor, the membrane tends to dry out at some point, because of the air flux removing the water contained in the membrane electrode assembly. Furthermore, compressor power needs risk to become excessive. Therefore, the H_2/air system has an intrinsic maximum operable altitude, that was not determined here.

3.2.6 On Direct Hydrogen Fuel Cell Vehicles - Modelling and Demonstration [Haraldsson 2005]

In this thesis, direct hydrogen Proton Exchange Membrane (PEM) fuel cell systems in vehicles are investigated through modelling, field tests and public acceptance surveys. A computer model of a 50 kW PEM fuel cell system was developed. The fuel cell system efficiency is approximately 50% between 10 and 45% of rated power. The fuel cell auxiliary system, e.g., compressor and pumps, was shown to clearly affect the overall fuel cell system's electrical efficiency. Two hydrogen on-board storage options, compressed and cryogenic hydrogen, were modelled for the above-mentioned system. Stored in pressurized, well-insulated tanks, hydrogen must be heated in order to obtain the system operating temperature.

Main conclusions of this master thesis:

The control strategy, duty cycles and ambient conditions affected the performance of the fuel cell vehicle in different ways. In terms of dimensioning fuel cell system components, three parameters were shown to be important:

- The limiting factor for the water balance was the maximum ambient air temperature, here 40°C. The relative humidity did not have a significant impact on the water balance.
- The limiting factor for the heat management was the minimum ambient air temperature, here 5°C. This was more pronounced in the high-power demanding US06 cycle and for the condenser and radiator.
- The limiting factor for the overall vehicle performance, i.e., the fuel consumption, was the maximum altitude of 3,000 m.

The water capacity in this study was a function of the size of the water reservoir and the control strategy of the condenser fan.

The fuel consumption increased by 10 to 19 % at increasing altitude from 0 to 3,000 m, depending on the duty cycle. This increase in fuel consumption was mainly attributed to the performance of the compressor. The load-following strategy of the compressor and the reduced pressure at high altitude force the machine to work harder and its power demand may rise up to 40 % at very high elevations.

3.3 Analysis of supply scheme for buses, components, and spare parts

The status of deployment of FC buses for those specific mining routes is by far too immature to discuss supply schemes for buses, components, and spare parts with the potential FC bus manufacturers. In parallel to the preparation and initiation of a pilot project (see chapter 3.4), a study on the market potential for these specific FC buses is highly recommended.

It should take into account at least the following aspects:

- Separate consideration of mining route services and public transport
- Segmentation of mining routes with regard to
  - maximum altitude
  - route length
- Investigation of current developments in BEV technology as improvements there may eat up the market potentials of FC buses
- Service schedules and operation patterns of buses in order to analyse if long charging times of battery electric buses lead to advantages of fast-refuelling FC buses
- Permitting requirements for BEV charging parks versus for FCB hydrogen refuelling stations at the mines and along the roads and in urban areas.

Furthermore, the boundaries for this market study are to be chosen very careful. As this market is not limited to Chile, it should at least include Argentine, Peru, and Bolivia which are dealing with comparable situations.

Such a study on the market potential would require the cooperation and input of the mining companies and the bus operators servicing the mining routes.

Only with such a study on the market potential at hand a serious projection for a supply scheme for FC buses is possible which then should be developed together with the most engaged FC bus manufacturers. This supply scheme would then also deal with the supply of specific components (if relevant) and the provision and stocking of spare parts enabling an undisturbed and smooth operation of the vehicle fleets.

3.4 Recommendations regarding partners for pilot project and roll-out

3.4.1 Operators' experiences with battery electric buses and problems identified

Bus operators in Chile have started the incorporation of electric buses over time. As an emerging technology, the problems are related in first place to the limited supply of buses by manufacturers and distributors that operate in the country. Some of the main problems are caused by an immature knowledge about the technology (engineering, logistics, maintenance, spare parts, etc.). Furthermore, the management of long charging times that endanger maintaining the availability of the fleet according to services promised are regarded as an additional obstacle. As most critical operational aspect was identified the hilly terrain with slopes greater than 15% which prevented the operators from maintaining the design speed and thus from complying with the scheduled operating times.

