The Program for Renewable Energies and Energy Efficiency in Chile

Potential of Article 6 and other financing instruments to promote Green Hydrogen in the Steel, Cement and Mining Industries

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LIST OF Abbreviations

CAEX : High-tonnage mining trucks

CAPEX : Capital expenses

CDM : Clean Development Mechanism

CF : Capacity factor

CMA : Conference of the Parties serving as the meeting of the Parties to the Paris Agreement

Ez : Electrolyser

GHG : Greenhouse gases

H2V : Green hydrogen

IPCC : Intergovernmental Panel on Climate Change

ITMO : Internationally Transferred Mitigation Outcomes

LCOE: : Levelised cost of electricity

LCOH : Levelised cost of hydrogen

MOPA : Mitigation Outcome Purchase Agreement

NCRE : Non-conventional renewable energy

NDC : Nationally Determined Contributions

OPEX : Operating expenses

PPA : Power Purchase Agreement

RE : Renewable energy

TCO : Total Cost of Ownership

TRL : Technology Readiness Level

1 Introduction

1.1 Context

In recent years, interest in hydrogen has focused on its capacity to reduce greenhouse gas (GHG) emissions in sectors of the economy where mitigation is the most challenging (Government of Chile, 2020) by considering sustainable methods of production in which hydrogen can be generated by renewable energy without producing GHG emissions, thus producing 'green' hydrogen (H2V) as opposed to hydrogen produced using methane, which is called grey hydrogen.

H2V is a strategic market in the Chilean Government's national energy and economic development policies. The main motivations for encouraging local production and use of this fuel are twofold: maintaining Chile's carbon neutrality target, officially set out in its updated Nationally Determined Contributions (NDC), which envisages a 21% contribution from hydrogen production and consumption to achieve carbon neutrality by 2050 (Ministry of the Environment, 2020a), and Chile's advantageous position in being able to produce H2V at competitive prices due to the low costs of electricity produced by renewable energy (RE).

International experts have thus granted Chile the status of 'hidden champion',[1] which it will seek to achieve by taking advantage of the quality and abundance of its RE, its stable business environment and its openness to free trade. Against this background, Chile launched its National Green Hydrogen Strategy[2] at the end of 2020, which declared the country's ambition to become a world leader in this new industry.

Non-Conventional Renewable Energy (NCRE)[3] has seen the highest growth compared with other energy sources in Chile's electricity grid, reaching 30% of the net installed capacity of electricity generated with about 8,000 MW by the end of 2021. Together with conventional RE sources (reservoir and run-of-river hydroelectricity), NCRE accounts for more than 50% of Chile's installed capacity, surpassing thermal power generation (coal, natural gas and diesel), which makes up around 47% of installed capacity (National Energy Commission, 2021). The country has a non-subsidised approach to developing an RE market, which has been strengthened since 2016 through competitive tenders for Power Purchase Agreements (PPAs) with long-term regulated customers, reducing the price of electricity for these customers.

In this scenario, private-sector actors have swiftly entered into RE purchase contracts enabling Chile to be one of the most competitive H2V producers in the world, with the potential to generate it at one of the lowest costs globally at USD 1.6/kg H_2 in the long term (IEA, 2019).

Over the last decade, and particularly in recent years, the country has implemented policy frameworks to address energy planning strategically. For example, its National Energy Policy 2050 (Ministry of Energy, 2016) is a long-term proposal that has been included as a key input in various areas of work on decarbonisation.

Projections indicate that H2V will be competitive, compared with grey hydrogen, within the next 10 years (Hydrogen Council, 2021). Accordingly, the main challenge is to secure investment and foster the development of new H2V projects in the country. Although conditions are promising for the

[1] The country is endowed with abundant renewable resources, providing a cheap supply of low-carbon electricity. Against this background, the International Energy Agency's (IEA) 2019 publication, *The Future of Hydrogen*, estimated that Chile can deliver 160 million tonnes per year of H2V, calling the country 'the hidden champion'.

[2] Available at: https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

[3] Non-Conventional Renewable Energy Sources (NCRE) are defined as wind, small hydro (plants up to 20 MW), biomass, biogas, geothermal, solar and ocean energy (Government of Chile, Ministry of Energy, 2021).

implementation of H2V projects in Chile, there are a number of gaps and challenges in adopting this type of energy to meet local demand. These are listed below (Hydrogen Council, 2021):

- high upfront costs and perceived financial risks;
- a lack of market signs to mobilise domestic/internal demand;
- the need to modernise existing infrastructure to support the development of H2V projects in the industry;
- the need to adapt the H2V regulatory framework further to take account of environmental, health and safety regulations.

Article 6 of the Paris Agreement (hereafter Article 6) recognises that its signatory countries may voluntarily choose to cooperate in the establishment of global carbon markets, in which emission reductions achieved through projects in one country can be purchased by other jurisdictions to meet their climate targets and thus provide an additional source of revenue for GHG mitigation projects. This form of transfer is known as Internationally Transferred Mitigation Outcomes (ITMOs). These Article 6 cooperative approaches provide a significant opportunity to attract international funding for H2V projects, enhancing and complementing traditional forms of financing.

The case studies on H2V projects in this report are analysed in the context of these Article 6 carbon markets, in which sales of certified emission reductions help to close the projects' economic feasibility gap (the amount that helps the project reach a net zero present value for the project's assessment period), contribute to technology transfer, generate economic returns and help to increase the level of ambition in relation to climate commitments and sustainable development.

Alongside carbon markets, other climate financing instruments, such as blended finance, can facilitate the mobilisation of private capital for innovative H2V projects. The main characteristics of blended finance mechanisms are that: (i) they comprise mixed or blended instruments, including traditional financial and de-risking[4] instruments used to create a hybrid structure; (ii) they reduce investment risk by efficiently allocating the project's risks to investors based on their risk-return expectations; and (iii) they manage to attract funds that would not otherwise be available were it not for this combination specially devised for these purposes.

The logic behind these mechanisms is to use concessional finance, mainly from public sources, such as multilateral funds, generic or thematic climate funds and national funds, to attract and leverage the involvement of commercial private capital, such as banks, private equity funds (institutions that provide capital to develop companies or businesses) and venture capital (private capital and a method of financing where investors provide capital to emerging and small companies with growth potential), among other financing structures for climate change adaptation or mitigation projects.

1.2 General objective

This study's objective is to produce technical inputs to develop pilot initiatives for international carbon markets and other alternative climate financing instruments created under Article 6 of the Paris Agreement, with case studies on the use of H2V in GHG emission-reduction projects in the cement, steel and mining industries.

As part of this study, a preliminary strategy has been developed to bring the adoption of these applications in each of the industries closer to the market, considering derivative financial instruments based on Article 6 as well as other blended finance mechanisms.

[4] De-risking financial instruments help investors to manage or mitigate the investment risk, generally for a fee, thus improving the perceived risk-return profile.

1.3 Description of the methodology

The methodology starts with a techno-economic analysis of three H2V applications linked to the cement industry, the steel industry and the transport of personnel in the mining industry, with the main input being the previously calculated levelised cost of hydrogen (LCOH). For each case, cost projections (CAPEX and OPEX) and a sensitivity analysis for critical variables are used to establish the optimal configurations for each model (Step 1 in Figure 1-1). This allows us to calculate each project's expected profitability and identify the main variables affecting that return (Step 2 in Figure 1-1). The analysis is a prospective exercise designed to help formulate pilots and evaluate their suitability as mitigation options able to generate certified offsets. The aim of this study is not to conduct an economic evaluation that enables an investment decision to be made as the different variables exhibit a high degree of uncertainty.

The information can be used to generate relevant technical inputs when formulating pilot climate financing initiatives. These inputs include technical specifications for each project setting out details of the design, methodology and calculation of emission reductions based on the Clean Development Mechanism (CDM) methodology baseline materials, which are chosen according to their relevance to each case study. These specification documents consider the following important elements: types of GHG emission mitigation actions, important conditions for the application of the methodology and definition of the baseline and project scenario. The aim is to meet the Paris Agreement requirements to prevent double counting and to safeguard the principles of environmental integrity, additionality, transparency and sustainability.

When calculating the GHG emission-reduction potential, there is a baseline for the certified emission reductions that could be obtained from the projects (Step 3 in Figure 1-1). Based on this information, and the results of the techno-economic assessment, a minimum price range is determined that the certificates should reach to close the economic feasibility gap of these H2V emission-reduction projects (Step 4 Figure 1-1).

This is followed by a survey with information on historical global carbon prices for various national instruments (CO_2 taxes and the social cost of carbon) and international carbon market instruments, both mandatory and voluntary. This, along with various projections developed at the international level, allowed scenarios for certificate prices to be generated under Article 6 for different time scales (Step 5 in Figure 1-1). The feasibility gap after the sale of the certificates is then reassessed ending with the carbon markets' contribution to the financing of the H2V projects selected (Step 6 in Figure 1-1).

The business model being developed assumes payments from a country that seeks to purchase certified emission reductions through ITMOs. This potential transaction provides a source of revenue that makes the projects more attractive and easier for developers to obtain the necessary upfront financing.

Finally, financing schemes are proposed based on carbon markets and other possible climate financing instruments, such as debt at preferential rates (soft debt), guarantees to cover technological or credit risks, grants or technical assistance. The proposed financing scheme is also based on blended finance for each application, with the aim of narrowing the projects' feasibility gap and improving their risk-return ratio.

Categories of financial instruments are identified to close the feasibility gap (and therefore make each final application more competitive) and to mitigate each initiative's endogenous risks. These are all the risks that the project developer can control to a certain degree (such as technological or credit risks) (GIZ, 2020). This analysis provides an understanding of where each project stands in terms of mobilising private finance to implement each case (Step 7 in Figure 1-1).

A summary of the methodology can be found in Figure 1-1:

Figure 1-1 Working methodology

Source: compiled by the authors

Translation:

Paso 1 – 7	Step 1 – 7
Análisis técnico-económico de las aplicaciones industriales del H2V y estimación del LCOH considerando diferentes escenarios	Techno-economic analysis of the industrial applications of H2V and estimate of the LCOH in different scenarios
Estimación de la rentabilidad esperada y brecha de viabilidad de los proyectos, identificando las principales variables que afectan a cada iniciativa	Estimate of the projects' expected profitability and feasibility gap, identifying the main variables affecting each initiative
Estimación de la reducción de emisiones de cada proyecto basada en la adaptación de metodologías internacionales	Estimate of each project's emission reduction by adapting international methodologies
Determinación del precio que deben tener los certificados para superar la brecha de viabilidad económica de los proyectos	Determination of the price needed for the certificates to close the projects' economic feasibility gap
Contraste con lo que se podría acceder en la realidad basándose en precios históricos y proyectados del carbono	Contrast with what could be achieved in reality based on historical and projected carbon prices
Evaluación de la contribución de los mercados de carbono y determinación de las brechas tras la venta de reducción de emisiones	Evaluation of the contribution of carbon markets and assessment of gaps after the sale of emission reductions
Propuesta de esquemas de financiamiento basados en los mercados de carbono	Proposed carbon market-based financing schemes

2 Techno-economic description of the selected case studies

The aim of this section is to examine how applicable H2V production may be to each selected industry (cement, steel and personnel transport in mining) by analysing the main costs and variables of H2V production. A model was therefore designed to provide information on the operating and investment costs of different H2V production projects in Chile (see Annex 2). The LCOH is calculated at the point when the hydrogen is produced by the electrolyser, so it is assumed that **neither storage** nor other costs associated with the final application are included. From a technical perspective, this assumption has significant implications for the results and should be considered as a sensitivity factor in a future analysis proposal.

This model has been applied to three geographical areas in the country and covers short-, or 'Present', (2020); medium- (2030) and long-term (2050) scenarios. The scenarios differ according to the year in which the project starts. The data and information sources for each case are specified in this report, while the data used for the scenario are the most up-to-date International Energy Agency (IEA) figures (IEA, 2020b).

The levelised hydrogen costs are the main input used to analyse the final H2V applications in the selected industries and are explained in detail in Annex 2.

There is a high degree of uncertainty in the model's projections and therefore in the results obtained. The main sources of uncertainty are set out below.

- Capital expenses (CAPEX) associated with the use of H2V. The model factors in the costs of replacing burners in furnaces, purchasing a fleet of buses and other technology needed to use H2V in the industry in question. They were estimated based on available sources and may vary from the current or future market reality, depending on the readiness of some technologies.
- Actual CAPEX associated with H2V production. The electrolyser and NCRE technology costs were estimated based on information currently available and may vary from current or future market realities. The scenarios and assumptions used to calculate the CAPEX for use and production are set out in Annex 3, Annex 4 and Annex 5 for the cement and steel industries and for personnel transport in the mining industry.
- Electricity costs. These are calculated based on production factors at representative power plants for each case study in Chile, and according to the projected investment costs in Chile's Long-Term Energy Policy (Ministry of Energy, 2021). In an actual project, these could vary considerably depending on the location, the need for electricity transmission or removing economies of scale for smaller projects. Annex 2 shows how electricity costs affect H2V production and consequently the project's feasibility gap.
- H2V transport costs. A scenario has been chosen for H2V production that is very close to the point of use. The transport cost was therefore not included, making this an optimistic assumption. In practice, compressed hydrogen may need to be transported by truck and electricity delivered through the transmission system, which would increase the project's costs.
- Fuel costs. The price of fossil fuels varies considerably, and the savings factored into the models could, in turn, be higher or lower. The prices anticipated in the Chilean Long-Term Energy Planning (Ministry of Energy, 2021) were used to project the fuel prices. These fuel costs are discussed in Annex 3, Annex 4 and Annex 5 for each different scenario, showing their impact on the feasibility gaps.
- Economies of scale. The models used are based on the information available on the costs of large-scale technologies. For smaller-scale projects, such as buses, the prices of producing H2V could be higher. Even in these cases, the business models could vary, e.g. an electricity company could sell H2V to the transport company at a competitive price, and the transport company would only operate the refuelling infrastructure and the buses.

- Project configurations. In reality the project configurations could vary, meaning it is not just one company that invests in the power plant, H2V production and use, but different companies who coordinate with one another in each section of the value chain through PPAs, purchase and sale contracts, transport contracts, etc. The evaluation of these projects included the overall investment in the value chain, the NCRE project, the green hydrogen production plant, and any system involved in the use of green hydrogen in the case being studied.

A detailed description of each application of H2V in the cement, steel and mining personnel transport industries is provided below, together with a definition of the chosen case study and a cost-benefit analysis for each. These descriptions are then used as input for subsequent analyses.

This analysis is intended to help formulate H2V pilot projects. Its purpose is not to conduct an economic feasibility assessment or to provide guidance on investment decisions. The high level of uncertainty regarding the variables used was complemented with sensitivity analyses to offer guidance on potential differences in actual future scenarios.

2.1 Techno-economic analysis for the cement industry

2.1.1 Current state of the cement production process

The cement industry is considered to be one of the most difficult industrial sectors to abate in terms of GHG emissions, as well as being particularly exposed to the risks arising from the transition to a low-carbon economy (GIZ, 2018a). The technical characteristics of the process do not permit drastic changes in the replacement of fossil fuels or in the abatement of emissions from chemical reactions in the process since carbon release from the raw materials results in unavoidable CO_2 emissions. In Chile, two industries are identified as having sources of CO_2 emissions that exceed 0.01 million tonnes per year and which are deemed unavoidable. These are the pulp and paper, and the cement industries (GIZ, 2021).

A general introduction to the cement production process is illustrated below (Figure 2-1), as described by several different entities (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019).

- **Preparing the raw materials.** Limestone, clay, sand, iron ore and gypsum are extracted, reduced and ground in raw mills and then mixed to obtain the required chemical composition. The process produces emissions from the raw material extraction.
- **Clinker production.** The raw material mixture is fed into the precalciner and kiln, which reaches temperatures of up to 1,450°C and converts the mixture into clinker. During this process, there are emissions associated with the use of petcoke as a fuel to heat the kiln, and the chemical transformation of the limestone or calcium carbonate ($CaCO_3$) into lime or calcium oxide (CaO).
- **Mixing the clinker with other materials to produce cement.** In this process, the clinker is mixed with other additives to produce cement.

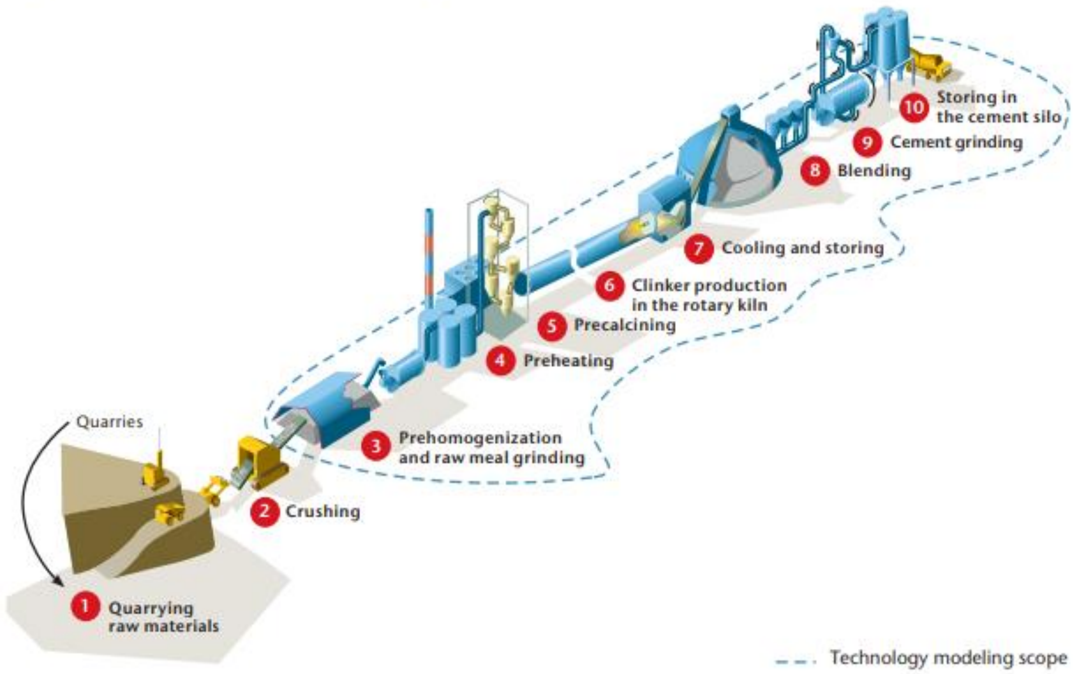


Figure 2-1 Cement production process

Source: **(International Energy Agency, 2018)**

The main companies currently competing in the Chilean cement market are Melón S.A., Cemento Polpaico S.A., Cemento La Unión S.A., Cementos Bicentenario S.A., Empresas Transex, Unicon S.A. and Cementos Biobío, with an installed production capacity of 10.4 million tonnes of cement per year. Clinker is only produced in four integrated plants (Cementos Biobío in Antofagasta, Cementos Melón in La Calera, Cementos Polpaico in Santiago and Cementos Biobío in Curicó – Teno). The remaining sites produce cement using clinker imported from other countries (mainly China) (Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020).

Cement manufacturing is an energy and GHG-intensive process, in which about 70% of total emissions are from the chemical transformation of the limestone (process emissions) and only 30% from the combustion of fossil fuels. The emissions from the chemical process of transforming the limestone cannot be avoided by switching fuel. This would require the use of technology that captures the gases emitted. At present, such technology is either not sufficiently developed for industrial use (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019) or is still in the pre-commercial development stage (GIZ, 2021).

Since the last stage in the above-mentioned process is the source of most of the emissions, the cement industry would be one of the most vulnerable to the effects of any potential green tax. This could incentivise imports of clinker from countries where environmental legislation is less stringent, increasing the cement sector's net emissions outside Chile's jurisdiction, an effect referred to as 'carbon leakage'.

The cement industry has therefore taken coordinated action to set emission-reduction targets associated with its operations. For example, the Inter-American Cement Federation (FICEM) and the Cement and Concrete Institute (ICH) have developed a roadmap for the cement production process that sets sectoral targets and identifies areas to focus on in order to reduce the emission intensities of the process (ICH & FICEM, 2019). In this roadmap, the main lines of approach are to reduce the clinker factor (use of additives in the clinker mix, allowing less clinker to be used per tonne of cement), to co-process waste as alternative fuels and to improve energy efficiency. Each course of action has different technological and process solutions, some in more advanced stages of development than others, so their relevance will depend on the market's characteristics and each operation's context.

In the context of increased urbanisation and population growth, there will be a need to develop various kinds of new infrastructure (housing, pavements, power plants and others) (IEA & CSI, 2018) and a sustained increase in demand for cement is therefore expected. The infrastructure will also need to provide the resilience and robustness needed to cope with the impact of increasingly frequent climate-related hydro-meteorological phenomena (e.g. on flood protection and prevention structures, coastal defences, hydraulic works and water management systems). Given this, technologies need to be implemented to reduce the emissions associated with cement production processes.

2.1.2 Applying H2V to the process

Latest advances in technology

A case that has aroused international interest in the use of hydrogen in the cement industry is the one developed by the company CEMEX. In July 2019, hydrogen was used in the production process in its cement plant in Alicante, Spain by injecting it into the kiln to produce clinker and thus replacing some fossil fuel use. The company in turn confirmed that it had the potential to reduce CO_2 emissions, and the technology was installed across all its plants in 2020 (CEMEX, 2021).

This process is part of the company's Climate Action Strategy where some of the goals included a 35% reduction in CO_2 emissions per tonne of cementitious materials in its global operations by 2030, a 55% reduction in emissions in its European operations and carbon neutrality by 2050.

As is well-known, oxygen is generated as a by-product when obtaining hydrogen from water electrolysis. This oxygen can be used to improve the efficiency of combustion processes, reducing the amount of fossil fuels required and, therefore, the associated emissions (CSI, ECRA, 2017). There are currently two applications where oxygen from electrolysis could be used to complement hydrogen injection.

- Oxygen-enriched processes. This technique consists of increasing the energy efficiency of the exhaust gas and the percentage of oxygen in the combustion air.
- Oxyfuel combustion: This consists of removing nitrogen from the air before the combustion process to obtain high-purity oxygen (95%), which is burned with the fuel and flue gas, making it easier to capture CO_2 afterwards (Jörn Rolker, 2011).

Despite the potential benefits of the selected application's by-product to the cement industry, these two possibilities are currently in the early stages of development and have not been described in detail in the main sector documents on low-carbon technologies (IEA & CSI, 2018). As such, they would require technological upgrades prior to implementation.

As a result, the most feasible and best-supported case to be analysed in this study is the use of green hydrogen injected to displace fossil fuels without involving the use of oxygen.

Description

The selected application consists of injecting H2V as a fuel into the kiln to produce process heat (stage 6 of Figure 2-1). As well as the advantages associated with being a low-emission fuel, this technique avoids adding moisture or emitting particulate matter (elements normally arising from the clinker production process). As a result, it could even increase the percentage of co-processing. Despite being a new application for the cement industry, it is thought to offer considerable potential for emission reduction in the combustion process.

Requirements for the implementation of H_2 injection

This application requires changing the burners in the system. The technology is currently available but has not yet been tested on an industrial scale in the cement market. It also requires designing the pipes to deliver the hydrogen to the corresponding facility.

2.1.3 Case study

The Teno plant, which belongs to Cementos Biobío and has a cement production capacity of 1.7 million tonnes per year, was chosen as a case study. The clinker/cement ratio used in Chile is 0.65, which is equivalent to approximately 1.1 million tonnes of clinker per year. For this facility, it was proposed to try switching 10% of the energy provided by fossil fuels in the clinker kiln with green hydrogen, given that CEMEX had achieved this with a similar percentage (see above). This is a conservative estimate since one study claims that the figure could even be increased to 50% (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019).

Although the southern zone is not the most economical option for green hydrogen production as it has higher levelised costs than the north or Magallanes regions (see Annex 2), it was chosen because in the opinion of industry experts[5] it would be an interesting case for the study. The operational variables were modelled using the information published by the European Cement Research Academy (CSI, ECRA, 2017).

Quantity of energy to be replaced

This case study analyses the effect of injecting H2V into the clinker kiln and replacing 10% of the energy consumption attributed to petcoke in the kiln from the first year of the project's implementation. The energy consumption (EC) was calculated as follows:

$$EC\ \left(\frac{MJ}{year}\right) = E \cdot Cap_{proj} \cdot 10\%$$

Where:

E: specific energy demand associated with the fuel (MJ/tonne clinker).

Cap_{proj}: project capacity (tonnes clinker/year)

As the project capacity is consistent in the three scenarios and equal to 1,106,047 (tonnes clinker/year), the variation in the EC is determined by the variation of E, which is equal to 3,550, 3,400 and 3,250 (MJ/tonne clinker) in the Present, Medium-term and Long-term scenarios respectively (CSI, ECRA, 2017). Thus, the quantity of energy to be replaced, based on a switch of 10%, will be equal to 109, 104.5 and 99.9 (MJ/year) in the Present, Medium-term and Long-term scenarios respectively.

Investments to adapt the furnace burners and renew the piping are included as a prerequisite for this hydrogen application.

Associated emission reduction

In this project, the reduction in emissions from the process is linked to switching the fuel. Apart from petcoke consumption, there is some co-processing involving the use of alternative fuels (AFs), such as solid industrial waste (tyres) and liquids (used lubricating oil). These AFs contribute the equivalent of

[5] Obtained during meetings with partners while preparing the study.

12.6%, the average figure for Chile in 2017 (Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020).

Figure 2-2 Emission-reduction trajectory of H2V application shows the emission-reduction trajectory for the application in tonnes of carbon dioxide equivalent (tCO_2e) for each year.

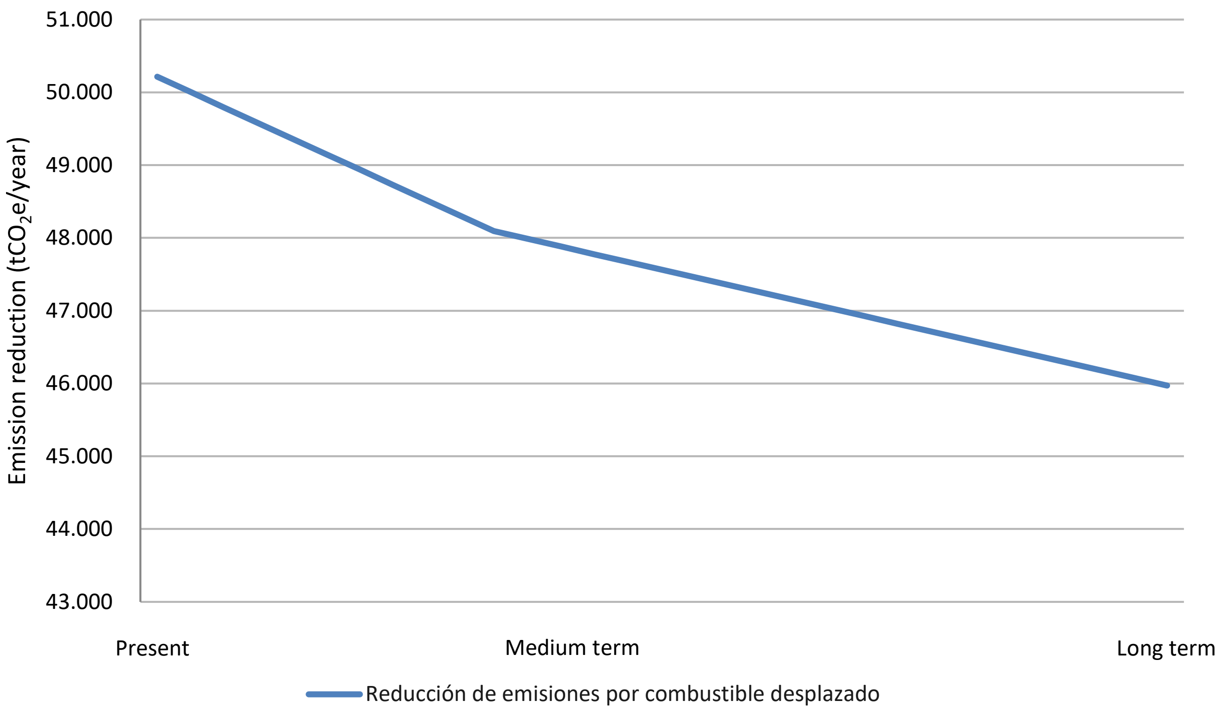


Figure 2-2 Emission-reduction trajectory of H2V application in the cement industry

Translation

Reducción de emisiones por combustible desplazado	Emission reduction achieved by displacing fuel

<u>Quantifying the demand for H2V</u>

The amount of green hydrogen required for the proposed application is determined by the following equation:

$$REQ_{H2V} = \frac{E \cdot Cap_{proj}}{CV \cdot 1.000} \cdot RK_{H2V}$$

Where:

REQ_{H2V}: demand for green hydrogen (tonnes H_2/year)
E: fuel-specific energy demand (MJ/tonne clinker)
Cap_{proj}: the cement plant's production capacity (tonnes clinker/year)
CV: calorific value of H_2 (MJ/kg H_2)
RK_{H2V}: H_2 use in rotary kiln (%)

The level of demand for H2V takes account of efficiency increases in the kiln over time and, therefore, a lower demand for fuel. This results in H2V demand of 3,272, 3,134 and 2,996 (tonnes H2/year) in the Present, Medium and Long-Term scenarios respectively.

Electricity generation and H2V production model

In this case study, it is proposed that the hydrogen production facility be located near the cement plant (point of use). The cost of transporting the hydrogen has therefore been disregarded at this level of analysis, and only minor storage costs have been included, with a minimum buffer to allow sufficient time for the fuel to be transported to the plant. However, it was decided that the NCRE generation plant would be physically located elsewhere, outside the cement and hydrogen production sectors but connected to the national electricity system (SEN) and with injection exclusively for the electrolyser. The transmission costs were therefore included and it is assumed that the hydrogen produced will therefore be classed as green.

NCRE measurements

The energy requirements need to be known before calculating the project's costs and profitability. Considering the production capacity of the plant being studied (1.7 million tonnes of cement per year) and its location (southern zone), the installed capacity required to supply the process's hydrogen demand in different scenarios is shown in Table 2-1 below.

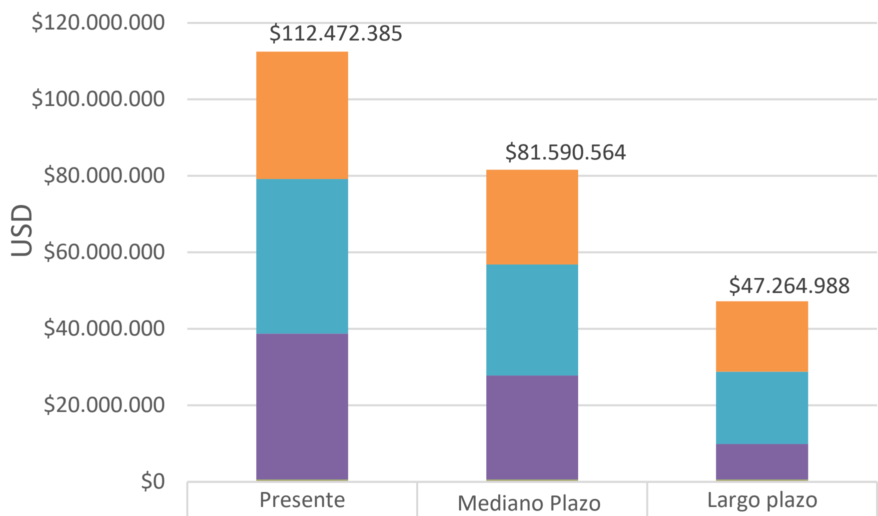
Table 2-1 Installed capacity by type of power source

Installed capacity	Present	Medium term	Long term
Quantity of hydrogen to be produced (tonnes H_2/year)	3,272	3,134	2,996
Electrolyser capacity in southern zone (MW)	44	39	35
Solar capacity to be installed in southern zone (MW)	46	41	37
Wind power capacity to be installed in southern zone (MW)	29	25	23

Source: compiled by the authors

Associated investment

The economic model developed for the case study on H2V use in the cement industry considered the investment costs associated with power generation, hydrogen production and the renovation work needed to adapt the rotary kiln. These are presented in disaggregated form below. Details of the model assumptions are set out in Annex 3.



	Presente	Mediano Plazo	Largo plazo
CAPEX generación eólica	33.244.463	24.770.860	18.488.767
CAPEX generación solar	40.496.171	29.035.719	18.884.976
CAPEX electrolizador	38.161.562	27.213.797	9.321.058
CAPEX tanque de almacenamiento de H2	191.930	191.930	191.930
CAPEX renovación de tuberías para uso de H2	96.050	96.050	96.050
CAPEX adaptación quemador a H2	282.208	282.208	282.208
Total CAPEX (USD)	112.472.385	81.590.564	47.264.988

Figure 2-3 Investment required for the use of H2V in the cement industry

Source: compiled by the authors

Translation:

Presente	Present
Mediano plazo	Medium term
Largo plazo	Long term
CAPEX generación eólica	CAPEX wind generation
CAPEX generación solar	CAPEX solar generation
CAPEX electrolizador	CAPEX electrolyser
CAPEX tanque de almacenamiento de H2	CAPEX H_2 storage tank
CAPEX renovación de tuberías para uso de H2	CAPEX pipe refit for H_2 use
CAPEX adaptación quemador a H2	CAPEX adapting burner to H_2

Figure 2-3 shows that the investment costs decrease over time, with a 42% reduction in the Long Term compared with the Present scenario. This is because the most significant costs – those associated with RE generation and the electrolyser – are expected to decrease over time due to mass production and efficiency improvements (for more information see 9.3).

TCO calculation and feasibility gap

To evaluate the project in economic terms, a lifetime of 20 years was assumed. The main analysis parameter used was the TCO, which is the cost of the investment plus operating expenses over the project's lifetime based on present-value figures for both the H2V project application case and the baseline case (i.e. not replacing petcoke with H2V). The difference in the results was used to calculate the project's feasibility gap, based on identified operational savings over the project's lifetime as a result of the switch from fossil fuel to H2V. The payback period was thus identified for each scenario.

The figures presented for the project's feasibility gap in

Table 2-2 show the negative value of the TCO difference between both scenarios (baseline case and H2V use). For all the time scenarios evaluated, there is an economic feasibility gap that will need to be covered through additional financing.

Table 2-2 Total cost of ownership and feasibility gap for H2V use in the cement industry

	Present	Medium term	Long term
TCO baseline case (USD)	$97,944,460	$75,148,477	$77,653,348
TCO H2V application (USD)	$198,754,278	$142,575,329	$107,001,022
Project feasibility gap (USD)	$-100,809,818	$-67,426,852	$-29,347,673
Payback (year)	Not achieved	Not achieved	Not achieved

Source: compiled by the authors

In the project's 20-year lifetime, there is no time scenario in which it is possible to recover the initial investment with positive cash flows from savings associated with the lower operating cost of H2V use.

Figure 2-4 shows that the gap decreases over time, so it can be assumed that unless there is additional revenue, the break-even point is reached after 2050.

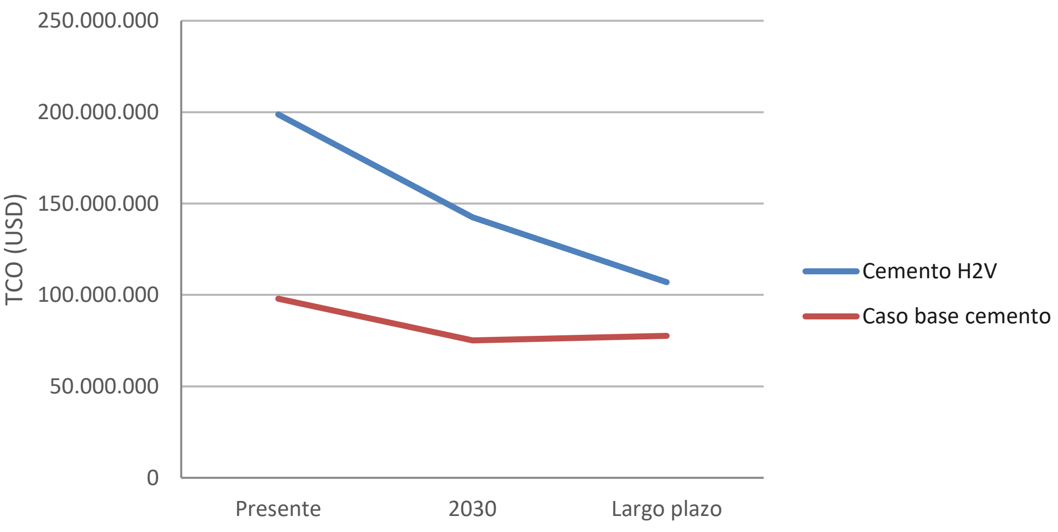


Figure 2-4 TCO comparison of hydrogen use and the baseline case in the cement industry

Source: compiled by the authors

Translation:

Cemento H2V	H2V cement
Caso base cemento	Cement baseline case
Presente	Present
Largo plazo	Long term

<u>Comparison between the baseline case and the case being studied</u>

Figure 2-5 shows the processes involved in the cement case study. Other decarbonisation opportunities in the cement process have also been incorporated by way of illustration, such as using the oxygen produced through water electrolysis to improve the combustion processes in the clinker kiln, as well as carbon capture for later use in the H2V synthetic fuel production process.

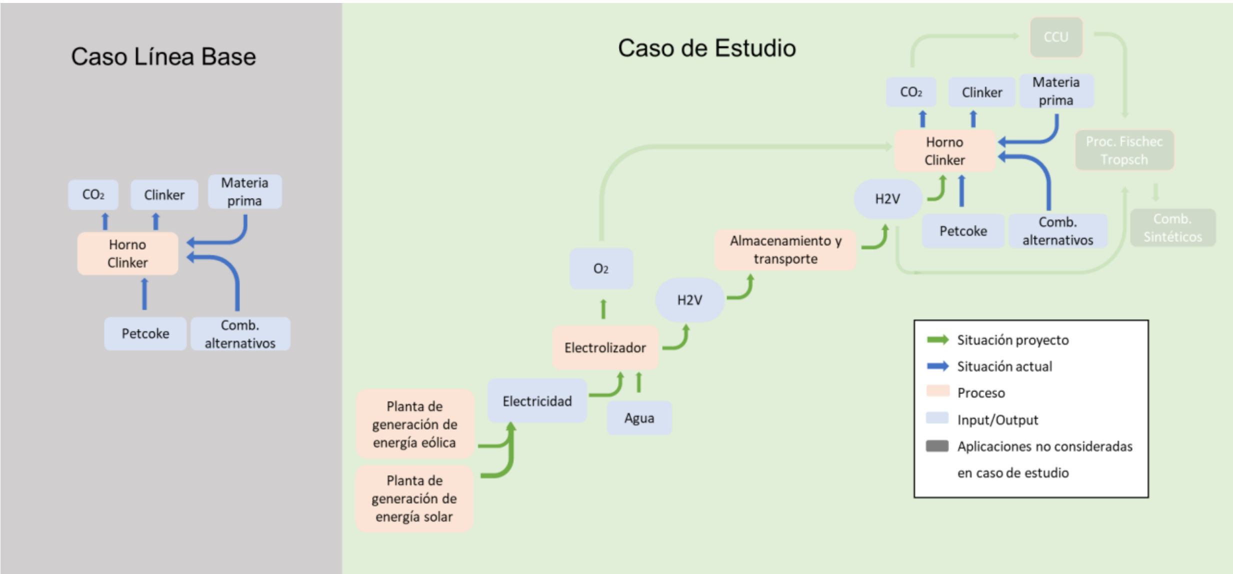


Figure 2-5 Diagram showing processes involved in the cement case study

Source: compiled by the authors

Translation:

Caso Línea Base	Baseline Case
Caso de Estudio	Case Study
Materia prima	Feedstock
Horno Clinker	Clinker Kiln
Comb. alternativos	Alternative fuels
Planta de generación de energía eólica	Wind power generation plant
Planta de generación de energía solar	Solar power generation plant
Electricidad	Electricity
Agua	Water
Electrolizador	Electrolyser
Almacenamiento y transporte	Storage and transport
Situación proyecto	Project situation
Situación actual	Current situation
Proceso	Process
Aplicaciones no consideradas en caso de estudio	Applications not included in the case study

Sensitivity analysis

Figure 2-6 shows a sensitivity analysis of the case study's main variables, which are the CAPEX of the electrolyser, the petcoke price and the CAPEX of the burners. These variable are the greatest sources of uncertainty for the cement industry. The sensitivity test is performed on the parameters independently. The horizontal axis shows the percentage change in the parameter, and the vertical axis is the feasibility gap calculated in the earliest scenario (Present).

