

# Optimization of Private Equity Investments for Industrial Carbon Emission Reduction

by

Peter Jacobson

B.S., Chemical Engineering  
Yale University, 2014

Submitted to the MIT Sloan School of Management and  
Department of Civil and Environmental Engineering  
in partial fulfillment of the requirements for the degrees of  
Master of Business Administration

and

Master of Science in Civil and Environmental Engineering  
in conjunction with the Leaders for Global Operations program  
at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2023

© Peter Jacobson, 2023. All rights reserved.

The author hereby grants to MIT a nonexclusive, worldwide, irrevocable, royalty-free license to exercise any and all rights under copyright, including to reproduce, preserve, distribute and publicly display copies of the thesis, or release the thesis under an open-access license.

Author .....  
MIT Sloan School of Management and  
Department of Civil and Environmental Engineering  
May 12, 2023

Certified by .....  
Jason Jay, Thesis Supervisor  
Senior Lecturer and Director, Sustainability Initiative at MIT Sloan

Certified by .....  
Saurabh Amin, Thesis Supervisor  
Professor of Civil and Environmental Engineering

Accepted by .....  
Maura Herson  
Assistant Dean, MBA Program, MIT Sloan School of Management

Accepted by .....  
Colette Heald  
Graduate Program Committee, Professor of Civil and Environmental Engineering



# Optimization of Private Equity Investments for Industrial Carbon Emission Reduction

by

Peter Jacobson

Submitted to the MIT Sloan School of Management and  
Department of Civil and Environmental Engineering  
on May 12, 2023, in partial fulfillment of the  
requirements for the degrees of  
Master of Business Administration  
and  
Master of Science in Civil and Environmental Engineering

## Abstract

Industrial businesses are responsible for a significant portion of global greenhouse gas emissions. They must reduce these emissions due to financial, regulatory, and customer pressures, but the pathways to net zero emissions are complex and costly. For companies held by private equity, the inaction is exacerbated by a lack of clarity on how emissions reduction initiatives influence investment returns. This research presents a carbon footprint calculator and an optimization model to analyze emissions reduction projects. We highlight that using these two tools as part of a strategic framework can help manufacturing companies create actionable and profitable emission reduction strategies. The carbon footprint calculator identifies a company's carbon emission sources and measures its carbon footprint, while the optimization model determines the most profitable investments to meet emissions goals. For our optimization, we use an integer linear programming model that schedules which furnace upgrades to implement each year, with an objective of minimizing total cost to the business. Our results highlight that ancillary process line benefits from furnace upgrades can significantly increase profitability of emissions reduction projects. We also show that, in the absence of new technology, there will need to be a combination of cleaner electricity and carbon pricing for manufacturing companies to profitably meet science-based emissions reduction goals.

Thesis Supervisor: Jason Jay

Title: Senior Lecturer and Director, Sustainability Initiative at MIT Sloan

Thesis Supervisor: Saurabh Amin

Title: Professor of Civil and Environmental Engineering



## Acknowledgments

I would like to thank the teams from Molycop and American Industrial Partners for their support of this project. From Molycop, Paul Griffiths, Ian Tooze, and Steve Ornduff, especially, were instrumental in the success of this project and unquestioning in their contribution of resources and time. This project would not have happened without Lee Evangelakos from American Industrial Partners, and it certainly would not have been as smooth or enjoyable without her undivided attention, advice, and endless assistance.

I would also like to thank my MIT management advisor, Jason Jay, and MIT engineering advisor, Saurabh Amin. They were always available to answer questions, and provided much needed guidance on which paths to take on my thesis journey.

Finally, a special thank you to my family for their loving support during my time at MIT.

THIS PAGE INTENTIONALLY LEFT BLANK

# Contents

<b>List of Figures</b>	<b>9</b>
<b>List of Tables</b>	<b>11</b>
<b>Acronyms</b>	<b>13</b>
<b>1 Introduction</b>	<b>15</b>
1.1 ESG in Private Equity . . . . .	16
1.2 Carbon Accounting and Management . . . . .	18
1.3 Optimization Methods . . . . .	20
1.4 Problem Statement and Summary . . . . .	21
<b>2 Methods</b>	<b>23</b>
2.1 Company Background . . . . .	23
2.1.1 American Industrial Partners . . . . .	23
2.1.2 Molycop . . . . .	25
2.2 Data . . . . .	28
2.2.1 Data Sources . . . . .	28
2.2.2 Data Availability . . . . .	31
2.3 Project Approach . . . . .	31
2.4 Carbon Footprint Calculator . . . . .	33
2.4.1 Molycop Value Chain Emissions . . . . .	33
2.4.2 Model Formulation . . . . .	34
2.5 Emission Reduction Optimization . . . . .	36

2.5.1	Emissions Reduction Measures . . . . .	36
2.5.2	Model Formulation . . . . .	38
2.6	Strategic Framework . . . . .	41
<b>3</b>	<b>Results</b>	<b>43</b>
3.1	Carbon Footprint Calculator . . . . .	43
3.2	Emission Reduction Model . . . . .	45
3.2.1	Overview of Emissions Results . . . . .	47
3.2.2	Overview of Financial Results . . . . .	50
3.2.3	Results by Scenario . . . . .	52
3.3	Final Decisions . . . . .	59
<b>4</b>	<b>Conclusions</b>	<b>61</b>
<b>A</b>	<b>Tables</b>	<b>65</b>
<b>B</b>	<b>Figures</b>	<b>71</b>

# List of Figures

1-1	Overview of GHG emission scopes. Source: EPA . . . . .	19
2-1	Stylized process diagram showing material flow for steel . . . . .	26
2-2	Overview of project approach . . . . .	32
2-3	View of the Emissions Calculator Front End . . . . .	36
3-1	Molycop Absolute Emissions and Emissions Intensity by Country . . . . .	44
3-2	Projections for Corporate Annual Absolute Emissions . . . . .	46
3-3	Optimization model results showing annual absolute Scope 1 & 2 emissions from furnaces . . . . .	48
3-4	Optimization model results showing annual operating plus capital costs of furnaces . . . . .	51
B-1	Example process furnaces . . . . .	72
B-2	Example of any oxygen lance installation for oxy-fuel technology. Source: Linde . . . . .	73
B-3	Comparison of Air vs. Oxygen Combustion. Source: Linde . . . . .	74
B-4	The recuperator used in Molycop’s USA plant . . . . .	75

THIS PAGE INTENTIONALLY LEFT BLANK

# List of Tables

2.1	Molycop plant locations . . . . .	25
2.2	Variable notation used for carbon footprint model formulation . . . . .	34
2.3	Variable notation used for optimization model formulation . . . . .	39
3.1	Example emissions intensities plus supply chain and production characteristics for Molycop products . . . . .	45
3.2	Emissions results for all scenarios, as compared to 2022 baseline year	47
3.3	Emissions and financial results for all scenarios, as compared to 2022 baseline . . . . .	50
3.4	Model decisions for furnace decarbonization projects for every scenario. EF = efficiency upgrade, OF = oxygen fuel, ELE = electrification . . . . .	53
3.5	Scenario 1 results for emissions reduction plus annual and cumulative operating and capital costs . . . . .	54
3.6	Scenario 2 results for emissions reduction plus annual and cumulative operating and capital costs . . . . .	55
3.7	Scenario 3a results for emissions reduction plus annual and cumulative operating and capital costs . . . . .	56
3.8	Scenario 3b results for emissions reduction plus annual and cumulative operating and capital costs . . . . .	57
3.9	Scenario 4a results for emissions reduction plus annual and cumulative operating and capital costs . . . . .	58
3.10	Scenario 4b results for emissions reduction plus annual and cumulative operating and capital costs . . . . .	59

A.1	List of Molycop process furnaces . . . . .	66
A.2	Gas usage reduction percentages for each furnace from each decarbonization project type . . . . .	67
A.3	Capital expenditure values used for each furnace from each decarbonization project type . . . . .	68
A.4	Values of emissions factors used in analysis . . . . .	69

# Acronyms

**AIP** American Industrial Partners. 23

**EBITDA** Earnings before interest, taxes, depreciation, amortization. 24

**ESG** Environmental, Social, Governance. 15, 24, 61

**GHG** Greenhouse gas. 33

**PPA** Power purchase agreements. 45, 46

THIS PAGE INTENTIONALLY LEFT BLANK

# Chapter 1

## Introduction

The world emits approximately 50 gigatons of greenhouse gas emissions per year, contributing to global temperature increase.<sup>1</sup> We need to limit this temperature increase to 1.5°C above pre-industrial levels to avert the worst impacts of climate change. This requires urgent, accelerated, and significant capital deployment to invest in the solutions that will reduce emissions by 45% by 2030 and reach net zero by 2050.<sup>2</sup> Much of this capital deployment needs to be directed to private firms, but a lack of clarity in the value of investments and how financial returns align with environmental performance has hampered the level of investment needed from private companies and their private equity (PE) owners.

PE firms have seen increasing pressure to measure, report, and reduce the carbon footprint of their portfolios as the global investment community becomes more aware of the disastrous consequences of climate change. For many reasons, it is important to study how private equity firms operationalize carbon emission reduction strategies to meet their climate change and Environmental, Social, Governance (ESG) goals. PE firms face less regulatory scrutiny than public companies and have fewer disclosure requirements, but continue to attract more global institutional investors that require ESG-related performance disclosures. PE firms also have large, if not controlling, ownership in private companies and have significant influence over management

---

<sup>1</sup><https://ourworldindata.org/greenhouse-gas-emissions>

<sup>2</sup><https://www.un.org/en/climatechange/net-zero-coalition>

practices as they relate to ESG goals (e.g., Abraham, Olbert, and Vasvari [1], Cohen, Kadach, and Ormazabal [5]). As private equity continues to grow and manage more assets, it becomes even more critical to ensure the industry uses well-understood tools, processes, standards, and strategies that accomplish their environmental and financial goals. We focus on the development of tools to help operationalize carbon reduction strategies for privately held manufacturing companies, due to the increasing importance of sustainability within their industries and within the private equity investment community.

## 1.1 ESG in Private Equity

The incorporation of ESG factors into public equity (as opposed to private equity) is better understood. In 2022, there were \$66.6 trillion of U.S. professionally managed assets, of which \$8.4 trillion were sustainable investing assets that had clear ESG incorporation. The three leading issues by number of shareholder proposals filed were labor and equal employment opportunity, corporate political activity, and climate change.<sup>3</sup> Even though less understood, ESG factors increasingly influence corporate management in private equity as well.

As Abraham, Olbert, and Vasvari [1] describe, the PE industry's economic influence continues to grow. Assets under management (AUM) in global PE funds have increased over the past decade at a rate of about 10% per year, reaching over \$5tn at the end of 2021. Forecasts indicate it could nearly double by 2025.<sup>4</sup> Although ESG factors are increasingly incorporated into PE investment strategies, it can be unclear why PE firms include ESG, how they include ESG considerations, the details of their ESG activities, which tools they use, and which barriers they face. To combat this opacity, many standards, networks, and organizations have been created. For example, the UN PRI (Principles for Responsible Investment) was created "to understand the investment implications of environmental, social and governance (ESG) factors [and]

---

<sup>3</sup><https://www.ussif.org/fastfacts>

<sup>4</sup>Economist, 2020

to support its international network of investor signatories in incorporating these factors into their investment and ownership decisions." As of 2022, the UN PRI had a total of 4,902 signatories, with an estimated total AUM of US\$121.3 trillion.<sup>5</sup>

Zaccone and Pedrini [23] performed a qualitative and quantitative research study on ESG in private equity because, as they note, ESG factor integration has largely been investigated as a driver of corporate performance [7] but few studies have examined ESG factor integration into PE activities. The study found that PE firms use checklists to assess ESG factors, only a few use external advice from industry experts, and many lack a comprehensive way to measure ESG issues. The study identifies two main private equity approaches to ESG integration. They are risk management and value creation, and the former is more dominant. This suggests that PE firms tend to identify the minimum levels of ESG integration that protects their portfolios from risks, but that there is opportunity for PE firms to more purposefully consider the value creation opportunities related to ESG. Without clear evidence of the relationship between environmental performance and financial outcomes, private asset managers will not invest in decarbonization initiatives at the potential expense of maximizing returns for their investors.