The high investment into the buses and into the charging points and mainly the autonomy restriction inherent to the buses currently available on the market combined with the long charging times are seen as an operational and financial challenge.

The incorporation of another technology that allows to eliminate these restrictions in autonomy would open the opportunity to consider the use of (fuel cell) electric buses in operations that currently have not been considered, precisely for this reason.

3.4.2 Study on market potential

As already indicated in chapter 3.3, preparing a study on the market potential of FC buses considering these very specific requirements of operating at high altitudes, long driving range and fast refuelling is recommended. Furthermore, also the specific requirements for hydrogen refuelling stations for (larger) fleets are to be considered, in comparison to space requirements, charging procedures, electrical installations and power demand for fleets of battery electric buses of the same size. It is of high importance and required to attract the various stakeholders, mainly the FC bus manufacturers. The manufacturers have to evaluate and decide if the efforts necessary to develop, produce and certify these products are justified by the expected market potential. If the market potential is too small, it might become difficult to motivate manufacturers to invest in such developments.

In addition to the aspects already provided in chapter 3.3, the study on the market potential should also elaborate on synergies that might exist for the operation of fuel cell systems in the power range of 50 – 150 kW in these high altitudes. These synergies could exist in power generation (stationary or mobile fuel cell systems), other on-road vehicles such as cars and trucks or in mining equipment (CAEX, loaders, cranes, tractors, dump trucks, etc.).

3.4.3 Initiation of pilot project

3.4.3.1 Required consortium

A successful consortium for a pilot project to operate FC buses on a mining route should ideally comprise

- a mining company,
- a mining fleet bus operator,
- a FC bus manufacturer,
- an HRS manufacturer,
- an HRS operator, and
- a hydrogen supplier.

If it is not possible that both a mining company and a mining fleet bus operator can join the consortium, it is a prerequisite that at least one mining company or one mining fleet bus operator is on board. They have to be the driving forces behind the project as they will be the customers of the FC buses.

Having a FC bus manufacturer on board of the consortium is not a prerequisite for a viable project. This is depending to some extent on the envisaged financing scheme. If a FC bus manufacturer can bring own resources e.g., due to specific public funding it might make sense to get the manufacturer on board of the project. If this is not the case, the project consortium has the free choice to select the most appropriate provider after the evaluation of concrete offers.

Hydrogen refuelling station manufacturer, hydrogen refuelling station operator and hydrogen supplier can all be in the hand of one single company or split up into up to three entities. That will be defined by the early birds in this field joining the consortium in an early phase. Keeping these three topics in one hand would of course reduce and simplify the complexity of the overall project but requires that the related partner has all required capacities and competencies combined under its roof.

3.4.3.2 FC bus manufacturers & mining fleet bus operators

All relevant contacts, the ones established to the various FC bus manufacturers interested in participating in an upcoming pilot project (see chapter 3.4.3.2) and the ones established to the most progressive mining fleet bus operators in Chile, need to be maintained.

The current paragraphs highlight specialties of the various FC bus manufacturers that have evidenced interest in participating in pilot and follow-on activities on Chilean mining routes. At this stage, data availability is insufficient to give clear recommendations for the one or the other manufacturer and decision making needs to take place at the right point in time following an overall approach (see chapter 3.4.3.4). Therefore, the following listing is in alphabetical order.

<u>B4F</u>

- Fast reacting start-up with very high commitment
- Fully dedicated to FC drivetrains and potential access to German funding schemes

<u>Fanalca</u>

- Very high commitment and regional proximity
- Convinced that current technology is already appropriate to serve high altitudes with some derating that can be compensated with batteries

<u>Foton</u>

- Extremely interested in Chilean market and preparing to offer products to Chile
- FC coach bus product already available

<u>Hyundai</u>

- Highly interested in participating in a pilot project
- FC coach bus (model Univers) to be introduced into the Korean market in 2022 and FC trucks already in commercial operation

<u>Hyzon</u>

- Fully dedicated to FC drivetrains and large experiences in heavy-duty FC applications
- FC coach bus product already available

3.4.3.3 Route selection

Great attention should be devoted to the selection of the mining route(s) for the pilot project. On one hand, it should be somewhat challenging that it cannot be served easily with battery electric buses, on the other hand it should be not too demanding for FC buses in order to attract several potential FC bus manufacturers. Here it might be wise for a first phase in the pilot project to choose a route that has to cover a long distance (or a tight schedule with limited room for charging), but does not incorporate high altitudes above 2,500 m.