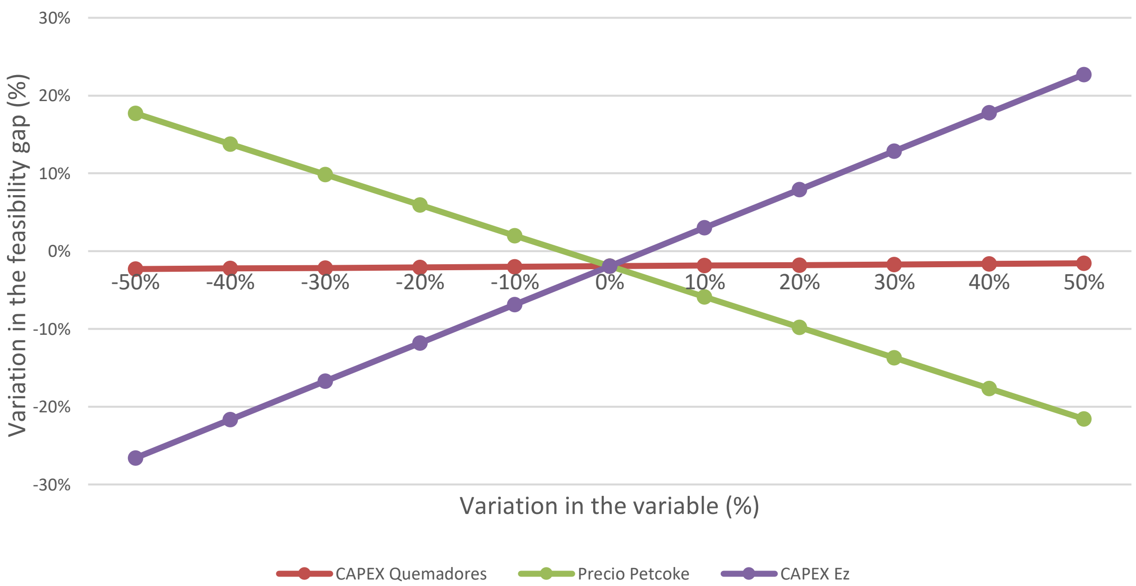


Figure 2-6 Cement sensitivity analysis Present scenario

Source: compiled by the authors

Translation:

CAPEX Quemadores	CAPEX burners
Precio Petcoke	Petcoke price
CAPEX Ez	CAPEX Electrolysers

The percentage variation in this case study's feasibility gap can be observed when the variables are subjected to a change of ±50%. The exercise shows how the CAPEX of the burners will not affect the projects' profitability, but the model is sensitive to the price of hydrogen (reflected in the investment cost of the electrolysers) and the price of fossil fuels.

As the petcoke price increases, the case study's feasibility gap decreases because the TCO of the baseline case rises. For example, a 20% increase in the price of petcoke decreases the project's feasibility gap by 9.8%. On the other hand, if the cost of the electrolysers rises, the feasibility gap increases. With a 20% increase in cost, the gap is 7.9% greater. The table below shows the impact of the two main variables on the project's observed feasibility gap. The figure in green is the model's original parameter.

Table 2-3 Bivariate analysis of main variables for the cement case study

Current NPV	$-100,809,818	Electrolyser price (USD)				
		630	741	872	1,003	1,153
Petcoke price (USD/tonne)	**54**	$-93,933,316	$-99,540,434	$-106,137,044	$-112,733,653	$-120,319,754
	64	$-91,485,672	$-97,092,790	$-103,689,399	$-110,286,009	$-117,872,109
	75	$-88,606,091	$-94,213,209	$-100,809,818	$-107,406,427	$-114,992,528
	86	$-85,726,509	$-91,333,627	$-97,930,237	$-104,526,846	$-112,112,947
	99	$-82,414,991	$-88,022,109	$-94,618,718	$-101,215,327	$-108,801,428

Although the sensitivity analysis shown here was conducted using the feasibility gap figures for the Present scenario, these results can be extrapolated to the other time scenarios analysed.

2.2 Techno-economic analysis for the steel industry

2.2.1 Current state of the steel production process

The steel industry is considered to be one of the difficult industrial sectors to abate in terms of GHG emissions intensity, and one particularly exposed to the risks arising from the transition to a low-carbon economy (GIZ, 2018a). There are two main methods of producing steel: an integrated process based on producing steel from iron ore and a semi-integrated process using scrap metal as the main source of iron.

The integrated process is significantly more emission-intensive. The global average for this production route is around 2.3 tonnes CO_2e/tonne liquid steel (Pardo, Moya, & Vatopoulos, 2012; Global Efficiency Intelligence, 2019), while the semi-integrated process has an average emissions intensity of 0.33 tonnes CO_2e/tonne liquid steel (Pardo, Moya, & Vatopoulos, 2012).

The integrated process accounts for around 70% of global steel production. The proportion is similar in Chile, where in 2019 it made up 68.9% of national production (World Steel Association, 2019a).

It is not possible to achieve decarbonisation of the sector exclusively by migrating from one method of production to another. It is estimated that, due to the availability of scrap and the long lifetime of finished steel products, it is not feasible to increase the collection and recycling rate to the level that would be required to meet future global steel demand through the semi-integrated process alone (A&P Global, s.f.). The integrated process therefore presents the greatest technological and economic challenges to reducing emissions while meeting the growing demand for steel in a sustainable manner over time.

The integrated process is characterised by the transformation of raw materials, mainly iron ore (e.g. in the form of lumps and pellets), limestone and metallurgical (coking) coal into steel. To achieve this, a series of consecutive stages must be carried out. The main stages are illustrated in

Figure 2-7 and are described below.

1. **Coke plant**. Metallurgical coal undergoes a dry distillation process to obtain metallurgical coke. A gas with a high calorific value is obtained as a by-product and is later reused as fuel.
2. **Blast furnace.** Large vertical reactors, in which the preheated air combusts coke at high temperatures to reduce the iron ore and obtain liquid iron or pig iron.
3. **Blast oxygen furnace (BOF)**. A process of refining pig iron by injecting oxygen to adjust the steel's carbon content. Scrap and ferroalloys are also added to produce the characteristics for each type of steel.
4. **Caster or continuous caster**. The liquid steel is solidified and directly water-cooled in copper moulds to obtain billets, which are semi-finished steel products.
5. **Rolling mill**. The billets are rolled into finished steel products, such as bars and coils.

Figure 2-7 Summary of the integrated steelmaking process.

Source: (BHP, 2020)

The most emission-intensive of the processes described is the blast furnace, followed by the coke plant. The coke supplied to the blast furnace serves several functions in the pig iron manufacturing process: it is the reducing agent that converts iron oxides into iron; it provides heat (through an exothermic reaction with oxygen) and is strong enough not to be crushed in the blast furnace. Iron ore is reduced in the pig iron (also called liquid steel) production process, and CO_2 is released as a consequence of the use of fossil fuels to reduce the iron.

An illustration of the emissions intensity benchmark for the main integrated route processes is shown below:

Table 2-4 Emission intensity benchmark per integrated route process.

Integrated route processes	Emission intensity (tonnes CO_2e/tonne liquid steel)
Coke plant (Coke oven)	0.824
Blast furnace	1.279
Blast oxygen furnace (BOF)	0.202
Rolling mill	0.09
Total	**2.395**

Source: adapted from (Pardo, Moya, & Vatopoulos, 2012)

About 89% of the energy input for an integrated system comes from coal, 7% from electricity, 3% from natural gas and 1% from other gases and sources. Up to 75% of the energy content of coal at an integrated plant is consumed in the blast furnace in the form of coke (World Steel Assosiation, 2019).

The critical issue in the integrated process is that coke and/or coal needs to be used in the blast furnace to reduce the iron oxide to metallic iron, regardless of whether the coke is produced on site or not. In the various process units, gases from the blast furnace, coke oven and steelworks are recirculated and consumed, which generates emissions due to their carbon content. Therefore, regardless of where the CO_2 is emitted and whether these gases are recirculated or not, to decarbonise the integrated process it is important that the technologies are able to **reduce coke consumption in the blast furnace**.

One of the main challenges in implementing such measures is that, as a commoditised industry,[6] the operating margins are relatively low compared with the production costs. In addition, most of the measures with substantial emissions reductions involve a transformation process; they lack technological readiness and therefore involve high investments that are not economically feasible (Bariloche Foundation, GIZ and Ministry of Energy, 2020).

In a previous study conducted for the Bariloche Foundation, GIZ and the Ministry of Energy – a roadmap to low-carbon development in the Chilean steel industry entitled *Hoja de ruta para el desarrollo bajo en carbono de la industria chilena del acero* (Bariloche Foundation, GIZ and Ministry of Energy, 2020) – several mitigation measures were identified for the sector, focusing mainly on the blast furnace in the integrated process. These included measures to **substitute the fuel**, e.g. hydrogen or natural gas injection through the tuyeres; **energy efficiency**, such as storage and greater use of the blast furnace and coke oven gases; and finally, **process transformation**, in particular replacing the blast furnace by H2V direct reduction and electric arc furnace melting.

In 2021, there are records of companies that have sought to use these types of technologies for low-emission steelmaking. ArcelorMittal in Belgium is building a large-scale facility to convert waste gases from its steel plant into synthetic fuels. Similarly, HBIS in China is building a hydrogen-based direct reduction project with a 1.2 Mt annual steel production capacity (World Steel Association, 2021).

2.2.2 Applying H2V to the process

<u>Latest advances in technology</u>

There are studies that support the claim that using H2V as a reducing agent in blast furnaces could decrease total CO_2 emissions in the process by up to 21.4%, where the optimal hydrogen ratio would be 27.5 kg H2V per tonne of pig iron produced (Yilmaz, Wendelstorf, & Turek, 2017). However, higher H2V replacement could present technological challenges to the process (Friedmann, 2021).

Success stories for this application include Thyssenkrupp Steel in Germany, where H2V injection was tested in one of the 28 tuyeres of one of its three operating blast furnaces. The company has stated that it will seek to replicate the project for all the tuyeres in this blast furnace by 2022 (Eurometal, 2019).

Similarly, Nippon Steel in Japan has begun to use H2V as a reducing agent in its blast furnaces with a demonstration test conducted in a 12 m^3 blast furnace at its Kimitsu plant, with the aim of scaling up this application to an industrial blast furnace by 2050 (Nippon Steel Corporation, 2021).

Another case of interest to Chile is the recent agreement between CAP Acero and Paul Würth, where studies are being conducted to assess the viability of making structural changes that involve the use of biomass to replace fossil fuels and, in the longer term, incorporating technologies with hydrogen as a reducing agent for iron (CAP, 2021).

6 Expression derived from the word 'commodities'

Description

The analysis focused on injecting hydrogen through the blast furnace tuyeres for the integrated process as this method is able to meet both the thermal and reducing agent requirements for the process and is at a stage of technological development that could reach promising techno-economic results in the short term (Friedmann, 2021).

2.2.3 Case study

The case study is at the Compañía Siderúrgica Huachipato S.A. (hereafter CSH) plant located in the Biobío region in the south of the country. This case was chosen with the aim of modelling the broader national situation in Chile, given that CSH is the main steel plant in Chile and the only integrated one in the country. The case is based on the plant's 2020 production levels, which are 664,500 tonnes of pig iron.

According to the description of the simulation, the amount of H2V to be injected through the tuyeres is 27.5 kg of hydrogen per tonne of pig iron (Yilmaz, Wendelstorf, & Turek, 2017).

Quantity of coke to be replaced

The use of hydrogen will displace some of the coke consumed, meaning a 21.7% decrease in coke consumption per tonne of pig iron, from 498.1 kg of coke per tonne of pig iron consumed in the baseline case to 389.8 kg of coke per tonne of pig iron produced, displacing 108.3 kg per tonne of pig iron each year.

Associated emission reduction

The reduction in emissions is constant in all the years of the assessment of the fuel being displaced, and is equivalent to 300,000 tonnes CO_2e/year.

Quantifying the demand for H2V

The amount of green hydrogen required for the proposed application is determined by the following equation:

$$REQ_{H2V} = \frac{Inj \cdot Cap_{plant}}{1{,}000}$$

Where:

REQ_{H2V}: demand for green hydrogen (tonnes/year)
Inj: H_2 injection in tuyeres (kg H_2/tonne HM)
Cap_{plant}: the steel plant's production capacity (tonne HM/year)

This produces an H2V demand of 18,274 (tonnes/year) for all scenarios.

As no steel measurements are available, the assumption is that the storage cost is the same as for cement, but adjusted to the H_2 demand required in this case, where the CAPEX of the H_2 storage tank is 0.113 (USD/tonne) (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019).

Electricity generation and H2V production model

In this case, it is proposed that the hydrogen production facility be located near the steel plant (point of use). The cost of transporting the hydrogen has therefore been disregarded, and only minor storage costs have been included with a minimum buffer to allow sufficient time for the fuel to be transported to the plant. However, it was decided that the NCRE generation plant would be located elsewhere, outside the steel and hydrogen production sectors but connected to the national electricity system (SEN) and with injection exclusively for the electrolyser. The transmission costs were therefore included, and it is assumed that the hydrogen produced will therefore be classed as green.

NCRE measurements

The energy requirements need to be known before calculating the project's costs and profitability. Taking into account the production capacity of the plant being studied (664,500 tonnes of pig iron per year) and its location (southern zone), the installed capacity required in order to meet the process's hydrogen demand in different scenarios is shown in Table 2-5 below.

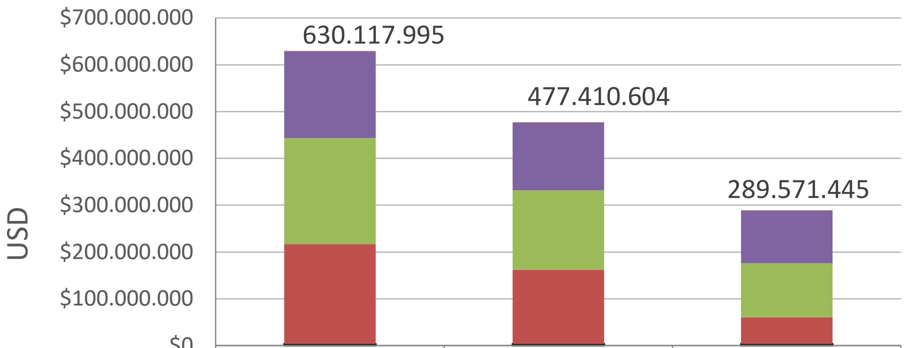
Table 2-5 Installed capacity by type of generating source

Installed capacity	Present	Medium term	Long term
H_2 demand			
Electrolyser capacity (southern zone)	245	227	212
Solar capacity to be installed (southern zone)	260	241	225
Wind power capacity to be installed (southern zone)	159	148	138

Source: compiled by the authors

Associated investment

The economic model developed for the case study on H2V use in the steel industry considered the investment costs associated with power generation, hydrogen production and adapting the tuyeres to inject hydrogen as an auxiliary reducing agent. These are presented in disaggregated form in Figure 2-8, and the details of the model assumptions are set out in Annex 4.



	Presente	Mediano Plazo	Largo plazo
CAPEX tanque de almacenamiento de H2 (USD)	1.071.889	1.071.889	1.071.889
CAPEX generación eólica	185.908.457	144.633.979	112.936.091
CAPEX generación solar	226.461.192	169.535.965	115.356.283
CAPEX electrolizador	213.405.677	158.897.991	56.936.402
CAPEX adaptación de toberas para H2	3.270.780	3.270.780	3.270.780
Total CAPEX (USD)	630.117.995	477.410.604	289.571.445

Figure 2-8 Disaggregated capital expenses for the use of H2V in the steel industry.

Source: compiled by the authors

Translation:

Presente	Present
Mediano plazo	Medium term
Largo plazo	Long term
CAPEX tanque de almacenamiento de H2 (USD)	CAPEX H_2 storage tank (USD)
CAPEX generación eólica	CAPEX wind generation
CAPEX generación solar	CAPEX solar generation
CAPEX electrolizador	CAPEX electrolyser
CAPEX adaptación de toberas para H2	CAPEX tuyere adaptation for H_2

<u>TCO calculation and feasibility gap</u>

Figure 2-8 shows that, as with the use of H2V in the cement industry, the main CAPEX when using H2V in blast furnaces in the steel industry are those associated with generating RE and with the electrolyser, both needed to produce H2V. These expenses decrease over time due to the lower costs of RE generation technologies and electrolysers. The total figure for CAPEX decreases by 46% between the 'Present' scenario and the 'Long-Term' scenario.

The substantial investment costs shown are directly related to the industry's high energy requirements, for which a large installed capacity of RE and electrolysers is needed. The model involves injecting 27.5 kg H2/tonne pig iron, which replaces 108.3 kg coke/tonne pig iron.

The TCO of the hydrogen case study was calculated using the investment and fuel consumption costs. A comparison of the TCO for the hydrogen application case and the baseline case is shown below.

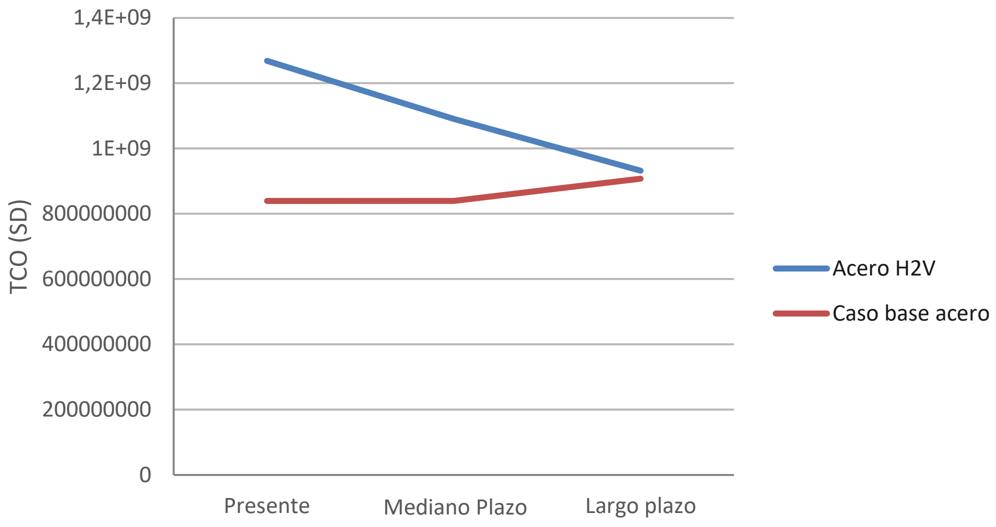


Figure 2-9 Comparison of TCO for hydrogen use and the baseline case in the steel industry.

Source: compiled by the authors

Translation:

Presente	Present
Mediano plazo	Medium term
Largo plazo	Long term
Acero H2V	H2V steel
Caso base acero	Steel baseline case

Figure 2-9 shows that the gap decreases over time until it reaches a break-even point after 2050. Consequently, unless there is additional revenue, the project may not be viable until after 2050. This can also be seen in the difference between the TCOs in each time scenario, which can be used to reach the project feasibility gap shown in

Table 2-6

Table 2-6 Total cost of ownership and feasibility gap for H2V use in the steel industry

	Present	**Medium term**	**Long term**
TCO baseline case (USD)	$839,440,012	$839,639,379	$907,670,795
TCO H2V application (USD)	$1,268,632,268	$1,090,929,499	$932,128,932
Project feasibility gap (USD)	$-429,192,255	$-251,290,119	$-24,458,137
Payback (year)	Not achieved	Not achieved	Not achieved

Source: compiled by the authors

Comparison between the baseline case and the case being studied

Figure 2-10 shows the processes involved in the steel case study.

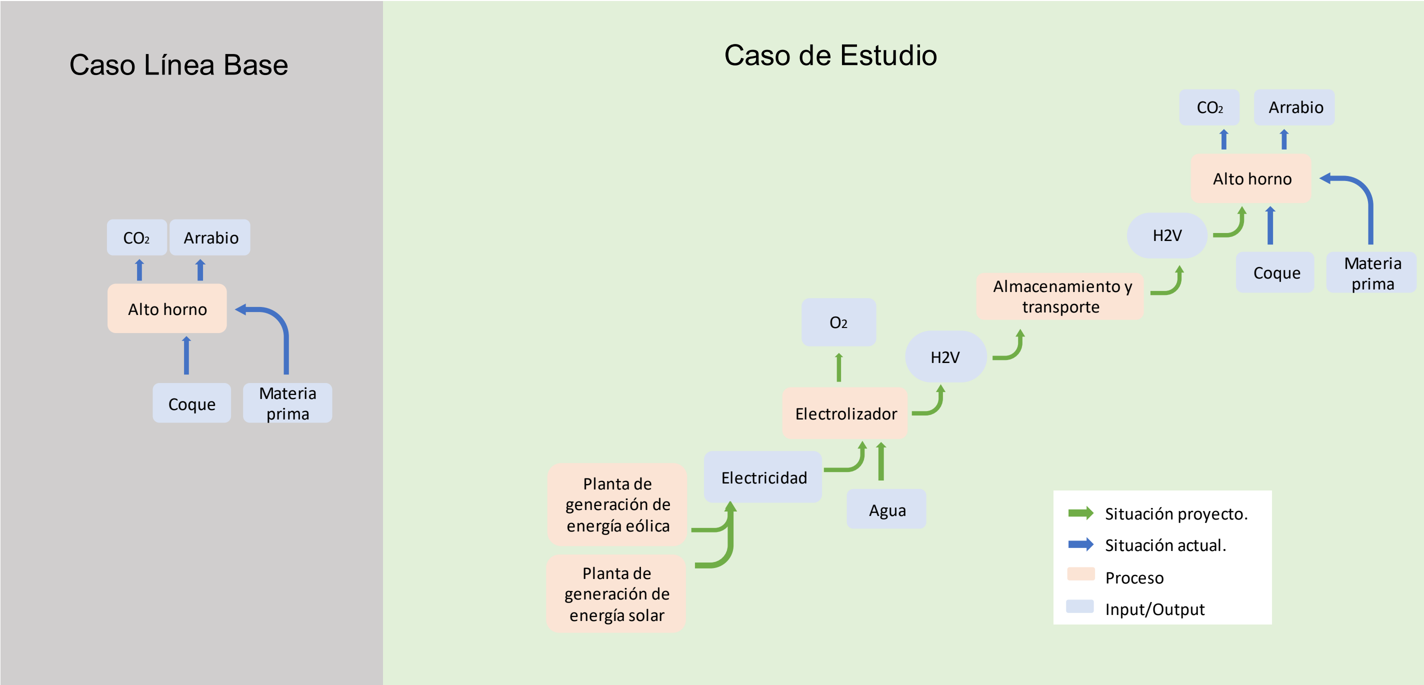


Figure 2-10 Diagram of the processes involved in the steel case study

Source: compiled by the authors

Translation:

Caso Línea Base	Baseline Case
Caso de Estudio	Case Study
Arrabio	Pig iron
Alto horno	Blast furnace
Coque	Coke
Materia prima	Feedstock
Planta de generación de energía eólica	Wind power generation plant
Planta de generación de energía solar	Solar power generation plant
Electricidad	Electricity
Agua	Water
Electrolizador	Electrolyser
Almacenamiento y transporte	Storage and transport
Situación proyecto	Project situation
Situación actual	Current situation
Proceso	Process
Aplicaciones no consideradas en caso de estudio	Applications not included in the case study

Sensitivity analysis

Figure 2-11 below shows a sensitivity analysis of the case study’s main variables, which are the CAPEX of the electrolyser, the coke price and the CAPEX of the burners. These variables are the greatest sources of uncertainty for the steel industry. The figure shows the percentage variation of the feasibility gap (assessed for the ‘Present’ scenario) when the variables are subjected to a variation of ±50%. The exercise shows how the CAPEX for the tuyeres will not affect the profitability of projects in the steel industry, but the model will be sensitive to the price of hydrogen (reflected in the investment cost of the electrolysers) and the price of fossil fuels.

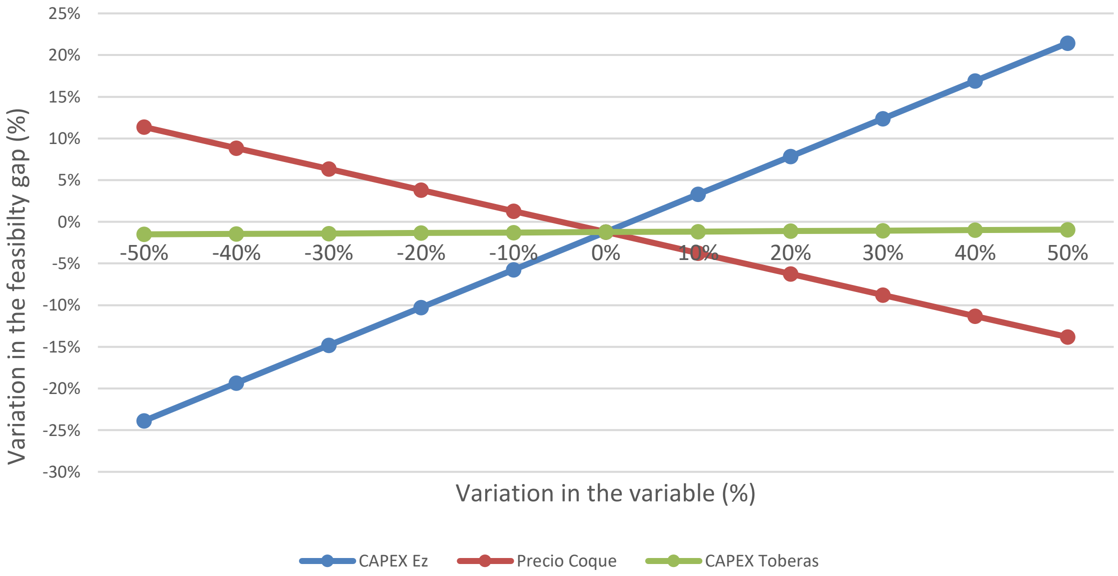


Figure 2-11 Steel sensitivity analysis for Present scenario

Source: compiled by the authors

Translation:

CAPEX Ez	CAPEX electrolyser
Precio Coque	Coke price
CAPEX Toberas	CAPEX tuyeres

The percentage variation in this case study's feasibility gap can be observed when the variables are subjected to a change of ±50%. The exercise shows that the two main variables that affect the project's profitability are associated with the cost of the electrolyser and the price of coke.

As the coke price increases, the case study's feasibility gap decreases because the TCO of the baseline case rises. For example, a 20% increase in the price of coke decreases the project's feasibility gap by 6.3%. On the other hand, if the cost of the electrolysers rises, the feasibility gap increases. With a 20% increase in cost, the gap is 7.8% greater. The table below shows the impact of the two main variables on the project's observed feasibility gap. The figure in green is the model's original parameter.

Table 2-7 Bivariate analysis of main variables for the steel case study

Current NPV	$-429,192,255.17	**Electrolyser price (USD)**				
		630	**741**	**872**	**1,003**	**1,153**
Coke price (USD/tonne)	**181**	$-428,389,361	$-459,745,278	$-496,634,593	$-533,523,907	$ -575.946.619
	213	$-397,402,341	$-428,758,258	$-465,647,573	$-502,536,887	$ -544.959.599
	250	$-360,947,023	$-392,302,941	$-429,192,255	$-466,081,570	$ -508.504.282
	288	$-324,491,705	$-355,847,623	$-392,736,938	$-429,626,252	$ -472.048.964
	331	$-282,568,090	$-313,924,008	$-350,813,322	$-387,702,637	$ -430.125.349

Although the sensitivity analysis was conducted using the feasibility gap figures for the Short-Term scenario, these results can be extrapolated to the other time scenarios analysed, where the feasibility gap will be strongly affected by the costs of the electrolyser (the higher the cost, the higher the gap) and the coke (the higher the cost, the lower the gap).

2.3 Techno-economic analysis for the transport of mining personnel

2.3.1 Transport for mining personnel – current situation

Mining is a key sector in the Chilean economy, responsible for 10% of national GDP and producing more than half of the country's exports. It is a major source of tax revenue, raising about USD 3 billion for the Chilean state in 2020 (Chilean Budget Directorate, 2020). The state-owned company Codelco employs around 20,000 people directly.

Chile is the world's largest copper producer, accounting for 28% of the world's copper market. The country also produces significant quantities of silver, iron and gold, and is the second largest exporter of lithium, with an estimated 51% of the world's reserves (International Trade Administration, 2021). The companies SQM and Albemarle are the main players in the Chilean lithium sector. The largest companies in the copper sector are state-owned Codelco and several multinationals, including Anglo American, BHP Billiton, Antofagasta PLC and Freeport.

It is estimated that the mining sector is directly responsible for 7% of Chile's GHG emissions, and 14% are considered indirect emissions, including those associated with personnel transport (Cerda, 2020). Recently, several large companies have updated their commitments to reduce emissions in Chile. BHP and Codelco in particular have committed to reducing their emissions by 70% by 2025 and 2030 respectively, while Anglo American aims to achieve carbon neutrality in all its international operations by 2040.

Although there is a wide range of H2V applications in the mining industry, including CAEX mining haul trucks and underground mining vehicles, this section focuses on the use of H2V as a fuel when transporting personnel during mining operations.

2.3.2 Applying H2V to the process

Latest advances in technology

The mining sector currently relies on intensive use of diesel in its personnel transport buses. This is an area where H2V can offer significant advantages over other fossil fuels or even low-carbon alternatives. The use of hydrogen fuel cells is an opportunity for companies in Chile's mining sector to move towards low-carbon mining and reduce both their GHG emissions from transport, whether from CAEX trucks, heavy machinery or transport buses, and their operating costs.

The definition of this type of case study takes account of the fact that refuelling a bus running on hydrogen fuel cells would take less time than recharging the batteries in an electric vehicle (Deloitte & Ballard, 2020) and that buses in the mining sector typically keep to a fixed route, which would allow refuelling stations to be constructed for this purpose.

Using H2V for low-carbon passenger transport has further advantages for the Chilean mining industry in particular. The sector is well placed to adopt H2V, not only because of its energy-intensive use but also for geographical reasons. With large mines located in remote sites in the north of the country, mining operations could benefit from on-site H2V generation, rather than importing large quantities of diesel.

Chile's northern regions have the country's highest concentration of mines and a significant presence of the renewable energies used in the electrolysis process. Thanks to this combination of factors, there is strong interest from the mining sector in using H2V for several applications.

Progress is being made in the use of electromobility solutions for mining operations. Both Chile and the international industry highlight the use of H2V in mining as an expanding market. In 2021, Anglo American began the process of adding 17 electric buses to its passenger transport fleet in Chile, and the company has a goal of replacing 50 conventional buses with electric alternatives (Revista Electricidad, 2021). The international mining sector is also looking to accelerate its decarbonisation process through the use of H2V. In 2020, the large mining companies Anglo American, BHP, Fortescue and Hatch formed a consortium to evaluate the use of H2V in their operations.

Overall, more than 36% of energy consumption in Chile comes from the transport sector, so the use of H2V in transport applications, such as intercity buses and road trucks, could have a mitigation potential of 3,352,120 tonnes of CO_2e (Comité Solar, 2020).

Description

Given the above, passenger transport in the mining sector represents an opportunity to move towards the decarbonisation goals set out in Chile’s 2017 electromobility strategy (Government of Chile, 2017), and it will therefore be analysed in the case study.

2.3.3 Case study

This case study used the Compañía Minera del Pacífico (CMP) as an example. The company has operations at Cerro Negro Norte mine in the Atacama region, and staff are transported daily to the site from the city of Copiapó. The project involves replacing 10 diesel buses with fuel cell buses that run on H2V, covering 150 kilometres per day throughout the year and transporting an average of 42 passengers per bus. CMP currently has a fleet of 23 diesel buses and one electric bus for a route similar to the baseline case described.

This case study was chosen because the company is willing to replace its current fleet of fossil fuel buses with low-carbon technology. CMP has already implemented electric buses on the route mentioned above and others, and hydrogen could be a carbon-neutral technology option for future developments.

Quantifying the diesel to be replaced

The buses currently being operated by CMP use 0.4 l/km. Given the route and the fleet, the diesel consumption to be replaced is 219,000 l/year for the 10 buses.

Associated emissions reduction

For this calculation, two scenarios were considered with two electromobility penetration targets: a 2030 scenario (less ambitious) and a 2050 scenario (more ambitious). These are based on Chile’s ambition level as stated in its NDC.

Figure 2-12 plots the emissions reduction trajectory in tonnes CO_2e for each year and scenario.

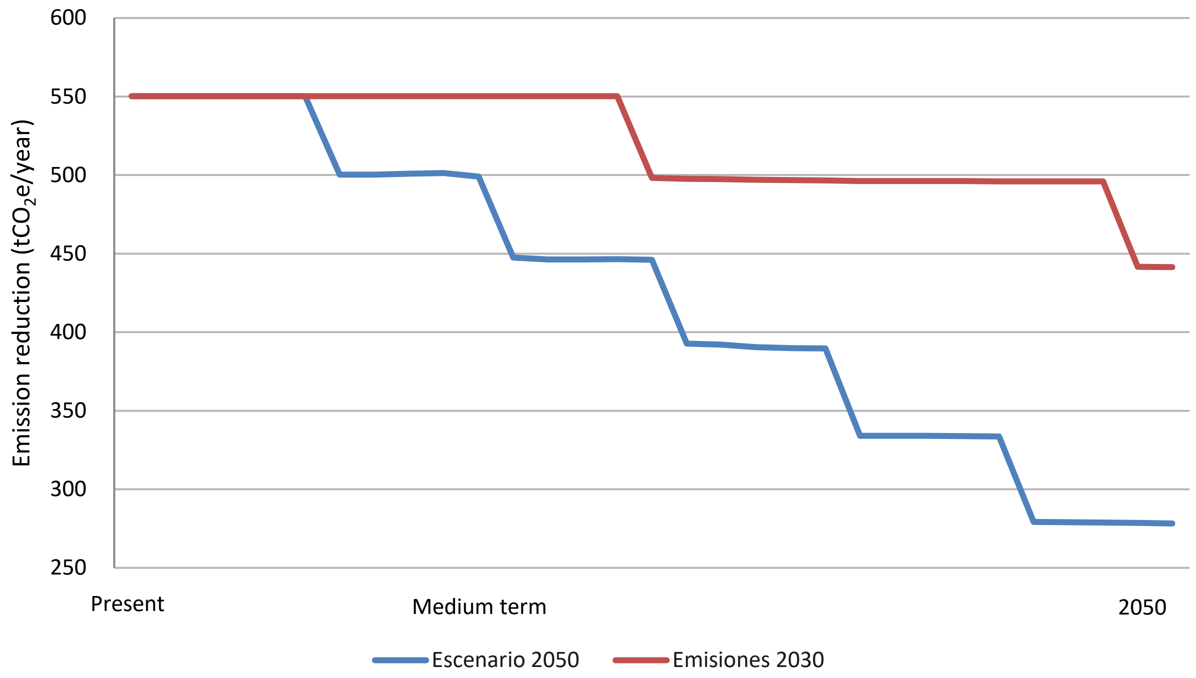


Figure 2-12 Emission-reduction trajectory for H2V used in personnel transport in the mining sector

Translation:

Escenario 2050	2050 scenario
Emisiones 2030	2030 emissions

<u>Quantifying the demand for H2V</u>

The amount of green hydrogen required for the proposed application is determined using the following equation:

$$REQ_{H2V} = Fleet \cdot Distance \cdot 365 \cdot Eff_{bus}$$

Where:

REQ_{H2V}: demand for hydrogen (tonne/year)
$Fleet$: number of buses
$Distance$: kilometres travelled by one bus in one day (km/bus)
Eff_{bus}: bus efficiency (kg/km)

This results in a constant H2V demand for all scenarios equal to 43.8 tonnes H2V/year.

<u>Electricity generation and H2V production model</u>

It is proposed that the hydrogen production facility be located near the point of use. The cost of transporting the hydrogen has therefore been disregarded at this level of analysis, and only minor storage costs have been included, with a minimum buffer to allow sufficient time for the fuel to be transported to the plant.

However, it was decided that the NCRE generation plant would be located elsewhere, outside the hydrogen production sector but connected to the national electricity system (SEN) and with injection exclusively for the electrolyser. The transmission costs were therefore included, and it is assumed that the hydrogen produced will be classed as green.

NCRE measurements

The energy requirements need to be known before calculating the project's costs and profitability. Taking into account the project's energy needs (replacing 219,150 litres of diesel per year) and its location (northern zone), the installed capacity required for each of the scenarios is shown in 8 below.

Table 2- 8 below.

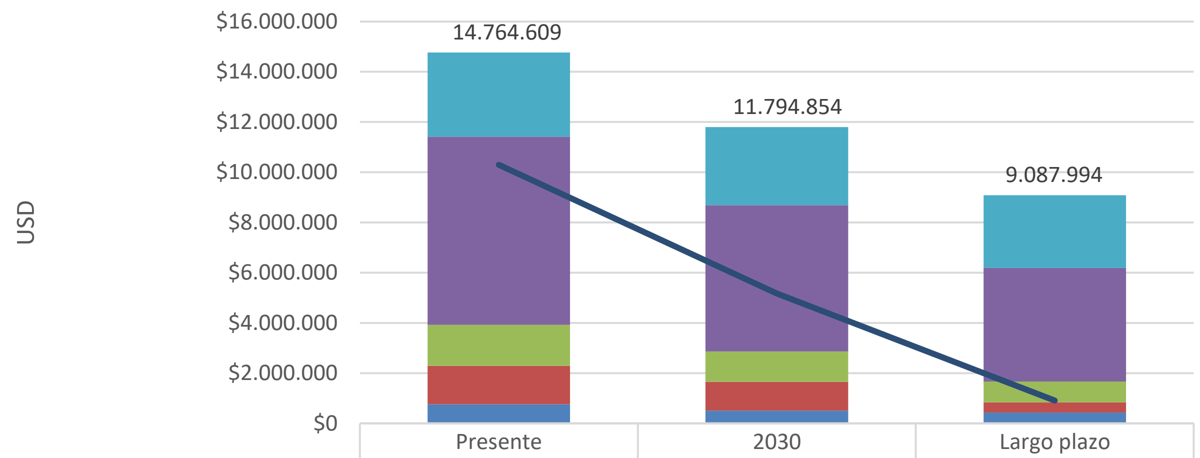
Table 2-8 Project's installed capacity

Capacity (MW)	Present	Medium term	Long term
Electrolyser capacity (northern zone)	0.657	0.610	0.568
Solar capacity to install (northern zone)	0.70	0.65	0.61

Source: compiled by the authors

Associated investment

The assumptions in Annex 5 were used to produce an economic model for the case study on the application of H2V in the mining industry. The economic model for this industry involves the use of H2V buses to transport personnel to the mining operations. For this model, the investment costs associated with generating solar energy and producing H2V were included as well as the cost of the bus fleet and the storage and distribution of H2V (refuelling terminal). These are presented in disaggregated form below.