This lack of action continues even as it becomes riskier to emit. In 2022, carbon pricing initiatives in 70 global jurisdictions covered 11.86 GtCO<sub>2</sub>e of emissions, representing 23% of global emissions. In 2005, there were carbon pricing initiatives in only nine global jurisdictions, showing that carbon pricing is having an accelerated impact on the economy.<sup>67</sup> In the United States, the Inflation Reduction Act includes a price on methane emissions, which should affect the price of natural gas across the US.<sup>8</sup> It is not hard to envision a future business environment where carbon pricing will increase cost of doing business or reduce profitability, premium pricing will be available in the markets for lower carbon product offerings, reduction targets will be a prerequisite to bid participation, and access to credit markets and cost of capital will be influenced

---

<sup>5</sup><https://www.unpri.org/about-us/about-the-pri>

<sup>6</sup><https://carbonpricingdashboard.worldbank.org>

<sup>7</sup><https://icapcarbonaction.com/en/ets>

<sup>8</sup><https://processecology.com/articles/the-introduction-of-methane-pricing-in-the-us-inflation-reduction-act>

by a company's decarbonization performance. Thus, private companies - and the private equity firms that invest in them - need to create sustainability strategies, set commitments, and invest in projects that reduce emissions and improve their competitive positioning in the marketplace.

To better connect the environmental metrics of ESG, their relationship to climate change, and influence on potential value creation and financial performance for a company, private equity firms must use tools and processes that accurately and sufficiently account for and manage carbon emissions.

## 1.2 Carbon Accounting and Management

The Greenhouse Gas Protocol is the most frequently used method for carbon accounting due to its extensive methodology and granularity across 15 different categories in a company's value chain (Mulrow et al. [18]). The standard outlines a framework for measuring and reporting emissions by categorizing the 15 categories into three broader "scopes."

- Scope 1 emissions are direct greenhouse (GHG) emissions that occur from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in boilers, furnaces, vehicles).
- Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling. Although scope 2 emissions do not physically occur at the facility where they are generated, they are accounted for in an organization's GHG inventory because they are a result of the organization's energy use <sup>9</sup>
- Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly impacts in its value chain. Scope 3 emissions include all sources not within an organization's scope 1 and 2 boundary <sup>10</sup>

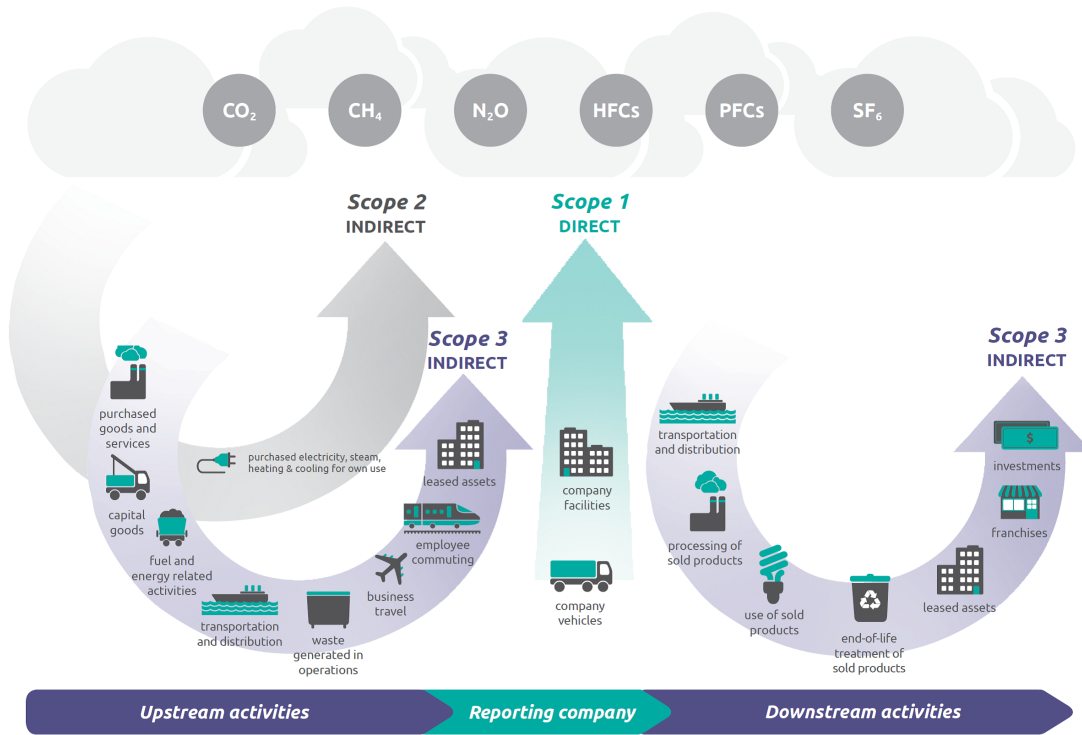
---

<sup>9</sup><https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance>

<sup>10</sup><https://www.epa.gov/climateleadership/scope-3-inventory>

The sources of emissions within each scope are shown in Figure 1-1.

Figure 1-1: Overview of GHG emission scopes. Source: EPA



Carbon management refers to the company practices used to mitigate CO<sub>2</sub> emissions. As He et al. [10] note, firms use various carbon accounting techniques to help managers collect and record carbon-related information (Burritt, Schaltegger, and Zvezdov [4]; Gibassier and Schaltegger [8]), evaluate performance (Lee and Wu [14]), perform green investment and project management (Vesty, Telgenkamp, and Roscoe [21], implement carbon strategies (Bui and Fowler [3]), conduct emissions trading (Engels [6]), manage exposure to risk (Kumarasiri and Gunasekarage [13]), control carbon costs (Ratnatunga and Balachandran [19]), and assist in adapting to climate change (Linnenluecke, Birt, and Griffiths [16]). The literature on carbon management shows how appropriate accounting practices can contribute to better carbon reduction outcomes. Various processes such as data collection, reporting, performance assessment, risk analysis, and target setting are integrated into carbon management frameworks that enhance the abilities of firms to manage challenges brought on by greenhouse gas

emissions. These standards and processes are well-established and widely available, but companies must also have the correct tools to analyze different carbon reduction pathways and find the optimal investment strategy for their circumstances. For this, we turn our focus to the availability of optimization methods to determine strategies that meet corporate environmental goals and maximize financial performance.

### 1.3 Optimization Methods

The development of optimization models to determine CO2 emission reduction strategies is a growing field of research. Many papers delve into energy conservation, renewable energy use, CO2 emission reduction, and financial profitability across multiple sectors.

The built environment is an oft researched sector. For example, Lin et al. [15] developed an algorithm to reduce building construction costs and CO2 emissions based on optimal building envelope design and air conditioning configuration. Jeong et al. [12] focus on multi-family housing and analyze four energy savings measures to determine the optimal CO2 reduction strategy while considering initial investment costs and savings. There are also papers that study power generation, since it is a large source of emissions and there are many opportunities to decarbonize. Hashim et al. [9] consider the problem of reducing CO2 emissions from a power grid consisting of coal, natural gas, nuclear, hydroelectric, and alternative energy plants.

Within the manufacturing industry, there are studies on how to optimize the most energy-intensive industrial processes. Both Hongming et al., [11] and Weijian et al. [22] offer carbon reduction analyses of iron and steel manufacturing processes. Shamsi et al. [20] developed a mathematical model for finding the optimal sizing of renewable energy technologies to achieve CO2 emission reduction targets for a manufacturing facility. However, this was for a facility that uses a combined heat and power plant for its electricity, whereas most manufacturing facilities rely on whatever electricity feed they get from the local utility.

Although similar in scope to our research question, none of these studies focus on

how to make profitable investment decisions for CO<sub>2</sub> emission reduction of industrial furnaces while also considering the process constraints and technology co-benefits. Industrial heating from furnaces is a large carbon emitter, accounting for 9% of the United States emissions footprint.<sup>11</sup> To accomplish this, the optimization algorithm would have to consider multiple technologies and include the additional costs and cost savings from process benefits such as throughput improvement and waste reduction.

## 1.4 Problem Statement and Summary

PE shops that invest in manufacturing and industrial companies have a more difficult environmental challenge because their investments are generally more emissions-intensive due to the complex supply chains and energy-intensive operations of the companies. The lack of universally adopted tools that connect investment decisions and management practices to emissions reductions and value creation leads to a lack of clarity for management and PE investors to take action on climate change. Specifically, successfully operating manufacturing lines is crucial for an industrial company's profitability, and the effects on value creation from emissions reduction investments for manufacturing processes are not well understood. This may lead to insufficient private capital deployment for global decarbonization goals.

In our study, we use well-established frameworks for carbon accounting and carbon management to calculate a corporate carbon footprint and product carbon footprint (which we call the Carbon Footprint Calculator). There are also a growing number of studies that utilize optimization algorithms for optimal CO<sub>2</sub> emission reduction decisions, but - beyond steel-making - more research can be done to study how manufacturing process characteristics influence industrial heating decarbonization. Thus, we focus on industrial process furnaces for our emission reduction research. We contribute an integer linear program that finds the most profitable strategy to reduce CO<sub>2</sub> emissions in process furnaces by scheduling furnace upgrades each year within

---

<sup>11</sup><https://www.energy.gov/articles/doe-launches-new-energy-earthshot-cut-industrial-heating-emissions-85-percent>

the planning horizon (which we call the Emission Reduction Model). The model is based on certain emission reduction technologies, fuel and carbon pricing, and process characteristics, and the results are determined by financial constraints such as annual budget. For clarity, the methods in Chapter 2 and results in Chapter 3 are broken out between the Carbon Footprint Calculator and the Emission Reduction Model.

# Chapter 2

## Methods

This research study was completed for American Industrial Partners (AIP), a private equity (PE) firm. It focused on Molycop, an AIP portfolio company and global steel processing company. AIP was selected as the host company for a six-month intensive and full-time research partnership. The benefits of this research approach include the opportunity to build tools and develop processes for a real-world private equity firm. We tested how these tools build confidence in decarbonization investments and whether the processes actually influence real-world decision-making. It is important to note that the research was completed for a single private equity firm, so we would want to extend this research before confidently claiming this approach can be generalized across private equity and for other industries.

Further background information for both companies are given below, followed by a discussion of the data sources, project approach, and model formulations.

### 2.1 Company Background

#### 2.1.1 American Industrial Partners

AIP is a leading middle market private equity firm focused on buying and improving industrial businesses headquartered in North America. The firm has deep roots in the North American industrial economy and has been active in private equity investing

across two decades, now with over \$10 billion in assets under management. AIP is a team comprised of engineers, operators, and financial professionals with extensive experience structuring and executing complex transactions. Through the collaborative application of investing and operating skills and experience, the AIP team seeks to acquire attractive but under-performing middle market industrial businesses and implement comprehensive operating agendas to build long-term value and generate differentiated risk-adjusted returns for its investors. The AIP Operating Agendas are a collection of operating activities that AIP performs over the course of its ownership of a business. The selected activities have the highest impact on improving EBITDA. AIP predominantly invests in companies that match the following profile:

- Manufacturing or industrial service companies with business-to-business selling relationships.
- Global operations with significant presence in North America.
- Revenues of \$300 million and higher for platforms (no size requirements for add-ons).
- Negative EBITDA to \$250 million EBITDA.
- Enterprise value up to \$2 billion.