This can be seen as trust building measure between the mining companies, the bus operators and the FC bus manufacturer and gets all of them acquainted with the next, more challenging steps namely the FC bus operations at the high altitudes.

During the course of the analysis also starting pilot projects on intercity connections has been discussed. Due to decreasing passenger figures caused by the COVID-19 pandemic and the resulting economic pressure on the public road transport sector this sector is not expected to be a frontrunner in the implementation of FC bus technology in Chile. Nevertheless, in the long run this sector may offer a market size in at least the same order of magnitude as the mining sector. Therefore, companies offering inter-urban / inter-city services may jump on as soon as cost for FC buses and hydrogen infrastructure are down, market players are well established and "the rules of the game" are better known.

3.4.3.4 Approach

After the finalisation of this prefeasibility analysis, it is highly recommended to initiate a study on the market potential for this specific type of buses as already outlined in chapter 3.4.2.

This study should provide the potential FC bus manufacturers (and all other stakeholders involved) with the expected market sizes for specific market segments (clusters) defined by technical requirements (e.g., max. altitude, max. driving range, max. gradient) that should allow them to compare their development and production efforts with the potential turnover to be generated.

The most important and challenging part of this exercise is the segment definition as, if done wisely, it already constitutes the key specifications for the later FC bus designs. Therefore, FC bus manufacturers should be involved or at least consulted for this process step.

A compromise has to be found for the definition of the segment borders that are on one hand appropriate for a wide range of applications respectively routes (segment's market size) and on the other hand do not cause an overengineering of the FC buses (and thereby too high costs) for most applications in this segment. An illustration of this route segmentation approach proposed is depicted in Figure 10. The maximum gradient of the routes could be introduced as a 3rd dimension.

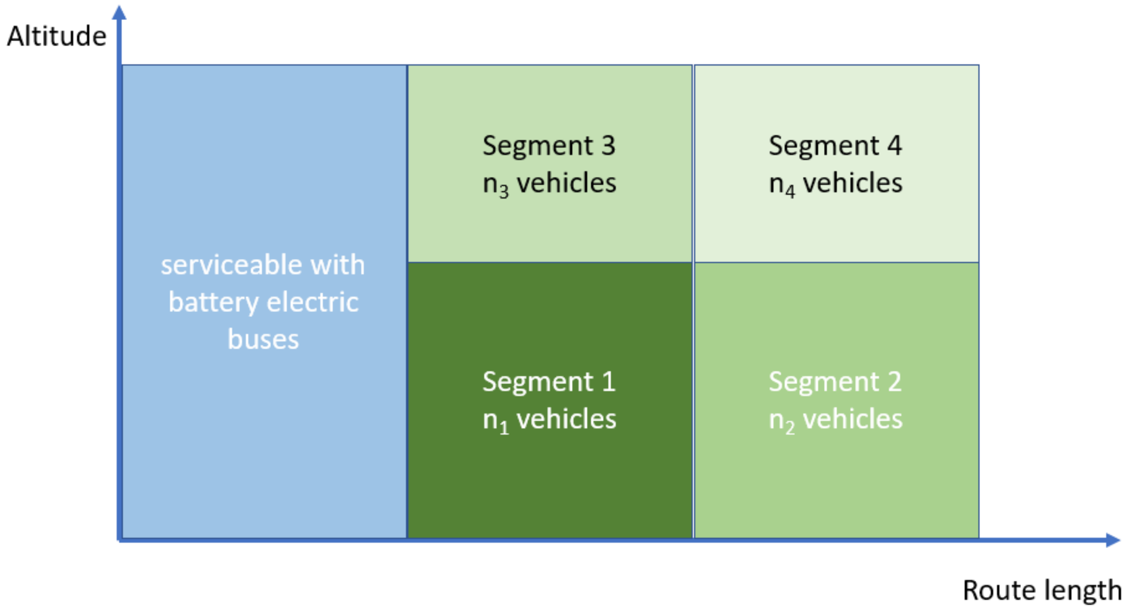

Figure 10: Market segmentation based on route length and maximum altitude of route