	Presente	2030	Largo plazo
CAPEX almacenamiento	3.348.243	3.105.617	2.895.778
CAPEX flota de buses	7.500.000	5.822.472	4.520.158
CAPEX generación solar	1.628.045	1.218.806	829.304
CAPEX electrolizador	1.528.320	1.137.959	407.754
CAPEX distribución	760.000	510.000	435.000
Total CAPEX (USD)	14.764.609	11.794.854	9.087.994
Brecha a la viabilidad (USD)	$10.296.012	$5.166.191	$909.466

Figure 2-13 Disaggregated capital expenses for the use of H2V in the mining industry

Source: compiled by the authors

Translation:

Presente	Present
Largo plazo	Long term
CAPEX almacenamiento	CAPEX storage
CAPEX flota de buses	CAPEX bus fleet
CAPEX generación solar	CAPEX solar generation
CAPEX electrolizador	CAPEX electrolyser
CAPEX distribución	CAPEX distribution
Brecha a la viabilidad	Feasibility gap

The baseline scenario excludes the project in our case study and therefore does not include retrofitting or investments beyond the purchase of diesel buses and fuel.

Figure 2-13 shows that the main capital expenses in the use of H2V in the mining industry are the bus fleet and distribution CAPEX (associated with the refuelling station). This contrasts with the CAPEX in the cement and steel industries, where RE generation and the electrolyser were the main costs. This is due to the lower demand for H2V in the mining application model compared with cement and steel.

The economic model includes bus renewal CAPEX that are not shown in Figure 2-13. This cost occurs after 10 years of bus fleet use and amounts to 90% of the initial fleet cost.

<u>TCO calculation and feasibility gap</u>

Finally, using the CAPEX and fuel consumption figures, the TCO was calculated for the H2V case study and the baseline case to identify the project's feasibility gap. A comparison of the TCO for the H2V case study and the baseline case is presented in Figure 2-14.

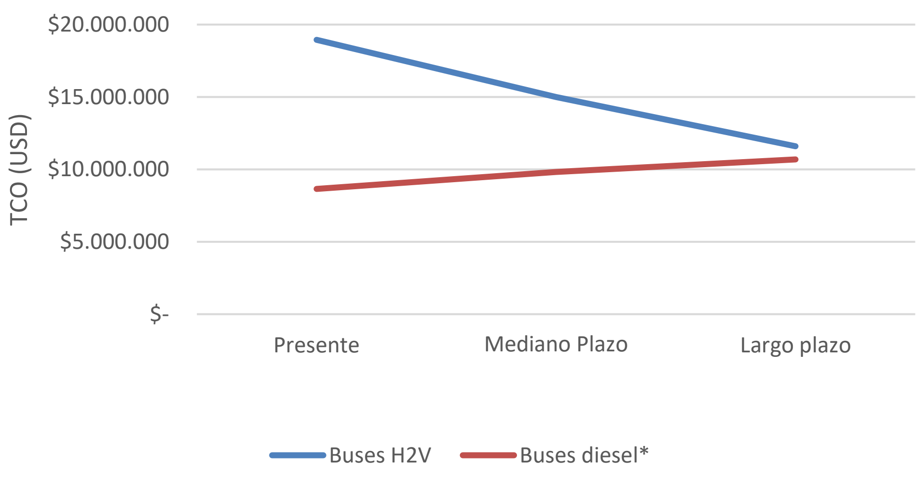


Figure 2-14 Comparison of TCO for H2V use and the baseline case in the mining industry

Source: compiled by the authors

Translation:

Presente	Present
Mediano plazo	Medium term
Largo plazo	Long term
Buses H2V	H2V buses
Buses diesel	Diesel buses

The gap between the TCOs for each time scenario is the project feasibility gap presented in Figure 2-14. This figure is positive when the TCO for the H2V application project is lower than for the baseline case and negative otherwise. In this case study, the feasibility gap is negative in all time scenarios analysed.

Table 2-9 below shows the feasibility gap comparing the baseline case with the use of H2V in each scenario.

Table 2-9 Total cost of ownership and profitability of H2V use in the mining industry

	Present	Medium term	Long term
TCO baseline case (USD)	$4,946,779	$5,390,119	$5,710,988
TCO H2V application (USD)	$14,186,618	$11,056,423	$8,592,993
Project feasibility gap (USD)	$-9,239,839	$-5,666,304	$-2,882,005
Payback (year)	Not achieved	Not achieved	Not achieved

Source: compiled by the authors

The feasibility gap is not closed in any of the time scenarios evaluated, nor is the initial investment recovered during the project period (20 years). Interviews with sector experts indicate that this type of project could also benefit from the use of refuelling stations or buses to provide other services to improve the project's return profiles (e.g. using the refuelling station to sell H2V to other transport services). These are alternatives that will be worth studying in order to make the projects being analysed economically viable in scenarios where the returns are otherwise negative.

Diagram comparing the baseline case and the case being studied

Figure 2-15 shows the processes involved in the mining case study.

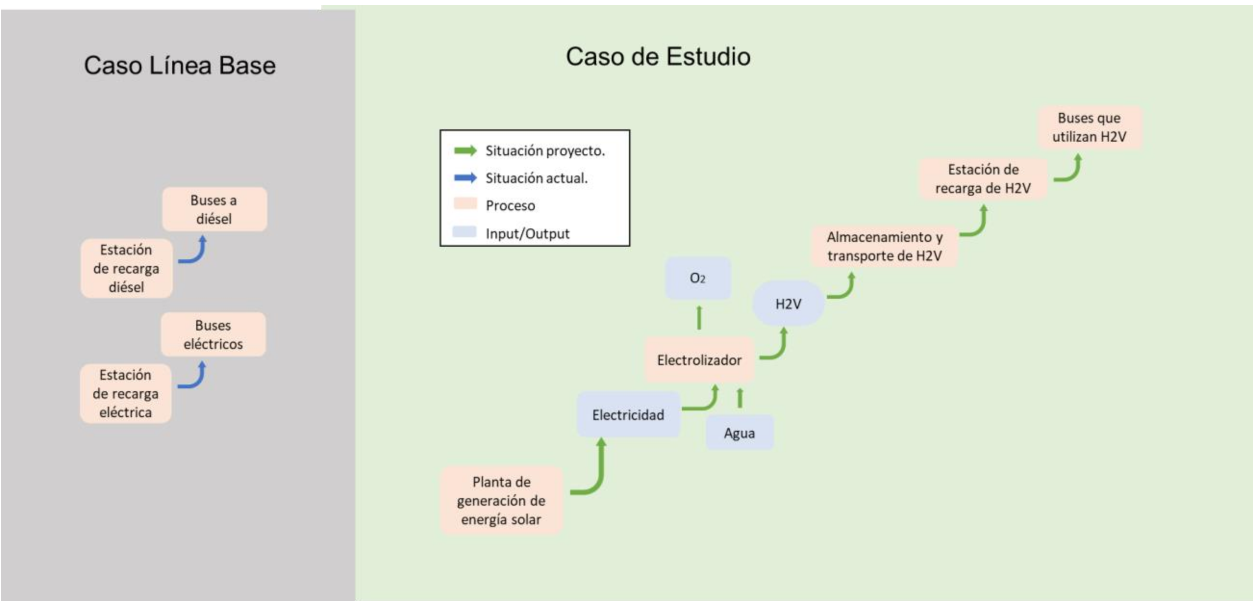


Figure 2-15 Diagram of the processes involved in the mining case study

Source: compiled by the authors

Translation:

Caso Línea Base	Baseline Case
Caso de Estudio	Case Study
Buses a diésel	Diesel buses
Estación de recarga diésel	Diesel refuelling station
Buses eléctricos	Electric buses
Estación de recarga eléctrica	Electric charging station
Planta de generación de energía solar	Solar power generation plant
Electricidad	Electricity
Agua	Water
Electrolizador	Electrolyser
Almacenamiento y transporte de H2V	H2V storage and transport
Estación de recarga de H2V	H2V refuelling station
Buses que utilizan H2V	Buses that use H2V
Situación proyecto	Project situation
Situación actual	Current situation
Proceso	Process

Sensitivity analysis

Figure 2-16 below shows a sensitivity analysis of the case study's main variables, which are the CAPEX for the electrolyser, refuelling station and fuel cell buses and the kilometres travelled. These factors are the greatest source of uncertainty for the use of buses in the mining industry. The sensitivity test is performed on the parameters independently. The horizontal axis shows the percentage change in the parameter, and the vertical axis is the feasibility gap in the 'Present' scenario.

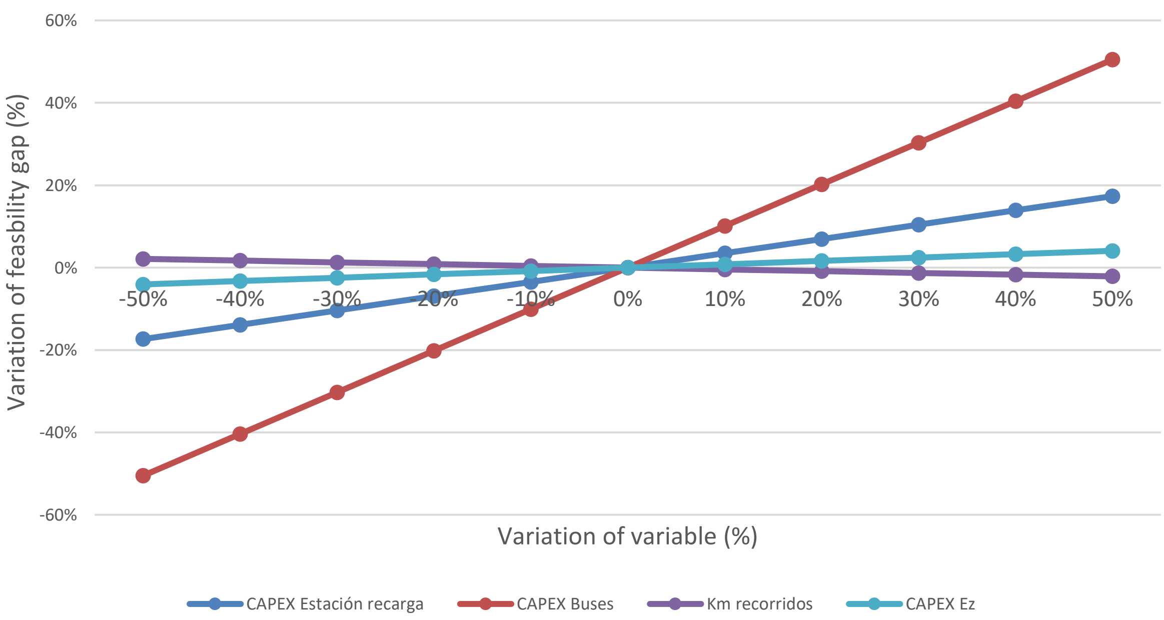


Figure 2-16 Bus sensitivity analysis for the Present scenario

Source: compiled by the authors

Translation:

CAPEX Estación recarga	CAPEX charging station
CAPEX Buses	CAPEX buses
Km recorridos	Km travelled
CAPEX Ez	CAPEX electrolyser

The analysis shows the percentage variation in the feasibility gap when the variables are subjected to a change of ±50%. The exercise shows that the main variable in terms of project profitability is the cost of the buses. The second main variable are the investment costs for the refuelling station, and the third is the cost of the electrolyser. The kilometres the buses travel (for the route being assessed) do not have a significant impact, since at variations of ±50% in this parameter the feasibility gap varies by ±2.1% respectively.

As the price of the buses rises, the case study's feasibility gap increases. The variation in this parameter has an almost 1:1 impact on the model, i.e. with a 20% increase in the costs of the buses, the gap increases by 20.2% in the 'Present' scenario. The same is true for decreases in the cost of the buses.

Secondly, there is the impact associated with the cost of the refuelling station. At variations of ±20%, the calculated feasibility gap varies by ±6.9%, and for variations of ±50%, the figure is ±17.4%. While the impact of this variable is less than in the bus cost sensitivity analysis, it is still considerable.

Finally, unlike in the cement and steel cases, the cost of the electrolyser does not have such a significant impact on the feasibility gap. With a 50% increase in the cost of the electrolysers, the gap increases by 4.1%. The table below shows the impact of the two main variables on the project's observed feasibility gap. The figure shown in green is the model's original parameter.

Table 2-6 Bivariate analysis of main variables for the mining case study

Current NPV	**$-11,172,627.80**	**CAPEX (USD)**				
		607,500	**675,000**	**750,000**	**825,000**	**907,500**
CAPEX buses (USD)	**923,400**	$-8,698,013	$-9,617,473	$-10,639,095	$-11,660,717	$-12,784,502
	1,026,000	$-8,950,739	$-9,870,199	$-10,891,821	$-11,913,443	$-13,037,228
	1,140,000	$-9,231,546	$-10,151,006	$-11,172,628	$-12,194,250	$-13,318,034
	1,254,000	$-9,512,352	$-10,431,812	$-11,453,434	$-12,475,057	$-13,598,841
	1,379,400	$-9,821,239	$-10,740,699	$-11,762,322	$-12,783,944	$-13,907,728

Although the sensitivity analysis was conducted using the feasibility gap figures for the short-term scenario, these results can be extrapolated to the other time scenarios analysed. Here, too, the feasibility gap will be strongly influenced by the costs of the buses.

3 Calculation of each project's emission reductions

This section will examine the main elements of a methodology that can be used to calculate the emission reductions for a low-carbon project in line with international standards and criteria and that allows for certified emission reductions to be traded under a potential Article 6 mechanism.

First of all, we will offer some general guidelines for designing an emission-reduction calculation methodology and explore the wider implications of using H2V as the main input in such a project. This methodology will then be applied to the case studies examined in the previous sections, establishing a baseline that reflects sectoral and national commitments (set out in the NDC) in order to calculate the emissions actually avoided by the project. The analysis will focus on emissions with an associated global warming potential, i.e. pollutants that can be represented as CO_2e and therefore lead to reductions that can then be traded in the Article 6 carbon markets.

3.1 General methodology for estimating the potential emission reduction

3.1.1 Description of the content of the methodologies

The new Article 6 market, sometimes referred to as the Sustainable Development Mechanism (SDM), will replace the Clean Development Mechanism (CDM), which operated under the predecessor to the Paris Agreement, known as the Kyoto Protocol. There is currently no methodology to calculate and quantify emission reductions for this new mechanism. We will therefore propose a methodology for the different projects on the basis of existing CDM methodologies, ensuring consistency with the principles of the methodologies under the CDM and with the general principles of the mechanisms proposed under Article 6.

The minimum elements to be included in applying these methodologies are set out below.

1. **Project description.** A general outline of the project must be provided including all project elements.
2. **The project's GHG mitigation.** The specific actions that the project undertakes to mitigate emissions. These actions may include replacing more energy-intensive fuels with cleaner fuels, energy efficiency, RE, removing GHG and avoiding GHG emissions.
3. **Important conditions for applying the methodology.** A particular methodology can only be applied under certain conditions. These conditions list the project details and constraints.
4. **Main parameters.** This is the list of the primary parameters to be considered in both the baseline and project calculations. They determine the changes that occur in both scenarios.
5. **Baseline emissions.** The baseline scenario represents the situation in the absence of the project activity, i.e. the emissions calculated with the key parameters corresponding to a scenario without a project. Each project's baseline will be determined according to the guidelines provided by the CDM (and voluntary market standards). These guidelines include data quality objectives, guidance, good practice on the data collection process and analysis conducted in order to develop a baseline.

   The **baseline must be sufficiently conservative to ensure that the emission reductions achieved are in addition to existing and planned policies and measures**. A conservative baseline is essential to avoid overestimating the emissions actually being reduced and thus to be able to sell reductions that are real and verifiable. However, an overly conservative baseline will reduce the value generated by Article 6 projects. The baseline will be calculated using current figures for key parameters and may need to be updated if the project is implemented in the future with different baseline conditions. An updated baseline that takes new policies and measures into account may leave less room for additional emission reductions.

6. **Project scenario.** This includes the calculation of emissions that can be reduced by implementing the project activity. It is important to emphasise that the methodology chosen will only be used to calculate emission reductions; it will not be used to submit an investment project for any scheme or standard registering emission reductions. It does not, for example, include preparing the project monitoring and verification plan.

In addition to the elements mentioned above, when designing Article 6 projects it is important to consider compliance with the requirements set out in the Paris Agreement and with subsequent standards and guidelines yet to be decided. These include:

- **Avoiding double-counting.** Double-counting safeguards are traceability requirements for certified emission reductions that limit the trading of other emission reduction market mechanisms to avoid offsets being counted two or more times.
- **Ensuring environmental integrity principles.** The principles of environmental integrity refer to the overall look and feel of an offset system, including the fact that offsets must be real, measurable, verifiable, additional, permanent, etc.
- **Additionality.** The determination that a project would not have been feasible without the offset scheme and would not have existed for other reasons. Therefore, additionality includes criteria that make it possible to discern whether the project goes beyond the baseline, e.g. it could include an analysis of legal or financial additionality.
- **Transparency.** This refers to criteria that seeks to disclose information and facilitate replication of the emission-reduction estimate.
- **Sustainability.** Criteria and principles to guarantee the system's environmental sustainability.

These elements are key to the reputation and validity of the ITMO results and should therefore be factored into the project analysis to ensure emission reductions can be certified and that projects are consequently bankable.

In this context, different CDM methodologies were chosen as a reference for the projects studied. To quantify emission reductions in the cement industry case study, where petcoke/coal fuel used in the rotary kilns is partially replaced with H2V, the methodology will be built by adapting two CDM references: 'Switching fossil fuels' (AMS-III.B) and 'Fossil fuel switch in existing manufacturing industries' (AMS-III.AN).

For the steel industry case study, where the coke is substituted by H2V in the blast furnace, the methodology will be constructed by adapting three CDM references: 'Use of charcoal from planted renewable sources in the production of inorganic compounds' (AM0082), 'Fossil fuel switch in existing manufacturing industries' (AMS-III.AN) and 'Switching fossil fuels' (AMS-III.B).

Finally, for the case study of buses in the mining industry, where buses using fossil fuel are substituted by others using H2V fuel cells, the methodology will be constructed by adapting two CDM references: 'Introduction of LNG buses to existing and new bus routes' (AMS-III.AY) and 'Introduction and operation of new less-greenhouse-gas-emitting vehicles (e.g. CNG, LPG, electric or hybrid) for commercial passengers and freight transport, operating on routes with comparable conditions. Retrofitting of existing vehicles is also applicable (AMS-III.S).'

Emission-reduction methodologies and calculations for the cement, steel and mining industry projects can be found in Annex 6, Annex 7 and Annex 8.

3.1.2 Green hydrogen and its impact on methodologies

To establish the benefits of using H2V in the production processes being studied it is first necessary to define what H2V is, what its attributes are and how these attributes are measured. There is currently no formal, central definition of H2V (World Bank, 2021). However, we can draw on the definition offered by

CertifHy, the main standard for low-carbon hydrogen certification, which defines low-carbon hydrogen as hydrogen produced with an emissions intensity that gives a 60% reduction compared with the average emissions of a conventional hydrogen production process. CertifHy defines these conventional emissions as 91 g CO_2e/MJ H_2. Therefore, if the emissions intensity associated with a hydrogen plant's production process is less than 36.4 g CO_2e/MJ H_2, the product is considered to be 'low-carbon hydrogen' (Barth, 2016). If this hydrogen is produced by non-renewable sources, it is still classified as 'low-carbon hydrogen', whereas if it is produced by renewable sources it is considered to be H2V. The methodology provided by CertifHy includes the use of RE certificates, such as a Guarantee of Origin (GO), to prove that the energy source for hydrogen production is low carbon.

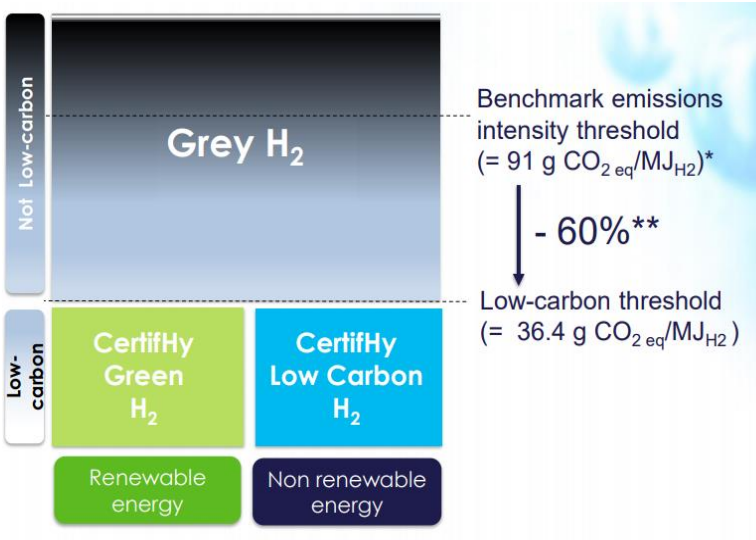


Figure 3-1 Hydrogen classifications according to energy source

Source: (CertifHy, 2016)

This study, and the cases to be analysed, consider the use of H2V for the processes being studied. The H2V is generated from renewable sources (wind and/or solar) and complies with the definition provided by CertifHy. The H2V emissions are deemed to be equal to 0 tonne CO_2e/tonne H_2. This figures only includes its use during operation and not the manufacture of the components involved in producing and using the H2V (Hydrogen Council, 2021; Low Carbon Vehicle Partnership, 2020).

One of the biggest challenges in the implementation and marketing of these projects is to be able to guarantee that the product meets the above-mentioned specifications. This is why it is so important to use monitoring, reporting and verification (MRV) systems that are reliable and consistent with the markets where the product will be marketed. The main issue is to be able to guarantee the origin of the energy used for the H2V production process.

Chile has a voluntary energy certificate market, but there is no single, centralised methodology for accrediting the origin of the energy, nor is this market regulated.[7] Among the main initiatives monitoring RE are: the *Huella Chile* programme implemented by the Ministry of Environment; a centralised emission-reduction calculation system being developed by the Ministry of Environment and the Capacity-building Initiative for Transparency (CBIT); the RENOVA system implemented by the National Electric Coordinator (CEN) in 2021 (World Bank, 2021); the Pulse traceability platform recently launched by Transelec based on the on-site metering of generation/consumption; and the methodologies used by institutions

[7] Not to be confused with the mandatory NCRE market according to Law 20.257, which is monitored via the National Electric Coordinator (CEN).

accrediting RE certificate transfers, such as the one used by I-REC, which are mainly based on the National Energy Balance[8] published annually by the Electricity Coordinator.

Regardless of the system used, the World Bank recommends always considering the following information in the monitoring, reporting and verification (MRV) of H2V production (World Bank, 2021):

- date the H2V production plant was commissioned
- type of energy used (accredited by an off-grid system connected to the plant or by RE certificates)
- date the H2V was produced
- electrolyser technology
- percentage of RE used
- financial support for the implementation of the project
- emissions associated with producing the H2V (g $CO_2e/MJ\ H_2$)
- additionality of the energy used (optional)
- conflict with water use (optional)
- conflict with land use (optional).

These inputs will be relevant for the project design and the MRV system during the project's implementation. The following sections describe the results obtained by applying the emission-reduction methodology to each case study.

3.2 Emission reductions from projects and carbon pricing to close the feasibility gap

The emission-reduction potential was calculated for the different scenarios in each of the case studies, defining a baseline and abatement potential according to the GHGs that may be avoided. Further information on assumptions and information to be included in the calculation methodology can be found in Annex 6 (Emission-reduction methodologies and calculations for the cement industry), Annex 7. (Emission-reduction methodologies and calculations for the steel industry) and Annex 8. (Emission-reduction methodologies and calculations for the mining industry).

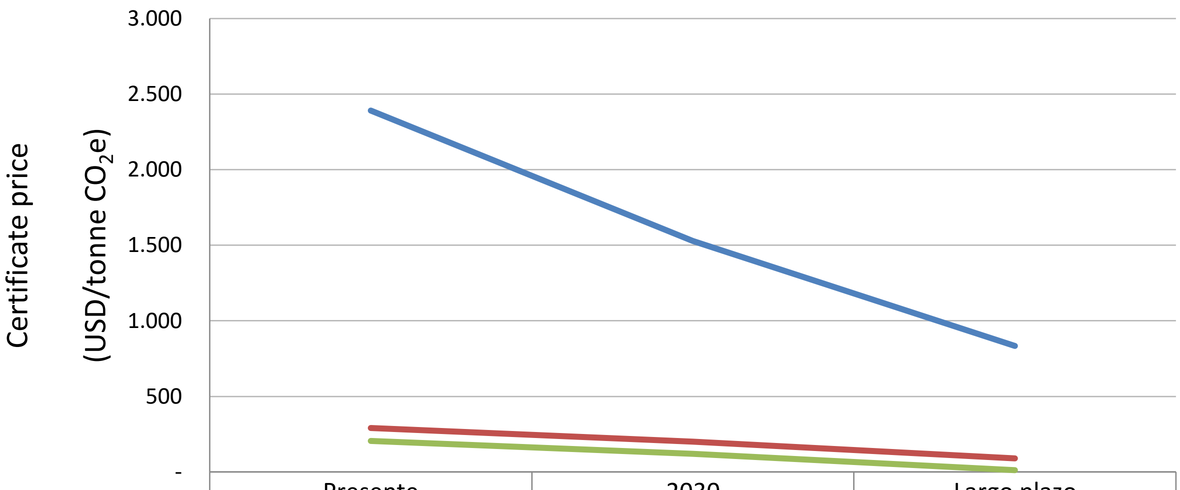
The table below shows the annual abatement potential for each case study. The emission factor for the steel case study includes only CO_2 emissions and not other pollutants in line with the emission factor (EF) database commonly used by the industry, as provided by the World Steel Association. Although the coking process may have associated methane and nitrous oxide emissions, these are negligible compared with the CO_2 emissions that occur. According to IPCC emission factors, the figures are 1 kg CH_4/TJ metallurgical coal and 1.4 kg N_2O/TJ metallurgical coal.

[8] Available at: https://www.coordinador.cl/mercados/documentos/transferencias-economicas/antecedentes-de-calculo-para-las-transferencias-economicas/2021-antecedentes-de-calculo-para-las-transferencias-economicas/ (in Spanish)

Table 3-1 Emission-reduction potential calculated for the projects

Case Study	Unit	Present	Medium term	Long term
Mining	tonne CO_2e	550	550	441
	tonne CO_2e of CO_2	542	542	435
	tonne CO_2e of CH_4	0	0	0
	tonne CO_2e of N_2O	8	8	7
Cement	tonne CO_2e	50,215	48,093	45,972
	tonne CO_2e of CO_2	50,070	47,954	45,838
	tonne CO_2e of CH_4	51	49	46
	tonne CO_2e of N_2O	95	91	87
Steel	tonne CO_2e	297,954	297,954	297,954
	tonne CO_2e of CO_2	297,954	297,954	297,954
	tonne CO_2e of CH_4	-	-	-
	tonne CO_2e of N_2O	-	-	-

An exercise was carried out to illustrate the order of magnitude of the prices at which the certified emission reductions would need to be set in order to close the projects' feasibility gap based on the results obtained in the previous exercise. This was done by taking the feasibility gap calculated in Section 2 and dividing it by the total emissions avoided over 10 years, starting from the year corresponding to each modelling scenario. The result is understood to be the certificate price that reduces the feasibility gap for the whole project. The results are shown in the graph below:



	Presente	2030	Largo plazo
Buses	2.391	1.527	834
Cemento	291	201	90
Acero	205	120	12

Figure 3-2 Carbon price required in order to close the feasibility gap

Source: compiled by the authors

Translation:

Presente	Present
Largo plazo	Long term
Buses	Buses
Cemento	Cement
Acero	Steel

In this theoretical exercise, the bus initiative is the least competitive given that it is a smaller project in terms of investment and mitigates fewer emissions over time. Moreover, this is the only project whose baseline is affected by country-level commitments in the NDC, so the amount of certificates that can be traded actually decreases over time as a result of the emission reduction in its baseline.

4 Opportunities to sell certified emission reductions under Paris Agreement Article 6 schemes

This section aims to evaluate different scenarios for future income from the sale of certified emission reductions in the context of a carbon market established by Article 6 mechanisms in the Paris Agreement. This section is divided into sub-sections, each with a complementary purpose, as listed below.

- Brief introduction to the carbon market schemes under Article 6 of the Paris Agreement.
- Determination of the price ranges associated with certified emission reductions.
- Determination of the ranges of crediting periods for which projects could qualify.
- Study of the compatibility of the schemes defined by Article 6 in the context of Chile and its climate policy.
- Recommendations on pricing and crediting periods in the case of Chile and the development of analysis scenarios to compare cash inflows from expected certificate sales with each project's feasibility gap.[9]

4.1 Introduction to market-based schemes under Article 6 of the Paris Agreement

Article 6 of the Paris Agreement envisages establishing a framework for voluntary cooperation between different jurisdictions to help them achieve the targets defined in their NDCs and pursue a higher level of ambition. Therefore, by using the schemes defined in Article 6 of the Paris Agreement, a jurisdiction may provide financial compensation for mitigation efforts in another jurisdiction in order to meet some of its own national targets.

Article 6 proposes three instruments to achieve global mitigation targets cost-effectively. The first two are carbon market schemes and the third is a non-market scheme, as explained below (Kizzier, Levin, & Rambharos, 2019).

- **Article 6.2** establishes an emission-reduction accounting framework to enable international cooperation through ITMOs. ITMOs could also facilitate international recognition of carbon prices, for example by linking two or more countries' local carbon markets (such as linking the EU cap-and-trade scheme with Swiss emission-reduction transfers).
- **Article 6.4** creates a central UN mechanism, which replaces the Kyoto Protocol's CDM, to trade credits from additional emission reductions generated through specific projects. For example, country A can pay for (purchase) emission-reduction credits generated by a wind farm located in country B. Country B benefits from the clean energy, and country A obtains the credits associated with the reductions that could allow it to meet its NDC commitments. The emission-reduction transactions, i.e. the buying and selling, can be carried out both by public and private entities.
- **Article 6.8** recognises a number of non-market measures and actions designed to facilitate compliance with the objectives of the Paris Agreement. In particular, it refers to the coordination of institutional arrangements and joint policies across jurisdictions.

The focus of this analysis will be limited to market-based schemes (Articles 6.2 and 6.4) where a business model can be set up to support an investment project's future flows. A comparative table of the characteristics associated with the sale of emission reductions in Article 6.2 and 6.4 schemes is set out below.

[9] The goal is for the sale of certified emission reductions to reduce the feasibility gap for the projects being studied.

Table 4-1 Comparison of characteristics associated with the sale of certificates under Article 6.2 and Article 6.4

Characteristics	Article 6.2	Article 6.4
Rules and guidelines	There will be certain expectations that projects must comply with (e.g. corresponding adjustments, robust accounting), but there may be some flexibility in how the terms are interpreted. The specific interpretation of the 'rules' for a given project or type of project would be agreed by the Chilean Government together with the collaborating governments and documented in Mitigation Outcome Purchase Agreements (MOPAs). Project proponents are likely to have the opportunity to influence decisions on key design issues according to the concept note and other project documentation.	There will be set rules (e.g. crediting period, use of methodologies, corresponding adjustments, share of proceeds, overall mitigation of global emissions) and procedures to be followed, as with the CDM. The rules will be known but could be restrictive and/or entail high transaction costs.
Project timing	Article 6.2 projects could be negotiated and start immediately. While general rules and guidelines are still being negotiated, projects could be initiated through international cooperation among two or more countries.[10] However, there is a risk associated with projects getting under way, and the rules and guidelines then being more (or less) restrictive than envisaged, forcing adjustments to be made to MOPAs and/or project designs.	Article 6.4 projects cannot start until the rules and guidelines have been negotiated and the governance mechanism and oversight bodies are in place and operational. There is therefore considerable uncertainty as to when such projects can begin. The earliest that rules and guidelines could be established would be at COP26 in Glasgow (1–12 November 2021). While negotiations are ongoing, voluntary markets continue to operate on the basis of existing standards and the transition to the new mechanism will have to be defined.
Price and payment terms	Cooperative approaches between countries offer a simple option to set agreed prices over the life of the MOPA (it is also possible to sell only a fraction of the anticipated mitigation outcomes through these cooperative arrangements). While it is more common for payments to be performance-based (based on	Private-sector companies can enter into contracts with private-sector partners, similar to the government's cooperative approach. Alternatively, project developers could plan to sell all or only a fraction of the resulting certified emission reductions, anticipating that prices may be

[10] The report published by Climate Focus (CF) and Perspectives Climate Group (PCG) contains background information on some international cooperation pilots currently being developed in connection with Article 6 (Greiner, 2020).

	actual documented emission reductions), governments could, subject to negotiation, agree to provide some upfront funds to help finance initial costs. The arrangements would offer price certainty to project participants. However, there is a risk that market prices could be higher than those that have been agreed.	higher in the future. While modelling and historic prices in other markets provide information on what carbon prices Article 6 might achieve, there have not yet been any Article 6 public transactions to enable these decisions to be made.

Source: compiled by the authors

While there is currently no certainty about what the rules will be for trading international emissions reductions through the schemes mentioned in Articles 6.2 and 6.4 of the Paris Agreement, there are pilots[11] under way that provide guidance on how these schemes (including price ranges and crediting period ranges) are likely to develop.

4.2 Price ranges

The following is an overview of carbon pricing in different markets and schemes, both nationally and internationally. The survey data can be used to sketch out Article 6 carbon price scenarios.

4.2.1 Suggested carbon prices in the IETA Article 6 modelling study

The International Emissions Trading Association (IETA) report entitled *The Economic Potential of Article 6 of the Paris Agreement and Implementation Challenges* (IETA, 2019) calculates carbon shadow prices[12] for countries and regions participating in the Paris Agreement. These prices are calculated by simulating four alternative scenarios, combining two NDC implementation scenarios and two levels of NDC ambition.

The NDC implementation scenarios are (1) the independent implementation scenario and (2) the cooperative implementation scenario. The independent implementation scenario assumes that countries implement their NDC targets independently and continue to decarbonise their economies on their own until they meet their targets for 2030 and beyond. Each country is assumed to reach its NDC emissions limit through economically efficient policies (e.g. carbon taxes on fossil and industrial emissions).

Conversely, the cooperative implementation scenario assumes that countries collaborate to meet their NDC targets and reduce these beyond 2030 as provided under Article 6 of the Paris Agreement. In this scenario, countries can buy and sell ITMOs, which accurately represent actual emission mitigations and are reliable instruments for achieving their decarbonisation targets.

Both the independent and cooperative implementation scenarios consider a baseline scenario of the original set of NDCs with ‘continued ambition’ until 2030, and an enhanced ambition sensitivity scenario, which increases the ambition of NDCs beyond 2030. The shadow carbon prices in the IETA analysis are presented below**.**

[11] Some of these pilots have been documented in the report *Landscape of Article 6 Pilots: A closer look at initial cooperative approaches* by the Nordic Environment Finance Corporation (NEFCO, 2019).

[12] A shadow price is understood to be a monetary value assigned to costs that are currently unknown or difficult to estimate in the absence of correct market prices, which would be the case for Article 6 programmes. Shadow prices are estimated based on the principle of willingness to pay on the demand side.

Table 4-2 Shadow prices resulting from the analysis of the global implementation of Article 6, in USD/tonne CO_2

Ambition scenario	Implementation scenario	2030	2050[13]
Baseline NDC scenario	Independent	0-101	0-111
	Cooperative	38	52
Enhanced NDC scenario (after 2030)	Independent	Not applicable	95-159
	Cooperative	Not applicable	110

Source: (IETA, 2019)

In some respects, the shadow prices of cooperative implementation could be considered low, as this assumes that all countries and regions follow the most efficient implementation strategies. In addition, the prices calculated in this study do not consider the impact of recent improvements in the NDCs that should increase the prices in the independent and cooperative implementation scenarios above those proposed in the baseline scenario. **A price of USD 38/tonne CO_2e can be considered to be the minimum expected price for an Article 6 project in 2030 while maintaining environmental integrity and safeguarding against double counting.**

4.2.2 Carbon pricing in mandatory regulated carbon market programmes

Among the Parties to the Paris Agreement that comply with Article 6 (Article 6.2), Sweden, Switzerland and Canada have, to date, been the most active, making progress with pilot projects and international cooperation agreements. All three countries participate in emissions trading systems (ETS). Sweden participates in the EU ETS, while the Swiss emissions trading programme is provisionally linked to the EU ETS. Canada has a market mandate that calls for all provinces to adopt carbon pricing. Quebec and California's existing ETS programmes (Western Climate Initiative – WCI) meet these requirements. Other potential buyers, such as New Zealand and South Korea, also have an ETS.

Over the past two years, the prices of these ETS programmes have ranged from USD 11–69/tonne CO_2e, and some programmes have shown considerable price volatility. In certain cases, prices have increased with expectations of more ambitious mitigation targets, and in others, prices have decreased over the period, potentially affected by broader economic trends, contributing to an oversupply of emission allowances. Below is a table summarising the highest and lowest prices during the period under review for each ETS, and Figure 4-1 below the table shows the evolution over time.

Table 4-3 Prices of carbon credits traded in the above ETSs from 1 January 2020 to the present day (USD/tonne CO_2e)

ETS Programme	Lowest ETS price	Date of lowest price	Highest ETS price	Date of highest price
WCI	$16.68	May 2020	$18.8	May 2021
EU ETS	$18.04	March 2020	$68.62	May 2021
Switzerland	$27.60	November 2020	$46.70	March 2021
New Zealand	$13.42	March 2020	$30.63	June 2021
South Korea	$9.36	June 2021	$33.20	March 2020

[13] The IETA price projections go up to 2040. For the purposes of this study, a linear projection is shown from 2030 to 2040 for the 2050 shadow carbon prices in the different scenarios modelled in this study.

Source: International Carbon Accounting Partnership, 2021.[14]

Figure 4-1 Prices of carbon credits traded in the ETSs from 1 January 2020 to the present day (USD/tonne CO_2e)

Source: International Carbon Accounting Partnership, 2021.