AIP is committed to assessing material Environmental, Social, Governance (ESG) risks and opportunities to improve operating agendas. AIP believes material ESG factors can be important to the value of their investments, and ultimately to the value AIP returns to their investors. They believe that integrating ESG considerations across deal screening, diligence, portfolio management and exit processes is aligned with their responsible stewardship of industrial assets. AIP's approach to ESG is aligned with the Sustainability Accounting Standards Board ("SASB") definition of materiality, which includes ESG "issues that are reasonably likely to impact the financial condition or operating performance of a company and therefore are most important to investors." During the AIP ownership period, the firm focuses on measurement,

business strengthening policies and practices, and value-creation as key tenants to their ESG approach. [2]

### 2.1.2 Molycop

AIP acquired Molycop in a carve-out from Arrium in January 2017. Molycop is the largest global supplier of forged grinding media to the mining industry, primarily supplying to copper and gold mines. Molycop also provides instrumentation, process control, data visualization and analytics services to the comminution circuit. The company supplies over 400 mines globally and maintains over 50% market share of grinding media in its core mining markets. Molycop differentiates itself through its industry-leading product quality, in-country manufacturing footprint, supply chain capabilities, and technical applications know-how. The company is headquartered in the United States and has twelve manufacturing sites across the world’s major mining regions, including North America, South America, Europe, Middle East, Asia and Australia. The locations of those sites are shown in Table 2.1:

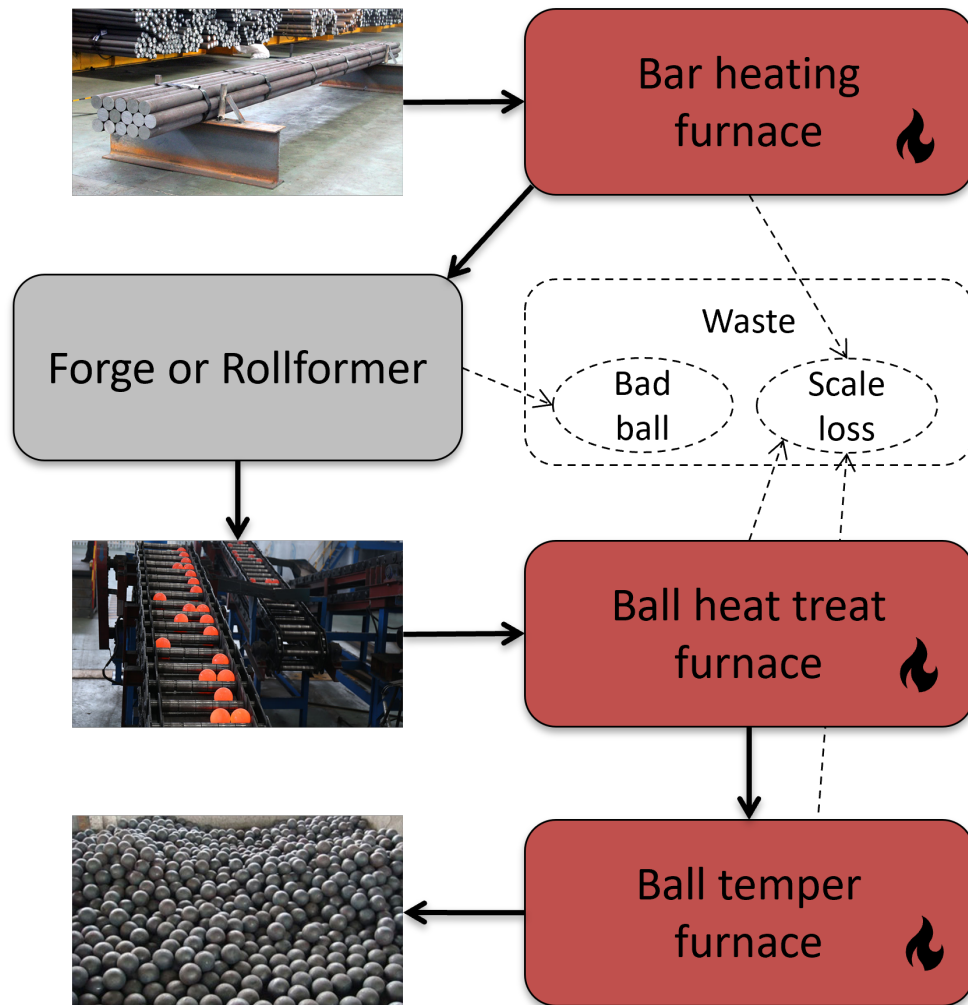
City	Country	Region
Kansas City	USA	North America
Kamloops	Canada	North America
El Salto	Mexico	North America
Talcahuano	Chile	South America
Mejillones	Chile	South America
Lima	Peru	South America
La Joya	Peru	South America
Sevilla	Spain	Europe
Bilbao	Spain	Europe
Cilegon	Indonesia	Southeast Asia
Waratah	Australia	Oceania
Bassendean	Australia	Oceania

Table 2.1: Molycop plant locations

Each of Molycop’s plants have multiple process lines to produce different grinding media product. Figure 2-1 shows a stylized material flow process diagram for grinding media. Molycop purchases steel bars, which are the input to their conversion process. The steel bars are heated in a bar heating furnace before they are conveyed to

equipment that converts the bars into balls. This equipment could either be a forge or a rollformer, depending on the desired size. Next, and to achieve the desired material properties, the balls are conveyed through a heat treat furnace and temper furnace. After exiting the temper furnace, the balls are conveyed to inventory, or directly to a rail car or truck for shipment. Figure B-1 shows examples of these furnaces.

Figure 2-1: Stylized process diagram showing material flow for steel



Molycop’s grinding media product serves an important role in the mining value chain because the grinding stage is critical to a mine’s throughput and recovery with a high cost of failure. The grinding environment is harsh and the narrowly specified and tightly controlled properties of grinding media heavily influence mineral recovery. Thus, Molycop offers specific ball sizes, alloying, heat treatment, and carbon content

to deliver best-suited products specifically engineered for mine customers' unique conditions.

Crushing and milling is the most common way to reduce ore to liberate minerals, with more than 80% of copper and gold metal processed via grinding circuits. The four main types of grinding circuits all use grinding media, and Molycop provides forged grinding media for these circuit types, including small/medium balls, large balls, and grinding rods. There are two categories of grinding media: forged grinding media and cast high chrome. Each product is used based on the specific application characteristics of the ore type and grinding circuit. Molycop currently supplies both cast and forged grinding media to customers.

Molycop does business in an industry that contributes heavily to global greenhouse gas emissions. Emissions from mining are about 28% of global emissions while steel making and processing represents about 8%.<sup>1</sup> For many of Molycop's customers, who have committed to material emission reduction targets in 2030 and 2050, grinding media is a top three source of their supplier emissions. One of Molycop's biggest customers has committed to a 19% reduction in emissions from their suppliers. Molycop would need to reduce their absolute emissions in 2030 by 42% compared to a 2020 baseline to meet the globally recognized commitments from the United Nations Paris Agreement, which were set to keep global temperature rise below two degrees Celsius.<sup>2</sup> Molycop must develop the tools and processes that will help meet that goal.

With this in mind, Molycop's growth strategy includes three imperatives: to protect and grow sales of the core grinding media product, to diversify the revenue base, and to differentiate on digital and sustainability solutions.

---

<sup>1</sup><https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel>

<sup>2</sup>According to the Science-Based Target Initiative

## 2.2 Data

### 2.2.1 Data Sources

The cost of electricity and gas usage are often significant contributors to a manufacturer's costs of operation. Therefore, many track granular utility usage down to the process equipment level. This granularity is necessary to improve the accuracy of calculating product carbon footprint, since each product is manufactured on different process lines. Data for electricity usage and gas usage comes from dedicated electricity and gas meters, when available, or from utility bills when not. For plants where building electricity usage was not separately metered from process electricity usage, calculations were made to separate them before inputting the data into the model. The price of electricity and price of gas come from each plant's utility bills.

To convert from utility usage to CO<sub>2</sub> emissions, we must know the carbon content of the energy usage - natural gas for Scope 1 emissions and electricity for Scope 2 emissions. Since none of Molycop's plants have on-site electricity generation, the carbon content of electricity for each plant differs based on the emissions from the mix of power generation that supplies the local utility grid. All of these values are shown in Table A.4, as well as the source of the value.

Data for scope 3 emissions came from many sources. The embodied carbon in purchased steel depends on the steel-making process of the suppliers, as well as their transport modes. The emissions intensities of steel suppliers vary widely, from 0.25 to 2.6 tons of CO<sub>2</sub> emissions per ton of steel.<sup>3</sup> The suppliers with higher emissions use more emissions intensive steel-making processes like basic oxygen furnaces, or use electric arc furnaces powered without renewable electricity. These suppliers are incumbents and have high annual production (e.g., 5 - 70 Mton/year). The suppliers with lowest emissions use a combination of cleaner steel production methods (like electric arc furnaces) combined with renewable electricity. Suppliers with the lowest emissions intensities generally have lower annual production (e.g., <1 Mton/year). CRU is an organization that provides business intelligence on global metals and keeps

---

<sup>3</sup><https://www.crugroup.com/>

emissions data for steel suppliers. We used a purchased report from CRU to determine the emission intensity values for all of Molycop's steel suppliers. The emissions factors of different transport modes, as well as the sources for those factors, are included in Table A.4.

Transport distances between sites were calculated using GPS coordinates. GPS coordinates for supplier facilities, Molycop plants, and customer mine sites were found using Google Maps searches. Data on emissions from Molycop competitors were taken from public sustainability reports. Data on the difference in emissions intensity between forged grinding media and cast high chrome grinding media came from a purchased report provided by CRU. To determine annual absolute emissions for each of Molycop's customers as a result of their consumption of Molycop products, we needed the customer's consumption of grinding media. To do this, we use the mines' rate of milling ore per year, which was obtained by a combination of CRU reports and customer interviews by the commercial team. We then multiplied the ore milling rate by the grinding media wear rate to estimate the annual consumption of grinding media.

Interviews and site visits were critical for the data collection effort. To understand how the production process works, we often shadowed the Kansas City operations team. This is how we identified some of the main process characteristics that are influenced by decarbonization projects, including energy costs, waste from scale loss, and throughput improvement. Specifically, there were opportunities at the Kansas City plant to reduce scale loss and improve throughput. Once these were identified, the operations lead of Molycop gave his thoughts on other plants that may have similar challenges to solve. We used this information to interview plant operations leads to understand their biggest process improvement opportunities. This is, for instance, how we discovered that there were throughput improvement opportunities at other plants. It was critical to constantly interact with the operations team and to ensure they were supportive through the whole project - since their main concern is to keep the process operating as smoothly as possible and to eliminate cost. The operations team also weighed in on project feasibility questions related to:

- whether the flame from oxygen combustion would damage furnace refractory
- the current amount of scale waste
- the reasons for and severity of bottlenecks
- the temperature needs of the furnace and whether electrification can meet them
- any physical space constraints of the furnaces within the process lines
- the availability of downtime for equipment upgrades

There were many other teams that had important information for this project, including finance, commercial, and metallurgy. When we needed to understand the potential costs of the bottleneck at the Kansas City plant, we talked to the finance team to determine the shipping costs that were incurred by transferring balls from Mexico to the USA to satisfy unmet demand due to the bottleneck. To understand the transport routes for each geography and from our suppliers and to our customers, we talked to the commercial team. We also engaged the commercial team to gauge customer interest on lower emissions products, for example. The metallurgy team provided invaluable input on how to maintain material properties of the balls in the process, but also to share their research on the important differences between forged balls made by Molycop and cast high chrome balls made by competitors. This allowed us to model the difference in life cycle emissions between the two types of products. With the necessary data collected and teams engaged, we could ensure our models and methods were using the correct information.

Capital expenditure data for all projects were taken directly from vendor quotes, if available, or estimated using vendor quotes for similar furnaces. Fuel savings percentages for the efficiency projects used historically measured fuel savings for similar projects that had already been completed. Fuel savings and process benefits for the oxy-fuel technology came from direct engagement with an oxy-fuel vendor who provided scientific modeling to determine the likely effects of installing their technology on Molycop's Kansas City furnaces. The savings for the balance of Molycop's fleet

were estimated using that vendor’s results. The CAPX and OPEX values used in this study are shown in Table A.2 and Table A.3.

### **2.2.2 Data Availability**

In some situations, there was a gap between our ideal data needs and the available data. For instance, we had to rely on modeled waste reduction numbers from an oxy-fuel vendor. Historical data from implementations of a project are more credible than prospective modeling by vendors, but that was our best option. Once a project is implemented, the tools can be calibrated based on new data. The most accurate method to track utility usage is to separately sub-meter the furnace natural gas and electricity usage. In some plants, this infrastructure was already installed, but it is costly. For the plants that did not have sub-meter infrastructure, we calculated utility usage for the process lines by weighting total utility usage by production tonnage per line.

Data sources were always tracked in our tools, to ensure users understood the accuracy and credibility of data upon which results were obtained.