Without such a study at hand, it is very difficult to define the pilot project properly. The definition of the FC bus design (specification) would be more or less arbitrary and knowledge on the market size related to the bus design would not exist. Therefore, it might become difficult to convince FC bus manufacturers to engage and commit themselves to such a pilot project.

The market study should take not more than 6 months' time.

A pilot project should be initiated in the most promising segment that involves the best ratio between bus manufacturer's development and production efforts and the expected turnover.

For the chosen market segment (see above) the most demanding framework conditions should be applied to compile a route specification which is then applicable to all routes in this segment.

Based on this route specification a simulation should be run taking also the most extreme environmental conditions (cold winter day, hot summer day, day with highest slipperiness) into account in order to achieve the core information (e.g., max. power demand, average power demand, power recovery possibilities, etc.) required for drafting the vehicle specification and finally for the drivetrain design. The outcome of this step should be a fully developed FC bus concept including an FC bus specification which is appropriate to be sent to potential FC bus manufacturers in order to request offers. Based on these offers the consortium has to take the decision with which FC bus manufacturer the consortium wants to proceed as supplier (in case the FC bus manufacturer is not part of the project consortium).

The next step towards a pilot project would involve the FC bus engineering and prototype manufacturing according to the specification. This prototype vehicle should then undergo a thorough testing at and around the manufacturer's facilities and testing tracks and at adequate test benches. If required, adaptations and further development are to be performed, upfront to the production of a 5-10 FC bus test fleet for the pilot project to be performed on an appropriate mining route in Chile. The FC bus manufacturer should closely accompany the pilot fleet operation in order to enable a smooth and fast transition of the lessons learned from real-world operations to the initiation of the series production of these specific FC buses taking place in parallel.

In case of a successful pilot project a framework contract for the supply of a significant number of these specific FC buses should be signed to enable the manufacturer to set up an according production line. If deemed appropriate, local partners could be involved. Furthermore, the pilot project should also serve as a showcase to attract further customers which have to serve comparably challenging bus routes.

If, but this was not in the focus of this analysis, stakeholders are keen on initiating a pilot project earlier on, this might be possible by selecting FC buses already available on the market and an appropriate, less demanding route. This should already result in numerous lessons learned and real-world experiences. Especially for the hydrogen supply and infrastructure build-up it could be of enormous value. Furthermore, the commercial contacts required for the later more challenging route services could be already established.

3.4.4 Initiation of fleet deployments

The initiation of fleet deployments is strongly depending on the development of the preceding activities, mainly the pilot project. A successful pilot project is of course a prerequisite for starting a fleet deployment. But as with the pilot project, the hand-in-hand roll-out of the FC vehicles and the hydrogen refuelling infrastructure is key. If infrastructure falls behind, appropriate hydrogen refuelling cannot be safeguarded; if vehicle roll-out is too slow, underutilized hydrogen infrastructure causes high hydrogen costs.

Therefore, some vehicle suppliers e.g., in the truck sector are already offering pay-per-use cost models to allow for a risk sharing by all shareholders involved in the production, handling and dispensing of hydrogen and the operation of the FC buses.

In any case: even at the very beginning of fleet deployments it has to be assured that the operation of FC buses is financially viable for the fleet operators as this is their core business. If the viability can be secured on its own, via clever cost sharing models or if it requires public support or industrial cross financing, is not the decisive factor for a successful implementation.

Furthermore, and as already mentioned above, the vehicle deployment has to watch out for potential synergies with e.g., other hydrogen customers at the same geographical area (see chapter 3.4.2) in order to bring costs further down.