As a result of the increased ambition in several countries' new NDCs, it seems likely that current EU ETS carbon prices, which are already high, will increase over the next decade. As reported by Bloomberg Green (Krukowska, 2021), the European Commission projects that carbon prices will be between EUR 50 and 85/tonne CO_2e in 2030 as a consequence of the recent ETS review. Carbon prices in the European region have doubled in the last two years to more than EUR 55/tonne CO_2e due to expectations that the reforms, which have already taken place, will strengthen the EU ETS and increase demand for emission permits.

Alongside emissions trading schemes, the various carbon taxes paid in countries around the world are also relevant. Although only a couple of carbon tax systems allow compliance by means of offsets, including Chile's carbon tax, these prices provide an idea of the countries' willingness to pay for GHG mitigation. To illustrate this point, the following table shows a selection of figures for existing levies in some jurisdictions (World Bank, 2021).

[14] Consulted 22 July 2021.

Table 4-4 Carbon taxes in USD (1 April 2021 nominal prices)

Jurisdiction	Carbon tax (USD/tonne CO_2)
Canadian Provinces	
British Columbia	35.81
New Brunswick	31.83
Labrador, Newfoundland, Northwest Territories and Prince Edward Island	23.88
Denmark	28.14
Finland	72.83 (transport fuel) 62.23 (other fossil fuels)
France	52.39
Iceland	34.83
Ireland	39.35
Liechtenstein	101.47
Luxembourg	40.12 (diesel fuel) 23.49 (other fossil fuels)
Netherlands	35.24
Norway	69.33
Portugal	28.19
Slovenia	20.32
Spain	17.62
Sweden	101.47
Switzerland	101.47
United Kingdom	24.80

Source: (World Bank, 2021)

4.2.3 Current prices in voluntary carbon markets

At the other end of the spectrum, voluntary offset programmes, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) as well as certain carbon tax and ETS programmes, are increasingly accepted as a means of compliance with certain mitigation obligations. For example, CORSIA accepts credits from the American Carbon Registry, Climate Action Reserve, Gold Standard and VCS, and credits from the latter two programmes are also accepted by Colombia and South Africa under their regulated markets. CORSIA also accepts China's Voluntary Greenhouse Gas Emission Reduction Programme, in addition to various Chinese pilot programmes. Of these programmes, only the Gold Standard has indicated that corresponding adjustments will be required for projects operating in the future. Prices in these markets for 2018 and 2019 have, on average, been below USD 5/tonne CO_2.

For the Gold Standard, prices are expected to rise according to changes in supply and demand in the different markets. For example, the aviation sector's carbon neutrality commitment (under which emissions above 2019 levels must be offset) will become mandatory for participating airlines from 2027 (Neutral Capital Partners, 2020). Prices could also increase over time as national ETS programmes become more stringent in line with national mitigation targets. Other factors affecting voluntary market prices include project size, location, age, the MRV methodology used,[15] project quality,[16] economies of scale, project communications and the value of non-carbon benefits. Gold Standard projects are offered for sale on the market at a price range of USD 10-47/tonne CO_2e (Gold Standard Marketplace Website, 2021), including brokerage costs. However, market prices incorporate the results of a fair trade carbon credit pricing model and sustainable development benefits, but not the specific attribute of having a corresponding adjustment to avoid double counting CO_2e.

Another important indicator for estimating the carbon price are 'compliance-specific' offsets used to comply with mandatory national or sub-national carbon pricing programmes. Some mandatory compliance programmes allow offsets to be used to meet part of the compliance obligation as, for example, in the case of Chile's carbon tax, which has an emissions offset programme that will come into force in 2023. These offsets usually arise from national offset programmes that have been set up for this purpose. In most cases (with the exception of offset credit transfers between California and Quebec), emission reductions from these programmes are not transferred internationally from one country to another and are therefore not subject to a price adjustment. Among the programmes studied, the exception would be the Swiss programme (with prices of USD 83–85/tonne CO_2). Countries may be willing to pay a higher price for domestic offsets (due to the expected co-benefits and lower transaction risk) than for international offsets.

[15] The use of a more conservative methodology that tends to underestimate the project's emission reductions will be valued more highly than one that risks overestimating the emission reductions achieved.

[16] In addition to making the corresponding adjustment to avoid double counting emission reductions, other project quality aspects include the approach(es) used to justify how the project offers additionality compared with business as usual.

Table 4-5 Details of mandatory programmes accepting offsets

Offset programmes	Mechanisms accepting offsets from offset programmes	Prices reported as at 2019 (range in USD/tonne CO_2 unless otherwise stated)
Alberta Emission Offset System	Alberta TIER	14-19
Australia ERF	Australia ERF Safeguard Mechanism	10-11
British Colombia Offset Program	Greenhouse Gas Industrial Reporting and Control Act (GGIRCA)	11.41 Canadian dollars (weighted average)
California Compliance Offset Program	California ETS, Quebec ETS	14.13 (weighted average)
J-Credit Scheme	Saitama ETS	16.66 (renewable energy) 13.26 (energy efficiency)[17]
Quebec Offset Crediting Mechanism	California ETS, Quebec ETS	12.79 (weighted average)
Republic of Korea Offset Crediting Mechanism	Republic of Korea ETS	25-33
Switzerland CO_2 Attestations Crediting Mechanism[18]	Producers and importers of fossil motor fuels	83-85
Tokyo Cap-and-Trade Program	Tokyo Cap-and-Trade Program	46-59

Source: (World Bank, 2020)

4.2.4 Social cost of carbon

The social cost of a greenhouse gas is the monetary value of the net damage to society associated with adding an amount of GHG to the atmosphere in a given year. Government agencies use these figures to estimate the social benefits (or harms) of actions that reduce (or increase) CO_2e emissions.

In Chile, the Ministry of Social Development estimates this figure in its report Estimate of the Social Cost of CO_2 (Ministerio de Desarrollo Social, 2016). The report established an intermediate figure for the social cost of CO_2 at USD 32.5/tCO_2, setting a marginal cost of CO_2 abatement that allows national mitigation targets to be met.

The United States recently presented an interim update of its estimates of the social cost of carbon (Interagency Working Group, 2021). As with previous US estimates, a discount rate of 3% was used to

[17] Calculated with a conversion rate of USD 0.009/yen.

[18] Switzerland's programme explicitly allows for compliance through emission reductions that take place abroad, in line with the Kyoto Protocol and the Paris Agreement. Emission reductions must be supplementary, promote sustainable development in the host country and cannot already have been claimed by another country (FOEN, 2020).

obtain a consumption rate of interest.[19] However, given that recent interest rates have been below 3%, many analysts argue that a lower discount rate should be used. Social costs and discount rates are expected to be re-evaluated in future updates of the social cost of carbon.

Table 4-6 Social cost of CO_2e in the United States, 2020-2050 (in USD 2020/tonne CO_2e)

Year of emissions	Discount rate and statistics			
	5%	3%	2.5%	3%
	Average	Average	Average	95th percentile
2020	14	51	76	152
2025	17	56	83	169
2030	19	62	89	187
2035	22	67	96	206
2040	25	73	103	225
2045	28	79	110	242
2050	32	85	116	260

Source: compiled by the authors based on external sources

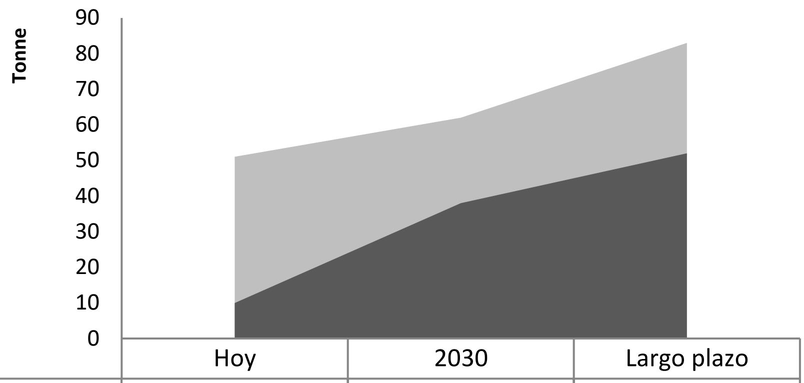
4.2.5 Price ranges for Article 6 financial analysis

Based on the reference prices presented in Section 4.2 above, the recommended approach is to assume two scenarios, a low-price scenario and a high-price scenario. The suggested low-price scenario starts with a carbon price that would be attractive to participants in a wide range of developed country ETS markets, based on emission allowances and offset prices (USD 10/tonneCO_2e). The price would increase in a linear fashion up to USD 38/tonne CO_2 (the market price for the global implementation of Article 6 in 2030), assuming that the targets set out in the NDCs are met. Thereafter, the trajectory increases in a linear fashion to USD 52/tonne CO_2 in 2050 (the carbon price in 2050 based on the effective global implementation of the original NDCs).[20]

For the high-price scenario, the price projections for the US social cost of carbon were used, starting at USD 51/tonne CO_2 in the Present scenario and reaching USD 83/tonne CO_2 in the Long-Term scenario. This is to ensure a significant difference between the two scenarios, including current and expected figures from the EU ETS and more ambitious scenarios from the IETA.

[19] A consumption rate of interest is the ratio according to which one unit of consumption in the present is exchanged for one unit of consumption in the future.

[20] Taking the prices of USD 38 and 52/tonne CO_2 for 2030 and 2050 respectively, corresponding to projections for shadow prices resulting from the analysis of the global application of Article 6 in a cooperative scenario for achieving the NDCs (IETA, 2019). The details are presented in the section entitled ‘Suggested carbon prices in the IETA Article 6 modelling study’.



	Hoy	2030	Largo plazo
Escenario optimista	51	62	83
Escenario pesimista	10	38	52

Figure 4-2 Certified price of emission reductions

Source: compiled by the authors based on secondary sources

Translation:

Hoy	Today
Largo plazo	Long term
Escenario optimista	Best-case scenario
Escenario pesimista	Worst-case scenario

4.3 Duration of the crediting period

The following is an overview of the possible crediting periods for Article 6 programmes according to the Article 6 negotiating draft and other literature reviewed.

4.3.1 Crediting period for Article 6.2 and Article 6.4 programmes according to the draft negotiating text

According to the draft negotiating text (Annex 9), Article 6.2 programmes have considerable flexibility in defining the crediting period. The different versions of the text do not provide any guidance on the length of the crediting period, apart from the requirement that it should not start before 2021. There is a possibility that this issue may be subject to further guidance by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA).

Article 6.4 projects[21] are subject to a maximum crediting period of:

- 10 years; or
- 5 years, with the option to renew twice for a total of 15 years.

Note that renewals are subject to a baseline adjustment and a review of project additionality, so the second and third periods are likely to generate incrementally fewer emission reductions. The detailed rules for approving renewals are not yet defined and will be presented by the CMA at a later stage. Renewals also require the approval of both the Supervisory Authority and the host government.

Host governments may adopt shorter crediting periods than the maximum allowed and can specify this before deciding to participate. They may also indicate whether the crediting period can be renewed. The

[21] The 13 December text includes wording that could lead to different crediting periods for forestry and land use projects.

host's specifications for the crediting period would include an explanation of how the choice is compatible with its NDC and long-term strategy.

4.3.2 Reference to crediting periods in the literature

The crediting period under various offset programmes ranges from four years for projects that reduce hydrofluorocarbons (HFCs) under the Chicago Climate Exchange (CCX) trading system (Kollmuss, Zink, & Polycarp, 2008) to 100 years for certain forestry projects. In some cases, the crediting period may be renewed for one or more periods, usually requiring revalidation with a new baseline. In other cases, the crediting period is fixed. The crediting periods of various offset programmes are shown in Annex 10.

Most of these programmes were developed before the Paris Agreement was signed and before developing countries were asked to adopt their own ambitious national mitigation targets. Consequently, developing countries hosting offset projects were not very disadvantaged when it came to approving the sale of emission-reduction units over long periods. Long-term crediting periods were seen to be advantageous both for the project developers and the buyer/user. With the Paris Agreement, this perception is changing.

In the current context, where both hosts and users are seeking emission reductions to meet short-term NDCs as well as long-term mitigation targets, long and renewable crediting periods will become less acceptable. Host countries will have to be strategic when deciding what investments are needed to overcome the barriers to a low-carbon transition. This includes defining the types, amounts and duration of the investments required. Host governments will have to consider the time frame for which incentives for emission reductions funded by ITMOs are likely to be needed in order to achieve national mitigation targets.

There is no publicly available information to date on crediting periods for Article 6 pilot projects being developed that involve a corresponding adjustment by the host country.

4.4 Decisions on transferring mitigation outcomes and other considerations for Chile

This section examines the particular considerations applicable to Chile, taking into account NDC commitments, the risks of participating in Article 6 and the possibility of selling products with a 'Green Premium' component,[22] i.e. selling products at a higher price due to their green attributes, having been produced by a project that reduces emissions (particularly for the steel and cement cases studied).

4.4.1 Price considerations in the context of Chile

In addition to considering the various external price points mentioned above, there are two internal factors specific to Chile that must be weighed up when deciding prices.

- **Certificate price vs the marginal abatement cost.** The certificate price should not be lower than the marginal abatement cost associated with applying the proposed technology, while recognising that there may be other co-benefits of the investments that could bear part of the cost.
- **Certificate price vs the cost of measures needed to comply with the NDC**. In the case of Chile, as presented in the updated NDC and in Figure 4-3 below, the marginal cost of the latest measures to comply with the NDC (district heating) are quite high at more than USD 200/tonne CO_2e abated.

[22] A 'green premium' refers to the sale of a product (often labelled as 'green') that meets responsible and/or sustainable production criteria and a defined standard, and for which a customer would be willing to pay more compared to the same product without this attribute.

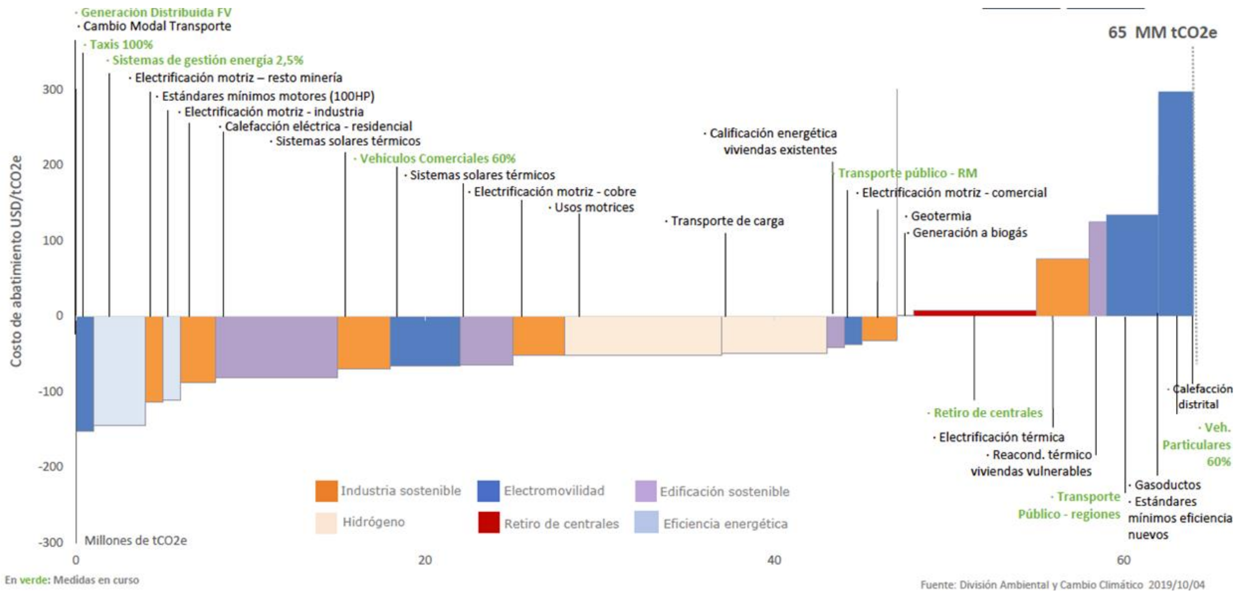


Figure 4-3. Marginal abatement cost curve

Source: (Ministry of Environment, 2020)

Translation:

Costo de abatimiento	Abatement cost
Generación distribuida FV	Distributed PV generation
Cambio Modal Transporte	Transport Modal Shift
Taxis	Taxis
Sistemas de gestión energía 2,5%	Energy management systems 2.5%
Electrificación motriz – resto minería	Powertrain electrification – rest of mining
Estándares mínimos motores	Minimum engine standards
Electrificación motriz – industria	Powertrain electrification – industry
Calefacción eléctrica – residencial	Electric heating – residential
Sistemas solares térmicos	Solar thermal systems
Vehículos Comerciales	Commercial vehicles
Sistemas solares térmicos	Solar thermal systems
Electrificación motriz – cobre	Powertrain electrification – copper
Usos motrices	Engine uses
Transporte de carga	Freight transport
Calificación energética viviendas existentes	Energy rating of existing dwellings
Transporte público – RM	Metropolitan public transport
Electrificación motriz – comercial	Powertrain electrification – commercial
Geotermia	Geothermal
Generación a biogás	Biogas generation
Retiro de centrales	Decommissioning of power plants
Electrificación térmica	Thermal electrification
Reacond. térmico viviendas vulnerables	Thermal retrofitting of vulnerable dwellings
Transporte público – regiones	Public transport – regions
Gasoductos	Gas pipelines
Estándares mínimos eficiencia nuevos	New minimum efficiency standards
Calefacción distrital	District heating
Veh. Particulares	Private vehicles
Millones de tCO2e	Million tCO_2e

En verde: Medidas en curso	Green: ongoing measures
Industria sostenible	Sustainable industry
Hidrógeno	Hydrogen
Electromovilidad	Electromobility
Retiro de centrales	Decommissioning of power plants
Edificación sostenible	Sustainable building
Eficiencia energética	Energy efficiency
Fuente: División Ambiental y Cambio Climático	Source: Environment and Climate Change Division

One of the objectives of Article 6 would be to help reduce the cost of measures that might be necessary to meet future NDCs. Consequently, the price obtained through Article 6 for a hydrogen project in addition to the current NDC does not necessarily have to be higher than the last measure identified in Figure 4-3, i.e. district heating with an abatement cost above USD 300/tonne CO_2e, but the latter measures do provide a benchmark range for projects additional to the NDC.

4.4.2 Considerations during the crediting period in the context of Chile

An analysis of Article 6 participation should ideally consider two scenarios for the length of the crediting period (a long-term crediting period and a short-term crediting period) to understand how this variable influences the project's feasibility. The maximum possible crediting period, which limits the maximum number of credits that can be sold, is the 15-year period specified in the draft negotiating text for Article 6.4, based on a five-year crediting period that can be renewed twice.

For the Chilean case in particular, it is important to note that to date there are no plans or commitments to adopt hydrogen in the NDC target sectors until 2030, so the baseline for the first five years of the crediting period for any project in the cement, steel and mining industries using H2V could have business-as-usual emission levels, assuming a project start date of 1 January 2026.

However, an updated baseline trajectory would need to be defined for the second and third crediting periods, potentially consistent with a linear reduction between 2031 and 2050, assuming that H2V is included in the country's emission-reduction targets and that those targets are achieved. This would be a conservative approach, using the best information available on projected future plans in order to maintain the projects' additionality.

Table 4-7 Planned measures for hydrogen in Chile (baseline and carbon-neutral scenarios)

Hydrogen	Freight transport	Energy	No associated measures	71% in freight transport by 2050
	Industry and mining transport	Energy	No associated measures	12% in industry and mining transport by 2050
	Heating via pipelines	Energy	No associated measures	7% in homes and 2% in industry by 2050

Source: (Ministry of Environment, 2020)

As can be seen in Table 4-7, given that the hydrogen measures being analysed in this study are understood to be entirely in addition to the NDC, issuing certified emission reductions under Article 6 would not compromise Chile's ability to meet the commitments stated in its NDC. Therefore, there is no opportunity cost as there might be for the measures deemed necessary to achieve the NDC. It is worth mentioning that the measures set out in the NDC are a good estimate of the initiatives that would contribute to meeting the national emission-reduction targets. This does not mean that Chile cannot decide to maintain reductions associated with other types of projects as part of its mitigation outcomes.

Undoubtedly, the policies, measures and incentives that Chile designs could affect the deployment of hydrogen-fuelled technologies. When calculating emission reductions for any projects to be developed, the most up-to-date information available for new crediting periods should be analysed as this could have implications for the baseline used.

For example, in recalculating a project's reductions after 2030, the emissions associated with the second and third baselines (depending on the number of crediting period renewals associated with the project) could differ compared to the first if new initiatives using H2V in activities such as those analysed in this study were to be included in the NDC.

4.5 Recommendations for Chile based on an analysis of Article 6 and of the scenario for the proposed projects

4.5.1 Recommendations for the carbon price point and crediting periods to be used in the projects being studied

The carbon price trajectories designed to analyse the sale of certified emission reductions for the projects in this study are summarised below. These projections will be used later to assess the revenues that the projects being analysed could expect to earn from the sale of certified emission reductions.

Table 4-8 Low and high carbon price trajectories suggested for the Article 6 financial analysis (in USD/tonne CO_2e)

Trajectory	2020	2025	2030	2035	2040	2050
Low-price trajectory	$10[23]	$24[24]	$38	$41.5	$45	$52
High-price trajectory	$51	$56	$62	$67	$73	$83

Source: compiled by the authors

The assessment is conducted for both price trajectories to highlight the variability and uncertainty associated with future carbon prices. It is worth mentioning that the prices in both scenarios are lower than those calculated for the abatement cost that would close the feasibility gap. It can therefore be concluded that other revenue will need to be considered to enable the project to be viable.

For the duration of the crediting period, the 15-year option (in three five-year periods) is recommended. As mentioned above, this is the maximum duration allowed by Article 6. This period is stipulated because even if the baseline between 2030 and 2050 undergoes modifications and is then more restrictive for the emission-reduction calculations of the second and third crediting periods, the price per certificate that could be obtained for the following crediting periods would be higher (both in a low-price and a high-price scenario).

For each financial analysis, the initial consideration is whether the maximum crediting period of 15 years is sufficient for hydrogen projects to be economically viable under the recommended carbon prices. If the answer is 'no', the recommendation may be to continue with the maximum crediting period allowed in order to have the best opportunity for the technology to develop. If the answer is 'yes', the team should determine the shortest crediting period that allows the projects to remain profitable under each suggested pricing.

[23] USD 10/tonne CO_2e is a price point that could be attractive for a wide range of carbon markets based on the market prices and offset prices in 4-3 and 4-5.

[24] Assumes a linear increase in prices between 2020 and 2030.

4.5.2 Analysis of scenarios for the projects being studied

The income from the sale of certified emission reductions was calculated for the two previously established sales scenarios (LOW for the low-price scenario and HIGH for the high-price scenario) using the information from the cost-benefit analysis in Section 2 and the projects' emission-reduction potential.

This was done for crediting periods of 5, 10 and 15 years. The reason behind the exercise is to raise awareness of the scenarios in which the feasibility gap is covered by the sale of emission reductions, and to be able to identify how much is needed to fill that gap in cases where the income from the sale of certificates is insufficient.

Cement case study

The costs of technology in the cement industry are expected to decrease in the future, and the application's competitiveness will increase considerably. It is anticipated that the gap will be smaller by 2050, and the sale of certified emission reductions would help to close much of the feasibility gap.

A colour scale is used in the tables below. Red represents a negative feasibility gap, and the gradual change in shade towards green shows progress towards the project's economic feasibility.

Table 4-9 Feasibility gap after the sale of certified emission reductions for the cement case study, at present value (PV)

		Present	2030	Long term
Economic feasibility gap		$ -100,812,471	$ -67,427,260	$ -29,378,724
Certificate value: low-price trajectory (USD/tonne CO_2)		$ 10	$ 38	$ 52
Certificate value: high-price trajectory (USD/tonne CO_2)		$ 51	$ 62	$ 83
Low-price trajectory	Emission reduction (5 years)	$ -98,769,780	$ -59,964,794	$ -19,577,126
	Emission reduction (10 years)	$ -97,344,383	$ -54,703,084	$ -12,588,722
	Emission reduction (15 years)	$ -96,346,083	$ -50,993,571	$ -7,606,086
High-price trajectory	Emission reduction (5 years)	$ -90,394,746	$ -55,251,657	$ -13,733,865
	Emission reduction (10 years)	$ -83,125,222	$ -46,666,763	$ -2,579,297
	Emission reduction (15 years)	$ -78,033,892	$ -40,614,400	$ 5,373,755

Source: compiled by the authors

Steel case study

The results are more optimistic in the steel industry. The feasibility gap is covered in the long term with sales periods of 10 and 15 years in low and high-price scenarios. It is important to consider the risks that could be associated with the sale of certificates in long crediting periods. These will be reviewed in the next section.

Table 4-10 Feasibility gap after the sale of certified emission reductions for the steel case study, at present values (PV)

		Present	2030	Long term
Economic feasibility gap		$ -429,180,321	$ -251,316,887	$ -24,527,007
Certificate value: low-price trajectory (USD/tonne CO_2)		$ 10	$ 38	$ 52
Certificate value: high-price trajectory (USD/tonne CO_2)		$ 51	$ 62	$ 83
Low-price trajectory	Emission reduction (5 years)	$ -417,011,590	$ -204,928,927	$ 38,978,340
	Emission reduction (10 years)	$ -408,301,248	$ -171,829,629	$ 84,272,117

	Emission reduction (15 years)	$ -402,090,894	$ -148,230,286	$ 116,565,954
High-price trajectory	Emission reduction (5 years)	$ -366,923,099	$ -175,608,836	$ 76,850,125
	Emission reduction (10 years)	$ -322,500,356	$ -121,604,716	$ 149,145,962
	Emission reduction (15 years)	$ -290,827,554	$ -83,100,526	$ 200,691,894

Source: compiled by the authors

Mining case study

It is important to note that two baseline scenarios were considered for the mining case study: one which only considered NDC commitments up to 2030 (NDC 2030 scenario) and another which also considers NDC commitments on carbon neutrality up to 2050 (NDC 2050 scenario).

This was done as the only binding commitments are for 2030, while those for 2050 only speculate on the measures that could be adopted to achieve carbon neutrality, but are not binding. A favourable scenario can therefore be achieved (NDC 2030) in which the commitments are less ambitious and where the baseline allows for the project's higher abatement potential. There is a more conservative scenario (NDC 2050) in which the baseline involves more ambitious goals and, therefore, a lower abatement potential.

The results obtained for the mining case study are presented below.

Table 4-11 Feasibility gap after the sale of certified emission reductions for the mining case study, at present values (PV)

		Present	2030	Long term	NDC scenario
Economic feasibility gap (USD)		$ -9,239,839	$ -5,666,304	$ -2,882,005	
Certificate value: low-price trajectory (USD/tonne CO_2)		$ 10	$ 38	$ 52	
Certificate value: high-price trajectory (USD/tonne CO_2)		$ 51	$ 62	$ 83	
Low-price trajectory	Emission reduction (5 years)	$ -9,217,280	$ -5,580,579	$ -2,787,890	NDC 2030
	Emission reduction (10 years)	$ -9,201,195	$ -5,525,317	$ -2,720,788	
	Emission reduction (15 years)	$ -9,189,727	$ -5,486,010	$ -2,672,945	
	Emission reduction (5 years)	$ -9,217,280	$ -5,594,852	$ -2,822,681	NDC 2050
	Emission reduction (10 years)	$ -9,202,315	$ -5,549,989	$ -2,780,384	
	Emission reduction (15 years)	$ -9,192,756	$ -5,522,532	$ -2,750,227	
High-price trajectory	Emission reduction (5 years)	$ -9,124,786	$ -5,526,436	$ -2,731,784	NDC 2030
	Emission reduction (10 years)	$ -9,042,756	$ -5,436,272	$ -2,624,678	
	Emission reduction (15 years)	$ -8,984,269	$ -5,372,140	$ -2,548,313	
	Emission reduction (5 years)	$ -9,124,786	$ -5,549,724	$ -2,787,315	NDC 2050
	Emission reduction (10 years)	$ -9,048,465	$ -5,476,527	$ -2,719,803	
	Emission reduction (15 years)	$ -8,999,716	$ -5,431,729	$ -2,671,668	

Source: compiled by the authors

In this scenario, the contribution from the sale of certified emission reductions is negligible compared with the feasibility gap calculated for all the cases analysed, reflecting the fact that this is a capital-intensive project with low emission-reduction potential. However, it is worth noting that an emission-reduction sales scheme such as the one being proposed could be of interest for a project that involved trips of more than 250 km per day.

4.5.3 Procedures for implementing an Article 6 pilot in Chile

The lack of consensus on defining how to implement Article 6 of the Paris Agreement has led to uncertainty in this market. Nevertheless, pilot projects have been developed that can provide experience and break down certain barriers between countries potentially issuing and receiving ITMOs. Since 2018, various initiatives have been developed to pilot Article 6-related activities, the most advanced of which include the Joint Crediting Mechanism (JCM) initiative, already operating in Japan, and the bilateral agreement recently signed between Switzerland and Peru (Climate Finance Innovators, 2020).

Chile has been proactive in participating in several of these initiatives, such as the JCM, a Swedish Energy Agency (SEA) pilot[25] and the waste sector emissions reduction programme signed with Canada.[26] Any of these could be a good catalyst for sales or transfer agreements of ITMOs under an Article 6 pilot, although it is not a requirement to participate in these initiatives to be able to access an Article 6 market. There are also new instances in which Chile could participate and benefit from the experience of being involved in these carbon market pilots. Among the new initiatives in which Chile could participate is the international club that protects emission-intensive industries being promoted by Germany (Clean Energy Wire, 2021). This seeks to standardise carbon-pricing mechanisms for emission-intensive industries and thus safeguard commitments to other countries or companies with less ambitious targets. It could be important for Chile to influence the conversation on CO_2 pricing as it would create a carbon funding stream to support developing energy technologies.

One important consideration for carbon-intensive industries exposed to international trade, such as the steel and cement industries, is the goal of creating an international framework to protect these sectors from other countries with more lax carbon policies that could result in carbon leakage. In terms of market mechanisms, it is vital to consider the effects of border tariff protection and green trading agreements (Meyer, 2021). These types of international discussions should be taken into account, in particular when looking to sell emission reductions linked to projects in these sectors (steel and cement).

The impact of local regulations is also critical as they could make the sale of certified emission reductions relatively attractive by influencing national standards and what would be deemed a baseline for these projects. An example is Germany, which seeks to retain a partial rebate associated with emission-intensive industries, such as steel and cement.

Figure 4-4 shows the steps needed to create an Article 6 pilot. It is very important to have the Chilean Government's support and involvement by clearly setting out the future commitments it could adopt towards achieving its NDC targets, and which could justify an update or adjustment to the project's environmental commitments.

[25] A Swedish Government initiative to identify and support pilots that can generate ITMOs (Climate Finance Innovators, 2020).

[26] Bilateral agreement on environmental cooperation. In this context, Canada offers technical and financial support to pilot initiatives under Article 6 criteria and reduce methane emissions in the waste sector through the Organic Recycling Programme. (Climate Finance Innovators, 2020).

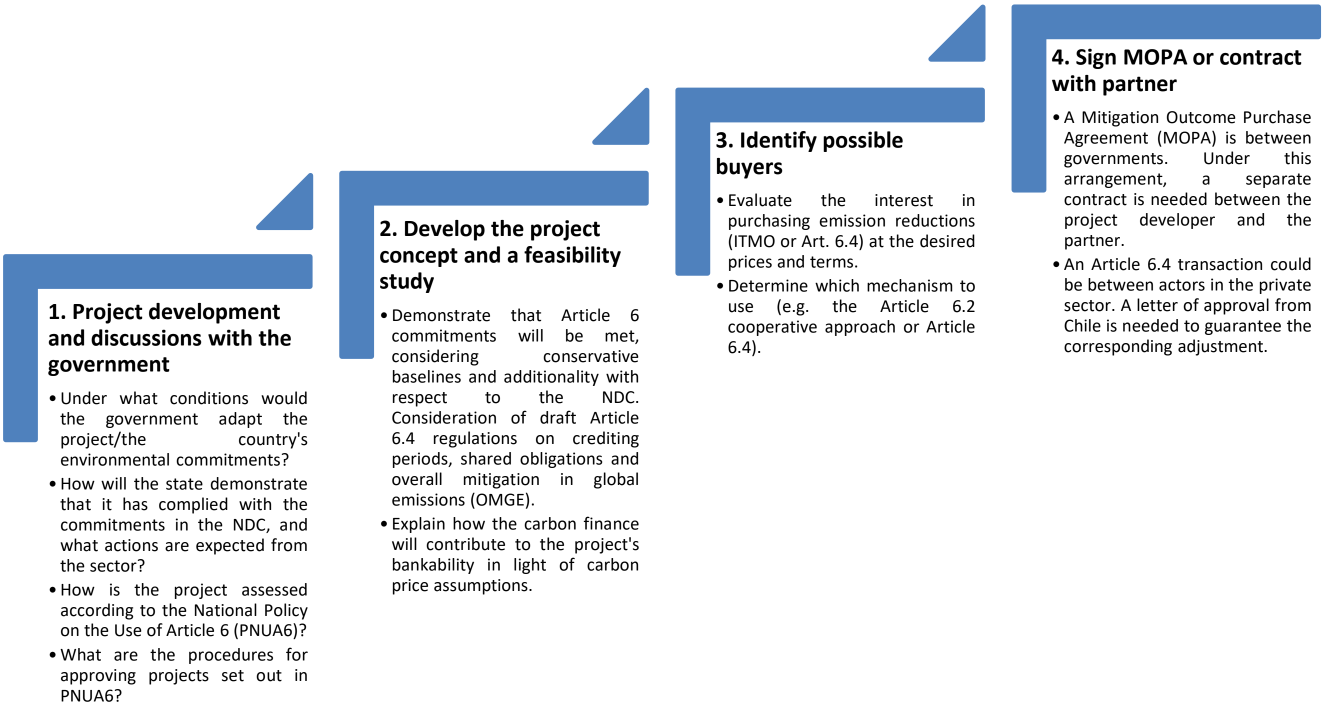


Figure 4-4 Procedure for generating an Article 6 pilot in Chile

Source: compiled by the authors

4.5.4 Risks associated with the sale of emission reductions

Due to high level of uncertainty in this market, the risks that could be associated with the sale of certified emission reductions need to be assessed and considered in order to mitigate them effectively when implementing an Article 6 pilot.

The main risks relate to crediting periods and the need to make adjustments to these projects during the renewal processes, the uncertainty of the prices achievable for the sale of ITMOs, local technical capacities to implement an Article 6 pilot, lack of access to other markets, such as green commodities (earning a green premium) and the effect of local emissions regulations (such as Chile's carbon tax).

Crediting period

As seen above, there are scenarios where the sale of certified emission reductions over long crediting periods (15 years) could be an effective way for the projects to become economically feasible. The problem is that sales over a long period also affect updates and adjustments to the calculation methodology, the baseline and Chile's willingness to share the project results to help meet its local targets. This could compromise the amount of ITMOs that could be traded after project year 5 or 10.

On the other hand, decisions on extended crediting periods should also reflect whether the lifetime of the project (or of any components that may need to be replaced) are in the crediting period range needed to close the feasibility gap without compromising the additionality of that project's results.[27]

[27] The additionality criteria establish that any change in technology needs to take place during this component's lifetime.

Pricing of certified emission reductions

There is great uncertainty about being able to achieve prices that would effectively reduce the projects' feasibility gaps. To manage this and make it possible to implement these projects, relationships will need to be established early on with jurisdictions that would be more willing to pay a 'high' price for the certified emission reductions. The countries most likely to purchase certified emission reductions at high prices could be Switzerland and Sweden. On the other hand, countries interested in the results of some of these projects (which have been little tested), or in being able to provide services or technology associated with the project would be interesting partners to consider when seeking to mitigate this risk. If there is a wish to hedge risks associated with the availability of these flows in the future, it is also possible to negotiate payment of the future flows associated with the project in advance. In this case, the price of the certified emission reductions is likely to be lower than future prices based on the greater maturity of future carbon markets (and the certified emission reductions are therefore sold at a lower price than could be achieved), but it provides assurance to the developers that this financial flow will be available to develop the project.

GREEN TAX IN CHILE

From 2023 onwards, the taxable event will be the **annual emissions threshold** being exceeded (and not the installed capacity, as has been the case until now). A Green Tax will therefore be levied on all emissions of polluting compounds emitting **(a) 100 or more tonnes of particulate matter per year or (b) 25,000 or more tonnes of CO_2 per year.**

There is currently no clarity on the criteria that will be used to define the combustion process or raw materials in law, and therefore which emissions will be subject to the carbon tax in the cement kiln or the blast furnace in the steel industry.

There will be risks involved in transaction costs, which include the effort involved in negotiating processes, capacity building, complying with standards or markets that certify the transactions made and the MRV systems involved. This is a delicate issue that must be taken into account during negotiations, as there are cases in which these costs can represent a large proportion of the expected flows from the sale of certificates. These costs are generally borne by the project developer, and the allocation of this risk will be made explicit in the final MOPA.

However, these transaction costs could come down as more experience is acquired in developing Article 6 pilots. It is also expected that countries seeking to take the lead in implementing these pilots would be willing to assume some of the transaction costs.

Other risks

MRV capacities

There are significant challenges involved in building sufficient capacity to implement pilots such as the one mentioned above, especially in the design and operation of Monitoring, Reporting and Verification (MRV) systems. It is crucial that the Chilean Government allocate sufficient resources to strengthen these capacities at the local level and create early involvement in Article 6 initiatives, such as developing pilot projects.

Amendments to national regulations

Amendments to local carbon regulations (such as carbon tax rises or changes to the sources) or to Chile's sectoral targets in its NDC could jeopardise the amount of ITMOs actually traded in the future.[28] Changes

[28] This relates to the associated risk for the selected crediting period.

to the local tax could mean that the state expects to retain part of the emission reductions depending on the contribution of the carbon price to the project.[29] If there is a strong likelihood of a high domestic carbon price in the future, this could be an argument for using a fixed 10-year crediting period without exposure to baseline adjustments.

When developing the Draft Framework Law on Climate Change, it is important to be explicit about the incentives for developing mitigation projects in Chile under Article 6. For example, at present,[30] Article 14 states:[31]

> *'The Ministry of Environment may authorise the use of certificates to reduce or remove emissions for projects implemented in other countries as part of the cooperation referred to in Article 6 of the Paris Agreement and links with this or other similar instruments at the international level.'*

This incentivises the purchase of certified emission reductions, but not the sale. There is therefore no clear sign of promoting Article 6 pilots in Chile. The definitions in the Regulation on Offsets currently being drafted are also important.

Potential incompatibility between selling emission reductions and receiving income from the sale of products with green attributes in the form of a 'green premium'.

Finally, there is a risk of not being able to participate in other markets associated with the green attribute that the project could deliver. An example of this would be not being able to sell the final product as a 'green' product given that the mitigation efforts are being traded through a carbon market. There is currently no explicit limitation to being able to participate both in a carbon market and in a green premium market, but there is a risk that in future both green premium product standards and Article 6 regulations or calculation methodologies could make it impossible to participate in both markets simultaneously. A more in-depth discussion of this issue can be found in Annex 11.

[29] For example, if it is estimated that a carbon price incentive of USD 100/tonne CO_2 is needed for the project to be viable, and the carbon tax system requires a tax of USD 20/tonne CO_2, the government could argue that one fifth of the emission reductions should remain in Chile below an updated crediting threshold, as those emission reductions would no longer be additional.