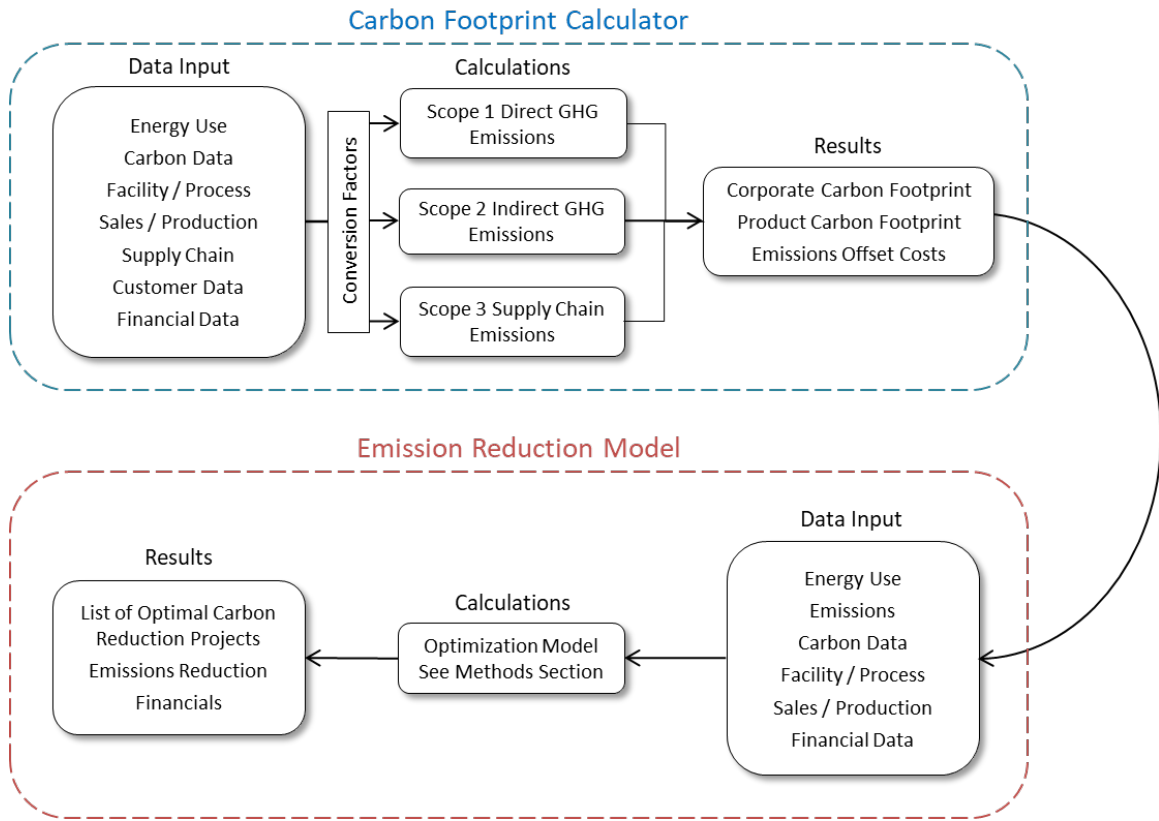
## **2.3 Project Approach**

This study describes a set of tools that give manufacturing companies the resources to confidently make decarbonization decisions. We built the tools to calculate the company’s carbon footprint and to determine the financial impacts of emission reduction projects. Our approach is outlined below and depicted in Figure 2-2.

First, we built a Carbon Footprint Calculator that measures the company’s corporate carbon footprint and product carbon footprint. This calculator allows us to see carbon footprint for each facility and the relative impacts of different emissions sources on the total emissions. A company can use this tool to identify their sources of emissions, set carbon reduction targets, and measure progress.

We then develop a list of carbon emissions reduction projects for process furnaces and build an optimization model that calculates the costs, savings, and emission

Figure 2-2: Overview of project approach



reduction potential of these projects. This Emission Reduction Model determines the most profitable way to reduce emissions based on available furnace upgrade technologies. The output includes a list of which projects should be implemented for which furnaces and in which year, which will vary based on inputs such as carbon pricing, utility pricing, oxygen pricing, process throughput improvements, process waste reduction, emission reduction, and more.

Combined, these two tools help the company measure their carbon footprint and then analyze which carbon reduction levers they can pull to meet reduction targets.

## 2.4 Carbon Footprint Calculator

### 2.4.1 Molycop Value Chain Emissions

The following emissions categories are relevant for Molycop's operations and are used in the model calculations:

#### Scope 1

- *Company facilities* Molycop has natural gas fired process furnaces and some facilities use natural gas for building heat and domestic hot water.

#### Scope 2

- *Purchased electricity, steam, heating, and cooling for own use* Molycop purchases electricity for their buildings.

#### Scope 3

- *Purchased good and services* Molycop purchases steel rods as raw material before they are turned into grinding media product.
- *Transportation and distribution* There are both upstream and downstream transportation needs, to get raw material to Molycop plants and to get Molycop product to customers. Transport modes include road, rail, and ocean.
- *Business travel*
- *Employee commuting*

Total GHG emissions are the sum of Scope 1, 2, and 3 emissions. Emissions can either be measured as absolute (in tons of CO<sub>2</sub>) or as an intensity (in tons of CO<sub>2</sub> per unit of activity). Because Molycop is in the business of selling grinding media by the ton of steel, we use tons of steel as the unit of activity. Thus, Molycop's emissions intensity has units of  $tons_{CO_2e}/ton_{steel}$ .

Molycop has competitors that sell products with different characteristics, including wear rate. A grinding ball that has a longer wear rate will grind more ore over its

useful life, and the customer will buy less grinding media product over the course of the year. Thus, the annual absolute emissions for a mine customer buying grinding media could differ between the two grinding media products even if the emissions intensities in  $tons_{CO_2e}/ton_{steel}$  are the same. To overcome this difference, we convert the unit of activity for the emissions intensity from *tons of steel* to *tons of ore grinded* through a consumption factor:

$$tons_{CO_2e}/ton_{ore\ grinded} = tons_{CO_2e}/ton_{steel} * tons_{steel}/ton_{ore\ grinded}$$

This allows Molycop customers to accurately compare annual absolute emissions from different grinding media suppliers. It also highlights the positive effect that improving product wear rate has on reducing greenhouse gas emissions.

## 2.4.2 Model Formulation

Notation	Brief Description	Units
$p$	Product index	-
$f$	Furnace index	-
$l$	Process line index	-
$b$	Building/plant index	-
$c$	Customer index	-
$S_1$	Scope 1 CO2 emissions	$tons_{CO_2e}$
$S_2$	Scope 2 CO2 emissions	$tons_{CO_2e}$
$S_3$	Scope 3 CO2 emissions	$tons_{CO_2e}$
$C_G$	CO2 emissions intensity of natural gas	$tons_{CO_2e}/GJ$
$C_E$	CO2 emissions intensity of electricity	$tons_{CO_2e}/kWh$
$C_S$	CO2 emissions intensity of purchased steel	$tons_{CO_2e}/ton_{steel}$
$C_{ro}$	CO2 emissions intensity of road transport	$tons_{CO_2e}/ton/mile$
$C_{ra}$	CO2 emissions intensity of rail transport	$tons_{CO_2e}/ton/mile$
$C_{oc}$	CO2 emissions intensity of ocean transport	$tons_{CO_2e}/ton/mile$
$D$	Distance of product transport	$miles$
$T$	Production tons of steel	$tons_{steel}$
$g$	Gas usage	$GJ$
$e$	Electricity usage	$kWh$
$O_p$	Customer consumption of product	$tons_p/ton_{ore}$

Table 2.2: Variable notation used for carbon footprint model formulation

We calculate total annual Scope 1 and Scope 2 emissions to manufacture product  $p$  for customer  $c$  with the following:

$$S1_{p,c,intensity} = C_G * ((\Sigma_f g_f / T_l) + (g_b / T_b))$$

$$S2_{p,c,intensity} = C_E * (((\Sigma_f e_f + e_l) / T_l) + (e_b / T_b))$$

where:

$T_l$  is total production on process line  $l$

$T_b$  is total production in plant  $b$

We calculate total annual Scope 3 emissions to manufacture and transport product  $p$  to customer  $c$  with the following:

$$S3_{p,c,intensity} = C_s + C_{ro} * (D_{1,ro} + D_{2,ro}) + C_{ra} * (D_{1,ra} + D_{2,ra}) + C_{oc} * (D_{1,oc} + D_{2,oc})$$

where:

$D_1$  is distance from steel supplier to Molycop plant

$D_2$  is distance from Molycop plant to customer

The emissions intensities are converted to annual absolute emissions by multiplying by the annual sales of the product to customer  $c$ :

$$S1_{c,absolute} = T_c * S1_{c,intensity}$$

$$S2_{c,absolute} = T_c * S2_{c,intensity}$$

$$S3_{c,absolute} = T_c * S3_{c,intensity}$$

$$Total\ annual\ absolute\ emissions = S1_{c,absolute} + S2_{c,absolute} + S3_{c,absolute}$$

To compare the emissions of different product types that have different wear rates, we must normalize by the amount of ore that each grinding media product can mill. The equation is:

$$Total\ product\ emissions\ per\ ton\ of\ ore\ milled =$$

$$O_p * (S1_{c,p,intensity} + S2_{c,p,intensity} + S3_{c,p,intensity})$$

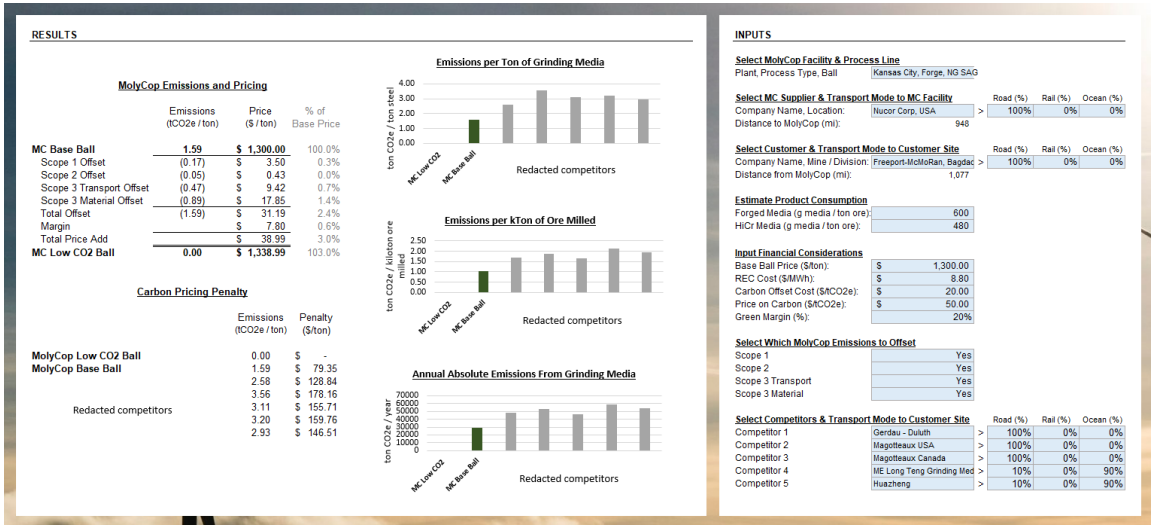
where:

$O_p$  is the amount of product  $p$  that the customer  $c$  consumes to mill one ton of ore.

The results of the model are visualized on an Excel-based front-end, which is shown in Figure 2-3. This front end shows emissions intensities by product based on user inputs for the Molycop plant and process, product type, purchased raw material, supplier location, customer location, transport modes, and more. It can also compare Molycop's product emissions to publicly available competitor emissions and normalize these values for a customer to show their annual absolute Scope 3 emissions from

grinding media.

Figure 2-3: View of the Emissions Calculator Front End



## 2.5 Emission Reduction Optimization

### 2.5.1 Emissions Reduction Measures

We built this optimization model to determine the optimal set of carbon reduction measures for Molycop’s fleet of furnaces. It has the flexibility to analyze many technologies, but this study only includes those measures that are currently a fit for Molycop’s operations. As background, a non-comprehensive set of pathways to decarbonize industrial heat are listed below:<sup>4</sup>

- Furnace energy efficiency upgrades
- "Oxy-fuel" oxygen combustion
- Electrification plus low-carbon electricity supply
- Low-carbon bio fuels

<sup>4</sup><https://www.energy.gov/eere/industrial-decarbonization-roadmap>

- Low-carbon hydrogen fuel
- Carbon capture and sequestration

Of this list, furnace energy efficiency upgrades, "oxy-fuel" oxygen combustion, and electrification were analyzed. Hydrogen fuel and carbon capture and sequestration are both nascent and costly technologies, and Molycop could not find technology providers willing to consider their plants as pilot sites. As the technologies improve and become more cost-competitive, the model has been built so that it can incorporate and analyze additional technologies in the future. The three project types that are included in the model are described below.

Molycop's portfolio of furnaces range in efficiency. By implementing furnace upgrades, Molycop can reduce the amount of natural gas needed per unit of heat and thus reduce CO<sub>2</sub> emissions. There are two high impact strategies to improve furnace efficiency; replace the burners with newer and more efficient natural gas burners and install recuperators. Recuperators are heat exchangers that pre-heat incoming cold combustion air with hot furnace exhaust air. The warmer combustion air results in a more efficient combustion process that requires less natural gas. Indicative capital expenditures needed for the equipment are \$0.5M per furnace. Figure B-4 shows the recuperator that was installed in Molycop's Kansas City plant.