4 LITERATURE

[Albayati et al. 2018]	Albayati, Ibrahim; Ali, Rashid; Zhang, Hongwei: Environmental Impact of High Altitudes on the Operation of PEM Fuel Cell Based UAS, Energy and Power Engineering, 10. 87-105. 10.4236/epe.2018.103007, 2018, last download on 16 JUL 2021, https://www.researchgate.net/publication/324083458_Environmental_Impact_of_High_Altitudes_on_the_Operation_of_PEM_Fuel_Cell_Based_UAS.
[Haraldsson 2005]	Haraldsson, K.: On Direct Hydrogen Fuel Cell Vehicles - Modelling and Demonstration, Doctoral Thesis, KTH - Royal Institute of Technology, Department of Chemical Engineering and Technology, Energy Processes, Stockholm, Sweden, last download on 17 JUL 2021, https://www.diva-portal.org/smash/get/diva2:7360/FULLTEXT01.pdf
[Hordé et al. 2012]	Hordé, T.; Achard, P.; Metkemeijer, R.: PEMFC application for aviation: Experimental and numerical study of sensitivity to altitude, International Journal of Hydrogen Energy, Volume 37, Issue 14, 2012, Pages 10818-10829, ISSN 0360-3199, availability checked on 17 JUL 2021, https://doi.org/10.1016/j.ijhydene.2012.04.085
[Pratt et al. 2005]	Pratt, J.; Brouwer, J.; Samuelsen, G.: Experimental Performance of an Air-Breathing PEM Fuel Cell at High Altitude Conditions, 43rd AIAA Aerospace Sciences Meeting and Exhibit - Meeting Papers, 10.2514/6.2005-953, 2005, availability checked on 17 JUL 2021, https://doi.org/10.2514/6.2005-953
[Pratt et al. 2007]	Pratt, J.W.; Brouwer, J.; Samuelsen, G.S.: Performance of proton exchange membrane fuel cell at high-altitude conditions, *Journal of Propulsion and Power*, 23(2), 437-444, 2007, last download on 17 JUL 2021, https://escholarship.org/uc/item/2g62m8k9
[Spiegel et al. 1999]	Spiegel, R. J.; Gilchrist, T.; House, D. E.: Fuel cell bus operation at high altitude. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *213*(1), 57–68, 1999, availability checked on 17 JUL 2021, https://doi.org/10.1243/0957650991537437

Annex I – Preliminary Vehicle Specification

Item	Requirement
Operation at high altitude	Adequate operation at 3,200 m.a.s.l.
Gradability	Mastering gradients of up to 18%
Average speed	Achievement of average speed of 50 km/h uphill for the given route profile
Fuel consumption	(Please provide expected route specific hydrogen consumption taking limited energy recovery into account)
Chassis Model	Type Heavy Duty (HD)
Engine	Fuel Cell Drive Train
Transmission	Automatic
Axes	2 axes
Performance	100 km/h, with limiter
Suspension	Front, rear, shock absorbers, stabilizer bar
	Pneumatic
	Vehicle height regulation
Fuel autonomy	200 km (uphill, see route specification)
Max. refuelling time	15 min (implying according HRS capability)
Max. turning radius	21 m
Year equipment manufacturing	New equipment
Type of bus	One floor
Dimensions (length x width x height)	13.00 x tbd. x 3.80 m
Passenger capacity	44+1 Passengers
Cabin and passenger separation	YES
Non-slip floor	YES, washable
Interior luggage rack	YES
Exterior luggage rack	Minimum two, with independent opening on both sides, vertical offset
Free distance between seats	37 +/- 2 cm minimum referential
Bathroom (WC)	No
Windscreen	Front shatterproof with defogger, according to NCh 70 to 80% visibility
	No rear windshield
Lights	Dashboard and instrumentation
	Low
	High
	Parking
	Emergency
	Brake
	Positioning / pulling / height
	Turning
	Reverse
	Front / rear fog lamp
	Patent
	Upper Access
	Lower Access
	Steps in access ladder
	Upper cab (different intensities and independent of the other lights)
	Other lights
	Driver's compartment
	Emergency exit indicator
	Upper passageway different intensities
	Lower passageway different intensities
	Reading by seats
	Seat numbering
	Luggage rack