[30] Developed in September 2021.

[31] Page 37 of the bill: https://leycambioclimatico.cl/wp-content/uploads/2020/07/ProyectoLeyCC_13012020.pdf

5 General framework for marketing the green attributes of pilots

This section offers a proposed framework for marketing the green attributes of the pilots being studied. The purpose is to identify the optimum configuration for marketing the certified emission reductions and generating additional income to close the feasibility gap of these pilots.

5.1 General structure for developing green hydrogen projects in Chile

Chile's emerging H2V market has initiatives being developed that present some initial business model configurations and could provide a basis to be replicated in the country's upcoming H2V projects. Figure 5-1 shows an integrated version of this business model structure and sets out the main components involved.

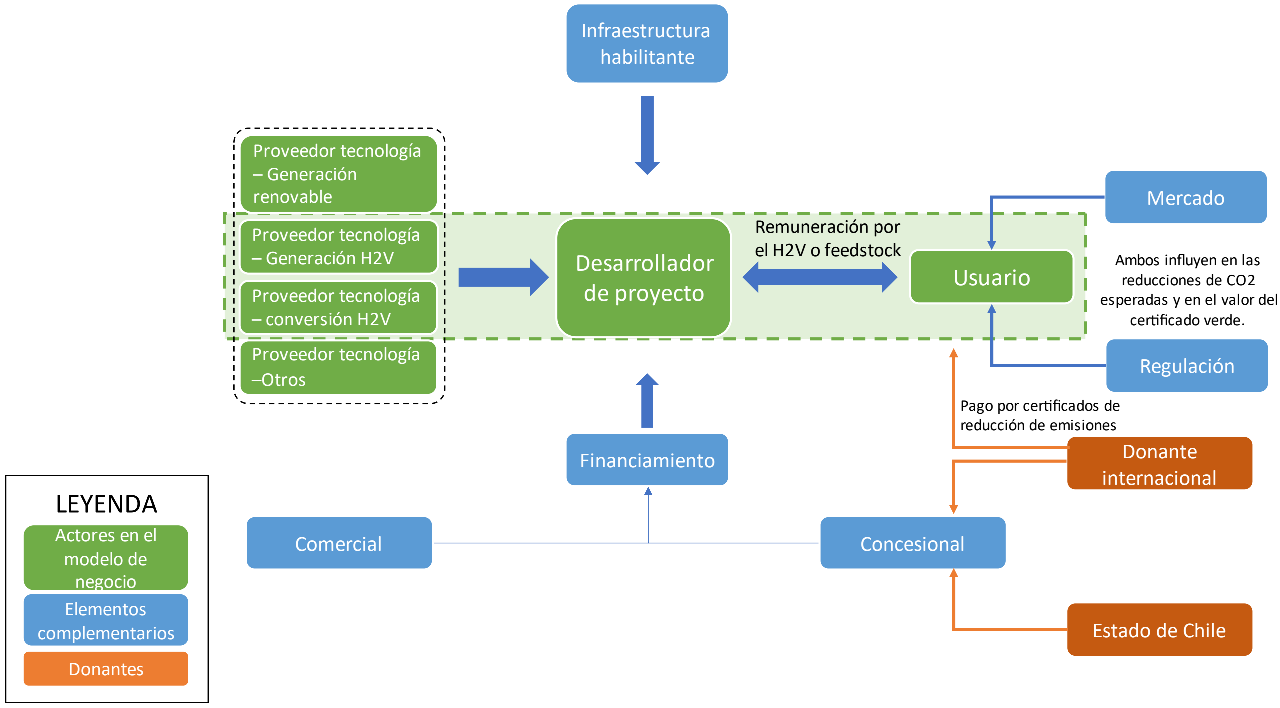


Figure 5-1 Reference configuration for the business model of a Chilean project to produce and use H2V

Source: compiled by the authors

Translation:

Infraestructura habilitante	Enabling infrastructure
Proveedor tecnología – Generación renovable	Technology supplier – Renewable generation
Proveedor tecnología – Generación H2V	Technology supplier – H2V generation
Proveedor tecnología – conversión H2V	Technology supplier – H2V conversion
Proveedor tecnología – Otros	Technology supplier – Others
Desarrollador de proyecto	Project developer
Remuneración por el H2V o feedstock	Remuneration for H2V or feedstock
Usuario	User
Mercado	Market
Ambos influyen en las reducciones de CO2 esperadas y en el valor del certificado verde	Both influence the expected CO_2 reductions and the value of the green certificate
Regulación	Regulation
Pago por certificados de reducción de emisiones	Payment for emission-reduction certificates
Donante internacional	International donor

Comercial	Commercial
Financiamiento	Financing
Concesional	Concessional
Estado de Chile	Chilean state
LEYENDA	LEGEND
Actores en el modelo de negocio	Business model actors
Elementos complementarios	Additional elements
Donantes	Donors

The centre of the diagram shows the project developer, or H2V supplier, who is also responsible for integrating the various components along the H2V value chain. An example would be the developer integrating the construction and operation of a renewable electricity generation plant and the electrolysis plant.[32] The end user of H2V or its derivatives is the customer (green box on the right), which could be any industry or sector.

On the right are also some of the factors that motivate the end user to pay for H2V or its derivatives. These factors are closely related to downstream market expectations for the development of the commodity, its sustainability attributes and any regulatory requirements in terms of CO_2 emissions.

On the left of the diagram are the different technology suppliers who provide the equipment and infrastructure directly linked to this project's implementation. This includes RE generation and 'balance of system' components, the electrolyser, and the infrastructure and technology needed to store and convert H2V into a usable feedstock. Technology providers play a key role in ensuring project performance and in preventing cost overruns.

Between the project developer (in the centre of the diagram) and the H2V user is a purchase transaction for H2V or its derivative. The implementation of each project component could, in principle, follow the logic of an EPCOM (Engineering-Procurement-Construction + Operation & Maintenance) scheme, in which a third party integrates the project's development, execution, operation and maintenance.

The lower part of the diagram represents the contribution of financing sources, including both private financial resources and those of a concessional nature,[33] to improve the investment's risk-return ratio. As the diagram shows, in the lower right-hand corner, concessional finance can come from local government as well as international donors.

The upper part of this diagram highlights the contribution of enabling infrastructure shared with other projects and uses. It includes all infrastructure needed for the project to be scalable beyond its pilot phase. This includes transmission lines, transmission pipelines, ports and any other shared infrastructure required.

To facilitate the project's implementation, there could be a partnership or joint venture between different operators or developers in the project value chain, between the project developer and the user, and even between the developer and the technology provider. This partnership is represented in the diagram by a shaded box that encompasses a group of suppliers, the project developer and the end user. Partnerships of this kind follow a framework based on each actor's interests, sharing the project's benefits and risks and thus dividing up investment responsibility across the project's various components.

[32] This could also include the manufacture of an H2V by-product (such as methanol, ammonia or other products produced by these three).

[33] Concessional finance includes grants and loans where the grants have no repayment conditions and the loans are provided on less stringent terms compared with commercial finance. ((UNDP), 2016).

In this generic structure, each actor in a partnership can take on more than one role. For example, a technology supplier could provide equity to implement a component of the H2V value chain. Also, an end user could monetise its long-term purchase commitment as an equity contribution to the project.

5.2 General set-up to close the pilots' feasibility gap

As discussed in the previous section, these pilots have a feasibility gap that can only be closed in the long term with revenues from the sale of certified emission reductions. This time horizon is not consistent with the idea of piloting trades or economic transfers for emission reductions regulated under Article 6 over the next few years, since it is expected that the mechanisms will already have matured by that date (2050 or long term).

On the other hand, the current price ranges of certified emission reductions for pilot projects under Article 6 are not sufficient to close the feasibility gap of these investments. This is why an additional source of revenue is required if the pilots are to be implemented and create a precedent that makes it easier for the projects to be replicated. This additional income will have to be provided by a participant in the business model with a particular interest in implementing this project (GIZ, 2020).

There are various options for securing involvement in the investment company by different potential stakeholders interested in implementing the pilots studied in this report. For example, involving the company that will operate the target facility, as the new installation will reduce the intensity of its GHG emissions, or that company's customers, as they will then have preferential access to a low-carbon product or commodity. The suppliers of the equipment associated with the project could also be involved, as the installation could boost demand for their technology and enable it to be replicated in other projects.

However, the pilots analysed are in traditional commodity sectors (steel, cement and mining), which must keep their operating costs low in order not to lose competitiveness. It is therefore unlikely that an H2V user in these industries will be more willing to subsidise the investment in order to close the feasibility gap in these developments.

At the same time, the approach of relying on customers to pay a premium for any products or services with a 'green' or low-emission attribute (steel, cement or transport of operators) as a way of achieving economic feasibility is not recommended. The reasons for this are listed below.

- **The pilots studied in this report relate to facilities whose end production is largely destined to satisfy domestic demand.** Cement production is inherently for domestic consumption, low-carbon transport is used in the domestic mining sector, and a large part (70%) of the steel production in the integrated process (CAP Acero) is destined for domestic consumption. To date, there are no market signs in Chile that would allow developers to rely on a price premium from domestic customers for these commodities' green attributes.
- **The end-customer of these products with green attributes will not be able to capitalise on ownership of these attributes**, at least not until there is an H2V certificate scheme, as it would not be possible to do so by purchasing certified emission reductions, as these are committed as part of the transaction under the Article 6 pilot.
- **There is currently no value attached to green product labelling.** There could be such a value in the future, but this will be in addition to the concept of emission reductions, and the current state of the market is such that it cannot be established if it could have a value in the short term.

The above considerations suggest that the remaining feasibility gap, which is not closed by the sale of certified emission reductions, should be covered by obtaining supplementary sources of support.

- Tax revenue from the Chilean state, e.g. grants for scalable pilots as in a recent call for proposals issued by Chile's Production Development Corporation (CORFO). This can also be a way of reducing the risk of exposing these industrial sectors to carbon leakage as they can invest in GHG mitigation technology and remain competitive.[34]

- An international donor represented by one of the technology providers or their countries of origin. This participation may be conditional on the use of technology provided by the donor country as part of a technology transfer strategy along the lines of the Japanese JCM scheme and similar to the export credit agency models. The international donor would also participate in trading certified emission reductions under Article 6 of the Paris Agreement. This contribution could, exceptionally, also be provided by the hydrogen user itself, as a company that sees an opportunity to stand out as a leader in adopting low-carbon development solutions. This is the case with CEN Mexico which covers part of the relevant additional costs of such an investment in the form of a grant for a solution that is not yet fully competitive. A financial contribution from an international donor, through the purchase of these certified emission reductions or through investment grants, can also be translated into an equity share in the project to make its implementation feasible.

Both sources of support (or donors) appear in the orange boxes in the bottom right-hand corner of Figure 5-1, which shows the contributions of the Chilean Government and of an international donor.

[34] This approach is being implemented by the European Commission, which has recently approved a regulation to introduce an offsetting mechanism to minimise the risk of carbon leakage for emission-intensive sectors exposed to international trade (under the EU's Emissions Trading System). For more information, see https://icapcarbonaction.com/en/news-archive/791-germany-adopts-carbon-leakage-rules-for-national-ets.

6 Financing schemes

The global hydrogen industry will receive an estimated USD 300 billion in investment by 2030 (Natixis, 2021), and H2V projects in Chile could receive a significant share of this public and private capital over the next decade. However, H2V projects in Chile's domestic cement, steel and mining industries are in their early stages and currently face an economic feasibility gap that limits their ability to attract investment. With private sector projects still in their pilot phase, the growth and competitiveness of Chile's H2V sector will depend on its access to a range of international and domestic financial instruments.

While it is important to develop business models to close the project's feasibility gap, there are also financing schemes for each H2V project type that establish technical guarantees, provide security to investors and mobilise a greater flow of capital. The aim of this section will be to identify which financing schemes and instruments can mitigate the risks of the projects being studied.

6.1 Climate finance

There is a variety of climate finance funds targeting H2V projects in the cement, steel and mining industries. There are international funds that are broader and finance a range of projects that are innovative with high emission-reduction potential (e.g. Breakthrough Energy Ventures, Climate Pledge Fund and Toyota Ventures Climate Fund). Other funds specifically target the nascent hydrogen industry (e.g. FiveT Hydrogen Fund or Green Hydrogen Accelerator). See Annex 12 for details of existing private and public climate finance funds.

The challenge for projects in the three industries in question will be to recognise the risks that each project would face and identify those that can be covered by climate finance (endogenous risks), thus improving these projects' risk-return ratio and enabling private investors to be involved. This follows the financial risk assessment rationale set out in Climate Finance Options for Innovative Projects in Chile's Energy Sector (GIZ, 2020), i.e. arranging blended finance mechanisms that ensure minimum concessionality in the projects and enable private sector participation.

In this section, we will analyse each project's political, regulatory, capital market, credit and technological risks in order to identify instruments or actors that would help mitigate these risks. The instruments to be considered include indirect political or institutional inputs, revenue support policies, concessional financing, bilateral contracts and credit enhancement instruments.

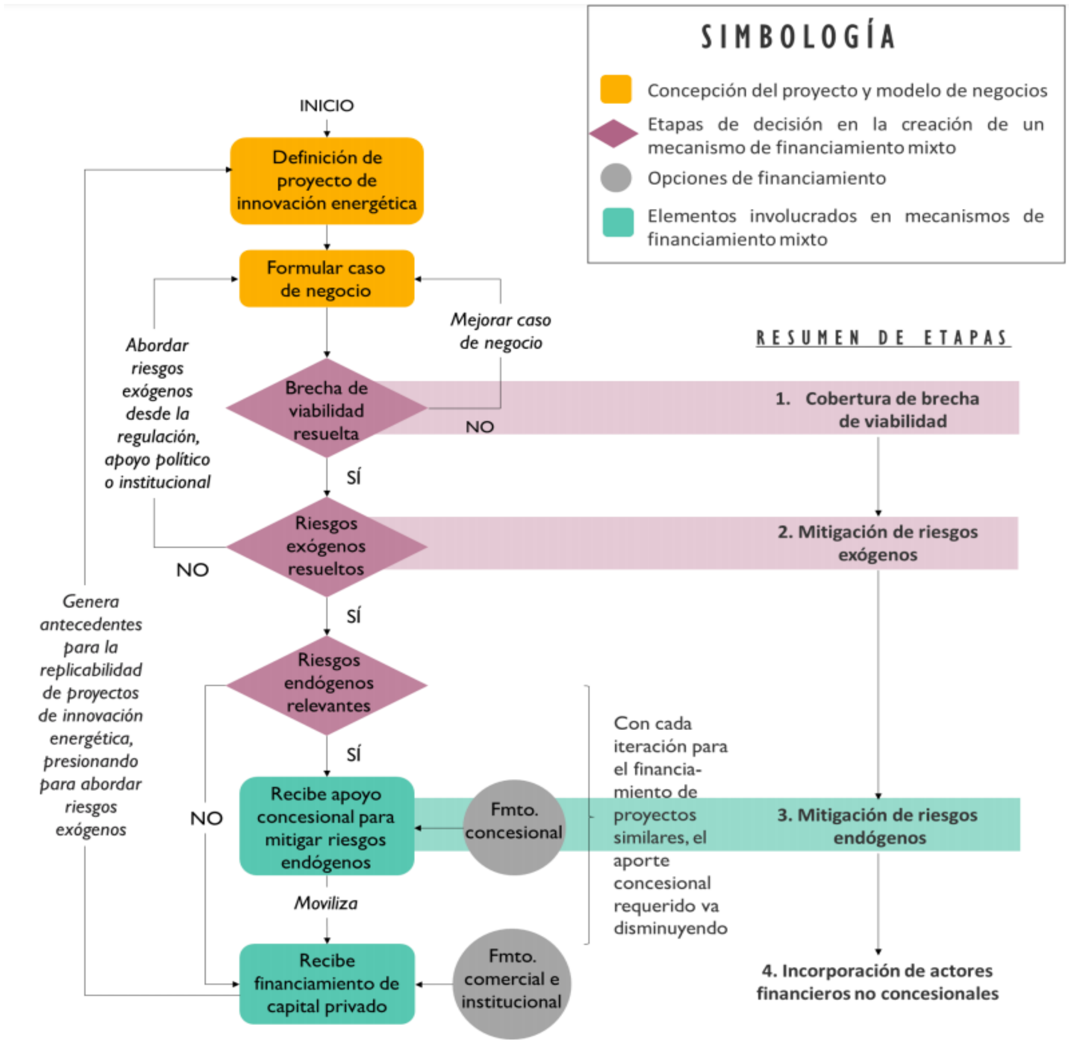


Figure 6-1 Flowchart showing the stages involved in establishing financing for energy innovation projects in Chile

Source: compiled by the authors

Translation:

SIMBOLOGÍA	LEGEND
Concepción de proyecto y modelo de negocios	Project design and business model
Etapas de decisión en la creación de un mecanismo de financiamiento mixto	Decision-making stages in the creation of a blended finance mechanism
Opciones de financiamiento	Financing options
Elementos involucrados en mecanismos de financiamiento mixto	Elements involved in blended finance mechanisms
INICIO	START
Definición de proyecto de innovación energética	Define an energy innovation project
Formular caso de negocio	Formulate the business case
Mejorar caso de negocio	Improve the business case
Abordar riesgos exógenos desde la regulación, apoyo político o institucional	Address exogenous risks through regulation, policy or institutional support
NO	NO
SÍ	YES
Brecha de viabilidad resuelta	Feasibility gap resolved
Riesgos exógenos resueltos	Exogenous risks addressed

Riesgos endógenos relevantes	Relevant endogenous risks
Genera antecedentes para la replicabilidad de proyectos de innovación energética, presionando para abordar riesgos exógenos	Produce background information to support the replicability of energy innovation projects, lobbying to address exogenous risks
Recibe apoyo concesional para mitigar riesgos endógenos	Receive concessional support to mitigate endogenous risks
Recibe financiamiento de capital privado	Receive private equity financing
Fmto. concesional	Concessional financing
Fmto. comercial e institucional	Commercial and institutional financing
Con cada iteración para el financiamiento de proyectos similares, el aporte concesional requerido va disminuyendo	The required concessional contribution decreases with each iteration to finance similar projects
RESUMEN DE ETAPAS	SUMMARY OF STAGES
1. Cobertura de brecha de viabilidad	1. Closing the feasibility gap
2. Mitigación de riesgos exógenos	2. Mitigating exogenous risks
3. Mitigación de riesgos endógenos	3. Mitigating endogenous risks
4. Incorporación de actores financieros no concesionales	4. Incorporating non-concessional financial providers

The risks identified in the use of H2V in the cement, steel and mining industries are set out in Table 6-1 below. The risks associated with the sale of certified emission reductions are credit risks, and considering they were there previously, they will not be included in this analysis. The risks below are classified according to risk type and are categorised as high, medium or low according to the following criteria (based on and adapted from the Risk Gaps document (CPI, 2013)).

- **High.** Project implementation is impossible, and no mitigation measures are identified.
- **Medium.** Project implementation is impossible, but concrete mitigation measures are identified.
- **Low.** Risk is not seen as a relevant barrier to project implementation.

Table 6-1. Risks identified for H2V application projects

Project type	Technology	Exogenous risks Political risk	Regulatory risk	Capital market risk	Endogenous risks Technological risk	Credit risk
Cement case study	Hydrogen injection in clinker kiln replacing 10% of petcoke.	Low. It was assessed as an emission mitigation initiative in Chile's NDC update, with a non-binding target of 2% for thermal use of hydrogen via pipelines in the industry by 2050 (Ministry of Environment, 2020). In addition, Chile was rated A+ by Standard and Poor in 2020 and A (upper medium rating) by Fitch. Moody's gave it a rating of A1 with a negative outlook in 2020. The National Green Hydrogen Strategy was published in 2020 (Ministry of Energy, 2020).	Medium. There are regulatory gaps, but these have been identified and are as follows for each value chain component. • Retrofitting and Production. There is no Chilean regulation covering hydrogen production. Although general safety regulations apply, the hydrogen production requirements are different. • Storage. No Chilean regulations apply. • Transport and distribution. Regulated by Decree 298/2002 applicable to the transport of hazardous substances. This seems sufficient for an increase in the volume of hydrogen to be transported. • Consumption. The same applies as for retrofitting and production. However, there is a plan to develop a regulatory framework to enable these projects to be implemented (GIZ, 2020).	Low. Chile has a developed investment market, ranked 33rd out of 141 countries in the Global Competitiveness Report 2019, and first in Latin America in the same ranking.	Medium. Companies have successfully applied H2V injection in furnaces (e.g. CEMEX). H2V production through alkaline or polymer membrane electrolysis is at technology readiness level (TRL) 9 in the 'early adoption' stage and 8 in the demonstration stage.	High. Considering the uncertainty associated with carbon markets, and that this project should involve various actors in different parts of the value chain, the credit risks should be lowered.

<table>
<tr><th rowspan="2">Project type</th><th rowspan="2">Technology</th><th colspan="3">Exogenous risks</th><th colspan="2">Endogenous risks</th></tr>
<tr><th>Political risk</th><th>Regulatory risk</th><th>Capital market risk</th><th>Technological risk</th><th>Credit risk</th></tr>
<tr><td>Steel case study</td><td>Injection of hydrogen into the blast furnace for the integrated process, replacing 21.7% of coke.</td><td>Low. The project was assessed as an emission mitigation initiative in Chile’s NDC update, with a non-binding target for thermal use of hydrogen via pipelines of 2% in the industry by 2050 (Ministry of Environment, 2020).
In addition, Chile was rated A+ by Standard and Poor in 2020 and A (upper medium rating) by Fitch. Moody's gave it a rating of A1 with a negative outlook in 2020. The National Green Hydrogen Strategy was published in 2020 (Ministry of Energy, 2020).</td><td>Medium. There are regulatory gaps, but these have been identified and are as follows for each value chain component.
• Retrofitting and Production. There is no Chilean regulation that applies to hydrogen production. Although general safety regulations apply, the hydrogen production requirements are different.
• Storage. No Chilean regulations apply.
• Transport and distribution. Regulated by Decree 298/2002 applicable to the transport of hazardous substances. This seems sufficient for an increase in the volume of hydrogen to be transported.
• Consumption. Similar to retrofitting and production. General safety regulations apply.
Despite the above, there is a plan to develop a regulatory framework to enable these projects to be implemented (GIZ, 2020).</td><td>Low. Chile has a developed investment market, ranked 33rd out of 141 countries in the Global Competitiveness Report 2019, and first in Latin America in the same ranking.</td><td>High. Substantial emission reductions are transformational and are in the early stages, meaning a high level of investment is required (Bariloche Foundation, GIZ and Ministry of Energy, 2020). Furthermore, there is only one known success story for this application at the industrial level: Thyssenkrupp Steel. H2V production through alkaline or polymer membrane electrolysis is at TRL level 9 in the early adoption stage and 8 in the demonstration stage.</td><td>High. Considering the uncertainty associated with carbon markets, and that this project should involve various actors in different parts of the value chain, the credit risks should be lowered.</td></tr>
</table>

Project type	Technology	Exogenous risks			Endogenous risks	
		Political risk	Regulatory risk	Capital market risk	Technological risk	Credit risk
Mining case study	Replacement of diesel fuel by green hydrogen fuel cells in buses to transport personnel in the mining industry.	Low. It was assessed as a key pillar for emissions mitigation in Chile’s NDC update, with targets for both electric transport and hydrogen use in the sector (Government of Chile, 2020). In addition, Chile was rated A+ by Standard and Poor in 2020 and A (upper medium rating) by Fitch. Moody's gave it a rating of A1 with a negative outlook in 2020. The National Green Hydrogen Strategy was published in 2020 (Ministry of Energy, 2020).	Medium. With regard to hydrogen-based transport, there is a plan to develop a regulatory framework conducive to green hydrogen generation. Although no regulation exists, it is identified in the roadmap.	Low. Chile has a developed investment market, ranked 33rd out of 141 countries in the Global Competitiveness Report 2019, and first in Latin America in the same ranking.	Medium. These buses are already commercially available, but at high prices compared with other low-carbon technology alternatives. Green hydrogen production through alkaline or polymer membrane electrolysis is at TRL level 9 in the early adoption stage and 8 in the demonstration stage.	High. Considering the uncertainty associated with carbon markets, and that this project should involve various actors in different parts of the value chain, the credit risks should be lowered.

Source: compiled by the authors

6.2 Recommendations for financing schemes

As discussed in the previous sections, specifically in Table 6-1, projects in each of the cement, steel and mining industries face their own obstacles and therefore obviously require different recommendations on financing schemes.

Table 6-2 below shows the main financial instruments that could be used to mitigate different risks according to the Climate Policy Initiative (CPI, 2013).

Table 6-2 Financial instruments for risk mitigation

Type of risk	Indirect political or institutional input	Revenue support policies	Concessional finance	Bilateral contracts	Credit enhancement instruments
Political risks	X				
Regulatory risks	X				
Technological risks	X			X	X
Credit risks		X	X	X	X
Capital market risks	X			X	

Source: compiled by the authors from (CPI, 2013)

With regard to the projects analysed above, the technological risks stand out as they are solutions that are still being developed and have been little used in real-life applications, as do the credit risks associated with the high degree of uncertainty in the carbon market, which is described in detail in Section 4.5.4. This suggests that the implementation of these technologies will depend heavily on the **political or institutional participation** of those interested in testing and developing them, especially as they are emission-intensive sectors where hydrogen is seen as a viable and effective solution to mitigate these emissions. This could translate into support from the Chilean Government to decarbonise the sector, defining a clear long-term policy that enables plans to be made – in time frames of at least 20 years – for the technology changes being studied. This would provide more clarification and certainty on how exposed these sectors will be to a future carbon tax, the level of ambition on future carbon prices, and whether they will be part of Chile's carbon-neutral commitments in the coming years in order to guarantee revenue from a potential carbon market.

Financial instruments can also help to mitigate technological risks. However, they are not suitable for innovative technologies such as those presented in this study. The suggested approach is therefore to use debt guarantee schemes (referred to above as credit enhancement instruments). These would be provided by a third party (a concessional finance provider such as the Green Climate Fund or GCF), which would assume responsibility for meeting obligations to the creditors if the project cannot do so for specific reasons, such as the materialisation of a technological risk (e.g. delay in construction and/or commissioning of the project, costs being underestimated, faulty operation and resulting lower production levels). The guarantee is usually established before formalising the obligation as it is a requirement for it to be accepted. It must also be considered whether it is a full or partial guarantee for the protected obligation.

In an analysis of the projects, credit risks also stand out, in particular those associated with uncertain revenues from the sale of certified emission reductions. To address this risk and provide more certainty about such revenue flows, debt guarantee schemes or concessional financing sources can be used to hedge the uncertainty around the sales price of certified emission reductions. One example of this approach was the IDB Invest support for an operation with Engie Energía Chile. IDB Invest mobilised USD 15 million of concessional financing from the Clean Technology Fund to contribute to the financing of a wind farm and support the sale of emission reductions (BID Invest, 2020).

Once the risks have been duly mitigated, the project would receive a loan at a competitive level from the private-sector arm (e.g. International Finance Corporation (IFC) or IDB Invest) of one of the leading multilateral development banks (MDBs). Export credit agencies (ECAs) can also secure cheap debt even in contexts where particular capacities are needed to assess the risks associated with this type of project.

Finally, technical assistance would help to pilot and test the above-mentioned applications in Chile. This would reduce the technological risk of project implementation and give investors more security to participate in these projects. As proposed in Annex 12, technical assistance funds could come from both national sources (such as the CORFO fund or the Energy Sustainability Agency – ASE) and international sources (such as KfW or GCF). In the latter case, funding could come from countries involved in the project (providing technologies or services) or from those on the project's corporate side, as was seen in the High Innovative Fuels project, where Germany provided funding to develop this project with German companies as suppliers.

7 Conclusions

This study provides technical input to help identify, formulate and develop case studies for green hydrogen projects in Chile that could act as pilots for a future carbon market under Article 6 of the Paris Agreement. This background allows a strategy to be formulated for developing and investing in green hydrogen applications in three key areas of domestic demand.

- Cement: replacing 10% of petcoke consumption in the clinker kiln with H2V.
- Steel: injecting H2V through blast furnace tuyeres to partially replace coke in the integrated steel process.
- Mining: replacing 10 diesel buses with fuel cell buses to transport personnel to the mining sites.

In particular, the study can help to identify the economic feasibility of these pilots under different H2V cost scenarios, calculate their GHG mitigation potential, estimate their potential revenue from the sale of certified emission reductions under different price range scenarios and propose blended financing mechanisms to address the projects' endogenous risks and attract private capital to enable their implementation.

With specific regard to the mining initiative, the conclusion from some preliminary exercises is that the impact of selling certified emission reductions is minor. This is a project with a low level of investment and low abatement potential compared with the other two projects, especially since it is expected to be a sector that will tend to decarbonise, reducing the capacity to trade emissions. The prices for certified emission reductions to close the project's feasibility gap are therefore above USD 1,000/tonnes CO_2e. To strengthen the case study, the business model needs to be altered by increasing the distance travelled or making the infrastructure (e.g. H2V refuelling stations) associated with the project available to other users.

Table 7-1 Overall results of the cases analysed

	Scenario	Present	2030	Long term
Cement	TCO H2V case (USD)	$198,748,352.70	$ 142,569,654	$ 106,995,597
	TCO base case (USD)	$ 97,944,460	$ 75,148,477	$ 77,653,348
	Feasibility gap (USD)	$ -100,803,893	$ -67,421,177	$ -29,342,249
	Average annual abatement potential tonnes CO_2e/year)		47,751	
	Certificate price needed to close feasibility gap (USD/ tonnes CO_2e)	$291	$201	$90
	Revenue from sales of offsets (HIGH scenario and 15 years) (USD)	$ 22,778,579	$ 26,812,860	$ 34,752,479
Steel	TCO H2V case (USD)	$ 1,268,620,333	$ 1,090,956,267	$ 932,197,801
	TCO base case (USD)	$ 839,440,012	$ 839,639,379	$ 907,670,795
	Feasibility gap (USD)	$ -429,180,321	$ -251,316,887	$ -24,527,007
	Average annual abatement potential tonnes CO_2e /year)		297,954	
	Certificate price needed to close feasibility gap (USD/ tonnes CO_2e)	$205	$120	$12

	Revenue from sales of offsets (HIGH scenario and 15 years) (USD)	$ 138,400,740	$ 168,251,880	$ 225,240,420
Mining	TCO H2V case (USD)	$ 14,186,618	$ 11,056,423	$ 8,592,993
	TCO base case(USD)	$ 4,946,779	$ 5,390,119	$ 5,710,988
	Feasibility gap (USD)	$ -9,239,839	$ -5,666,304	$ -2,882,005
	Average annual abatement potential tonnes CO_2e /year)		519	
	Certificate price needed to close feasibility gap (USD/ tonnes CO_2e)	$2,391	$1,527	$834
	Revenue from sales of offsets (HIGH scenario and 15 years) (USD)	$240,123	$234,575	$210,337

For the cement and steel projects, an Article 6 pilot will not be able to close the feasibility gap on its own, and other sources of revenue will need to be identified to make the projects viable, such as a green premium market, a business set-up that enables grants to be obtained from other governments or entities, or incorporating partners who have an added interest in the project and who are willing to accept the project's credit risk.

In the medium to long term, there are real opportunities that a carbon market under Article 6 of the Paris Agreement could help to implement low-carbon projects in the cement and steel industries. Even in the long term, a steel project could be viable on its own without needing to evaluate other upsides.

It is crucial to increase the prices of certified emission reductions and decrease LCOHs to ensure the economic feasibility of the pilots being analysed. Recent studies suggest maintaining these pilots on an industrial scale (compatible with the current operational situation as addressed in this study) in order to test relevant aspects such as the project value chain, the transformational effect on public policy and the ability to send a market sign (Stockholm Environment Institute, 2020).

The Chilean green hydrogen industry is in its inception and, as such, is subject to significant levels of uncertainty with respect to the development and feasibility of investment projects in domestic applications. This report identifies three levels of uncertainty.

The first level of uncertainty is associated with project costs. This includes the equipment costs of each pilot studied (electrolysers in particular), as well as the energy resources that would be replaced and the competitiveness of the chosen renewable electricity configuration. These sources of cost uncertainty relate to the productive capacity of suppliers, the pace of development and technological readiness, the regulation of transmission tolls and the market for fossil fuels (petcoke and coke).

There is also a second level of uncertainty in terms of the policies and market signals that could enable more sustainable business models to emerge over time and create a situation, for example, where commodities such as cement and steel with low-carbon attributes can have a higher economic value to local sources of demand (i.e. a green premium). There is also uncertainty associated with the traceability of emissions from green hydrogen production. This could be addressed through a coordinated framework for certifying the green origin of hydrogen.

Finally, there is a third level of uncertainty regarding the rules, conditions and prices in the future carbon market set out in Article 6 of the Paris Agreement. For pilots of this kind, it is crucial to have price signals for the sale of certified emission reductions in order to contribute further to closing the economic feasibility gap. At this level, it is also important that the sectoral targets defined in Chile's NDC do not compromise the additionality of future pilots under Article 6, or that they can at least be structured as efforts to increase the level of ambition of the NDC (conditional on cooperation in carbon markets).

To contribute to the development of these pilots, the following actions are recommended in order to reduce the associated levels of uncertainty, make progress on the strategy suggested in this document and close the feasibility gap.

I. Validate methodological developments (for defining the baseline and estimating emission reductions) that can be accepted by international donors interested in cooperating under Article 6 market mechanisms. The quantifying of emission reductions in this study has followed a conservative approach, e.g. by considering the most promising baseline scenarios for the adoption of low-carbon technologies in these industries, such as the trend towards increased co-processing in the cement industry and the use of electric buses for passenger transport. It is important to have more certainty in describing these scenarios and avoid underestimating the GHG mitigation potential.
II. Promote cooperation with G20 member countries that wish to take a lead role in bilateral relations with regard to the piloting of market-based schemes under Article 6.[35]
III. The adoption of H2V in the niche areas studied and its economic feasibility depend to a large extent on the availability of competitive H2V (i.e. produced on a scale that allows for a low LCOH). To key to achieving this is to identify possible synergies with closely related H2V generation and consumption projects so they can share the same infrastructure and therefore achieve the required level of cost-effectiveness.
IV. Make representations to ensure that the definitions of additionality established under Article 6 do not undermine the feasibility of submitting projects in sectors subject to local carbon pricing instruments (e.g. by stipulating that emission reductions in sources subject to a carbon tax cannot result in the sale of offsets). In this context, it is recommended that the regulator be able to define its strategy towards projects subject to a carbon tax[36] and provide greater clarity on the procedures and validity of the sale of certified emission reductions under the developing Climate Change Framework Law.
V. Provide a clear regulatory framework and definitions – agreed between the Ministry of Energy and the Ministry of Environment (MMA) – stipulating which industrial sources are subject to the carbon tax, so that companies can establish long-term investment strategies. The definition of combustion[37] in the Green Tax states that the raw materials needed for production processes are excluded from the taxed emission sources, but does not state succinctly whether the emissions from industrial processes in which fuels are used as part of the feedstock, in particular coke (for steel) or petcoke (for cement), will be subject to the tax. This can be settled with an explicit definition by the MMA in the regulation.

[35] There are proposals for G20 countries to accelerate their leadership in the development of Article 6 pilots and methodologies for estimating emission reductions from these projects. More information can be found at: https://www.g20-insights.org/wp-content/uploads/2020/12/promoting-carbon-neutral-hydrogen-through-unfccc-and-national-level-policies-1607609816.pdf

[36] Clarify whether these projects will be able to sell certified emission reductions under Article 6, and under what conditions (e.g. Chile could decide to keep part of the certificates issued based on the impact of the carbon tax on the project). For example, with a certificate sales price in an international market of USD 50/tonne CO_2e, and a domestic carbon tax of USD 5/tonne CO_2e, the project will seek to capitalise on its results in an international market rather than a domestic market (through tax exemption). This assumes that the project's additionality principles are maintained.

[37] According to the Act, combustion is defined as 'a process of oxidation of solid, liquid or gaseous substances, or matter, which gives off heat and in which its internal energy is released to produce electricity, steam or useful heat, with the exception of the raw material which is necessary for the production process'.

VI. It is important to monitor the international debate around carbon border adjustments and green marketing agreements (Meyer, 2021), in particular when seeking to sell emission reductions linked to projects in these sectors (steel and cement).

VII. Explore the feasibility of policies that promote the adoption of low-carbon development technologies through support mechanisms that help to close these projects' feasibility gaps, and at the same time maintain the competitiveness of domestic industries vulnerable to carbon leakage. It is worth highlighting the German state grants provided to support and financially compensate some companies that are vulnerable to the low-carbon transition and at risk from carbon leakage.

VIII. Promote the existence of an international H2V certification scheme, which would ensure the traceability of a green hydrogen source and thus provide guarantees of origin to support the higher price of commodities using this energy resource (or the Green Premium).

The study puts forward a proposal that would support the development of pilots for domestic H2V consumption and promote technological learning through innovative solutions for Chile's strategic industries. The use of H2V in domestic industrial applications is an opportunity to decarbonise, increase the level of ambition in the NDC and promote innovation. It is essential that there are market signals and that appropriate regulations are developed to encourage projects such as those being evaluated (and others along the same lines) as part of the cooperative approaches developed under Article 6 of the Paris Agreement. It is therefore important and urgent to carry out further analyses, studies and calculations and use them to produce the best and most robust information so that progress can be made towards adopting innovative and emerging technologies in an international carbon market.

Finally, there is an emphasis on the methodology developed to conduct the study and the opportunity that this could present to replicate this exploratory analysis in other industries, technologies and even contexts, such as applying it in other countries. Considering that the data, figures and results are subject to considerable variation and uncertainty, future updates to the study are proposed in order to track its progress, while at the same time delineating and improving the understanding of the implementation framework, in line with the finalising of the Paris Agreement Rulebook and future regulations that will govern Article 6 and its cooperative approaches.

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9 Annexes

9.1 Annex 1. Emission-reduction methodologies

CDM reference methodologies:

- Booklet: https://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf

- AMS-III.B: Switching fossil fuels
https://cdm.unfccc.int/methodologies/DB/1T8IU3YG99FQOYHN12FM3T0QZFFPBX

- AMS-III.AN: Fossil fuel switch in existing manufacturing industries
https://cdm.unfccc.int/methodologies/DB/C8IOOM4JXFT8QM23QN0D1LCPOYVKUT

- AMS-III.AY: Introduction of LNG buses to existing and new bus routes
https://cdm.unfccc.int/methodologies/DB/LNSTE8UK3HYYUUZRRHK4JXOAJZCY31

- AMS-III.S: Introduction of low-emission vehicles/technologies to commercial vehicle fleets https://cdm.unfccc.int/methodologies/DB/CAEL7OU5NIMXWM9E4RU2C4MV9WHXJN

STEEL/CEMENT METHODOLOGY

CDM REFERENCE

- AMS-III.B: Switching Fossil Fuels
- AMS-III.AN: Fossil fuel switch in existing manufacturing industries

1. **Project description**: Switching from carbon-intensive fossil fuels to a less carbon-intensive fuel in industries, specifically H2V.
2. **Type of mitigation action:**
    1. Switch to fuel with lower GHG intensity (greenfield project or retrofit/replacement activities)
3. **Applicability conditions for the methodology**

    - Scope
        - The methodology comprises fossil fuel switching in industrial applications.
        - The fuel switch may be in a single element process or may include several element processes within the facility. Multiple fossil fuel switching in an element process however is not covered under this methodology. Only element processes that use a single fuel in the baseline are eligible. Dual or multiple fuel use over the project's lifetime are not covered.
        - The project boundary comprises the physical, geographical site where the switching of energy source takes place. It includes all installations, processes or equipment affected by the switching.
    - Conditions
        - Fossil fuel switch used in a process to produce an end product.
        - Limited to fuel-switching measures which require capital investments.
        - Only energy efficiency improvements related to the fuel switch are eligible.
        - Only retrofits and replacements without integrated process change are eligible.
        - For project activities where the estimated annual emission reductions of each of the element processes are more than 600 tCO_2e per year, the energy use/output should be directly measured; otherwise it is not eligible.