"Oxy-fuel" technology burns pure oxygen in lieu of ambient air by installing an oxygen injector into the furnace (as demonstrated in Figure B-2). Because ambient air is 78% nitrogen by volume, energy is wasted in the combustion process when nitrogen is heated and emitted in the flue gasses. Replacing the ambient air with pure oxygen creates a more efficient burn and requires less natural gas, as shown in Figure B-3. Fuel and emissions savings range from 10-50%, depending on the furnace type. The benefits of oxygen combustion include energy cost savings, scale reduction, and productivity improvement. As the steel moves through the furnaces, scale builds up on the outside of the product, leading to waste. This waste cannot be sold or recovered and becomes a cost of doing business. Because oxygen combustion is a more efficient burn, the process waste from scale losses are decreased and Molycop can save

money by buying less steel. For furnaces that are the bottleneck in a process line, oxygen combustion can improve the product yield. Oxygen combustion has a higher burn point, so the steel in the furnace can heat faster and ease the furnace bottleneck. Oxygen combustion requires a supply of oxygen, which can be delivered one of three ways. It can come from an oxygen pipeline that delivers oxygen directly to the plant, or from oxygen canisters delivered via truck, or from on-site oxygen production. Two of Molycop plants (in the US and Australia) have existing oxygen pipelines that can be utilized. The remaining plants would need to purchase oxygen canisters or install equipment to produce oxygen on-site. Indicative capital expenditures needed for the furnace equipment range from approximately \$0.5M - \$2M per furnace. This does not include equipment needed for on-site oxygen production.

To achieve 100% scope 1 emission reduction, the natural gas fired furnaces can be completely replaced by electric induction heating. All of Molycop's heating needs operate at temperatures that can be achieved by induction heating. Depending on the furnace, induction heating may require more physical space than natural gas fired furnaces, which could be a constraint for some process lines. To achieve 100% scope 2 emission reduction, the electricity supply needs to be 100% carbon free. Indicative capital expenditures needed for electrification range from approximately \$0.5M - \$6M per furnace, excluding investments into making the electricity supply carbon free. The full list of Molycop furnaces is included in Table A.1.

## 2.5.2 Model Formulation

Table 2.3 summarizes the notations used for the model formulation. This model uses a decision variable denoted as  $X_{tfm}$ , which is a binary variable that takes a value of 1 if reduction measure  $m$  is installed for furnace  $f$  in year  $t$  and takes a value of 0 otherwise. The full mathematical model is:

**Objective:** schedule furnace carbon reduction projects that minimize total cost within the planning horizon.

$$\text{minimize } \sum_t \sum_f [(g_{tf} + c_{tf} * a) * (G_{tf} - \sum_m R_{fm} * X_{tfm}) + (e_{tf} + c_{tf} * b_{tf}) * (E_{tf} + \sum_m E_{fm} * X_{tfm}) + (\sum_m o_{tf} * O_{tfm} * X_{tfm}) + (\sum_m M_{fm} * X_{tfm}) - (s_{fm} * S * X_{tfm}) - (p_{fm} * P * X_{tfm})]$$

Notation	Brief Description
$f$	Furnace index
$m$	Decarbonization project index
$t$	Year index
$T$	Planning horizon
$X_{tfm}$	Binary decision variable taking value 1 if furnace decarbonization measure $m$ is installed for furnace $f$ in year $t$ , 0 otherwise
$g_{tf}$	Gas price for furnace $f$ in year $t$
$e_{tf}$	Electricity price for furnace $f$ in year $t$
$o_{tf}$	Oxygen price for furnace $f$ in year $t$
$c_{tf}$	Carbon price for furnace $f$ in year $t$
$G_{tf}$	Gas usage for furnace $f$ in year $t$
$E_{tf}$	Electricity usage for furnace $f$ in year $t$
$O_{tf}$	Oxygen usage for furnace $f$ in year $t$
$C_{tf}$	Carbon emissions for furnace $f$ in year $t$
$R_{fm}$	Gas usage reduction for furnace $f$ from measure $m$
$E_{fm}$	Electricity usage increase for furnace $f$ from measure $m$
$s_{fm}$	Scale savings for furnace $f$ from measure $m$
$S$	Cost of steel bar
$p_{fm}$	Productivity improvement for furnace $f$ from measure $m$
$P$	Product profit
$M_{fm}$	Capital expenditure for furnace $f$ from measure $m$
$a$	Carbon content of natural gas
$b_{tf}$	Carbon content of electricity delivered to furnace $f$ in year $t$
$B_t$	Annual budget for furnace measures
$r$	Annual growth rate of production

Table 2.3: Variable notation used for optimization model formulation

subject to the constraints:

1. Each project can only be installed once per furnace over the planning horizon:

$$\sum_f \sum_m \sum_t X_{tfm} \leq 1$$

2. Only one project can be installed per furnace each year:

$$\sum_t \sum_f \sum_m X_{tfm} \leq 1$$

3. Do not install gas carbon reduction measures and electrification measures on the same furnace:

$$\sum_t X_{tf(m1)} + \sum_t X_{tf(m3)} \leq 1 \quad \forall f$$

$$\sum_t^T X_{tf(m2)} + \sum_t^T X_{tf(m3)} \leq 1 \quad \forall f$$

where  $m1 = \text{gas efficiency}$ ,  $m2 = \text{oxygen combustion}$ ,  $m3 = \text{electrification}$

4. The annual CAPX for projects must not exceed the annual budget:

$$0 \leq \sum_f \sum_m M_{fm} * X_{tfm} \leq B_t \quad \forall t$$

5. Can not install projects that increase  $CO_2$  emissions:

$$(c_{tf} * a) * (G_{tf} - \sum_m R_{fm} * X_{tfm}) + (c_{tf} * b_{tf}) * (E_{tf} + \sum_m E_{fm} * X_{tfm}) \leq r * [(c_{(t-1)f} * a) * (G_{(t-1)f} - \sum_m R_{fm} * X_{(t-1)fm}) + (c_{(t-1)f} * b_{(t-1)f}) * (E_{(t-1)f} + \sum_m E_{fm} * X_{(t-1)fm})]$$

for  $t > 0$

6. Binary constraints for furnace project decisions:

$$X_{tfm} \in 0, 1 \quad \forall t, f, m$$

where:

- $(G_{tf} - \sum_m R_{fm} * X_{tfm})$  and  $(E_{tf} + \sum_m E_{fm} * X_{tfm})$  are annual gas usage and electricity usage after reduction measures are installed.
- $(g_{tf} + c_{tf} * a)$  are terms to convert gas usage to gas utility cost and gas  $CO_2$  emissions cost.
- $(e_{tf} + c_{tf} * b_{tf})$  are terms to convert electricity usage to electricity cost and electricity  $CO_2$  emissions cost.
- $(\sum_m o_{tf} * O_{tfm} * X_{tfm})$  represents oxygen cost
- $(\sum_m M_{fm} * X_{tfm})$  represents annual capital expenditures from projects.
- $(s_{fm} * S * X_{tfm})$  represents cost savings from scale reduction.
- $(p_{fm} * P * X_{tfm})$  represents profit increase due to productivity improvements.

The baseline operating scenario for Molycop includes no furnace energy efficiency measure interventions over the planning horizon and an assumed 2% annual growth rate of production. Therefore, the baseline scenario has no cost impacts related

to utility usage reduction, oxygen consumption, scale reduction, and productivity improvements.

The model includes 1,170 decision variables (39 furnaces, three furnace upgrade options, 10 year planning horizon) and six constraints. It is an optimal job scheduling model: our list of furnace upgrades are the jobs to schedule, and the fleet of furnaces are the machines on which to schedule the jobs.<sup>5</sup> The required output is a schedule, or an assignment of furnace upgrades per year. The optimization model objective is to select and schedule the set of furnace carbon reduction measures across all of Molycop’s global fleet of furnaces that minimize total cost to the business within the planning horizon. For this model, the total furnace costs over the planning horizon is the sum of each year’s gas cost, electricity cost, oxygen cost, carbon tax, and capital expenditures for the furnaces, less the cost improvements from process improvements such as furnace scale reduction and productivity increases.

The model captures key trade-offs related to each technology. For oxy-fuel technology, there is an increase in costs from oxygen consumption, but a decrease in costs from reduced natural gas usage, improved process operations, and reduced emission if there is a carbon price. For electrification, there is a trade-off between higher electricity prices (as compared to natural gas) and additional costs from PPAs compared to savings from emissions reduction under carbon pricing. The magnitude of these trade-offs differ based on each furnace, due to local electricity, gas, and oxygen prices, plus furnace efficiencies and potential for process operation improvements. Each project has different capital expenditure needs, and all of these investment decisions are constrained by the company’s annual budget and requirement that all investments must be profitable over the planning horizon.

## 2.6 Strategic Framework

Building the proper emissions models can be critical for a company to identify the scope of their challenge and set of relevant of solutions, but it is not sufficient in order to

---

<sup>5</sup>[https://en.wikipedia.org/wiki/Optimal\\_job\\_scheduling](https://en.wikipedia.org/wiki/Optimal_job_scheduling)

create sustainable and repeatable practices that lead to the continued implementation of emission reduction projects. There should be a feedback loop between executive engagement, capital allocation, and operational decision-making. There should be efforts to set top-down goals but it should be balanced with a focus on bottom up projects to drive momentum. The Environmental Defense Fund refers to this feedback loop as the "Virtuous Cycle." [17]

Our tools have been built with this Virtuous Cycle in mind; they give an organization the ability to share data on calculated emissions reduction from specific projects, which are then tied back to top-down emissions goals. In addition, we aimed to leverage this feedback loop to amplify the findings of our research within the company. On a recurring basis, we engaged executives on the emission reduction goals and shared how they would be linked to implementation plans. Investment opportunities, capital allocation, strategic positioning amongst competitors, and needs of customers were also discussed at this level. We engaged a cross-functional team across the company to encourage ownership of problem-solving, to stress test ideas, and to build wide support of potential solutions. Discussion of project opportunities were always based on model results that included accurate energy data, known co-benefits, verified technology, industry best practices, and recognized standards. This confidence led to more earnest discussions of funding needs, internal dedicated budgets, and access to external capital or grants. We believe the modeling tools we research in this study were just a piece, albeit critical, of the strategic framework needed to drive change.

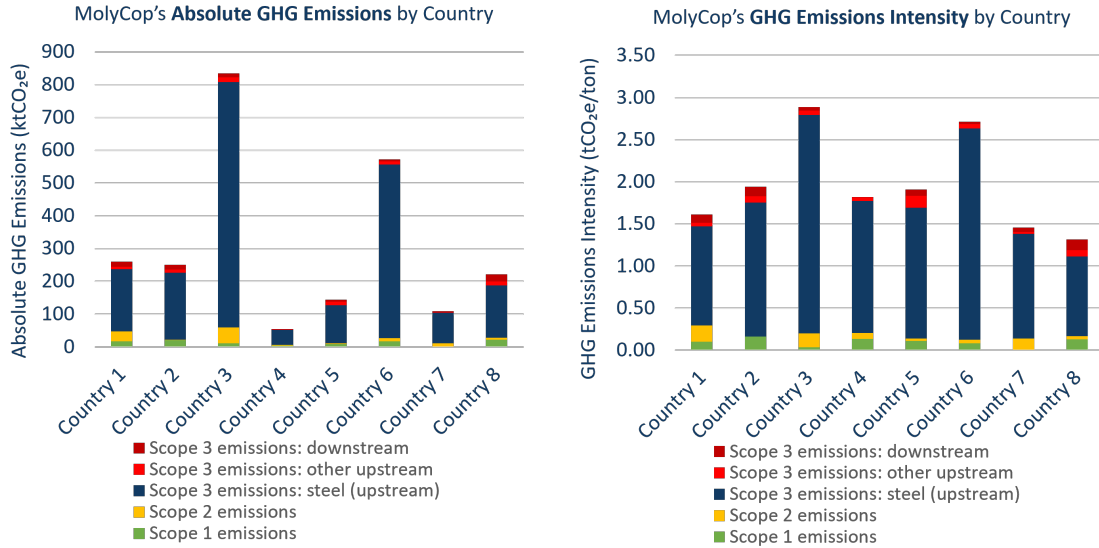
# Chapter 3

## Results

### 3.1 Carbon Footprint Calculator

All of Molycop's facilities have different emissions profiles, as shown in Figure 3-1. The absolute emissions (total emissions) and emissions intensities (emissions per ton of steel produced) yield different results because some plants have higher production than others. For instance, one facility has the most absolute emissions (825 kton of CO<sub>2</sub> per year) and the highest emissions intensity (2.9 ton of CO<sub>2</sub> / ton of steel produced). Another facility has the lowest absolute emissions at around 75kton of CO<sub>2</sub> per year due to its lower production, but a different facility has the lowest emissions intensity at about 1.25 tons of CO<sub>2</sub> per ton of steel produced. The emissions are primarily determined by consumption of purchased steel (80% of total corporate emissions), natural gas usage from process furnaces (8%), electricity usage (7%), and transportation needs (5%). Steel consumption is highest in Chile and Peru because there is a higher proportion of steel suppliers that make steel using more emissions intensive basic oxygen furnaces (BOF). Electricity emissions are highest in Australia because Molycop makes its own steel in that facility, as well as Chile and Spain because those plants have induction furnaces. Transport emissions vary by country depending on the primary mode of transport used to move goods. Ocean transport is the least emissions intensive per ton of cargo, followed by rail transport, then road transport (the emissions factors used are in Table A.4). This highlights that procurement of

Figure 3-1: Molycop Absolute Emissions and Emissions Intensity by Country



steel makes up the majority of emissions from steel processing companies, and a procurement team’s decisions on where to supply steel (and the resulting emissions intensity of that steel) will have the highest impact on reducing emissions in the future.