Item	Requirement
	Engine compartment
Commands	Dimmable dashboard lights
	Speedometer
	RPM meter
	On/off light selector
	Two-speed windshield wiper plus one intermittent speed
	Odometer
	FC system temperature indicator
	Energy (recovery) indicator
	Fuel level indicator
	Tire pressure indicator
	Drive train failure warning
	Maintenance warning
	Side / rear view mirror with electric controls
	Battery charge indicator
	Kilometers of autonomy available
	Headlight indicator lights on
	Digital clock
	Power cut-off
	Parking brake
	Windshield washer
	Key start system
Steering wheel	Cruise control
	On-board computer control
	Horn
	Air bag (no exclusive)
	Adjustable steering wheel
	Ergonomic steering wheel
	Anti-slip
	Collapsible column
Driver's seat	Ergonomic seat type
	Head rest
	Adjustable height
	Adjustable back rest
	Cushioning
	Heavy duty fabric
Pneumatics	Radial M+S
	22.5" hoop
	Spare wheel
	Mud guard
	Nut blocker
Digital tachograph	Speed
	Time on track
	Stops
	Distances travelled
	during 24 hrs 7 days minimum
	USB download or other digital media
	Calibration certificate
Main door	Right front
	Single sheet
	With minimum 35% glass
	With plate
	Non-slip bus access sill
	Lateral displacement
	Pneumatic operation
	Exterior / interior opening command
Secondary door	Separation of cabin / users
	With glass
	With handle

Item	Requirement
	Handrail right side
Batteries	Maintenance free
	With terminal covers
	Power cut-off in conductor compartment
	Fastening to structure
	Location in external compartment
Bodywork	Anti-corrosive epoxy coating on lower exterior
	Front and rear pull hooks
	Thermal insulation
	Self-extinguishing and fire retardant
	Bus interior noise level according to current law
	Water tightness of the bus according to regulations
Fuel	Power supply must not pass inside the passenger compartment
Seat belt	Driver's seat belt: three-point seat belt, factory-fitted
	Passenger seat belt: three-point seat belt attached to the seat
	Retractable and with collision restraint
Rear view mirrors	One on each side of the bus
	Electrically adjustable from cab
	Auxiliary panoramic
	Defroster (anti-fogging)
	Internal rear view mirror in cab
	With auxiliary indicator and courtesy light
Brake	Service with ABS system
	Parking
	Choking
	Retarder
Side glasses	Shatterproof 50% visibility
	With solar protection
	Single plane
	No-move windows
Accessories	Parking sensor
	Back-up alarm between 65 and 85 db
	Rear camera with driver's dashboard display
	Passenger USB port
	Non-slip brake and accelerator pedals
	Driver cup holder
	Sunshade on both sides
	Illuminated information sign
	Interior luggage rack
	Windshield wiper
	Audio system for cab and body MP3, AM, FM, CD
Passenger seat	Arm rest on both sides
	Rocker type foot rest
	High density sponge cushion 8 cm thick
	Without cup holder
	Head rest cover
	Reclining back rest
	Magazine pocket
	Heavy duty fabric
	Width 43 cm; +2 cm; -1 cm
Air conditioning system	Cool / heat: minimum summer 15°C and maximum winter 25°C
	Upper, lower, independent from each other, and upper injection for each seat

Item	Requirement
Security	Side emergency exit
	Upper emergency exit
	Fire extinguisher in body (passengers)
	Fire extinguisher in cab
	Automatic fire extinguisher in engine compartment
	Audible alarm for starting without seat belt for driver and desirable panel light for passenger seat belts as an indication to the driver
Other requirements	Transport vehicle identification number
	Reflective tape
	Impact protection film
	GPS (speed monitoring system): only preparation for the future installation by the operator
	Cargo securing systems (protective nets, slings, belts, boxes or trunks)
	Non-slip wedges (2 per vehicle)
	Road cones (4 per vehicle) and reflective triangle
	Pole with flashing light and flag
	Beacon
	Rear-view spotlight
	Current cut-off device
	Automatic fire extinguishing system in the engine compartment (suppressor)
	Certification ECE R 66.02