    - This methodology is applicable to

- The retrofit or replacement of existing installation.
- New facilities or project activities involving capacity additions.
- Fuel switching may also result in energy efficiency improvements. If the project activity primarily aims at reducing emissions through fuel switching, it falls into this methodology.
- The requirements concerning demonstration of the remaining lifetime of the replaced equipment shall be met as described in the latest approved version of the Tool to Determine the Remaining Lifetime of Equipment. If the remaining lifetime of the affected systems increases due to the project activity, the crediting period shall be limited to the estimated remaining lifetime, (i.e. the time when the affected systems would have been replaced in the absence of the project activity).
- The following fuel types listed in the 2006 IPCC Guidelines for Greenhouse Gas Inventories (Volume 2, Chapter 1, Table 1.1) are eligible under this methodology:
  - Liquid fuel (crude oil and petroleum products);
  - Solid fuel (coal and coal products);
  - Gas (natural gas).
- The element process or other downstream/upstream processes do not change as a result of the fossil fuel switch.
- The baseline fossil fuel and the project's low-carbon energy source are consumed in thermal energy conversion equipment (e.g. furnaces, dryers) used in the manufacture of products.
- Regulations do not require the use of a project low-carbon energy source (e.g. natural gas, electricity or any other fuel) or restrict the use of the baseline fuel.
- The product(s) (e.g. ceramic insulators, tiles, steel ingots, aluminium cookware) produced in the industrial facility throughout the crediting period shall be equivalent to the product(s) produced in the baseline. For the purposes of this methodology, equivalent products are defined as products having the same use, the same general physical properties, and which function in a similar manner and have the same quality.
- The type of input materials used in the project shall be homogeneous and similar to the input material that was used in the baseline, and any deviation during the crediting period of input material type, composition or amount used per unit of product output shall be within the range of +/- 10% of the baseline characteristics and values.
- For each element process, the ratio of energy input to product output in the project activity shall be equal to or less than the ratio of energy input to product output in the baseline. In other words, it cannot decrease efficiency.

The methodology is not applicable to projects whose output goes to other systems, such as to an electricity grid.

1. Important parameters

- To be validated:
  - Historical net energy production.
  - Efficiency of element process.
  - Net calorific value of baseline and project fuels.
  - Annual baseline feedstock consumption and annual production quantity.

- Monitoring:
  - Quantity of fossil fuel used (m^3 or kg in year).
  - Efficiency of each element process or using sampling if the element process has annual emission reductions less than 3,000 tonnes CO_2e.

BUS METHODOLOGY

CDM Reference

- AMS-III.AY: Introduction of LNG buses to existing and new bus routes.
- AMS-III.S: Introduction and operation of new less-greenhouse-gas-emitting vehicles (e.g. CNG, LPG, electric or hybrid) for commercial passengers and freight transport, operating on routes with comparable conditions. Retrofitting of existing vehicles is also applicable.

1. **Project description:** Introduction and operation of new less-greenhouse-gas-emitting passenger electric buses, using H2V fuel supplied in fuel cells, for new and existing routes in project activities.

2. **Type of mitigation action**
    - Fuel switch
    - Displacement of more GHG-intensive vehicles

3. **Applicability conditions for the methodology**
    - Existing and new routes are fixed. Annual distances to be travelled are established in advance and are fixed.
    - Buses using H2V are for passenger transport only.
    - Only one type of bus and one type of fuel (e.g. petrol or diesel) is used for each route in the baseline and project scenarios.
    - It must be demonstrated that any new routes implemented by the project activity had already been planned before the start of the project activity and were to be serviced by buses running on fossil fuels.
    - If there are both electric and fossil fuel buses in the baseline bus fleet, only the latter will be considered for replacement.
    - The project and baseline buses for each route are comparable, meaning that the buses in the two scenarios must have comparable passenger capacity and power ratings with a variation of no more than +/-10%. If the baseline buses are air-conditioned, the project buses will also be air-conditioned.
    - The buses' frequency of operation should be the same in the project and baseline scenarios.
    - Procedures should be implemented (e.g. a contractual agreement or unique identification of the buses) to avoid potential double counting of emission reductions by involved parties. These procedures should establish who is responsible for the emission reductions and should be described in the project design document.

    Boundary conditions

    - Measurements are limited to those that result in emission reductions of less than or equal to 60 ktonnes CO_2e equivalent annually.
    - The project boundary includes the following:
        - buses using H2V as fuel;
        - H2V storage and refuelling terminal;
        - geographical area covering the routes on which H2V buses are to operate;
        - auxiliary facilities such as fuelling stations, workshops and service stations used by the project buses.

4. **Important parameters**
    - To be validated:
        - Baseline fuel data, such as emission factor and Net Calorific Value (NCV).
        - Fuel data in the H2V project, plus refuelling details.

- Monitored:
  - Specific consumption of the baseline and project buses.
  - Total annual distance travelled by the baseline buses.
  - Performance of baseline and project buses.
  - Number of passengers to be carried by the baseline and project buses.
  - Number of buses to be replaced in the fleet.

9.2 Annex 2. Techno-economic analysis for H2V production

The main sources of information used to calculate the levelised cost of hydrogen (LCOH)[38] in different parts of Chile (north, centre and south) are presented in Table 9-1.

Table 9-1 Key assumptions for LCOH calculation

Assumption	Source
CAPEX[39] electrolyser (USD/kW)	Global average levelised cost of hydrogen production by energy source and technology (IEA, 2020b) CAPEX includes auxiliary costs (IEA & NEA, 2020)
OPEX[40] electrolyser (%CAPEX)	Global average levelised cost of hydrogen production by energy source and technology (IEA, 2020b)
Electrolyser efficiency (%)	G20 Hydrogen report (IEA, 2020a)
Stack lifetime (OP hrs)	G20 Hydrogen report (IEA, 2020a)
Replacement cost (%CAPEX)	(Armijo & Philibert, 2020)
CAPEX wind energy (USD/kW)	Report on the costs of power generation technologies, CNE (National Energy Commission, 2020)
OPEX wind energy (%CAPEX)	(Armijo & Philibert, 2020)
CAPEX solar energy (USD/kW)	Report on the costs of power generation technologies, CNE (National Energy Commission, 2020)

Source: compiled by the authors

The formulas and calculations for LCOH and LCOE[41] are as follows:

Equation 9-1 LCOH calculation (USD/kg H_2)

$$LCOH = \frac{CAPEX_{Ez} \cdot [CRF(1 + \frac{\%Replacement\ cost_r}{(1+WACC)^{Nr}}) + \%OPEX_{Ez}]}{CF_{Ez} \cdot 365 * 24} \cdot \frac{LHV}{\eta} + LCOE \cdot (1 + \%discharge) \cdot \frac{LHV}{\eta} + C_{H20} \cdot Q_{H20} - P_{02} \cdot Q_{02}$$

Equation 9-2 LCOE calculation (USD/MWh)

$$LCOE = \frac{CAPEX_{VRE}(CRF + \%OPEX_{VRE})}{CF_{VRE} * (365 * 24)}$$

Where, using figures proposed by different sources (Armijo & Philibert, 2020; GIZ, 2018; IEA, 2020a):

- $CAPEX_{Ez}$: investment cost of the electrolyser (USD)

[38] The levelised cost is the operating cost plus the costs of investment in present values. It represents the sales price of the product that allows the investment to be recovered.
39 Capital expenses (hereafter CAPEX).
40 Operating expenses (hereafter OPEX).
41 Levelised cost of electricity for the variable renewable energy (VRE) plant.

- CRF: is the capital recovery factor at a discount rate of 7%[42] and the lifetime of the electrolyser plant estimated to be 30 years (Armijo & Philibert, 2020)
- $\%Replacement\ cost$: is the replacement cost, as a percentage of the CAPEX (40%), at time Nr (calculated as the quotient: battery life hours/annual operating hours at full charge)
- $OPEX_{Ez}$: electrolyser operating cost (USD)
- $WACC$: weighted average cost of capital
- CF_{Ez}: is the optimal capacity factor of the electrolyser for the renewable energy (RE) sources available in each region (optimal is solar energy in the northern, central and southern zones and wind energy in Magallanes)
- LHV: is the calorific value of hydrogen (33.381 kWh/kg)
- $LCOE$: levelised cost of electricity for the VRE plant
- η: efficiency of the electrolyser
- $C_{H20}Q_{H20}$: is the cost of water supply at a rate of 17 l/kg H_2 and the cost of water depending on the region (USD 5/m^3 in the north and USD 1.5/m^3 in the rest of the country)
- $P_{02}Q_{02}$: is the revenue from oxygen sales at a production rate of 7.8 kg O_2/kg H_2 and an oxygen price of USD 0.03/kg O_2 for all regions.[43]

Using a hybrid production model of the best wind and solar energy[44] available in each macrozone, the best combination of resources was obtained involving off-grid generation and the optimal oversizing capability of renewables to achieve the lowest levelised production costs for H2V. The results obtained from the optimised dimensioning model for all regions in the '2030' scenario are presented in Table 9-2.

Table 9-2 Optimal VRE dimensioning for hybrid H2V production on site, 2030 scenario.

Production	North	Centre	South	Magallanes
Electrolyser capacity (MW)	1.00	1.00	1.00	1.00
Optimal solar capacity (MW)	1.07	0.94	1.06	0.00
Optimal wind power capacity (MW)	0.00	0.70	0.65	1.18
Hybrid electrolyser capacity factor (%)	39.7%	50.6%	44.5%	61.1%
Power spillage at generation site (%)	2.23%	5.66%	6.65%	0.10%
Hybrid LCOE '2030' (USD/MWh)	21.68	29.89	34.57	22.81
Hybrid LCOE '2030' (USD/kg)	1.90	2.11	2.47	1.56

Source: compiled by the authors using hourly generation data for selected VRE plants in the northern, central and southern macrozones, together with results from (Armijo & Philibert, 2020) for Magallanes. Cost data (IEA, 2020b)

The 'power spillage' figure is the result of the RE generation plant exceeding the electrolyser capacity. From this analysis it can be concluded that hybrid production is the optimal configuration for the central

[42] A representative private discount rate of 7% was used for all the projects based on the work of Armijo and Philibert (Armijo & Philibert, 2020). This figure is representative of the industry in Chile and is estimated to be a good proxy for H2V projects that will be backed by long-term contracts, as is the case in the electricity market.

43 The prices presented are assumed to be constant as no inflation is included in the model. In addition, a sensitivity analysis is presented that includes oxygen and water prices to see their impact on the result.

[44] Hybrid production is used to ensure constant energy production throughout the day. Solar energy ensures energy production during daylight hours, while covering production for the rest of the time with wind energy.

and southern macrozones, while solar is the dominant technology in the north and wind power in Magallanes.

Using a discount rate of 7% and a lifetime of 25 years for RE plants (Armijo & Philibert, 2020) the resulting levelised costs of electricity (LCOE) are presented in Table 9-3.

Table 9-3 Levelised cost of electricity (LCOE) in selected zones

	North	Centre	South	Magallanes
Solar capacity factor	38.1%	28.8%	23.9%	17.4%
'Present' solar LCOE (USD/MWh)	26.86	35.44	42.85	58.75
'2030' solar LCOE (USD/MWh)	21.68	28.60	34.58	47.42
'Long-term' solar LCOE (USD/MWh)	15.82	20.87	25.24	34.60
Wind capacity factor	37.2%	37.9%	34.2%	51.8%
'Present' wind LCOE (USD/MWh)	37.85	37.21	41.20	27.19
'2030' wind LCOE (USD/MWh)	31.75	31.21	34.56	22.81
'Long-term' wind LCOE (USD/MWh)	26.59	26.13	28.94	19.10

Source: compiled by the authors

The results of the LCOH for each zone and time scenario are presented in Figure 9-1 below.

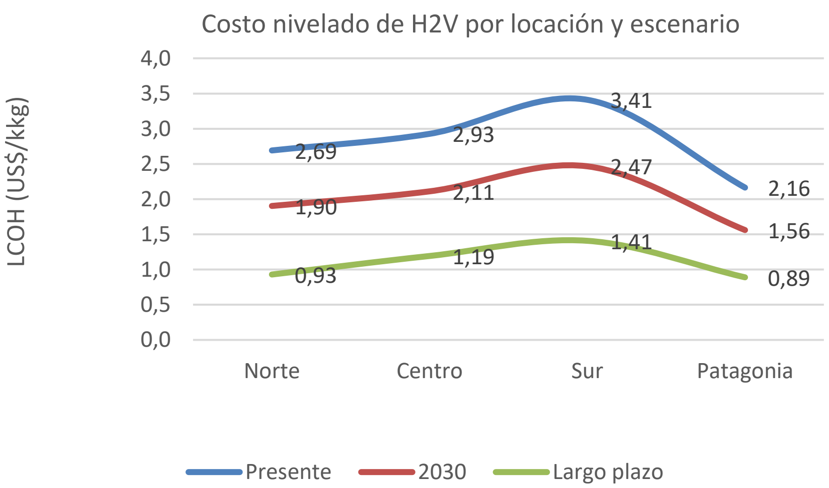

Figure 9-1 Levelised cost of H2V by location and scenario

Source: compiled by the authors

Translation:

Costo nivelado de H2V por locación y escenario	Levelised cost of H2V by location and scenario
Norte	North
Centro	Centre

Sur	South
Presente	Present
Largo plazo	Long term

As shown above, in the 'Present' scenario the lowest-cost hydrogen production is in the Chilean Patagonia region. In the long term, the decrease in CAPEX associated with solar energy production allows a lower LCOH to be achieved in the northern zone. The southern zone is the least competitive for hydrogen production in all scenarios.

Figure 9-2 is a graph that shows the disaggregated levelised cost of hydrogen in the northern zone. This analysis enables the weight of the different components in the final cost of the H2V to be identified.

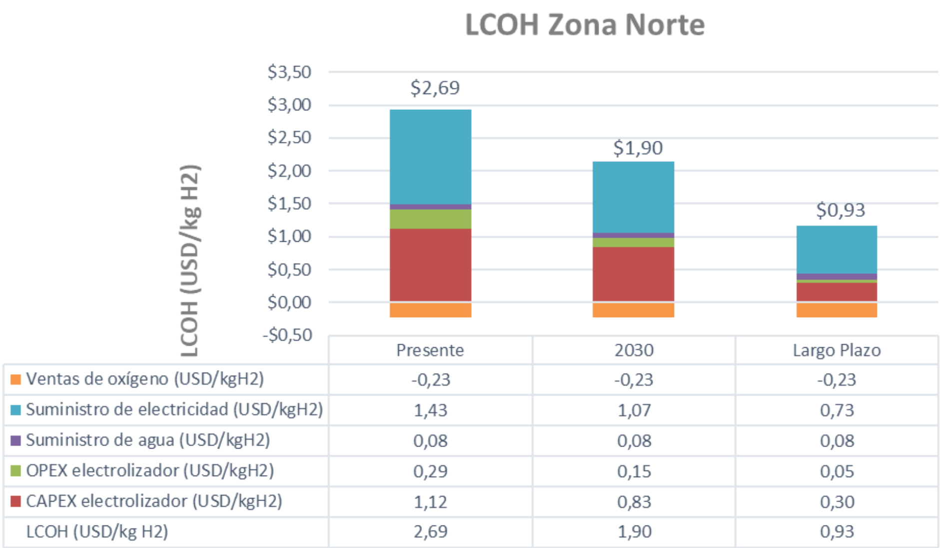

Figure 9-2 Disaggregated LCOH, northern zone

Source: compiled by the authors

Translation:

LCOH Zona Norte	LCOH Northern Zone
Presente	Present
Largo Plazo	Long term
Ventas de oxígeno	Oxygen sales
Suministro de electricidad	Electricity supply
Suministro de agua	Water supply
OPEX electrolizador	OPEX electrolyser
CAPEX electrolizador	CAPEX electrolyser

The northern zone is deemed to have higher water costs than the rest of the country (USD 5/m^3 compared with USD 1.4/m^3) due to the water scarcity in this region. Nevertheless, the impact on operating costs is relatively low and all OPEX costs could be offset if the associated oxygen production could be sold at a price of USD 0.03/kg.

Regarding the costs associated with H2V transport, given the grid tariff structure in Chile, it is likely that on-site H2V production at optimal renewable resource locations, with compressed H2V transport by truck to the end-use location, will be the main solution for project developers versus 24/7 PPAs that allow H2V to be generated constantly close to the point of use. This is because the Electricity Law includes a scheme of transmission tolls, based on the voltage level at which the consumption is connected, which are paid for by the end user as a stamp fee per unit of energy consumed. This fee can add between USD 12 and USD 20/MWh to the final energy price, depending on whether the consumption occurs at the regional or national transmission level, and USD 50/MWh if consumption is at the distribution level. This cost is added to the energy price, which makes the final cost of H2V less competitive.

Transport costs of H2V in dedicated trucks are estimated at USD 0.6/kg H_2 per 100 km travelled (IEA International Energy Agency, 2019). The graph below (Figure 9-3) shows that for an H2V producer in Chile's central zone, transporting H2V by truck would be a more convenient option than using 24/7 PPAs for consumption at a distance of less than 200 km from a production site, while on-site H2V production would be the most cost-efficient option. For this reason, the on-site generation model will be assumed for H2V production as it is the most economical of the models presented with lower costs.

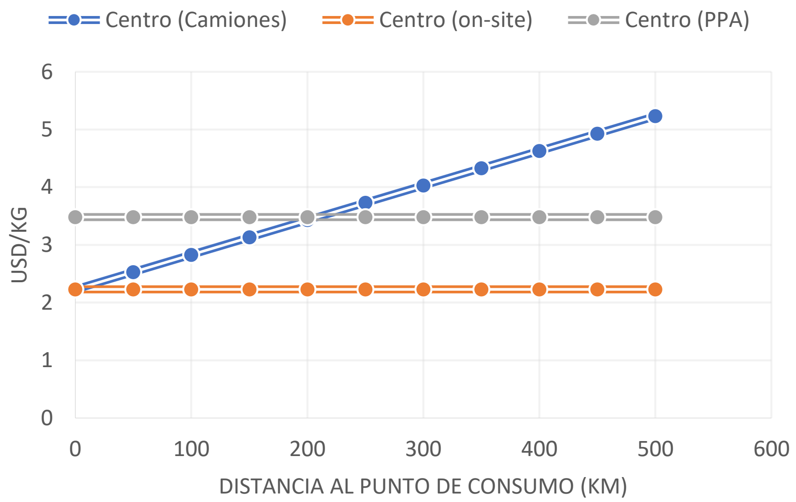

Figure 9-3 Analysis of H2V transport costs versus on-site production

Source: compiled by the authors

Translation:

Centro (Camiones)	Centre (trucks)
Centro (on-site)	Centre (on-site)
Centro (PPA)	Centre (PPA)
DISTANCIA AL PUNTO DE CONSUMO	DISTANCE TO POINT OF USE

The final figure for the LCOH is shown for different project scenarios in Chile to illustrate the effects that changing the case studies would have. This analysis considers different geographical areas for the project and the transport requirements, depending on whether the NCRE project and the electrolyser are located at the point of use (on-site), whether the NCRE plant is located far from the H2V production and point of use (PPA), and whether both the NCRE plant and the electrolyser are located far from the point of use (a distance of 150 km is assumed) and trucks are used to transport the H2V. This analysis is performed for the 'Present' scenario and shows comparable results for the medium- and long-term scenarios.

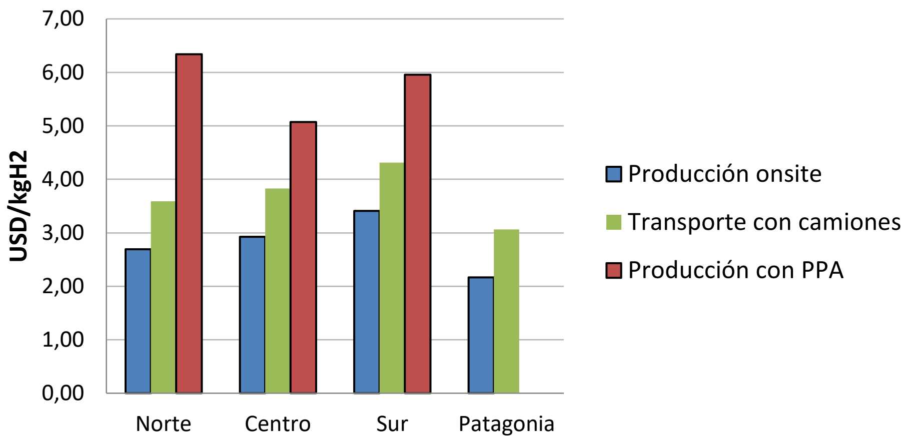

Figure 9-4 Scenarios for H2V production and use in Chile

Source: compiled by the authors

Translation:

Producción onsite	On-site production
Transporte con camiones	Transport in trucks
Producción con PPA	Production with PPA
Norte	North
Centro	Centre
Sur	South

Figure 9-5 shows a sensitivity analysis of the levelised cost of hydrogen in response to percentage variations in the different parameters of the models, using as an example the LCOH measured in Chilean Patagonia in the 'Medium-term' scenario. This shows that the most relevant components for the H2V production cost are the **electrolyser capacity factor** (FC Ez), the **discount rate**, the **electricity cost** and the **electrolyser capital expenses** (CAPEX Ez). These results are applicable to all regions and time scenarios.

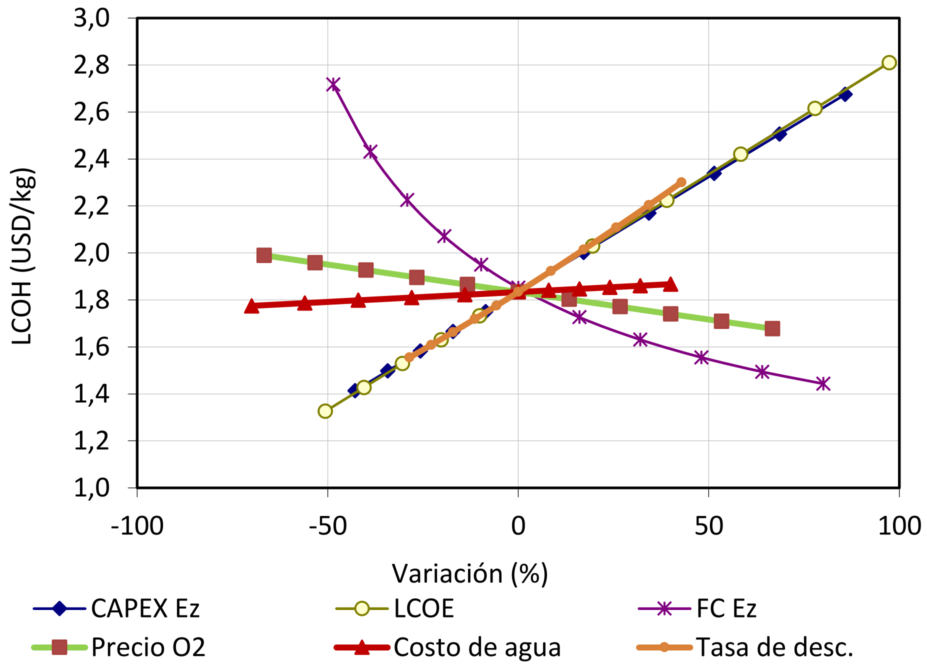

Figure 9-5 LCH sensitivity analysis

Source: compiled by the authors

Translation:

Variación	Variation
CAPEX Ez	CAPEX electrolyser
FC Ez	Electrolyser capacity factor
Precio O2	O_2 price
Costo de agua	Cost of water
Tasa de desc.	Discount rate

Finally, the LCOH results obtained were contrasted with the price projections for the fossil fuel being replaced to obtain the certificate price in dollars per tonne of CO_2 that would close the price gap between both fuels. This is a **figurative** and **approximate** exercise that only provides information on the certificate price needed to close the gap for the **project's operating costs**. The analysis conducted in section 3 is much more thorough and uses solid calculation methodologies for emission reductions (i.e. not just operating costs) and for the investment required (e.g. purchasing buses, replacing tuyeres) in order to use hydrogen in the application.

The calculation involves working out the relative difference between the prices of the two fuels, standardising both prices according to calorific value and applying this difference to an equivalent certificate price using the emission factor of the displaced fuel. As an example, the following procedure was used to calculate the feasibility gap for cement:

$$Feasibility\ gap\ \left[\frac{USD}{tonne_{CO_2}}\right] = \frac{P_{H2}\left[\frac{USD}{tonne_{H_2}}\right]\cdot\left(\frac{CV_{PK}\left[\frac{MJ}{tonne_{PK}}\right]}{CV_{H_2}\left[\frac{MJ}{tonne_{H_2}}\right]}\right) - P_{PK}\left[\frac{USD}{tonne_{PK}}\right]}{EF_{PK}\left[\frac{tonne\ CO_2}{tonne_{PK}}\right]}$$

Where:

$CV_{PK} = Petcoke\ calorific\ value\ \left[\frac{MJ}{tonne\ petcoke}\right]$

$CV_{H_2} = Hydrogen\ calorific\ value\ \left[\frac{MJ}{tonne\ H_2}\right]$

$P_{PK} = Price\ Petcoke\ \left[\frac{USD}{tonne\ petcoke}\right]$

$P_{H_2} = Price\ Hydrogen\ \left[\frac{USD}{tonne\ green\ H_2}\right]$

$EF_{PK} = Emission\ factor\ Petcoke\ \left[\frac{tonne\ CO_2}{tonne\ petcoke}\right]$

This exercise will also corroborate that the results obtained in Section 3 are consistent with the results in this preliminary exercise. The results are shown in the figure below.

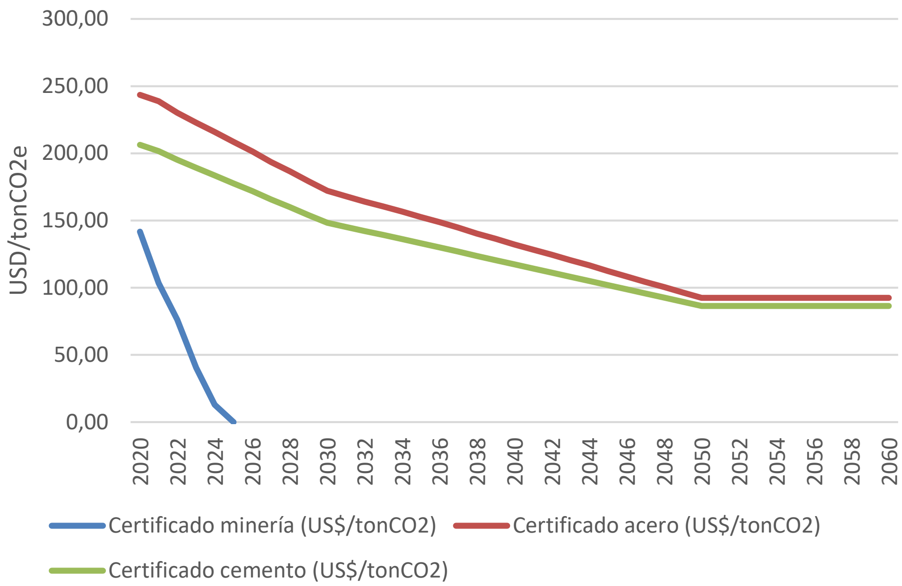

Figure 9-6 Price of certificates reaching parity between fossil and replacement fuels (H2V)

Source: compiled by the authors

Translation:

Certificado minería	Mining certificate
Certificado acero	Steel certificate
Certificado cemento	Cement certificate

This exercise shows that, with the hydrogen price projections, and the petcoke and coke price projections, the project upsides will need to be valued at a level that closes the price gap between the different fuels for hydrogen projects to achieve savings compared with similar fossil fuel-based projects in the cement and steel industries. By contrast, hydrogen will compete more closely with diesel and may reach parity by 2030 (also considering projected diesel price rises).

Even if hydrogen reaches parity with diesel sooner, transport projects will not necessarily be more attractive. The cases analysed show that, given the high infrastructure costs (purchase of buses and refuelling station), transport projects will have to reduce their costs significantly if they are to be economically attractive. On the other hand, given that steel and cement projects do not involve major investments in order to use hydrogen (replacing burners and tuyeres), the project's competitiveness will be based on the competitiveness of hydrogen compared with the displaced fuel.

9.3 Annex 3. Assumptions used to build an economic model in the cement sector case study

The main assumptions made to produce the economic model are presented in Table 9-4 below.

Table 9-4 Main assumptions for the cement application model

Assumption	Value			Source
	Present	Medium term	Long term	
Specific energy demand associated with fuel (MJ/tonne clinker)	3,550	3,400	3,250	Cement Sustainability Initiative (CSI)/European Cement Research Academy (ECRA). (2017)
Petcoke price (USD/tonne)	74.75	71.75	71.75	National Energy Commission (2020). Short-term node price setting.
Petcoke calorific value (MJ/kg)	27	27	27	National Energy Commission (2020). Short-term node price setting.
Rotary kiln lifetime (years)	40	40	40	CSI/ECRA. (2017)
Emission intensity associated with fuel (kg CO_2e/tonne clinker)	306	306	306	CSI/ECRA. (2017)
Average co-processing in Chile, 2017 (%)	12.6%	30%	30%	Roadmap towards low emissions in the Chilean cement industry (Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020)
Clinker/cement ratio in Chile (tonne clinker/tonne cement)	0.65	0.65	0.65	Roadmap towards low emissions in the Chilean cement industry (Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020)

CAPEX of new H2V burner (USD)	282,208	282,208	282,208	Options for switching UK cement production sites (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019)
CAPEX pipeline renewal for H_2 use (USD/tonne)	0.0565	0.0565	0.0565	Options for switching UK cement production sites (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019)
CAPEX H_2 storage tank (USD/tonne)	0.1129	0.1129	0.1129	Options for switching UK cement production sites (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019)

Source: compiled by the authors from (Mineral Products Association; Cinar Ltd; VDZ gGmbH, 2019; Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020; CSI, ECRA, 2017)

The economic model was mainly based on the technological studies *Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead* conducted by the European Cement Research Academy (CSI, ECRA, 2017), the techno-economic analysis *Options for switching UK cement production sites to near zero CO_2 emission fuel: Technical and financial feasibility* conducted by the UK Mineral Products Association (Mineral Products Association; Cinar Ltd; VDZ gGmbH , 2019) and the roadmap towards low emissions in the Chilean cement industry prepared by the Ministry of Energy together with GIZ (Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020).

The European Cement Research Academy (ECRA) studies provide the key parameters for a model cement plant, drawing on information from multiple cement production companies around the world.

A study by the Mineral Products Association in the United Kingdom sheds light on barriers to the use of hydrogen as a replacement for all fossil fuels in rotary kilns, such as the low radiation of the flame and relatively high ignition temperature (585°C), meaning that hydrogen could be used, but in conjunction with other fuels that increase its radiation and facilitate ignition. This study therefore provides an estimate of the renewal CAPEX required to use hydrogen in a rotary kiln.

In addition, a change in fossil fuel prices (petcoke in this case) was considered based on the projected coal price variations in the baseline scenario for the Long-Term Strategic Planning designed by the Ministry of Energy (Ministry of Energy, 2021).

Finally, the cement industry roadmap for Chile contains figures that are specific to Chilean production, such as the clinker/cement ratio, which is different from the rest of the world due to access to replacement raw materials such as blast furnace slag and ash.

9.4 Annex 4. Assumptions used to build an economic model in the steel sector case study

The main assumptions made to produce the economic model are presented in Table 9-5 below.

Table 9-5 Main assumptions for the steel model

Assumption	Value			Source
	Present	Medium term	Long term	
Coke consumption baseline case (kg coke/tonne HM)	498.1	498.1	498.1	Modelling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions (Yilmaz, Wendelstorf, & Turek, 2017)
Coke price (USD/tonne)	250	250	250	Information obtained through interviews during the study.
Amount of pig iron (HM) per unit of crude steel (tonne HM/tonne crude steel)	1.1	1.1	1.1	Based on Steel and Raw Materials Fact Sheet (World Steel Association, 2021)
Emission intensity baseline case (kg CO_2e/tonne crude steel)	1,830.0	1,830.0	1,830.0	Sustainability indicators report (World Steel Association, 2020)
Coke consumption with H2V injection (kg coke/tonne HM)	389.8	389.8	389.8	Modelling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions (Yilmaz, Wendelstorf, & Turek, 2017)
H2V injection into tuyeres (kg H_2/tonne HM)	27.5	27.5	27.5	Modelling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions (Yilmaz, Wendelstorf, & Turek, 2017)
CAPEX tuyere retrofitting for H2V injection (USD)	3,270,780	3,270,780	3,270,780	Estimate from interviews.
OPEX H2V injection in tuyeres (USD/tonne HM)	0.073	0.073	0.073	Estimate from interviews.

Emission intensity after H2V injection ($kg\ CO_2e$/tonne HM)	1,063.2	1,063.2	1,063.2	Modelling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions (Yilmaz, Wendelstorf, & Turek, 2017)

Source: compiled by the authors from (Yilmaz, Wendelstorf, & Turek, 2017; KPMG, 2020; World Steel Association, 2020; World Steel Association, 2021)

The economic model for H2V application in the steel industry was mainly based on the study *Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions* by Can Yilmaz (Yilmaz, Wendelstorf, & Turek, 2017). The study models the emission reductions and variations in coke consumption associated with different proportions of hydrogen injection into the tuyeres of a blast furnace. Estimated consumption can thus be obtained for the H2V application.

A change in fossil fuel prices (coke in this case) was also included on the basis of projected coal price variations in the baseline scenario for the Long-Term Strategic Planning designed by the Ministry of Energy (Ministry of Energy, 2021).

Finally, data associated with emissions intensity in the steel industry, coke price projections and renovation cost estimates were obtained from sources associated with the industry or interviews with industry professionals.

9.5 Annex 5. Assumptions used to build an economic model in the mining industry case study

The main assumptions made to produce the economic model are presented in Table 9-6.

Table 9-6 Main assumptions for the mining application model

Assumption	Value			Source
	Present	Medium term	Long term	
CAPEX H2V buses (USD/bus)	750,000	582,247	452,016	Bus cost provided by GIZ (USD 750k) Price projections from Strategies for joint procurement of fuel cell buses (FCH, 2018)
CAPEX diesel buses (USD/bus)	200,000	200,000	200,000	Strategies for joint procurement of fuel cell buses (FCH, 2018)
Diesel cost (USD/bus)	0.766	1.106	1.377	Long-term Energy Planning (Ministry of Energy, 2019)
Diesel bus efficiency (l/km)	0.400	0.400	0.400	Figure obtained by the industry
CAPEX batteries (USD/kW)	1,000	737	544	Strategies for joint procurement of fuel cell buses (FCH, 2018)
OPEX batteries (% CAPEX)	1.5%	1.5%	1.5%	Strategies for joint procurement of fuel cell buses (FCH, 2018)
CAPEX fuel cells (USD/kW)	1,000	737	544	Strategies for joint procurement of fuel cell buses (FCH, 2018)
OPEX fuel cells (% CAPEX)	2.5%	2.5%	2.5%	Strategies for joint procurement of fuel cell buses (FCH, 2018)
CAPEX (USD)	355,000	283,000	248,000	Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs, G. Parks et al. (National Renewable Energy Laboratory (NREL), 2014)
OPEX distribution (% CAPEX)	3.0%	3.0%	3.0%	Hydrogen at Scale for Fuel Cell Electric Buses A California Case Study (Nel Hydrogen, 2019)

Source: compiled by the authors from (FCH, 2018; Ministry of Energy, 2019; Nel Hydrogen, 2019)

The main assumptions of the H2V application model in the mining industry relate to the capital and operating expenses associated with H2V buses and their component parts. The main source of information for the capital, operating and performance cost assumptions of H2V and diesel-based buses were obtained from the study *Strategies for joint procurement of fuel cell buses* (FCH, 2018) conducted by the Fuel Cells and Hydrogen Joint Undertaking.

In addition, a change in fossil fuel prices (diesel in this case) was factored in with reference to the carbon price changes projected in the baseline scenario for the Long-Term Strategic Plan designed by the Ministry of Energy (Ministry of Energy, 2021).

9.6 Annex 6. Emission-reduction methodologies and calculations for the cement industry

Emission-reduction methodology for the cement industry

Project methodology

Project description

This project envisages a switch from carbon-intensive fossil fuel to a less carbon-intensive fuel in the cement industry, specifically from petcoke/coal to H2V in clinker kilns.

Type of mitigation action

Fuel switch to one with lower GHG intensity in replacement activities.

Applicability conditions for the methodology

There are a number of conditions that must be met in order to apply the methodology correctly to the project. The boundary conditions that define the project's scope are also described below.

A. The methodology involves fossil fuel switching in the cement industry.
B. The fossil fuel switch takes place in a process to produce clinker.
C. The fuel switch may be in a single element process or may include several element processes within the facility. Multiple fossil fuel switching in an element process however is not covered under this methodology.
D. The project boundary comprises the physical, geographical site where the switching of energy source takes place. It includes all installations, processes or equipment affected by the switching.
E. The methodology is limited to fuel-switching measures which require capital investments, i.e. the switch cannot take place at existing facilities without an investment in refits, replacements or other measures.
F. Even if the project includes biomass, alternative fuels (e.g. waste-based) or waste energy/gas, these fuels will not be eligible for fuel switching.
G. Process efficiency gains not associated with the project will not be considered. Only energy efficiency gains related to the fuel switch are considered.
H. Only retrofits and replacements that do not affect the original clinker production process are eligible.
I. This methodology is applicable to the retrofit or replacement of existing and new facilities or project activities involving capacity additions.
J. Fuel switching can also result in energy efficiency improvements. If the project activity is primarily aimed at reducing emissions through fuel switching, it comes under this methodology.
K. The requirements concerning demonstration of the remaining lifetime of the replaced equipment shall be met as described in the latest approved version of the Tool to Determine the Remaining Lifetime of Equipment. If the remaining lifetime of the affected systems increases due to the project activity, the crediting period shall be limited to the estimated remaining lifetime, (i.e. the time when the affected systems would have been replaced in the absence of the project activity).
L. The eligible fuels for this methodology are solid fuels (coal and coal products).
M. The element process or other downstream/upstream processes in the production chain do not change as a result of the fossil fuel switch.
N. The project's baseline fossil fuel and low-carbon energy source are consumed in thermal energy conversion equipment (e.g. furnaces, dryers) used in the manufacture of products.
O. Regulations do not require the use of project low-carbon energy source (e.g. natural gas, electricity or any other fuel) or restrict the use of the baseline fuel.
P. The product(s) produced at the industrial facility throughout the crediting period shall be equivalent to the product(s) produced in the baseline. For the purposes of this methodology,

equivalent products are defined as products having the same use, the same general physical properties, and which function in a similar manner, and have the same quality.