In addition to the variance by country and by plant, the emissions also vary depending on the product and customer. Different products are made on different process lines that consume energy at different rates. Customer sites have different locations and may require different transport modes to get the product to them. Thus, the emissions calculator that we built can take all these factors into account. To illustrate the differences, we show the calculated emissions intensities of two different Molycop products with supply chain and production characteristics as detailed in Table 3.1. Product 1, produced in Country 8 for a customer in the same geography, has a carbon footprint of 1.59 tons of CO<sub>2</sub> per ton of steel. Product 2, produced in the Country 6 for a customer in Country 3 has a carbon footprint of 2.47 tons of CO<sub>2</sub> per ton of steel, or 55% higher than Product 1.

If we zoom back out to the corporate carbon footprint, Molycop emitted about 410,000 tons of Scope 1 and 2 emissions in 2021. Under anticipated growth and without emissions intervention, Molycop’s emissions per year would grow to about

Characteristic	Product 1	Product 2
Emissions intensity (tonCO <sub>2</sub> e/ton)	1.59	2.47
Steel supplier location	Country 8	Country 3
Steel supply transport mode	Road	95% Ocean, 5% Road
Molycop plant location	Country 8	Country 6
Process type	Forge	Rollform
Customer location	Country 8	Country 3
Finished product transport mode	100% Road	100% Road

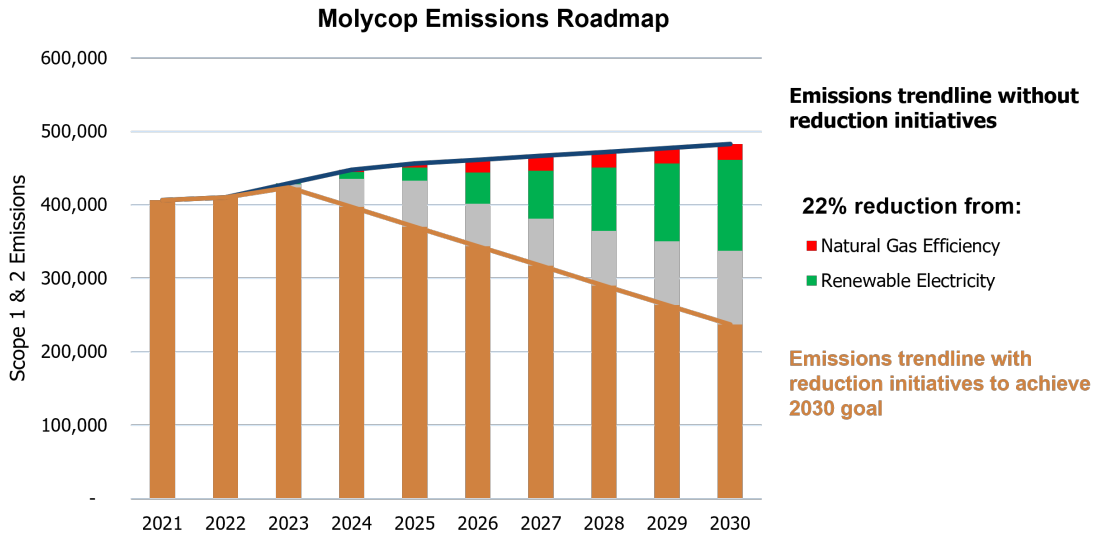
Table 3.1: Example emissions intensities plus supply chain and production characteristics for Molycop products

483,000 tons of CO<sub>2</sub> in 2030 (shown in Figure 3-2). The figure also shows a pathway to meet its 2030 goal of a 42% absolute emission reduction compared to the baseline in year 2022, which equates to a 51% emissions intensity reduction. That pathway includes a 22% absolute reduction in emissions intensity from furnaces through furnace efficiency upgrades and electric furnaces powered by renewable electricity (equivalently, a 30% emissions intensity reduction). The balance of reductions come from renewable electricity for buildings, innovations in feed stock for steel-making, and carbon credits. This research focuses on the feasibility of furnace upgrades and renewable electricity to meet Molycop environmental and financial goals. Although equally important, this research excludes a discussion on steel-making innovations and carbon credit purchases. Thus, we use a combined reduction in emissions intensity of 30% (furnace upgrades plus renewable electricity) as the threshold upon which to judge the feasibility of Molycop meeting its emission reduction target in 2030. The following Section 3.2 discusses which furnace emission reduction scenarios can meet the 30% reduction target.

## 3.2 Emission Reduction Model

We used the optimization model to analyze seven scenarios in order to understand how changes in key inputs altered the investment strategy for furnace decarbonization projects. Specifically, we were interested in sensitivity analyses to show the effects that process benefits, carbon pricing, and purchasing renewable energy PPAs have on

Figure 3-2: Projections for Corporate Annual Absolute Emissions



the furnace investments. The scenarios are outlined below.

- **Scenario 0** is the baseline scenario that describes the growth of corporate emissions with a growth in production but no investment in furnace emission reduction projects.
- **Scenario 1** results are based on the model inputs as described in Chapter 2. This includes modeling all process benefits, including throughput improvements and steel waste reduction. It also includes a carbon price of \$0/ton, and no PPA purchases.
- **Scenario 2** is modeled the same as Scenario 1, except all process benefits have been removed in order to understand how investment decisions would be made without a full understanding of process implications.
- **Scenarios 3a and 3b** are modeled the same as Scenario 1, except Scenario 3a has a carbon price of \$100/ton and Scenario 3b has a carbon price of \$200/ton.
- **Scenarios 4a and 4b** are modeled the same as Scenarios 3a and 3b, except the purchased electricity represents the updated electricity pricing and electricity carbon content from engaging in renewable energy PPAs.

<i>2030 Values (unless noted)</i>	Emissions Intensity		Absolute Emissions	
Baseline (2022)	1.83	-	198,733	-
Baseline	1.83	0%	228,281	15%
Scenario 1	1.74	-5%	216,715	9%
Scenario 2	1.77	-3%	220,406	11%
Scenario 3a	1.71	-7%	213,116	7%
Scenario 3b	1.56	-15%	194,686	-2%
Scenario 4a	1.29	-30%	161,114	-19%
Scenario 4b	1.25	-32%	155,637	-22%

Table 3.2: Emissions results for all scenarios, as compared to 2022 baseline year

The remaining discussion is divided into three sections, and begins with an overview of the emissions results for all scenarios, then continues with an overview of the financial results for all scenarios, and ends with more in-depth discussion of each scenario.

### 3.2.1 Overview of Emissions Results

The emission reduction results for all scenarios are detailed in Table 3.2.

The annual emissions for all scenarios are visualized in Figure 3-3. The blue baseline shows steady growth in year over year emissions with no emission reduction interventions. The orange lines show how annual emissions due to reduction interventions for each modeled scenario. Emissions decrease year over year (as visualized by the convex nature of the orange lines) when emissions project reductions are greater than emissions growth from increased year-over-year production capacity. When growth is larger than emissions reduction, than annual emissions for the given scenario (orange line) increases year over year. When there are no emissions reduction projects implemented in a given year, the growth rate of emissions for the modeled scenario will be the same as the growth rate of emissions for the baseline. Scenario 4 starts at a lower emissions value than the baseline due to the power purchase agreements that lower emissions from existing induction furnaces, before any new furnace upgrades are implemented.

If we consider all process benefits associated with furnace improvements, and there are carbon pricing mechanisms or PPA arrangements (Scenario 1), the optimal

**Annual CO2 Emissions**

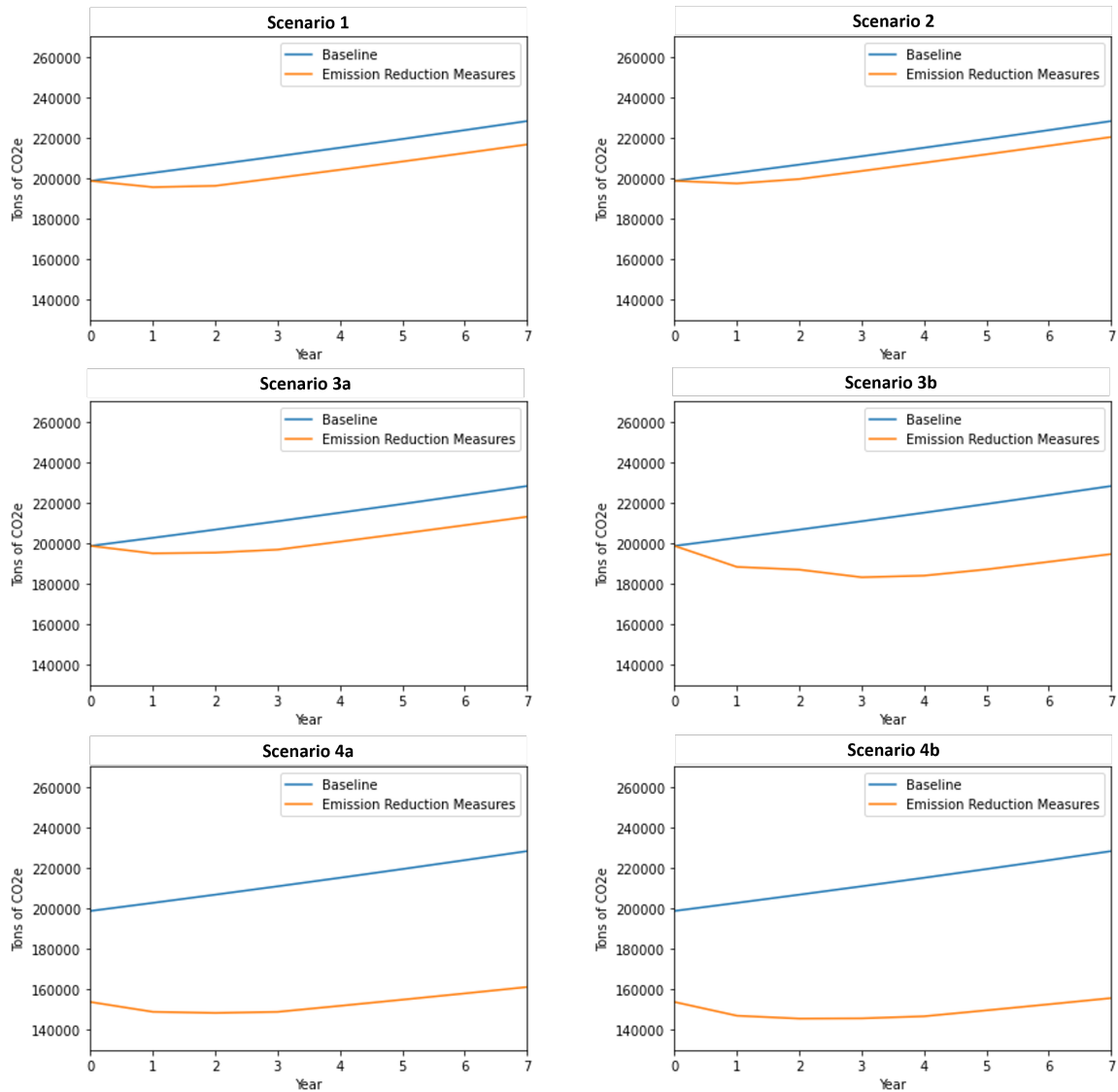


Figure 3-3: Optimization model results showing annual absolute Scope 1 & 2 emissions from furnaces