ANNEX II – OVERVIEW OF CHINESE INTER-URBAN FC BUS MANUFACTURERS

Manufacturer	Model	Year	Length [m]	Range [km]	FC Power [kW]	Storage Pressure [MPa]
Asiastar	YBL6818HFCEV	2018	8.11	300	30	35
	YBL6818HFCEV	2019	8.11	300	30	35
Foton	FC Club Bus	2016	8.52	--	--	35
	FC Club Bus blue	2017	8.52	--	--	35
	FC Intercity Bus blue	2017	8.52	--	--	35
	FC Intercity Bus EV100 Forum 2018 [BJ6852U& Club Bus]	2018	8.52	--	--	35
	BJ6906FCEVUH-1	2019	8.995	--	114 Toyota	?
	BJ6906FCEVUH-1	2020	8.995	650	60 SinoHytec	?
	BJ6956FCEVUH	2020	9.55	?	80 SinoHytec	?
	BJ6116FCEVUH-1	2020	10.99	1,100	60 SinoHytec	?
	BJ6122FCEVUH	2020	12.00	?	2 x 40 Toyota	70
SunLong	SLK6903AFCEVH	2018	8.995	?	? SinoHytec	?
	SLK6128AFCEVH	2019	11.995	?	? SinoHytec	?
	SLK6128AFCEVH SMTD.BAAS	2020	11.995	?	? SinoHytec	?
Xiamen Golden Dragon	XML6112JFCEV20	2019	10.99	?	? Troowin	?
	XML6112JFCEV20	2020	10.99	?	? Troowin	?
Young MAN	JNP6850LFCEV	2019	8.50	?	?	?
Yutong	ZK6826FCEVQ1	2016	8.245	?	? SinoHytec	35
	ZK6906FCEVQ1	2018	8.995	?	? Re-Fire	?
Zhongtong	LCK6900FCEV	2017	8.995	?	?	?
	LCK6720FCE	2019	7.20	400	30 SinoHytec	? [120 l]
	LCK6117	2020	10.69	?	?	35 [24.8 kg]
Zhongzhi	SPK6890FCEVP	2018	8.99	?	? SinoSynergy	?
	SPK6891FCEVP SPK6891FCEVP1	2018 2019 2020	8.99	?	? SinoHytec	?

COMPANY PROFILE OF LBST

Ludwig-Bölkow-Systemtechnik GmbH (LBST) is an expert consultant for sustainable energy and mobility. With our expertise bridging technologies, markets, and policy we support international clients from industry, finance, politics, and non-governmental organisations in strategy, feasibility, and market assessments. International blue-chip companies trust in our reliable judgment.

Our cutting-edge competence is based on over three decades of continuous experience, and on our interdisciplinary team of leading experts.

LBST supports its clients with

SYSTEM & TECHNOLOGY STUDIES	techno-economic assessment; due diligence; energy and infrastructure concepts; feasibility studies;
POLICY CONSULTING	techno-economic assessment; future scenarios and strategies; analysis and support to the development of regulatory frameworks; evaluations;
STRATEGY CONSULTING	product portfolio analysis, identifying new products and services; market analysis, decision support, and policy support;
SUSTAINABILITY CONSULTING	life cycle and carbon footprint analysis; natural resources assessment (energy, minerals, water); sustainability due diligence;
COORDINATION	project management, monitoring and assessment; and
CAPACITY BUILDING	studies, briefings, expert workshops, trainings.

Particular expertise exists in energy (renewables, energy storage, hydrogen and fuel cells) and mobility (fuels and drives, infrastructure, mobility concepts), with our work in sustainability cutting across all sectors.

A key common denominator of all activities is the rigorous system approach, making sure all relevant elements of a tightly networked system are taken into account, providing our customers with a comprehensive and complete basis for their decisions.

With our deep understanding of developments and technologies and our truly independent advice, we help our clients with sustainable decisions to secure their future.

Ludwig-Bölkow-Systemtechnik GmbH

Daimlerstrasse 15 · 85521 Ottobrunn · Germany
phone: +49 89 6081100 · fax: +49 89 6099731
email: info@lbst.de · web: http://www.lbst.de