Q. The type of input materials used in the project shall be homogeneous and similar to the input material that was used in the baseline and any deviation during the crediting period of input material type, composition or amount used per unit of product output shall be within the range of +/- 10% of the baseline characteristics and values.

R. This methodology is only applicable if the baseline scenario identified is clinker production based on a system that is fully or partially dependent on the use of fossil fuels. In the case of partial dependence, such as co-processing with an alternative fuel, the fuel switch is only for the fossil fuel, and the use of the alternative fuel does not vary between the baseline and the project scenario.

S. Hydrogen leakage is not considered.

<u>Important parameters</u>

Important parameters for calculating the baseline and project scenario are presented below:

A. emission factor associated with the combustion of the fossil fuel, in this case petcoke
B. emission factor associated with the combustion of the replacement fuel, in this case H2V
C. net calorific value of the fuel type for both scenarios, i.e. baseline and project
D. energy demand associated with each fuel
E. annual baseline feedstock consumption and annual production quantity

The parameters to be monitored over time are listed below:

A. amount of fossil fuel used in both scenarios
B. amount of replacement fuel in the project scenario
C. efficiency of each element process or using a sampling approach if the element process accrues annual emission reductions below 3,000 tonnes CO_2e.

<u>How to calculate the baseline scenario</u>

The baseline scenario considers the emissions related to cement production based on the fuels it uses for each year of the emission-reduction project. This scenario covers emissions from cement production which would continue to occur if the H2V fuel switch project did not take place. The calculation is as follows:

$$BE_y = \sum_i BQ_{AF,i,y} * EF_{AF,y} + BQ_{FF,i,y} * EF_{FF,y}$$

Where:

BE_y: annual baseline emissions in year *y*
$BQ_{AF,i,y}$: quantity of alternative fuel (AF) used in the baseline for element process *i* in year *y* (unit of mass or volume)
$EF_{AF,y}$: CO_2 emission factor of the alternative fuel combusted in year *y*
$BQ_{FF,i,y}$: quantity of fossil fuel (FF) used in the baseline (petcoke), consumed in element process *i* in year *y* (unit of mass or volume)
$EF_{FF,y}$: CO_2 emission factor of the fossil fuel (petcoke) combusted in year *y*

The quantity of fuel used in the baseline is calculated as follows:

$$BQ_{AF,i,y} = ED_{AF,i,y} / NCV_{AF}$$

$$BQ_{FF,i,y} = ED_{FF,i,y} / NCV_{FF}$$

Where:

$ED_{AF,i,y}$: alternative fuel (AF) energy demand (ED) in element process *i* in the project activity for year *y*

NCV_{AF}: net calorific value of the alternative fuel (AF) used

$ED_{FF,i,y}$: energy demand (ED) of the fossil fuel (FF, petcoke) in element process *i* in the project activity for year *y*

NCV_{FF} : net calorific value of the fossil fuel (petcoke) used

<u>How to calculate the project scenario</u>

The project emissions here are based on hydrogen replacing petcoke/coal. The calculation to be performed is as follows:

$$PE_y = \sum_i BQ_{AF,i,y} * EF_{AF,y} + PQ_{FF,i,y} * EF_{FF,y} + PQ_{H2V,i,y} * EF_{H2V,y}$$

Where:

PE_y: emissions from project activities in year *y*

$BQ_{AF,i,y}$: baseline quantity (this figure is maintained as the fuel is not switched) of an alternative fuel consumed in element process *i* in project activity year *y* (unit of mass or volume)

$EF_{AF,y}$: CO_2 emission factor of the alternative fuel combusted in year *y*

$PQ_{FF,i,y}$: quantity used in the fossil fuel project (petcoke) consumed in element process *i* in the project activity in year *y* (unit of mass or volume)

$EF_{FF,y}$: CO_2 emission factor of the fossil fuel (petcoke) combusted in year *y*

$PQ_{H2V,i,y}$: quantity of H2V fuel used in the project consumed in element process *i* in the project activity of year *y* (unit of mass or volume)

$EF_{H2V,y}$: CO_2e emission factor of the H2V fuel used in the project activity in year *y*

The fuel quantities used in the project are calculated as follows:

$$PQ_{FF,i,y} = ED_{FF,i,y} / NCV_{FF,PJ}$$

$$PQ_{H2V,i,y} = ED_{H2V,i,y} / NCV_{H2V,PJ}$$

Where:

$ED_{FF,i,y}$: energy demand of fossil fuel in element process *i* in the project activity for year *y*

$NCV_{FF,PJ}$: net calorific value of the fossil fuel used in the project

$ED_{H2V,i,y}$: energy demand of H2V fuel in element process *i* in the project activity for year *y*

$NCV_{H2V,PJ}$: net calorific value of the H2V fuel used in the project

<u>How to calculate the emission reductions</u>

The emission reductions attributed to replacing the buses are calculated as follows:

$$ER_y = BE_y - PE_y$$

Where:

ER_y: emission reductions in year *y* (tonnes CO_2/*y*)
BE_y: annual baseline emissions in year *y* (tonnes CO_2)
PE_Y: total project emissions in year y (tonnes CO_2)

If we make the following switch in the above formula, and simplify it, we obtain:

$$ER_y = \sum_i \left(BQ_{FF,i,y} - PQ_{FF,i,y}\right) * EF_{FF,y} - PQ_{H2V,i,y} * EF_{H2V,y}$$

Calculations of potential emission reductions in baseline and project scenarios

This section shows the calculations made to obtain the emissions for the baseline and project scenarios. The formulas and methodologies mentioned above were used in these calculations, with the parameters and assumptions set out below. On this basis we can then measure the project's emission-reduction potential.

Baseline parameters and assumptions

The following table presents the parameters and assumptions used to calculate the annual baseline emissions. The first column shows whether the figures in the row are Parameters (**P**) or if they have been Calculated (**C**) based on the parameters. These parameters and calculations are presented for three years (2020, 2030 and 2050), highlighting in green the parameters that vary over time.

Table 9-7 Parameters and assumptions for calculating emissions in the baseline scenario for the cement industry

Type	Baseline scenario cement industry	Unit	2020	2030	2050
P	Clinker production	tonne	1,106,047	1,106,047	1,106,047
P	Specific energy demand associated with fuel	Megajoule (MJ)/tonne	3,550	3,400	3,250
C	Production energy demand	MJ	3,926,466,965	3,760,559,910	3,594,652,856
C	Rotary kiln energy demand	MJ	1,570,586,786	1,504,223,964	1,437,861,142
P	Alternative fuel use in the rotary kiln	%	13%	30%	30%
C	Fossil fuel use in the rotary kiln	%	87%	70%	70%
C	Energy demand for alternative fuel in rotary kiln	MJ	197,893,935	451,267,189	431,358,343
C	Energy demand for fossil fuel in rotary kiln	MJ	1,372,692,851	1,052,956,775	1,006,502,800
P	Calorific value of alternative fuel	MJ/kg	15.00	15.00	15.00
P	Calorific value fossil fuel (petcoke)	MJ/kg	26.57	26.57	26.57
C	Amount of alternative fuel used	Tonne	13,193	30,084	28,757
C	Amount of fossil fuel (petcoke) used	Tonne	51,663	39,630	37,881
P	Alternative fuel emission factor	tonne CO_2/tonne	0.07	0.07	0.07
P	Fossil fuel emission factor	tonne CO_2/tonne	3.40	3.40	3.40
C	Emissions	tonne CO_2	176,404	136,622	130,595

Source: compiled by the authors

The sources of information from which the parameters were obtained are described below.

- Clinker production. Clinker production is obtained from the baseline figure for cement production, estimated to be 1,700,000 tonnes of cement per year. According to the roadmap for low emissions in the Chilean cement industry, the ratio of clinker to cement production in Chile is 0.65 tonnes clinker/tonne cement (Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020). Annual clinker production is calculated by multiplying cement production by the above-mentioned ratio.

- Specific energy demand for fuel. This parameter relates to the total energy required to produce clinker across the entire production chain. The figure is obtained from international publications and corroborated by Chilean publications (CSI, ECRA, 2017; Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020). This figure is expected to decrease over time due to improved equipment efficiency.

- Rotary kiln energy requirement as % of total thermal energy required for clinker production. This is the percentage of 'Specific energy demand associated with fuel' for the rotary kiln. The rotary kiln is where the project's fuel switch takes place and is therefore the control volume. The figure is an international average benchmark for the cement industry (CSI, ECRA, 2017).

- Alternative fuel use in the rotary kiln. The estimate of the percentage of alternative fuels used in the rotary kiln comes from interviews and the opinions of experts in the cement industry. The use of alternative fuels is also projected to grow, thus increasing the level of co-processing in the cement industry.

- Calorific value of alternative fuel. This is the average calorific value of different biomass sources (Grimmeissen, Jensen, & Wehner, Hoja de ruta para el desarrollo de bajas emisiones en la Industria Chilena del Cemento, 2020).

- Calorific value of fossil fuel (petcoke). This is the calorific value reported by the IEA.

- Alternative fuel emission factor. This is the average of the emission factors reported by DEFRA for biofuels.

- Fossil fuel emission factor. This is the emission factor reported by DEFRA.

The intermediate figures are calculated as follows before obtaining the emissions for the scenario.

- Production energy demand is calculated by multiplying 'Clinker production' by the 'Specific energy demand associated with fuel'. This gives the absolute value of energy required for production.

- Rotary kiln energy demand is obtained by multiplying 'Production energy demand' by the '% of total thermal energy of clinker production in the rotary kiln'. This gives the absolute value of energy required by the rotary kiln.

- Fossil fuel use in the rotary kiln is calculated by subtracting 'Alternative fuel use in the rotary kiln' from 100%.

- Alternative fuel energy demand in the rotary kiln is calculated by multiplying 'Rotary kiln energy demand' by the percentage of 'Alternative fuel use in the rotary kiln' to produce the specific alternative fuel energy demand required by the kiln.

- Fossil fuel energy demand in the rotary kiln is calculated by multiplying 'Rotary kiln energy demand' by the percentage of 'Fossil fuel use in the rotary kiln' to produce the specific fossil fuel energy demand required by the rotary kiln.

- Amount of alternative fuel used is obtained by dividing 'Alternative fuel energy demand in the rotary kiln' by 'Calorific value of alternative fuel'.

- Amount of fossil fuel (petcoke) used is obtained by dividing 'Fossil fuel energy demand in the rotary kiln' by 'Calorific value of fossil fuel (petcoke)'.

The figure for emissions can then be obtained according to the formula presented above for the baseline.

Parameter values and assumptions for the project scenario

The following table presents the parameters and assumptions used to calculate the project's annual emissions. As in the baseline scenario, the first column in the table indicates whether the figures in the row are Parameters (**P**) or Calculated (**C**) from the parameters, and these are presented for three different years.

Table 9-8 Parameters and assumptions used to calculate the emissions of the cement industry project scenario

	Cement industry project scenario	**Unit**	**2020**	**2030**	**2050**
P	Clinker production	tonne	1,106,047	1,106,047	1,106,047
P	Specific energy demand for fuel	MJ/tonne	**3,550**	**3,400**	**3,250**
C	Production energy demand	MJ	3,926,466,965	3,760,559,910	3,594,652,856
P	Rotary kiln energy requirement as % of total thermal energy required for clinker production	%	40%	40%	40%
C	Rotary kiln energy demand	MJ	1,570,586,786	1,504,223,964	1,437,861,142
P	Alternative fuel use in the rotary kiln	%	13%	30%	30%
P	H2V use in the rotary kiln	%	**10%**	**10%**	**10%**
C	Fossil fuel use in the rotary kiln	%	77%	60%	60%
C	Alternative fuel energy demand in the rotary kiln	MJ	197,893,935	451,267,189	431,358,343
C	H2V energy demand in the rotary kiln	MJ	157,058,679	150,422,396	143,786,114
C	Fossil fuel energy demand in the rotary kiln	MJ	1,215,634,172	902,534,378	862,716,685
P	Calorific value of alternative fuel	MJ/kg	**15.00**	**15.00**	**15.00**
P	Calorific value of H2V	MJ/kg	**120.00**	**120.00**	**120.00**
P	Calorific value of fossil fuel (petcoke)	MJ/kg	**26.57**	**26.57**	**26.57**
C	Amount of alternative fuel used	Tonne	13,193	30,084	28,757
C	Amount of H2V	tonne	1,309	1,254	1,198
C	Amount of fossil fuel (petcoke) used	tonne	45,752	33,968	32,470
P	Alternative fuel emission factor	tonnes CO_2/tonne	0.07	0.07	0.07

P	H2V emission factor	tonnes CO_2/tonne	0.00	0.00	0.00
P	Fossil fuel emission factor	tonnes CO_2/tonne	3.40	3.40	3.40
C	Emissions	tonne CO_2	156,320	117,386	112,207

Source: compiled by the authors

In the table above, the rows of parameters and calculations that vary compared with the baseline scenario are shown in blue. The information from which the new parameters were obtained is explained below:

- H2V use in the rotary kiln. The estimate of the percentage of use of H2V in the rotary kiln comes from interviews and the opinions of experts in the cement industry.

- Calorific value of H2V. This is the calorific value reported by the IEA.

- H2V emission factor. This is equal to 0 tonne CO_2/kg H_2 as described in the section Green hydrogen and its impact on methodologies.

The method for calculating the new intermediate values (those that differ from the baseline scenario) before calculating the project's emissions is shown below.

- Fossil fuel use in the rotary kiln. This is calculated by subtracting 'Alternative fuel use in the rotary kiln' and 'H2V use in the rotary kiln' from 100% to obtain the percentage of fossil fuel that is displaced by H_2.

- H2V energy demand in rotary kiln. This is calculated by multiplying 'Rotary kiln energy demand' by the percentage of 'H2V use in the rotary kiln' to obtain the specific H2V energy demand required by the rotary kiln.

- Amount of H2V. This figure is obtained by dividing 'H2V energy demand in rotary kiln' by 'Calorific value of H2V'.

Finally, the emissions are obtained using the formula for the project scenario (see above).

Emission reductions and figures to close the project feasibility gap

Below are the results for emission reductions. As shown in the formulas, the emission reduction is calculated by subtracting the project emissions from the baseline emissions. It can also be obtained using the following formula:

$$ER_y = \sum_i \left(BQ_{FF,i,y} - PQ_{FF,i,y}\right) * EF_{FF,y} - PQ_{H2V,i,y} * EF_{H2V,y}$$

For the specific case of hydrogen, where the emission factor is taken to be zero, this can be simplified as follows:

$$ER_y = \sum_i \left(BQ_{FF,i,y} - PQ_{FF,i,y}\right) * EF_{FF,y}$$

This would be the displaced fossil fuel (fossil fuel used in the baseline minus the fossil fuel used in the project) multiplied by the emission factor of the fossil fuel, in this case petcoke. The table shows that these two ways of calculating emission reductions produce the same figure. Therefore, the percentage of alternative fuel used is negligible when calculating emission reductions as long as it remains constant in both the baseline and project scenarios.

Table 9-9 Emission-reduction calculation for the cement industry

Emission-reduction calculation for the cement industry	Unit	2020	2030	2050
Baseline emissions minus project emissions	**tonnes CO_2**	20,085	19,236	18,387
Displaced fuel (petcoke)	**tonnes**	5,911	5,661	5,412
Emission factor displaced fuel	**tonnes CO_2/tonne**	3,40	3.40	3.40
Emission reductions per displaced fuel	**tonnes CO_2**	20,085	19,236	18,387

Source: compiled by the authors

9.7 Annex 7. Emission-reduction methodologies and calculations for the steel industry

Emission-reduction methodology for the steel industry

Project methodology

Project description

The project is defined as using H2V as a partial switch for fossil fuel-based reducing agents in the pig iron production process. This process involves replacing coke with H2V in the blast furnace as a source of energy and as a reactant in iron oxide reduction to produce pig iron. The project includes adapting the blast furnace tuyeres to inject H2V.

Type of mitigation action

The mitigation actions here involve switching from a fossil fuel to H2V, i.e. switching to a fuel with lower emission intensity.

Applicability conditions for the methodology

The conditions that must be met to apply the methodology correctly to the project are set out below. The boundary conditions that define the scope of the project are also described.

A. The methodology involves fossil fuel switching in the steel industry.
B. The fossil fuel switch is used in a process to produce a final product.
C. The fuel switch may be in a single element process or may include several element processes within the facility. Multiple fossil fuel switching in an element process however is not covered under this methodology.
D. The project boundary comprises the physical, geographical site where the switching of energy source takes place. It includes all installations, processes or equipment affected by the switching.
E. The methodology is limited to fuel-switching measures which require capital investments, i.e. the switch cannot take place at existing facilities without an investment in refits, replacements or other measures.
F. Coke is the fuel replaced by H2V. The emissions avoided in the process of drying metallurgical coal or coking coal (to obtain coke), and the combustion of this coke, are therefore included in the emission reduction.
G. Only retrofits and replacements that do not affect the original steel production process (integrated process) are eligible.
H. This methodology is applicable to the retrofit or replacement of existing and new facilities or project activities involving capacity additions.
I. Fuel switching can also result in energy efficiency improvements, which will be considered in the emission reduction calculation.
J. The element process or other downstream/upstream processes in the production chain do not change as a result of the fossil fuel switch.
K. The project's baseline fossil fuel and low-carbon energy source are consumed in thermal energy conversion equipment (e.g. furnaces, dryers) used in the manufacture of products.
L. Regulations do not require the use of a project low-carbon energy source (e.g. natural gas, electricity or any other fuel) or restrict the use of the baseline fuel.
M. The product(s) produced in the industrial facility throughout the crediting period shall be equivalent to the product(s) produced in the baseline. For the purposes of this methodology, equivalent products are defined as products having the same use, the same general physical properties, and which function in a similar manner, and have the same quality.
N. The type of input materials used in the project shall be homogeneous and similar to the input material that was used in the baseline and any deviation during the crediting period of input

material type, composition or amount used per unit of product output shall be within the range of +/- 10% of the baseline characteristics and values.

O. Hydrogen leakage is not considered.
P. The process of producing CO_2 from fossil fuel sources does not lead to any energy by-products.
Q. This methodology is only applicable if the baseline scenario identified is pig iron production based on an iron ore reduction system that is fully or partially dependent on the use of fossil fuels.

Important parameters

A. Coke emission factor for the pig iron production process (including thermal use and as a reducing agent in the fuel).
B. Emission factor in the upstream coke drying process.
C. H2V emission factor for the pig iron production process (including thermal use and as a fuel reducing agent).
D. Annual baseline feedstock consumption and annual amount of pig iron production.
E. Fuel consumption in pig iron production.

The parameters to be monitored over time are presented below:

A. Amount of fossil fuel used in both scenarios.
B. Amount of H2V in project scenario.
C. Efficiency of each element process or using a sampling approach if the element process accrues annual emission reductions below 3,000 tonnes CO_2e.
D. Project's pig iron production.

How to calculate the baseline scenario

This scenario considers the emissions from the manufacture of pig iron using coke as a fuel, i.e. if there is no H2V switch. The calculation to be performed is as follows:

$$BE_y = BE_{IR,y} + UBE_{PG,y}$$

Where:

BE_y : baseline emissions in year *y*
$BE_{IR,y}$: emissions from the baseline process in the iron ore reduction facility
$UBE_{PG,y}$: upstream baseline emissions associated with fossil fuel production in year *y*

The components of the equation are then calculated as follows:

$$BE_{IR,y} = \sum_i BQ_{FF,i,y} * EF_{FF,y}$$

Where:

$BQ_{FF,i,y}$: amount of fossil fuel (FF) used in the baseline (coke) and consumed in element *i* of the pig iron production process in year *y* (unit of mass or volume).
$EF_{FF,y}$: CO_2 emission factor of the pig iron production process for the fossil fuel used (coke) in year *y*

$$UBE_{PG,y} = \sum_{i} BQ_{FF,i,y} * BC_{FF,y} * EF_{SFF,y}$$

Where:

$BQ_{FF,i,y}$: amount of fossil fuel (FF) used in the baseline (coke) and consumed in element *i* of the pig iron production process in year *y* (unit of mass or volume).

$BC_{FF,y}$: conversion rate of bituminous coal to coke for baseline in year y

$EF_{SFF,y}$: CO_2 emission factor of bituminous coal combustion for the production of fossil fuel (coke) in year y

<u>How to calculate the project scenario</u>

This scenario considers the emissions from steel production when a percentage of the coke used as fuel has been replaced by H2V. The calculation is as follows:

$$PE_y = PE_{IR,y} + UPE_{PG,y}$$

Where:

PE_y: project emissions in year *y*

$PE_{IR,y}$: project emissions in the iron ore reduction facility

$UPE_{PG,y}$: upstream project emissions associated with fossil fuel production in year *y*

The components of the equation are then calculated as follows:

$$PE_{IR,y} = \sum_{i} PQ_{FF,i,y} * EF_{FF,y} + PQ_{H2V,i,y} * EF_{H2V,y}$$

Where:

$PQ_{FF,i,y}$: amount of fossil fuel (FF) used in the project (coke), consumed in element *i* of the pig iron production process in year *y* (unit of mass or volume)

$EF_{FF,y}$: CO_2 emission factor of the pig iron production process for the fossil fuel used

$PQ_{H2V,i,y}$: amount of H2V used in the project, consumed in element *i* of the pig iron production process in year *y* (unit of mass or volume)

$EF_{H2V,y}$: CO2 emission factor of the H2V pig iron production process.

$$UPE_{PG,y} = \sum_{i} PQ_{FF,i,y} * BC_{FF,y} * EF_{SFF,y}$$

Where:

$PQ_{FF,i,y}$: amount of fossil fuel (FF) used in the project (coke), consumed in element *i* of the pig iron production process in year *y* (unit of mass or volume).

$BC_{FF,y}$: conversion rate of bituminous coal to coke for baseline in year *y*

$EF_{SFF,y}$: CO_2 emission factor of bituminous coal combustion to produce the fossil fuel (coke) in year *y*

<u>How to calculate the emission reductions</u>

The emission reductions attributed to replacing the buses is calculated as follows:

$$ER_y = BE_y - PE_y$$

Where:

ER_y: emission reductions in year *y* (tonnes CO_2/y)
BE_y: annual baseline emissions in year *y* (tonnes CO_2)
PE_Y: total project emissions in year *y* (tonnes CO_2)

Calculations of potential emission reductions in baseline and project scenarios

This section shows the calculations made to obtain the emissions for the baseline and project scenarios. The formulas and methodologies mentioned above were used in these calculations, with the parameters and assumptions set out below. On this basis we can then measure the project's emission-reduction potential.

Baseline parameters and assumptions

The following table presents the parameters and assumptions used to calculate the annual baseline emissions. The first column shows whether the figures in the row are Parameters (**P**) or if they have been Calculated (**C**) based on the parameters. These parameters and calculations are presented for three years (2020, 2030 and 2050). The parameters remain constant in the steel industry baseline scenario.

Table 9-10 Parameters and assumptions for calculating emissions in the baseline scenario for the steel industry

Type	Baseline scenario steel industry	Unit	2020	2030	2050
P	**Pig iron production (HM)**	**tonne**	664,500	664,500	664,500
P	**Coke consumption by tonne of production**	**kg/tonne of pig iron**	498	498	498
C	**Coke consumed**	**tonne**	330,987	330,987	330,987
P	**Coking coal to coke conversion factor**	**tonnes coking coal/tonne coke**	1.35	1.35	1.35
C	**Coking coal consumed**	**tonne**	447,833	447,833	447,833
P	**Coking coal emission factor[45]**	**tonnes CO_2/tonne coking coal**	3.06	3.06	3.06
C	**Emissions**	**tonnes CO_2**	1,370,369	1,370,369	1,370,369

Source: compiled by the authors

The sources of information from which the parameters were obtained are described below.

- Pig iron production (HM). CAP Acero's average annual production.

- Coke consumption per tonne of production. This figure is obtained from international sources (Yilmaz, Wendelstorf, & Turek, 2017) and validated with CAP Acero's actual consumption.

- Coking coal to coke conversion factor. The tonnes of coking coal used to produce one tonne of coke. This figure is obtained from the actual coke production at CAP Acero.

- Coking coal emission factor (includes coke production and coke emissions in the blast furnace produced by combustion and the reduction of iron ore). This figure is obtained from the IEA.

The intermediate figures shown in the table (and used to calculate emissions for the scenario) are explained below.

[45] Including both coke production and blast furnace coke emissions from combustion and the reduction of iron ore.

- Coke consumed. This figure is obtained by multiplying 'Hot metal production (HM)' by 'Coke consumption per tonne of production'.

- Coking coal consumed. This figure is obtained by multiplying 'Coke consumed' by 'Coking coal to coke conversion factor'.

As the coking coal emission factor includes both the coke production process and the emissions produced by the coke in the blast furnace, the emission reduction is calculated as follows:

$$BE_y = \sum_i BQ_{FF,i,y} * EF_{FF,y} + BQ_{FF,i,y} * BC_{FF,y} * EF_{SFF,y} = \sum_i BQ_{SFF,y} * EF_{T,SFF,y}$$

Where:

BE_y: annual baseline emissions in year *y* (tonnes CO_2)
$BQ_{FF,i,y}$: amount of fossil fuel (FF) used in the baseline (coke), consumed in element *i* of the pig iron production process in year *y* (unit of mass or volume)
$EF_{FF,y}$: CO_2 emission factor for the pig iron production process of the fossil fuel used (coke) in year *y*
$BC_{FF,y}$: coking coal to coke conversion rate for baseline in year *y*
$EF_{SFF,y}$: CO_2 emission factor from the combustion of coking coal for the production of fossil fuel (coke) in year *y*
$BQ_{SFF,y}$: amount of coking coal for fossil fuel production in the baseline for year *y.*
$EF_{T,SFF,y}$: CO_2 emission factor including combustion of coking coal for fossil fuel (coke) production in year *y* and emissions from the pig iron production process in year *y*

Parameter values and assumptions of the project scenario

The following table shows the parameters and assumptions used to calculate the project's annual emissions. As in the baseline scenario, the first column in the table indicates whether the figures in the row are Parameters (**P**) or Calculated (**C**) from the parameters, and these are presented for three different years.

Table 9-11 Parameters and assumptions for calculating emissions in the steel industry project scenario

Type	Steel industry project scenario	Unit	2020	2030	2050
P	Pig iron production (HM)	tonne	664,500	664,500	664,500
P	Coke consumption per tonne of production	kg/tonne of pig iron	389.8	389.8	389.8
C	Coke consumed	tonne	259,022	259,022	259,022
P	H2V consumption per tonne of production	kg H_2/tonne HM	27.5	27.5	27.5
C	H2V consumed	tonne	18,274	18,274	18,274
P	Coking coal to coke conversion factor	tonnes coking coal/tonne coke	1.35	1.35	1.35
C	Coking coal consumed	tonne	350,462	350,462	350,462
P	Coking coal emission factor (includes coke production and coke emissions in blast furnace due to combustion and reduction of iron ore)	tonnes CO_2/tonne coking coal	3.06	3.06	3.06
P	H2V emission factor	tonnes CO_2/tonne H_2	0	0	0
C	Emissions	tonnes CO_2	1,072,415	1,072,415	1,072,415

Source: compiled by the authors

In the table above, the rows of parameters and calculations that vary compared with the baseline scenario are shown in blue. The sources from which the new parameters were obtained are given below.

- Coke consumption per production: obtained from international references where H2V injection through the tuyeres has been included (Yilmaz, Wendelstorf, & Turek, 2017)

- H2V consumption per production: obtained from international references where H2V injection through the tuyeres has been included (Yilmaz, Wendelstorf, & Turek, 2017)

- H2V emission factor: equal to 0 tonnes CO_2e/kg H_2 as discussed in the section 'Green hydrogen and its impact on methodologies'.

The method for calculating the new intermediate values (those that differ from the baseline scenario) before calculating the project's emissions is shown below.

- H2V consumed: obtained by multiplying 'Pig iron production (HM)' by 'H2V consumption per tonne of production'.

Finally, the emissions are obtained using the formula presented above for the project scenario.

Emission reductions and figures to close the project feasibility gap

The results for emission reductions are set out below. As shown in the formulas, the emission reduction is calculated by subtracting the project emissions from the baseline emissions. It can also be calculated using the following formula:

$$ER_y = BE_y - PE_y = \sum_i BQ_{SFF,y} * EF_{T,SFF,y} - \sum_i PQ_{SFF,y} * EF_{T,SFF,y} + PQ_{H2V,i,y} * EF_{H2V,y}$$

Where:

ER_y: emission reductions in year *y*
BE_y: annual baseline emissions in year *y*
PE_y: total project emissions in year *y*
$EF_{T,SFF,y}$: CO_2 emission factor including coking coal combustion to produce fossil fuel (coke) in year *y* and emissions from the pig iron production process in year *y*
$BQ_{SFF,y}$: amount of coking coal for fossil fuel production in the baseline for year *y.*
$PQ_{SFF,y}$: amount of coking coal for fossil fuel production in the project for year *y.*
$PQ_{H2V,i,y}$: amount of H2V used in the project, consumed in element *i* of the pig iron production process for year *y* (unit of mass or volume).
$EF_{H2V,y}$: CO_2 emission factor of the H2V pig iron production process.

For the specific case of H2V, where the emission factor is taken to be zero, this equation can be simplified as follows:

$$ER_y = \sum_i (BQ_{SFF,y} - PQ_{SFF,y}) * EF_{T,SFF,y}$$

This would be the displaced fossil fuel (fossil fuel used in the baseline minus the fossil fuel used in the project) multiplied by the emission factor of the fossil fuel, in this case coking coal. The table shows that these two ways of calculating emission reductions produce the same figure. Therefore, the percentage of alternative fuel used is negligible when calculating emission reductions as long as it remains constant in both the baseline and project scenarios.

Table 9-12 Emission-reduction calculation for the steel industry

Emission-reduction calculation for the steel industry	Unit	2020	2030	2050
Emissions reduced	**tonnes CO_2**	297,954	298	298
Displaced fuel (coking coal)	**tonne**	97,371	97,371	97,371
Emission factor fuel switch	**tonnes CO_2/tonne coking coal**	3.06	3.06	3.06
Emission reductions per displaced fuel	**tonnes CO_2**	297,954	297,954	297,954

Source: compiled by the authors

9.8 Annex 8. Emission-reduction methodologies and calculations for the mining industry

Emission-reduction methodology for the mining industry

Project description

The project involves introducing and running H2V buses to transport passengers in mining operations. The new buses will have a lower greenhouse gas emission factor than the buses being replaced. They will use H2V fuel in fuel cells to transport passengers on new and existing routes.

Type of mitigation action

There are two types of mitigation actions, fuel switching and the displacement of more GHG-intensive vehicles.

Applicability conditions for the methodology

A. New and existing routes are established in advance, so the annual distance travelled is fixed.
B. The buses are used for passenger transport only.
C. For each route, the buses used in the baseline are diesel or electric buses, and these are replaced by H2V buses.
D. It must be demonstrated that any new routes implemented for the project activity had already been planned before the start date of the project activity.
E. The project and baseline buses for each route are comparable, meaning that the buses in the two scenarios must have comparable passenger capacity with a variation of no more than +/- 10%; i.e. if the baseline buses are air-conditioned, the project buses must be air-conditioned too.
F. The buses' frequency of operation should be the same in the project and baseline scenarios.
G. Procedures such as a contractual agreement or unique identification of the buses should be implemented to avoid potential double counting of emission reductions by the parties involved. These procedures, which establish who is responsible for the emission reductions, should be described in the project design document.
H. There is a single recharging/refuelling terminal.
I. Measurements are limited to those that result in emission reductions less than or equal to 60 ktonnes CO_2 equivalent annually.
J. The project boundary includes the following: buses using H2V as fuel; the H2V storage and refuelling terminal; the geographical area covering the routes the hydrogen buses are to use and auxiliary facilities such as fuelling stations, workshops and service stations used by the project buses.
K. H2V is produced within or near the project facilities.
L. Hydrogen leakage is not considered.

Important parameters

A. Annual number of buses in the fleet
B. Emission factor of the fuels used in the baseline fleet
C. Emission factor of H2V used in the project fleet
D. Annual distance travelled by each bus in the baseline and project scenario
E. Specific consumption (per kilometre) for the baseline buses
F. Specific consumption (per kilometre) for the project buses

Of the above, the following should be monitored over time

G. Annual number of buses in the fleet
H. Annual distance travelled by each bus

I. Specific consumption (per kilometre) of the baseline buses
J. Specific consumption (per kilometre) of the project buses

How to calculate the baseline scenario

The baseline scenario considers the historic emissions that would continue to occur if there is no project using H2V buses. The formula used to calculate the baseline emissions is shown below:

$$BE_y = \sum_k EF_{k,y} * SC_{d,k,y} * TD_{k,y}$$

Where:

BE_y: annual baseline emissions in year *y*
$EF_{k,y}$: emission factor of the fuel used by bus type *k* (electric or diesel) for the baseline in year *y*
$SC_{d,k,y}$: specific fuel consumption for the distance travelled by bus type *k* (electric or diesel) for the baseline in year *y*
$TD_{k,y}$: total annual distance travelled by bus type *k* (electric or diesel) for the baseline in year *y*

How to calculate the project scenario

The project scenario considers a total replacement of the bus fleet by H2V buses. The formula used to calculate the baseline emissions is shown below:

$$PE_y = \sum_k EF_{H2V,y} * SC_{d,H2V,y} * TD_{H2V,y}$$

Where:

PE_y: project emissions in year *y*
$EF_{H2V,y}$: emission factor of the fuel used by the H2V bus in the project in year *y*
$SC_{d,H2V,y}$: specific fuel consumption per distance travelled by the H2V bus in the project in year *y*
$TD_{H2V,y}$: total annual distance travelled by the H2V bus in the project in year *y*

How to calculate the emission reductions

The emission reductions attributed to replacing the baseline buses with H2V buses are calculated as follows:

$$ER_y = BE_y - PE_Y$$

Where:
ER_y: emission reductions in year *y* (tonne CO_2e/y)
BE_y: annual baseline emissions in year *y* (tonnes CO_2e)
PE_Y : total project emissions in year *y* (tonnes CO_2e)

Calculation of potential emission reductions in baseline and project scenarios

This section presents the calculations made in order to obtain the emissions in the baseline and project scenarios. For these calculations, the formulas and methodologies mentioned above were used, with the parameter values and assumptions presented below. On this basis we can then measure the project's emission-reduction potential.

Baseline parameters and assumptions

The following table presents the parameters and assumptions used to calculate the annual baseline emissions. The first column shows whether the figures in the row are Parameters (**P**) or if they have been Calculated (**C**) based on the parameters. These parameters and calculations are presented for three years (2020, 2030 and 2050). Two baseline scenarios are considered for buses in line with Chile's NDC. The 2030 case represents the current commitments while the 2050 case uses more ambitious sectoral reduction targets.

Table 9-13 Parameters and assumptions for calculating emissions in the baseline scenario for the mining industry

Type	Baseline	Unit	2020	2030	2050
P	**Total buses**	#	10	10	10
P	**Electric buses as % of fleet (2030)**	%	0.0%	7.0%	21.0%
P	**Electric buses as % of fleet (2050)**	%	0.0%	19.3%	58.0%
C	**Total electric buses (2030)**	#	0	0	2
C	**Total electric buses (2050)**	#	0	1	5
C	**Total diesel buses (2030)**	#	10	10	8
C	**Total diesel buses (2050)**	#	10	9	5
P	**Annual bus travel**	km/year-bus	54,750	54,750	54,750
C	**Electric travel (2030)**	km/year	-	-	109,500
C	**Electric travel (2050)**	km/year	-	54,750	273,750
C	**Diesel travel (2030)**	km/year	547,500	547,500	438,000
C	**Diesel travel (2050)**	km/year	547,500	492,750	273,750
P	**Specific electricity consumption**	kwh/km	0.93	0.93	0.93
P	**Specific diesel consumption**	l/km	0.400	0.400	0.400
C	**Electricity consumption (2030)**	kwh	-	-	110,595
C	**Electricity consumption (2050)**	kwh	-	54,750	276,487.50
C	**Diesel consumption (2030)**	l	205,313	219,000	164,250
C	**Diesel consumption (2050)**	l	205,313	197,100	102,656
P	**Electricity emission factor**	kg CO_2e/kWh	0.276	0.076	0.012
P	**Diesel emission factor**	kg CO_2e/l	2.688	2.688	2.688
C	**Emissions (2030)**	kg CO_2e	550,200	550,200	441,416
C	**Emissions (2050)**	kg CO_2e	550,200	499,034	278,239

Source: compiled by the authors

The sources of information from which the parameters were obtained are described below.

- Total buses: information provided by the Chilean mining company Compañía Minera del Pacífico (CMP)

- Electric buses as % of fleet (2030 and 2050): calculated applying linear growth until the electric fleet targets stipulated in the Chilean NDC are reached, both for current targets (2030) and for the more ambitious proposed targets (2050)
- Annual bus travel: information provided by CMP
- Specific electricity consumption: information provided by CMP
- Specific diesel consumption: obtained from international references (FCH, 2018)
- Electricity emission factor: obtained from the Ministry of Energy projection for the National Electricity System (SEN)
- Diesel emission factor: emission factor reported by DEFRA

The intermediate figures are calculated as follows before obtaining the emissions for the scenario.

- Total electric buses (2030 and 2050): obtained by multiplying 'Total buses' by 'Electric buses as % of fleet' for each case (2030 and 2050)
- Total diesel buses (2030 and 2050): obtained by subtracting from 'Total buses' the figure calculated for 'Total electric buses' for each case (2030 and 2050)
- Electric travel (2030 and 2050): obtained by multiplying 'Annual bus travel', which represents the amount travelled annually by each bus, by 'Total electric buses' for each case (2030 and 2050)
- Diesel travel (2030 and 2050): obtained by multiplying 'Annual bus travel', which represents the amount travelled annually by each bus, by 'Total diesel buses' for each case (2030 and 2050)
- Electricity consumption (2030 and 2050): obtained by multiplying 'Electric travel' for each case (2030 and 2050) by 'Specific electricity consumption'
- Diesel consumption (2030 and 2050): obtained by multiplying 'Diesel travel' for each case (2030 and 2050) by 'Specific diesel consumption'

The figure for emissions can then be obtained according to the formula presented above for the baseline.

Parameter values and assumptions for the project scenario

The following table presents the parameters and assumptions used to calculate the project's annual emissions. As in the baseline scenario, the first column in the table shows whether the figures in the row are Parameters (**P**) or Calculated (**C**) from the parameters, and these are presented for three different years.

Table 9-14 Calculation of emission reductions for the mining industry

Type	Mining industry project scenario	Unit	2020	2030	2050
P	Total buses	#	10	10	10
C	Distance travelled	km	547,500	547,500	547,500
P	H_2 specific consumption	kg/km	0.08	0.08	0.08
C	H_2 consumption	kg	43,800	43,800	43,800
P	H_2 emission factor	kg CO_2e/kg	0	0	0
C	Emissions	kg CO_2e	-	-	-

Source: compiled by the authors

In the table above, the rows of parameters and calculations that vary compared with the baseline scenario are highlighted in blue. The sources of information from which the new parameters were obtained are described below.