investment strategy results in a reduction in emissions intensity of 5.1% and an absolute increase of 9.0% when compared to the 2022 baseline. When removing the process benefits (Scenario 2), there is instead a reduction in emissions intensity of 3.5% and an absolute increase of 10.9%. This happens because some furnace investments that occurred in Scenario 1 become uneconomical in Scenario 2 when ignoring process benefits. To understand the impact of a carbon tax, we add back the process benefits and run the model with carbon prices of \$100/ton (Scenario 3a) and \$200/ton (Scenario 3b). In Scenario 3a, emissions intensity is reduced by 6.6% and absolute emissions increase by 7.2% as compared to the 2022 baseline. In Scenario 3b, emissions intensity is reduced by 14.7% and absolute emissions decrease by 2.0%. This is the first scenario in which absolute emissions decrease as compared to the 2022 baseline. In both Scenario 3a and 3b, the optimal investment strategy includes more projects because it becomes more profitable to avoid emissions that are taxed by a carbon pricing mechanism. In Scenarios 4a and 4b, we analyze the effects of renewable energy PPAs, since electrification of the furnace only helps avoid emissions if the electricity is clean. Also, it is only economical if the combined price of natural gas and a carbon price (for a gas-powered furnace) is higher than the cost of electricity (for an induction furnace). As will be discussed in further detail in this section, the previous scenarios show that, in general, the carbon content of electricity provided to Molycop and the low cost of natural gas that Molycop purchases result in few electrification projects. Thus, Scenarios 4a and 4b must include a carbon price to understand how that further incentivizes the switch to electric. Scenario 4a (at a carbon price of \$100/ton) results in an emissions intensity reduction of 29.4% and an absolute emissions reduction of 18.9% as compared to the 2022 baseline. Scenario 4b (at a carbon price of \$200/ton) results in an emissions intensity reduction of 31.8% and an absolute emissions reduction of 21.7%. All scenarios result in emissions intensity reductions. Only Scenarios 3b, 4a, and 4b result in absolute emissions reduction when comparing to the baseline year 2022 because of the carbon pricing that made more furnace decarbonization projects economically attractive.

<i>2030 Values (unless noted)</i>	Emissions Intensity	Absolute Emissions	CAPX	Cumulative Savings
Baseline (2022)	1.83	198,733	\$ -	\$ -
Baseline	1.83	228,281	\$ -	\$ -
Scenario 1	1.74	216,715	\$ 9,400,000	\$ 15,944,520
Scenario 2	1.77	220,406	\$ 6,900,000	\$ 6,952,952
Scenario 3a	1.71	213,116	\$ 13,200,000	\$ 25,384,014
Scenario 3b	1.56	194,686	\$ 21,900,000	\$ 41,116,209
Scenario 4a	1.29	161,114	\$ 13,200,000	\$ 38,341,804
Scenario 4b	1.25	155,637	\$ 19,100,000	\$ 89,352,698

Table 3.3: Emissions and financial results for all scenarios, as compared to 2022 baseline

### 3.2.2 Overview of Financial Results

Figure 3-4 visualizes the annual furnace costs (operating expenditures plus capital expenditures) from 2022 through 2030, while cumulative finances are detailed in Table 3.3. The blue baseline shows steady annual growth in utility costs due to increases in production every year. The orange line represents the annual costs as a result of emission reduction interventions, where annual costs include gas, electricity, oxygen, process improvements, and capital expenditures. When the orange line is greater than the blue line for a given year, the annual costs due to the furnace upgrades were higher than the baseline year. When the orange line is less than the blue line, annual costs were lower than the baseline year.

Under Scenario 1, where process benefits are considered and there is no carbon pricing or PPA arrangements, Molycop would need to invest \$9.4M of CAPX to achieve cumulative OPEX savings of \$15.9M through 2030, with a break even cash flow in year 5. In Scenario 2, with all process benefits removed, the cumulative savings drops to \$7.0M with a CAPX investment of \$6.9M, representing a break even cash flow in year 8. This highlights the importance of understanding the auxiliary process benefits to model full financial benefits. In this case, improvements in scale reduction and throughput double the cumulative OPEX savings and improve the break even cash flow point by three years. In a regulatory environment with carbon pricing, as modeled in Scenario 3, more furnace projects become financially viable. Scenario

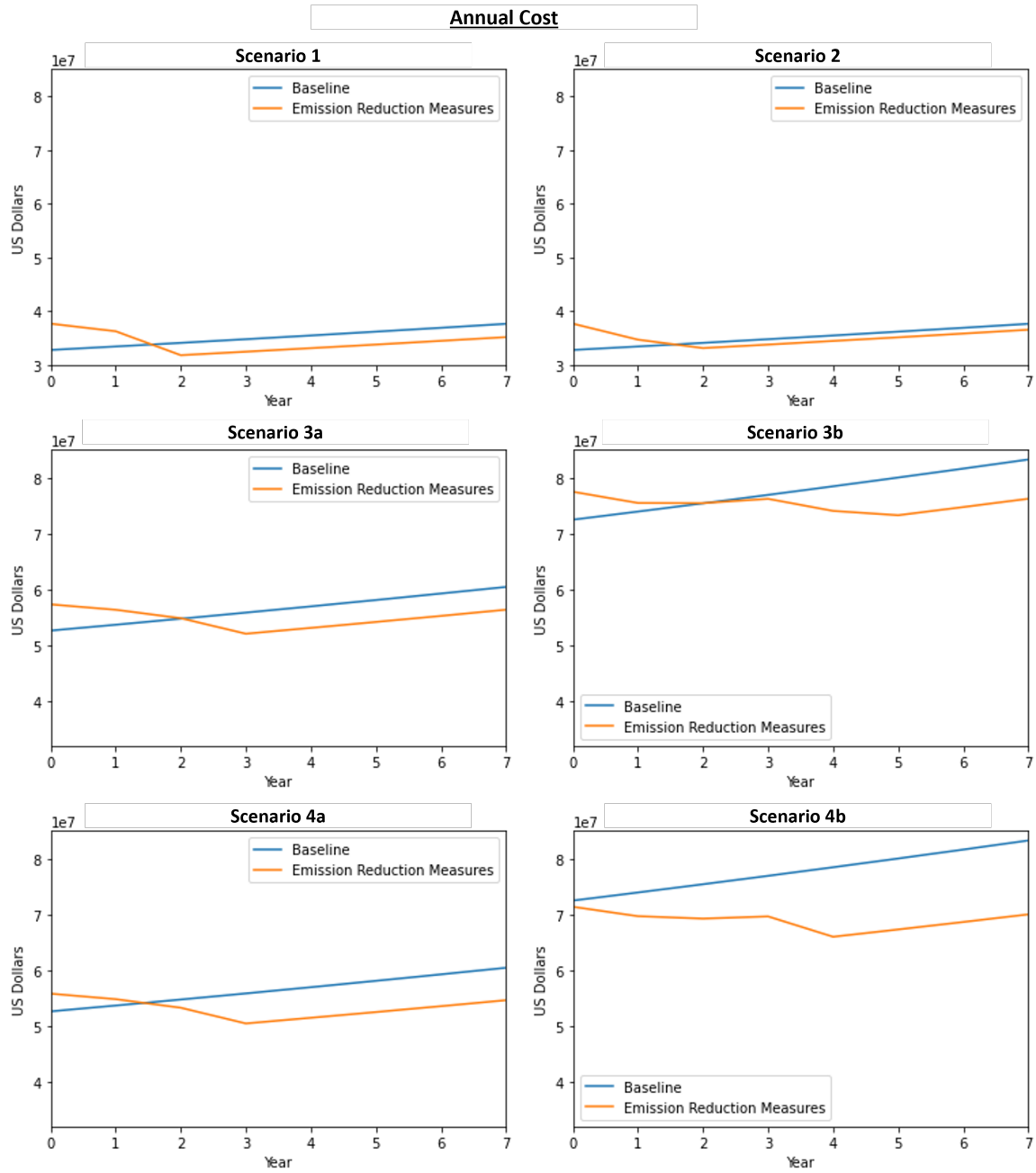


Figure 3-4: Optimization model results showing annual operating plus capital costs of furnaces

3a (\$100/ton) would realize \$25.4M in OPEX savings with a CAPX investment of \$13.2M and a break even in year 4. Scenario 3b (\$200/ton) would realize \$41.1M in OPEX savings with a CAPX investment of \$21.9M and a break even point in year 5. We model the costs and benefits of PPAs, including the increased electricity prices as well as the reduced carbon emissions of the power generation, in Scenario 4. With no carbon price, there are no additional electrification projects that are financially viable because natural gas costs are low. With a carbon price, however, electrification becomes more attractive. The optimal investment strategy in Scenario 4a with carbon prices of \$100/ton would result in \$38.3M of OPEX savings with a CAPX investment of \$13.2M. If carbon prices reach \$200/ton, as in Scenario 4b, then a CAPX investment of \$19.1M would yield cumulative OPEX savings of \$89.3M.

### **3.2.3 Results by Scenario**

The list of optimal furnace decarbonization projects that yield these reductions are different for each scenario, and is shown in Table 3.4.

#### **Scenario 1**

In this scenario, there should be gas efficiency upgrades for the bar heating furnaces in Peru (La Joya), Mexico, Canada, Australia, and Chile (Mejillones). The furnaces in Australia and Indonesia are inefficient because they burn cold air; adding recuperators will increase their efficiency by up to 25% by preheating incoming combustion air for a more efficient burn. As reference, the recuperator that is used in the USA plant is shown in Figure B-4. The remaining furnaces would see a more modest boost to their combustion efficiencies by upgrading old burners to newer technology.

The model also determined that Molycop should install oxygen combustion technology (oxy-fuel) at the USA and Australia plants for the bar heating, heat treat, and temper furnaces. This makes intuitive sense due to the combination of higher gas prices, access to oxygen delivered by pipeline, and ancillary process benefits. Australia and USA were previously steel-making plants, so they have existing oxygen pipeline

Furnace Identifier	Scen. 1	Scen. 2	Scen. 3a	Scen. 3b	Scen. 4a	Scen. 4b
gb_mcc_2	EF	EF	EF	EF,OF	EF	EF,OF
gb_mcusa	OF	-	OF	OF	OF	OF
gb_mcp_lj	EF,OF	EF	EF,OF	EF,OF	EF,OF	EF,OF
gb_mcp_sag	-	-	-	EF,OF	-	EF,OF
gb_mcm_rf	EF	EF	EF,OF	EF,OF	EF,OF	EF,OF
gb_mcc_1	EF	EF	EF,OF	ELE	EF,OF	EF,OF
gb_mcm_f	-	-	-	EF,OF	-	EF,OF
gb_mca_4	EF,OF	EF,OF	EF,OF	EF,OF	EF,OF	EF,OF
gb_mci_7	EF	EF	EF	EF,OF	EF	EF,OF
gb_mci_6	EF	EF	EF	EF,OF	EF,OF	EF,OF
gb_mcp_p1	ELE	ELE	ELE	ELE	ELE	ELE
ht_mca_4	EF,OF	EF,OF	EF,OF	EF,OF	EF,OF	EF,OF
ht_mcusa	OF	-	EF,OF	EF,OF	EF,OF	EF,OF
ht_mcch_m_f6	EF	EF	EF,OF	EF,OF	EF,OF	EF,OF
ht_mcp_sag	-	-	-	EF	-	EF
ht_mcc_2	-	-	EF	ELE	EF	ELE
ht_mcm_f	-	-	-	OF	-	EF,OF
ht_mcch_t_f5	-	-	EF,OF	EF,OF	EF,OF	EF,OF
ht_mcp_p1	-	-	-	EF	EF	EF
t_mcc_1	-	-	-	ELE	-	ELE
t_mcusa	OF	-	OF	OF	OF	EF,OF
t_mcp_p1	-	-	-	-	-	-
t_mcm_f	-	-	-	-	-	-
t_mcc_2	-	-	-	ELE	-	ELE
t_mca_4	OF	-	OF	OF	OF	OF
t_mcp_sag	-	-	-	-	-	-
t_mcch_t_f5	-	-	-	-	ELE	ELE
t_mcch_m_f6	EF	-	EF	EF	EF	EF
ib_mcusa	-	-	-	-	-	-
ib_mcp_l_rf1	-	-	-	-	-	-
ib_mcp_l_rf2	-	-	-	-	-	-
ib_mcch_m_rf3	-	-	-	-	-	-
ib_mcch_m_f6	-	-	-	-	-	-
ib_mcch_t_rf1	-	-	-	-	-	-
ib_mcch_t_rf2	-	-	-	-	-	-
ib_mcch_t_f5	-	-	-	-	-	-
ib_mca_3	-	-	-	-	-	-
ib_mcs_b	-	-	-	-	-	-
ib_mcs_s	-	-	-	-	-	-