- H2V specific consumption: obtained from international references on H2V buses (FCH, 2018; Nel Hydrogen, 2019).
- H2V emission factor: equal to 0 tonnes CO_2e/kg H_2, as stated in Section 3.1.2.

The method for calculating the new intermediate values (those that differ from the baseline scenario) before calculating the project's emissions is shown below.

- Distance travelled: obtained by multiplying 'Total buses' in the fleet by 'Annual bus travel' in the baseline.
- H2V consumption: obtained by multiplying 'Distance travelled' by 'H2V specific consumption'.

Finally, the emissions are obtained using the formula presented above for the project scenario.

Emission reductions

The results for emission reductions for the 2020, 2030 and 2050 scenarios, calculated as the baseline emissions minus the project emissions, are presented below. The project feasibility gap is calculated in Table in the body of the report.

Table 9-15 Emission-reduction calculation for the mining industry

Emission-reduction calculation for the mining industry	Unit	2020	2030	2050
Reduced emissions (2030)	tonnes CO_2e	550	550	441
Reduced emissions (2050)	tonnes CO_2e	550	499	278

Source: compiled by the authors

9.9 Annex 9. Details of the negotiating text on crediting periods (draft)

No agreement was reached on Article 6 at COP25. Reference was made to several draft versions of the draft decisions on Articles 6.2 and 6.4, which involve international transfers of emission reductions. Links to these texts can be found below.

The draft decisions, which set out guidance on cooperative approaches referred to in Article 6, paragraph 2 of the Paris Agreement, are available at the following links:

- https://unfccc.int/documents/204687 (Third iteration, 15 December 2019)
- https://unfccc.int/documents/202115 (Second iteration, 14 December 2019)
  https://unfccc.int/documents/204639 (First iteration, 13 December 2019).

The rules, modalities and procedures for the mechanism established by Article 6, paragraph 4, of the Paris Agreement are available at the following links:

- https://unfccc.int/documents/204686 (Third iteration, 15 December 2019)
- https://unfccc.int/documents/201918 (Second iteration, 14 December 2019)
- https://unfccc.int/documents/204644 (First iteration, 13 December 2019).

A compilation of the main draft references to the crediting periods is provided below.

Article 6.2

Version 3

15 December 2019 at 00:50 hrs

1. Internationally transferred mitigation outcomes (ITMOs) from a cooperative approach are:

(e) Generated in respect of or representing mitigation from 2021 onwards;

17. Each participating Party shall ensure that the use of cooperative approaches does not lead to a net increase in emissions of participating Parties within and between NDC implementation periods and shall ensure transparency, accuracy, consistency, completeness and comparability in tracking progress in implementation and achievement of its NDC by applying the limits set out in further guidance by the CMA.

Version 2

14 December 2019 at 09:15 hrs

1. Internationally transferred mitigation outcomes (ITMOs) are:

(e) Generated in respect of or representing mitigation from 2021 onwards;

17. Each participating Party shall ensure that the use of cooperative approaches does not lead to a net increase in emissions of participating Parties within and between NDC implementation periods and shall ensure transparency, accuracy consistency, completeness and comparability in tracking progress in implementation and achievement of its NDC by applying the limits set out in further guidance by the CMA.

Version 1

13 December 2019 at 11:15 hrs

1. Internationally transferred mitigation outcomes (hereinafter referred to as ITMOs) are:

(e) Generated in respect of or representing mitigation from 2021 onwards;

17. Each participating Party shall ensure [that the use of cooperative approaches does not lead to a net increase in emissions within and between NDC implementation periods and shall ensure] transparency, accuracy consistency, completeness and comparability in tracking progress in implementation and achievement of its NDC by applying the limits set out in further guidance by the CMA.

Article 6.4.

Version 3

15 December 2019 at 1:10 hrs

27. A host Party may specify to the Supervisory Body, prior to participating in the mechanism:

(b) Crediting periods to be applied for Article 6, paragraph 4, activities that it intends to host, including whether the crediting periods may be renewed, subject to these rules, modalities and procedures and under the supervision of the Supervisory Body, and in accordance with further relevant decisions of the CMA, with an explanation of how those crediting periods are compatible with its NDC and its long-term low greenhouse gas (GHG) emission development strategy, if applicable;

31. The activity:

(f) Shall apply a crediting period for the issuance of A6.4ERs, that is a maximum of 5 years, renewable a maximum of twice, or a maximum of 10 years with no option of renewal, that is appropriate to the activity, and that is subject to approval by the Supervisory Body, or any shorter crediting period specified by the host Party pursuant to paragraph 27(b) above shall be applied. The crediting period shall not start before 2020.

53. The crediting period of a registered Article 6, paragraph 4, activity may be renewed in accordance with further relevant decisions of the CMA and relevant requirements adopted by the Supervisory Body, if the host Party has so approved in accordance with paragraph 39(b) above.

54. The renewal of a crediting period shall be approved by the Supervisory Body and the host Party following a technical assessment to determine necessary updates to the baseline, the additionality and the quantification of emission reductions.

Version 2

14 December 2019 at 9:00 hrs

27. [A host Party may specify to the Supervisory Body, prior to participating in the mechanism:

b) Crediting periods to be applied for Article 6, paragraph 4, activities that it intends to host, including whether the crediting periods may be renewed, subject to these rules, modalities and procedures and under the supervision of the Supervisory Body, and in accordance with further relevant decisions of the CMA, with an explanation of how those crediting periods are compatible with its NDC and its long-term low greenhouse gas (GHG) emission development strategy, if applicable;

32 The activity:

(f) Shall apply a crediting period for the issuance of A6.4ERs, that is a maximum of 5 years, renewable a maximum of twice, or a maximum of 10 years with no option of renewal, that is appropriate to the activity, and that is subject to approval by the Supervisory Body, or any shorter crediting period specified by the host Party pursuant to paragraph 27(b) above shall be applied. The crediting period shall not start before 2020.

48. The host Party shall provide to the Supervisory Body the approval of the activity prior to a request for registration. The approval shall include:

(b) The approval of any potential renewal, if the Party intends to allow the activity to continue to generate A6.4ERs beyond its first crediting period, where the Party has specified that the crediting periods of Article 6, paragraph 4, activities that it intends to host may be renewed pursuant to paragraph 27(b) above;

62. The crediting period of a registered Article 6, paragraph 4, activity may be renewed in accordance with further relevant decisions of the CMA and relevant requirements adopted by the Supervisory Body, if the host Party has so approved in accordance with paragraph 48(b) above.

63. The renewal of a crediting period shall be approved by the Supervisory Body and the host Party following a technical assessment to determine necessary updates to the baseline, the additionality and the quantification of emission reductions.

Version 1

13 December 2019 at 11:45 hrs

27. [A host Party may specify to the Supervisory Body, prior to participating in the mechanism:

(b) Crediting periods to be applied for Article 6, paragraph 4, activities that it intends to host, including whether the crediting periods may be renewed, subject to these rules, modalities and procedures and under the supervision of the Supervisory Body, and in accordance with further relevant decisions of the CMA, with an explanation of how those crediting periods are compatible with its NDC and its long-term low greenhouse gas emission development strategy, if applicable;

32. The activity:

(g) Shall apply a crediting period for the issuance of A6.4ERs, that is a maximum of 5 years, renewable a maximum of 2 times, or a maximum of 10 years with no option of renewal, that is appropriate to the activity, and that is subject to approval by the Supervisory Body[, or any shorter crediting period specified by the host Party pursuant to paragraph 27(b) above shall be applied]. The crediting period shall not start before 2020.

49. The host Party shall provide to the Supervisory Body the approval of the activity prior to a request for registration. The approval shall include:

(b) [The approval of any potential renewal, if the Party intends to allow the activity to continue to generate A6.4ERs beyond its first crediting period, where the Party has specified that the crediting periods of Article 6, paragraph 4, activities that it intends to host may be renewed pursuant to paragraph 27(b) above;]

66. The crediting period of a registered Article 6, paragraph 4, activity may be renewed in accordance with further relevant decisions of the CMA and relevant requirements adopted by the Supervisory Body[, if the host Party has so approved in accordance with paragraph 49(b) above].

67. [The renewal of a crediting period shall be approved by the Supervisory Body and the host Party following a technical assessment to determine necessary updates to the baseline, the additionality and the quantification of emission reductions.]

7. Requests the Subsidiary Body for Scientific and Technological Advice to develop, on the basis of the rules, modalities and procedures contained in the annex, recommendations on further elements to be included as an integral part of the rules, modalities and procedures, for consideration and adoption by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement at its third session (November 2020):

(a) Further elaboration of the rules of procedure of the Supervisory Body taking into account the recommendations of the Supervisory Body referred to in paragraph 6(a) above;

(b) Further consideration of the special circumstances of the least developed countries and small island developing States;

(c) Further responsibilities of the Supervisory Body and host Parties in order for host Parties to elaborate and apply national arrangements for the mechanism under the approval and supervision of the Supervisory Body;

(d) [Appropriate crediting periods for forestry and land use related activities];

9.10 Annex 10. Summary of the duration of the crediting period for offset programmes and voluntary markets

Table 9-16 Summary of the length of the crediting period for offset schemes and voluntary markets

Scope & Eligibility	Scope of activities	Temporal scope (crediting period duration)	Geographical eligibility	Sectoral eligibility
ACR	Projects	The standard crediting period is 10 years, except for AFOLU projects, renewal is possible	Worldwide, some sectors only United States	Fuel combustion, industrial processes, land use, land use change and forestry, carbon capture and storage, livestock, waste handling and disposal
AU CFI	Projects	The standard crediting period is 7 years, for reforestation and revegetation projects 15-years, for native forest protection projects 20 years.	Australia	Land and waste sector (CFI), the ERF is expanding the scope across the economy.
BC	Projects	The crediting period may be up to 25 years for sequestration projects and up to 10 years for other project types	British Columbia	All sectors, as long as it drives clean economic opportunities while cutting emissions
California	Projects	Non-sequestration 7 - 10 years, unless specified otherwise. Sequestration 10 - 30 years	California and Quebec	Sectors not covered under California's ETS
CDM	Projects and PoAs	7 years (20 years forestry) renewable up to 2 times or 10 years (30 years forestry) non-renewable	Developing countries (KP non-Annex B)	All except nuclear, some limits on forestry projects (only A/R allowed)
China	Projects	Same as CDM. Most schemes only allow for credits issued after 2013	Seven piloting regions allowing use of CCER. Most pilots restrict eligible credits to credits issued in the region	Varying between the seven piloting regions allowing use of CCER. Regulation allows trading activities of GHG emissions from CO_2, CH_4, N_2O, HFCs, PFCs, and SF. All pilots exclude credits from large hydropower projects
GIS	Any	Not defined	Developed countries (KP Annex B)	No explicit exclusions
GS	Projects and PoAs	Same as CDM.	Global	RE; EE; Industrial Waste handling and LULUCF
JCM	Projects	The crediting period for a JCM project is determined by the project lifetime	International JCM partner countries	No explicit exclusions
JI	Projects and PoAs	5 years (2008-2012)	Developed countries (KP Annex B)	All except nuclear
Ontario	Projects	Defined in each specific methodology, but up to 30 years for GHG sequestration initiatives and up to 10 years for non-sequestration initiatives.	Ontario	Sectors not covered under Ontario's ETS

Scope & Eligibility	Scope of activities	Temporal scope (crediting period duration)	Geographical eligibility	Sectoral eligibility
Quebec	Projects	10 years for manure and landfill projects. 5 years for ODS projects.	Quebec and California	Sectors not covered under Quebec's ETS
Spain	Projects	Up to 7 years	Mainly Spain, but open to international credits.	For the National Territory (sectors outside the EU-ETS). For International Territory EE, RE and waste management projects will be prioritized
Switzerland	Projects and PoAs	7 years (renewable for 3 years at a time after re-validation during the project life time)	Switzerland	All except for nuclear; CCS; R&D activities; Biofuels; Fuel switch to natural gas in transport and building sector
US (CAR)	Projects	Defined in each methodology. In general: 2 times 10 years for non-AFOLU projects. For AFOLU projects, crediting period may be 5 yrs x 3 (agriculture) and up to 100 yrs (forestry)	U.S. and Mexico	Sectors and Projects eligible under California's OP + Landfill gas, Livestock, Nitrogen and Organic waste in the US and Mexico
VCS	Projects and PoAs	Two times 10 years for non-AFOLU projects, 20-100 years for AFOLU projects, with renewal of baseline every 10 years.	Global	All CDM sectoral scopes

Source: compiled by the authors from (Michaelowa, Shishlov, Hoch, Bofill, & Espelage, 2019)

9.11 Annex 11. Selling green attributes in other markets (green premium)

Selling green or responsible products depends entirely on the process that was used to manufacture the product, if indeed it is possible to accredit and certify that the process was fully implemented, and whether both the MRV system and the commitments made by the company are in line with a recognised industry standard.

An example of such a standard is the **Responsible Steel Standard**, which includes the use of offsets only to mitigate steel companies' own actions and never mentions that a steel company may, or may not, sell such certificates. Furthermore, it states that to qualify under the standard, companies must establish a science-based emission-reduction pathway. It is worth questioning whether the methodologies for setting emission-reduction targets should include the sale or purchase of offsets in their calculation. The answer is that they do not. **Science-Based Targets** (SBT) state that neither the sale nor the purchase of offsets should count towards companies' emission-reduction targets.

In conclusion, it could be assumed that both markets are completely separate and that it is possible to participate in both markets with the same mitigation project, i.e. sell offsets and at the same time apply an added value premium to the price of a product by labelling it a green product. This could provide the project with additional income and further reduce the feasibility gap identified. However, a lack of definition both in the standards and in the Article 6 regulation suggests that in future there could be a pronouncement on such practices, prohibiting these double sales and undermining the project's development.

According to the GHG Protocol, offsets are reported in a project's Scope 4 and the purchase of a green product should be reported in Scope 3. The two are therefore seen as completely different products.

Background on green premium sales in the steel market

ArcelorMittal announced plans to market green steel under two 'standards':

● XCarb™ recycled and renewably produced: steel that is 100% recycled and 100% renewably produced. This is a low-carbon steel product.

● Certified XCarb™ Green Steel: steel from a decarbonised blast furnace.

'Green Steel' will be produced by ArcelorMittal plants in Europe using direct hydrogen reduction technologies or electric arc furnaces (EAF) to produce steel with electricity that can be certified as coming from renewable sources. The CO_2e savings from these measures will be aggregated, independently guaranteed and then converted into XCarb™ green steel certificates using a conversion factor representing the average CO_2e intensity of integrated steelmaking in Europe (ArcelorMittal S.A., 2021). The company expects to receive funding for these investments from EU ETS revenues.

ArcelorMittal is offering to sell green steel certificates to its customers, essentially bundling the CO_2e reduction attribute with its product. This would allow customers to report lower Scope 3 emissions. Presumably, if some customers do not want to pay the premium price for green steel, the company could sell the attributes elsewhere. Either they sell green steel (the steel product included with the green steel certificates) or they sell dirty steel and sell the associated attributes separately. Operating within this framework, it would not be possible to sell the green steel (through green steel certificates) and low-carbon attributes separately.

9.12 Annex 12. Climate financing instruments for case studies

There are different sources of climate financing in the cement, steel and mining industries that can mitigate the risks identified in the previous section. The proposed financing instruments follow a logic of bridging feasibility gaps, mitigating endogenous risks and identifying exogenous risks. The instruments can be grouped into two broad categories:

- private investment funds: equity and venture capital, concessional debt, contract for difference, technical assistance;
- public financing: equity, grants, guarantees, concessional debt, green bonds, technical assistance.

For the former, there are several venture capital funds (financed by international companies and philanthropists) which prioritise projects that reduce emissions. A selection of these instruments, relevant to projects in this report's three core industries, is presented in

Table 9-17.

With respect to public financing, there are institutions that provide debt or equity contributions (generally from public or philanthropic institutions) under more favourable conditions than those available in the market, improving the project's risk-return ratio. Given that Chile is no longer on the Official Development Assistance (ODA) list, there are currently few instruments available that can provide grants for the projects studied, especially those capable of closing the financing gap.

Table 9-18 identifies which public instruments are relevant to the industries in question. The Green Climate Fund (GCF) could be the most flexible and complete instrument when it comes to providing not only grants but also other financial instruments to mitigate project risks.

Table 9-17 Private investment funds

Entity	Relationship to the steel, cement and mining transport industries	Project size/investment	Types of financing	Additional notes/application process
Breakthrough Energy Ventures (BEV)	*Steel and cement:* BEV's Catalyst Program (currently under development) funds low-carbon technologies, including H2V, storage and carbon capture for the steel and cement industries. *Transport:* BEV includes transport as a prioritised investment sector, e.g. low-carbon fuel and fuel cells.	-Initial amount of USD 2 bn in total capital. -Previous rounds of investments of up to USD 30 m. -Long-term profitability outlook of 20 years.	-Venture capital -Concessional debt -Contract for Difference ('Green Premium')	-Fund launched in 2015, with first investments in 2018. -Fund invites projects to apply.
The Climate Pledge Fund (Amazon)	*Steel, cement, transport:* priority areas are manufacturing and materials, transport and logistics, as well as energy generation and storage, buildings and agriculture.	-Initial USD 2 bn in total capital -Diversity in project size, from funding start-ups to scaling up established companies.	-Venture capital	-Fund launched in June 2020, with several investments in startups shortly after. -Fund invites projects to apply.
Climate Innovation Fund (Microsoft)	*Steel, cement:* priority areas are industrial materials, plus advanced energy systems, circular economy, carbon capture.	USD 1 bn in total capital.	-Venture capital -Concessional debt	-Fund launched in 2020, with first investments shortly after. -Fund invites projects to apply, but there are open consultations as well.
Toyota Ventures Climate Fund	*Steel, cement and transport:* prioritises H2V projects; fund targets early-stage companies, including generation, storage and transport, plus renewable energy and carbon capture technologies.	USD 150 m for Climate Fund	-Venture capital	-Announced in June 2021. -Form for early-stage companies.
IDB Invest	*Transport:* clean energy projects financed with loans from IDB or multilateral banks. IDB Invest prioritises renewable energy, storage and transmission projects in LAC.	-IDB Invest: USD 13 bn in assets.	-Concessional debt	In Chile, a loan was created linked to the generation of offsets by Engie with the closure of its coal plants; the scheme would be replicable for other renewable energy projects in Chile.
FiveT Hydrogen Fund	*Transport:* investment priorities are H2V generation, storage and distribution assets, with a focus on large projects.	EUR 260 m raised; aims to raise a total of EUR 1 bn in capital.	-Capital	-Fund launched in 2021. -First round to close by the end of 2021, with first investments from 2022.
HydrogenOne Capital	*Steel, cement and transport:* priorities include H2V projects for transport and industry, as well as clean H2V generation, storage and distribution.	Aims to raise USD 315 m of capital in total.	-Capital	-Fund launched in 2020. -2021: raise capital, first round of investments pending. -Contact

Source: compiled by the authors

Table 9-18 Public funding

Entity	Relationship to the steel, cement and mining transport industries	Project size/investment	Types of financing	Additional notes/application process
Green Climate Fund (GCF) – Private Sector Facility	*Transport:* priority sectors are low-carbon transport, infrastructure and buildings, energy generation and access.	More than USD 2.2 bn of funds mobilised for private sector financing.	- Concessional debt - Equity - Guarantees - Grants	Application process
German Government/KfW	*Steel, cement and transport:* initiative to lay the groundwork for H2V imports from trading partners.	EUR 2 bn in funding for H2V projects abroad.	- Grants - Contracts for difference - Concessional debt	Financing (through Germany's H2Global initiative) will prioritise H2V exports to Germany and development of electrolyser technologies.
U.S. International Development Finance Corporation	*Steel, cement:* DFC is developing a platform to share risks with private sector partners and reduce barriers to climate projects. Focus on clean energy generation projects that reduce CO_2e emissions in emerging markets and enhance adaptation and resilience.	Financing of more than USD 50 m for projects, including energy.	- Guarantees - Concessional debt	- DFC prioritises projects in low and lower middle-income countries, but also supports projects in upper middle-income countries if the project addresses agency priorities (Chile previously received almost USD 1 bn in funding for NCRE projects). - Application process
Corporación de fomento de la producción (CORFO) (Production Development Corporation), Chile	*Steel, cement and transport:* will enable the energy transformation of the transport and industry sectors and open a new export market contributing to GHG reduction. It includes H2V production projects.	The call is for up to USD 50 m to domestic and foreign companies to finance and leverage one or more H2V projects in Chile. The contribution will cofinance a maximum of USD 30 m per project.	Grants	- Applications for the funds can be submitted up to 6 September 2021. One of the requirements is to have more than 600,000 UF (Chilean units of account) in annual sales. - Application process
Fundación Chile	*Steel, cement and transport:* the fund is aimed at Chilean companies that run profitable H2V projects.	USD 300 m fund to invest in H2V projects.	Venture capital	Aim is to invest in 12-15 companies and launch in 2022.
Competition for cofinancing of investment studies AGCID+UE	*Steel, cement and transport:* competition aimed at projects related to H2V; any related applications covering electricity generation, transport, heat in industrial processes or production of green inputs for industry; cofinancing for pre-investment studies of projects for the production, storage, transport and/or use of H2V.	Cofinancing contribution EUR 300,000.	Technical assistance	- Applicants must commit to cofinance their pre-investment studies. The applicant will be required to contribute at least 50% of the total cost of the pre-investment study. - Application process
Infrastructure Fund – country development	Fund for those entering the H2V sector.	Plans to raise USD 645 m.	Capital	Through a joint venture with private partners.. No launch date announced.
Green Hydrogen Accelerator – Agencia de Sostenibilidad Energética (ASE) or Energy Sustainability Agency	*Steel, cement and transport:* H2V projects; includes projects involving furnaces, boilers and buses transporting personnel.	The fund has CLP 300 m to distribute.	-Technical assistance	- ESA provides consultancy support during the first stage, and in the second stage applicants have access to the funds. - Application process

Source: compiled by the authors

Until H2V projects become profitable on a large scale, public funding and the involvement of concessional finance will be key to mobilising private capital. As both tables show, a variety of public and private entities offer concessional finance (e.g. Breakthrough Energy Ventures, international development agencies and multilateral banks). Other public and public-private entities in Chile offer grants (e.g. *CORFO*, *Fundación Chile*). Concessional finance is especially critical between the early stage and the bankability stage to improve the project's risk-return ratio and thus involve the private sector. If concessional resources are not injected, it is not possible to advance to the bankability stage. The tables below examine the instruments available for the three industries in question.

9.13 Annex 13. Factsheets for the three case studies

9.13.1 Cement

Basic Information	
Project name	Switching from fossil fuel to H2V at the Teno plant, Cementos Biobío.
Summary of the project activity (Briefly describe the project activity, the technologies used and how GHG reduction is achieved.)	The project activity consists of the manufacture of cement using H2V as an input to replace 10% of the energy requirement from petcoke. The production process consists of preparing the raw material and processing it in raw mills. Alongside the raw material preparation, hydrogen is produced using an electrolyser powered by a wind and solar plant and following storage and transport is then injected into the kiln. This process generates emissions from the fuel used to heat the kiln and from the chemical transformation of limestone into lime. Finally, the clinker is mixed with other additives and cement is produced. GHG reduction is achieved by replacing the fossil fuel with H2V in the clinker kiln.
Project location (Project location details)	Teno, Curicó Province, Maule Region.
Objective (Briefly describe the project objective.)	To trial a technology that has been little tested worldwide with a view to facilitating its adoption and the mitigation of greenhouse gases in the cement sector, a sector that is recognised as difficult to abate.
The project's contribution to national objectives, targets and/or plans (Please indicate how the project contributes to fulfilling national objectives and targets (e.g. NDC commitments) and to the implementation of climate change mitigation and/or adaptation plans (national, sectoral or other).)	- While the cement sector has not been linked to sectoral obligations that contribute to the NDC target, there is a contribution to the overall target of achieving a carbon-neutral scenario with emissions of 95 Mtonnes CO_2e by 2030, reaching a peak in 2025. - Contribution to the objective of the National Hydrogen Strategy - Alignment with the roadmap of the Inter-American Cement Federation (FICEM)
Estimated time frame (Please insert the estimated time frame for project implementation.)	A project lifetime of 20 years from 2030, with a crediting period of 15 years for certificate sales
Greenhouse gas (GHG) emission-reduction potential (Please insert the project's estimated GHG-reduction potential over the time frame, in tonnes CO_2e.)	710,260 tonnes CO_2e during the crediting period (15 years)

PROJECT BENEFITS AND IMPACTS

GHG reductions

Project activity (Please describe the project and the technologies that will be used.)	Fuel switch to a fuel with lower GHG intensity in replacement activities. In addition, H2V will be produced using a wind and solar-powered electrolyser. Includes storage, transport and use.
Methodology used or reference methodology (Please indicate the methodology used – either directly or as a reference – to calculate the project's emission reductions.)	The references were obtained from the Clean Development Mechanism (CDM) Methodology Booklet. Two references were adapted: Switching fossil fuels (AMS-III.B) and Fossil fuel switch in manufacturing industries (AMS-III.AN).
Main sources of GHG emissions (Please describe the main sources of project-related GHG emissions.	Emissions are generated in the kiln during clinker production and will change when the project replaces a percentage of petcoke with hydrogen.
Greenhouse gas(es) reduced (Please indicate the greenhouse gases included in the emissions calculation. Include only CO_2 by default and include other gases only if relevant and a conservative assumption.)	The emission factor is in units of CO_2e, so kg CO_2, kg CH_4 and kg NO_2 are included.
Baseline scenario (Please indicate and briefly explain which baseline scenario is used when calculating the emission reduction.)	The baseline scenario corresponds to the kiln operating using only fossil fuels and alternative fuels for cement production. Incremental co-processing penetration is considered to reach 30% by 2030 (sectoral target).
Baseline emissions (Please provide an estimate of GHG emissions in the baseline scenario over the project's lifetime (add as many rows as necessary). Please provide an annex with a description of the methodology followed to estimate the baseline GHG emissions.)	5,044,462 tonnes CO_2e total
Project scenario (Please indicate and briefly explain which project scenario is used when calculating the emission reduction.)	The project scenario consists of the renewable energy-based production, storage and transport of hydrogen to be injected into the clinker furnace by replacing 10% of the petcoke consumed in the clinker furnace with H2V to produce the clinker mixture.
Project emissions (Please provide an estimate of the GHG emissions in the project scenario over the project's lifetime (add as many rows as necessary). Please provide an annex with a description of the methodology used to estimate the project's GHG emissions.)	4,334,202 tCO_2e total

GHG emission-reduction estimate (Please provide an estimate of the GHG emission reduction (at project level) over the project's lifetime. Add as many rows as necessary.)

Year	Annual GHG emission reduction (tonnes CO_2e/year)	Cumulative GHG emission reduction (tonnes CO_2)
Year 1	48,093	48,093
Year 2	47,987	96,080
Year 3	47,881	143,962
Year 4	47,775	191,737
Year 5	47,669	239,405
Year 6	47,563	286,968
Year 7	47,457	334,425
Year 8	47,351	381,776
Year 9	47,245	429,020
Year 10	47,138	476,159
Year 11	47,032	523,191
Year 12	46,926	570,117
Year 13	46,820	616,938
Year 14	46,714	663,652
Year 15	46,608	710,260

Co-benefits

	Sustainable Development Goal	Contribution of the project activity
Contribution of the project activity to the Sustainable Development Goals (SDGs) (Please indicate how the project activity contributes to achieving the SDGs. Add as many rows as necessary.)	Goal 13: Take urgent action to combat climate change and its impacts	Replacing petcoke with H2V leads to a reduction in GHG emissions, i.e. it is a way of combating climate change.
	Goal 8: Decent work and economic growth	Using NCRE to create H_2, and then injecting that into the system, stimulates sustainable economic growth by increasing productivity levels and technological innovation. It also fosters job creation in replacement and retrofitting.

9.13.2 Steel

Basic Information	
Project name	Compañía Siderúrgica Huachipato S.A.
Summary of the project activity (Briefly describe the project activity, the technologies used and how GHG reduction is achieved.)	The project consists of the manufacture of steel and production of green hydrogen for injection into the blast furnace tuyeres. The hydrogen is produced in an electrolyser, powered by electricity produced by wind and solar energy. It is then stored and transported. Alongside this, metallurgical coal is put through a dry distillation process to obtain coke. A gas with a high calorific value is obtained as a by-product and is reused. Coke combustion takes place in the blast furnace, where, unlike the baseline case, green hydrogen can be used as a reducing agent and as a source of heat. It is used to replace a percentage of the coke and reduce the iron ore to obtain liquid iron or pig iron. The pig iron is then refined by injecting oxygen, and scrap and ferroalloys are added to obtain the different types of steel.
Project location (Project location details.)	Bahía San Vicente, Talcahuano, Biobío Region.
Objective (Briefly describe the project objective.)	To trial a technology that has been little tested worldwide with a view to facilitating its adoption and the mitigation of greenhouse gases in the steel sector, a sector that is recognised as difficult to abate.
The project's contribution to national objectives, targets and/or plans (Please indicate how the project contributes to fulfilling national objectives and targets (e.g. NDC commitments), and to the implementation of climate change mitigation and/or adaptation plans (national, sectoral or other).)	Although the steel sector has not, in principle, been specifically considered for sectoral obligations that contribute to the NDC target, there is a contribution to the overall goal of reaching a carbon-neutral scenario with emissions of 95 Mtonnes CO_2e by 2030, reaching a peak in 2025. Contribution to the objective of the National Hydrogen Strategy.
Estimated time frame (Please insert the estimated time frame for project implementation.)	A project lifetime of 20 years from 2030, with a crediting period of 15 years for certificate sales.
Greenhouse gas (GHG) emission-reduction potential (Please insert the project's estimated GHG-reduction potential over the time frame, in tonnes CO_2e.)	4,171,357 tonnes CO_2e total

PROJECT BENEFITS AND IMPACTS	
GHG reductions	
Project activity (Please describe the project and the technologies that will be used.)	The mitigation actions involve replacing a fossil fuel with H2V, i.e. switching to a fuel with lower emissions intensity. In addition, the H2V will be produced by means of an electrolyser powered by wind and solar energy. Includes storage, transport and use.
Methodology used or reference methodology (Please indicate the methodology used – either directly or as a reference – to calculate the project's emission reductions.)	The references were obtained from the Clean Development Mechanism (CDM) Methodology Booklet. Three references were adapted: Switching fossil fuels (AMS-III.B), Fossil fuel switch in manufacturing industries (AMS-III.AN) and Use of charcoal from planted renewable biomass in the iron ore reduction process through the establishment of a new iron ore reduction system (AM0082).
Main sources of GHG emissions (Please describe the main sources of project-related GHG emissions.)	The most emission-intensive process is the blast furnace when reducing iron ore. This process will replace a percentage of coke by H2V and reduce emissions.
Greenhouse gas(es) reduced (Please indicate the greenhouse gases included in the emissions calculation. Include only CO_2 by default and include other gases only if relevant and a conservative assumption.)	The emission factor is in units of CO_2e, so kg CO_2, kg CH_4 and kg NO_2 are included.
Baseline scenario (Please indicate and briefly explain which baseline scenario is used to calculate the emission reduction.)	The baseline scenario consists of steel production exclusively using fossil fuels, specifically coke. This practice is common in Chile, as the only integrated steelwork in the country is CAP Acero, which uses this production process, which is 'much more emission-intensive, due to the coke plant and the reduction of iron ore to transform it into pig iron' (GIZ, 2018a).
Baseline emissions (Please provide an estimate of GHG emissions in the baseline scenario over the project's lifetime (add as many rows as necessary). Please provide an annex with a description of the methodology followed to estimate the baseline GHG emissions.)	20,555,529 tonnes CO_2e total
Project scenario (Please indicate and briefly explain which project scenario is used to calculate the emission reduction.)	The project scenario consists of hydrogen production using electrolysis based on wind and solar power generation, then storing and transporting the hydrogen through the upper tuyeres of the blast furnace in the integrated process with a fixed percentage of coke replaced.
Project emissions (Please provide an estimate of the GHG emissions in the project scenario over the project's lifetime (add as many rows as necessary.) Please provide an annex with a description of the methodology used to estimate the project's GHG emissions.)	16,086,218 tonnes CO_2e total

GHG emission-reduction estimate
(Please provide an estimate of the GHG emission reduction (at project level) over the project's lifetime. Add as many rows as necessary.)

Year	Annual GHG emission reduction (tonnes CO_2e/year)	Cumulative GHG emission reduction (tonnes CO_2)
Year 1	297,954	297,954
Year 2	297,954	595,908
Year 3	297,954	893,862
Year 4	297,954	1,191,816
Year 5	297,954	1,489,770
Year 6	297,954	1,787,724
Year 7	297,954	2,085,678
Year 8	297,954	2,383,633
Year 9	297,954	2,681,587
Year 10	297,954	2,979,541
Year 11	297,954	3,277,495
Year 12	297,954	3,575,449
Year 13	297,954	3,873,403
Year 14	297,954	4,171,357

Co-benefits

Contribution of the project activity to the Sustainable Development Goals (SDGs)
(Please indicate how the project activity contributes to achieving the SDGs. Add as many rows as necessary.)

Sustainable Development Goal	Contribution of the project activity
Goal 13: Take urgent action to combat climate change and its impacts	Replacing the coke in the blast furnace with H2V leads to a reduction in GHG emissions, i.e. it is a way of combating climate change.
Goal 8: Decent work and economic growth	Using NCRE to create H_2 and then injecting that into the system stimulates sustainable economic growth by increasing productivity and technological innovation. It also fosters job creation in replacement and retrofitting.

9.13.3 Mining

Basic information	
Project name	Transporting mining industry personnel
Summary of the project activity (Briefly describe the project activity, the technologies used and how the GHG reduction is achieved.)	The project activity consists of replacing 10 buses that have diesel engines with buses running on H2V fuel cells. The replacement is evaluated based on the case study of Compañía Minera del Pacífico (CMP) and its transport of passengers from the mine in Copiapó to its operations at the Cerro Negro Norte mine. The hydrogen would be produced by an electrolyser, which would be powered by hybrid energy (solar and wind) sources, thus achieving a reduction in GHGs and anticipated sales of certified emission reductions.
Project location (Project location details.)	From Copiapó to Minera Cerro Negro Norte, Atacama Region.
Objective (Briefly describe the project's objective.)	The project's objective is to replace the diesel buses with electric buses using H2V cells and thus gain experience of replacing diesel and using H2V in the transport sector.
The project's contribution to national objectives, targets and/or plans (Please indicate how the project contributes to fulfilling national objectives and targets (e.g. NDC commitments), and to implementing climate change mitigation and/or adaptation plans (national, sectoral or other).)	- Contribution to the overall goal of achieving a carbon-neutral scenario with emissions of 95 M tonnes CO_2e by 2030, reaching a peak in 2025. - Contribution to the carbon neutrality scenario in the NDC by 2050 with 12% hydrogen use in transport in industry and mining. - Contribution to the objective of the National Hydrogen Strategy.
Estimated time frame (Please insert the estimated time frame for project implementation.)	A project lifetime of 20 years from 2030 is considered, with a crediting period of 15 years for certificate sales.
Greenhouse gas (GHG) emission-reduction potential (Please insert the project's estimated GHG-reduction potential over the time frame, in tonnes CO_2e.)	7,987 tonnes CO_2e total

PROJECT BENEFITS AND IMPACTS

GHG reductions

Project activity (Please describe the project and the technologies that will be used.)	There are two types of mitigation actions, fuel switching and displacing more GHG-intensive vehicles used for passenger transport on routes with comparable conditions.
Methodology used or reference methodology (Please indicate the methodology used – either directly or as a reference – to calculate the project's emission reductions.)	The references were obtained from the Clean Development Mechanism (CDM) Methodology Booklet. Two references: Introduction of LNG buses to existing and new bus routes (AMS-III.AY) and Introduction and operation of new less-greenhouse-gas-emitting vehicles (e.g. CNG, LPG, electric or hybrid) for commercial passengers and freight transport, operating on routes with comparable conditions. Retrofitting of existing vehicles is also applicable (AMS-III.S).
Main sources of GHG emissions (Please describe the main sources of project-related GHG emissions.)	The emissions to be addressed come from the exhaust gases of the internal combustion engines in the bus fleet.
Greenhouse gas(es) reduced (Please indicate the greenhouse gases included in the emissions calculation. Include only CO_2 by default and include other gases only if relevant and a conservative assumption.)	The emission factor is in units of CO_2e, so kg CO_2, kg CH_4 and kg NO_2 are included.
Baseline scenario (Please indicate and briefly explain which baseline scenario is used to calculate the emission reduction.)	The baseline scenario represents the diesel bus fleet and current commitments on electromobility in Chile's NDCs. These commitments involve a 21% replacement of the fleet with electric buses by 2050. This fleet currently consists of 10 diesel buses, which cover 150 kilometres per day. In addition, according to the national decarbonisation plan, a decreasing emission factor is considered for the electricity grid over time.
Baseline emissions (Please provide an estimate of GHG emissions in the baseline scenario over the project's lifetime (add as many rows as necessary). Please provide an annex with a description of the methodology followed to estimate the baseline GHG emissions.)	7,719 tonnes CO_2e total
Project scenario (Please indicate and briefly explain which project scenario is used to calculate the emission reduction.)	The project scenario consists of hydrogen production using electrolysis. The electrolyser will run on wind and solar energy. The green hydrogen produced will be stored and subsequently used in the fuel cell buses.
Project emissions (Please provide an estimate of the GHG emissions in the project scenario over the project's lifetime (add as many rows as necessary.) Please provide an annex with a description of the methodology used to estimate the project GHG emissions.)	0 tonnes CO_2e total, as for the stated case study framework, corresponding to replacing 10 diesel buses by H2V buses. No GHG would be emitted either in the production of H2, or in the use of H_2 in the buses

GHG emission-reduction estimate
(Please provide an estimate of the GHG emission reductions (at project level) over the project's lifetime. Add as many rows as necessary.)

Year	Annual GHG emission reduction (tonnes CO_2e/year)	Cumulative GHG emission reduction (tonnes CO_2)
Year 1	550	550
Year 2	550	1,100
Year 3	550	1,651
Year 4	550	2,201
Year 5	550	2,751
Year 6	498	3,249
Year 7	498	3,747
Year 8	497	4,244
Year 9	497	4,741
Year 10	497	5,238
Year 11	497	5,735
Year 12	496	6,231
Year 13	496	6,727
Year 14	496	7,223
Year 15	496	7,719

Co-benefits

Contribution of the project activity to the Sustainable Development Goals (SDGs)
(Please indicate how the project activity contributes to achieving the SDGs. Add as many rows as necessary.)

Sustainable Development Goal	Contribution of the project activity
Goal 13: Take urgent action to combat climate change and its impacts	Replacing diesel with green hydrogen leads to a reduction in GHG emissions, i.e. it is a way of combating climate change. The comparison is between a baseline of 21% electric buses and replacement of the fleet with hydrogen buses.
Objective 8: Decent work and economic growth	Using NCRE to create H_2 and then using that to operate the buses stimulates sustainable economic growth by increasing productivity and technological innovation. It also fosters job creation in replacement and retrofitting.