Table 3.4: Model decisions for furnace decarbonization projects for every scenario. EF = efficiency upgrade, OF = oxygen fuel, ELE = electrification

	Baseline	Scenario 1	Change
<b>2030 Annual</b>			
Gas usage (GJ)	2,482,769	2,215,926	-10.7%
Electricity usage (kWh)	228,833,638	234,290,238	2.4%
CO2 Emissions (tons)	228,281	216,715	-5.1%
Gas cost	\$ 20,266,810	\$ 17,896,363	-11.7%
Electricity cost	\$ 17,369,380	\$ 17,761,878	2.3%
Cost of carbon	\$ -	\$ -	
Costs (benefits) to process	\$ -	\$ (495,657)	
Total operating cost	\$ 37,636,190	\$5,162,584	-6.6%
<b>2030 Cumulative</b>			
Cumulative CAPX	\$-	\$ 9,400,000	
Cumulative OPEX	\$ 281,217,277	\$ 265,272,757	-5.7%
Cumulative OPEX savings	\$ -	\$ 15,944,520	
Breakeven (years)		5	
<b>Emissions Reductions</b>			
Emissions Intensity	1.83 (2022)	1.74 (2030)	-5.1%
Absolute Emissions	198,733 (2022)	216,715 (2030)	9.0%

Table 3.5: Scenario 1 results for emissions reduction plus annual and cumulative operating and capital costs

infrastructure that terminates at their site. By re-commissioning these pipelines, the cost of delivered oxygen is cut by more than half, making oxy-fuel more attractive. In addition, the heat treat furnace in the USA plant is currently a bottleneck because of the slow time it takes to get the balls to temperature through that process step. By increasing the heating temperature for that furnace, Molycop can produce more balls and eliminate transfer costs of balls from other countries. An additional ancillary process benefit for both plants is the reduction of scale due to the combustion of pure oxygen. Scale is wasted metal that falls off the bars, and by reducing the scale, Molycop is reducing waste and saving material costs.

There is one plant where it makes sense to convert gas furnaces to induction furnaces. At the Lima, Peru plant, there is a very inefficient furnace that uses old technology and needs replacement. Although natural gas prices are relatively cheap, the CAPX needed for electrification of this furnace are low, and the efficiency gain by going to electric are high.

The impacts of these projects on 2030 operational costs are shown in Table 3.5. Gas

costs decrease due to efficiency measures, electricity costs increase due to electrification projects, and ancillary benefits increase due to process improvements. The total annual operating cost in 2030 is 6.6% less than the baseline, and break even cash flow occurs in year 5. By 2030, these investments would yield a 5.1% reduction in emissions intensity as compared to 2022, but there would still be an absolute increase in emissions by 9.0% compared to 2022.

	Baseline	Scenario 2	Change
<b>2030 Annual</b>			
Gas usage (GJ)	2,482,769	2,289,317	-7.8%
Electricity usage (kWh)	228,833,638	234,290,238	2.4%
CO2 Emissions (tons)	228,281	220,406	-3.4%
Gas cost	\$ 20,266,810	\$ 18,442,568	-9.0%
Electricity cost	\$ 17,369,380	\$ 17,761,878	2.3%
Cost of carbon	\$ -	\$-	
Costs (benefits) to process	\$ -	\$ 327,042	
Total operating cost	\$ 37,636,190	\$ 36,531,488	-2.9%
<b>2030 Cumulative</b>			
Cumulative CAPX	\$ -	\$ 6,900,000	
Cumulative OPEX	\$ 281,217,277	\$ 274,264,325	-2.5%
Cumulative OPEX savings	\$ -	\$ 6,952,952	
Breakeven (years)		7	
<b>2030 Emissions Reductions</b>			
Emissions Intensity	1.83 (2022)	1.77 (2030)	-3.5%
Absolute Emissions	198,733 (2022)	220,406 (2030)	10.9%

Table 3.6: Scenario 2 results for emissions reduction plus annual and cumulative operating and capital costs

## Scenario 2

The effects of process benefits are highlighted by excluding them in Scenario 2. In this analysis, we do not include cost savings from scale reduction or improved throughput. The optimal solution to minimize total cost no longer includes oxygen combustion technology at the USA, Peru, and Australia plants. This happens because the increase in cost from paying for the pure oxygen is no longer offset by the cost savings from the process improvements. As a consequence, OPEX savings are cut by 66% as compared to Scenario 1, from \$15.9M to \$6.9M. The Scenario 2 financial results are detailed in

Table 3.6. Emission intensity and absolute emissions reductions are also cut by 32% and 17%, respectively, as compared to Scenario 1.

### Scenario 3

	Baseline	Scenario 3a	Change
<b>2030 Annual</b>			
Gas usage (GJ)	2,482,769	2,169,491	-12.6%
Electricity usage (kWh)	228,833,638	231,105,499	1.0%
CO2 Emissions (tons)	228,281	213,116	-6.6%
Gas cost	\$ 20,266,810	\$ 17,629,977	-13.0%
Electricity cost	\$ 17,369,380	\$ 17,507,736	0.8%
Cost of carbon	\$ 22,828,191	\$ 21,311,668	-6.6%
Costs (benefits) to process	\$ -	\$ (71,039)	
Total operating cost	\$ 60,464,381	\$ 56,378,342	-6.8%
<b>2030 Cumulative</b>			
Cumulative CAPX	\$ -	\$ 13,200,000	
Cumulative OPEX	\$ 451,789,317	\$ 426,405,303	-5.6%
Cumulative OPEX savings	\$ -	\$ 25,384,014	
Breakeven (years)		4	
<b>2030 Emissions Reductions</b>			
Emissions Intensity	1.83 (2022)	1.71 (2030)	-6.6%
Absolute Emissions	198,733 (2022)	213,116 (2030)	7.2%

Table 3.7: Scenario 3a results for emissions reduction plus annual and cumulative operating and capital costs

These scenarios model the effects of carbon pricing. In scenario 3a, with an average carbon price of \$100/ton applied to all of Molycop’s plants, additional projects become feasible. Thus, compared to Scenario 1, CAPX investment and OPEX savings both increases and more emissions are avoided. The projects that were not selected in Scenario 1 that become feasible in Scenario 3a include oxy-fuel at the La Joya, Peru and Talcahuana, Chile plants, plus efficiency upgrades at the Canada and Mejillones, Chile plants. Table 3.7 detail the results.

Scenario 3b, with an average carbon price of \$200/ton applied to all of Molycop’s plants, yields even more feasible projects. At this carbon price, it becomes financially attractive to implement both efficiency upgrades and oxy-fuel technology at 12 of the 28 gas furnaces, as shown in Table 3.4. Oxy-fuel technology would exclusively

	Baseline	Scenario 3b	Change
<b>2030 Annual</b>			
Gas usage (GJ)	2,482,769	1,780,707	-28.3%
Electricity usage (kWh)	228,833,638	291,519,892	27.4%
CO2 Emissions (tons)	228,281	194,686	-14.7%
Gas cost	\$ 20,266,810	\$ 15,405,568	-24.0%
Electricity cost	\$ 17,369,380	\$ 21,797,158	25.5%
Cost of carbon	\$ 45,656,382	\$ 38,937,389	-14.7%
Costs (benefits) to process	\$ -	\$ 122,405	
Total operating cost	\$ 83,292,572	\$ 76,262,520	-8.4%
<b>2030 Cumulative</b>			
Cumulative CAPX		\$ 21,900,000	
Cumulative OPEX	\$ 622,361,357	\$ 581,245,148	-6.6%
Cumulative OPEX savings		\$ 41,116,209	
Breakeven (years)		5	
<b>2030 Emissions Reductions</b>			
Emissions Intensity	1.83 (2022)	1.56 (2030)	-14.7%
Absolute Emissions (tons)	198,733 (2022)	194,686 (2030)	-2.0%

Table 3.8: Scenario 3b results for emissions reduction plus annual and cumulative operating and capital costs

be applied to four more furnaces and five furnaces, in Canada and Peru, would be converted to electric induction. The remaining 4 furnaces (in Peru and Mexico) did not have any furnace decarbonization projects due to the combination of higher efficiency, lower natural gas prices, and higher electricity prices. Table 3.8 detail the results.

## Scenario 4

Scenario 4 explores how cleaner electricity changes the optimal furnace decarbonization strategy. We hypothesized that cleaner electricity would make it more attractive to electrify furnaces. Specifically, the carbon content of electricity in this scenario is reduced by 50%, which reflects a PPA arrangement where Molycop purchases renewable electricity to cover 50% of its consumption at each plant. As modeled, purchasing renewable electricity would, on average, add \$30/MWh to Molycop's utility bill, for each MWh that is purchased. It has been shown in previous scenarios that high electricity prices and low natural gas prices discourage the model from choosing electrification projects in the optimal solution set. Thus, making the electricity prices higher due to

renewables will not change the optimal solution. To encourage electrification, there needs to be carbon pricing. Scenario 4a and 4b model a carbon price of \$100/ton of CO2 and \$200/ton of CO2, respectively. As compared to Scenario 1, the optimal solution includes electrification for furnaces in Peru and Chile (at \$100/ton) and for furnaces in Peru, Chile, and Canada (at \$200/ton). The only differences in the optimal list of electrification projects between Scenario 4 and Scenario 3 (which models the same carbon prices but no renewable PPA) occurs at the Talcahuano, Chile plant: Scenario 4 includes electrification, whereas Scenario 3 does not. This indicates that, in Molycop’s situation and at 50% reduced carbon content of electricity, carbon pricing drives electrification decisions as opposed to the carbon content of the electricity. This makes intuitive sense, since the objective is to minimize total cost instead of total emissions. Table 3.9 and Table 3.10 detail the results for Scenario 4a and Scenario 4b, respectively.

	Baseline	Scenario 4a	Change
<b>2030 Annual</b>			
Gas usage (GJ)	2,482,769	2,169,491	-12.6%
Electricity usage (kWh)	228,833,638	231,105,499	1.0%
CO2 Emissions (tons)	228,281	161,114	-29.4%
Gas cost	\$ 20,266,810	\$ 17,629,977	-13.0%
Electricity cost	\$ 17,369,380	\$ 20,974,319	20.8%
Cost of carbon	\$ 22,828,191	\$ 16,111,433	-29.4%
Costs (benefits) to process	\$ -	\$ (71,039)	
Total operating cost	\$ 60,464,381	\$ 54,644,690	-9.6%
<b>2030 Cumulative</b>			
Cumulative CAPX	\$ -	\$ 13,200,000	
Cumulative OPEX	\$ 451,789,317	\$ 413,447,513	-8.5%
Cumulative OPEX savings	\$ -	\$ 38,341,804	
Breakeven (years)		3	
<b>2030 Emissions Reductions</b>			
Emissions Intensity	1.83 (2022)	1.29 (2030)	-29.4%
Absolute Emissions	198,733 (2022)	161,114 (2030)	-18.9%

Table 3.9: Scenario 4a results for emissions reduction plus annual and cumulative operating and capital costs

	Baseline	Scenario 4b	Change
<b>2030 Annual</b>			
Gas usage (GJ)	2,482,769	2,046,966	-17.6%
Electricity usage (kWh)	228,833,638	240,124,973	4.9%
CO2 Emissions (tons)	228,281	155,637	-31.8%
Gas cost	\$ 20,266,810	\$ 16,733,240	-17.4%
Electricity cost	\$ 17,369,380	\$ 21,778,019	25.4%
Cost of carbon	\$ 45,656,382	\$ 31,127,573	-31.8%
Costs (benefits) to process	\$ -	\$ 396,863	
Total operating cost	\$ 83,292,572	\$ 70,035,695	-15.9%
<b>2030 Cumulative</b>			
Cumulative CAPX		\$ 19,100,000	
Cumulative OPEX	\$ 622,361,357	\$ 533,008,659	-14.4%
Cumulative OPEX savings		\$ 89,352,698	
Breakeven (years)		1	
<b>2030 Emissions Reductions</b>			
Emissions Intensity	1.83 (2022)	1.25 (2030)	-31.8%
Absolute Emissions	198,733 (2022)	155,637 (2030)	-21.7%

Table 3.10: Scenario 4b results for emissions reduction plus annual and cumulative operating and capital costs

### 3.3 Final Decisions

During our research, we witnessed increased conviction across the organization, from the executive suite to the operations teams, related to moving forward on available pathways to meet environmental needs within financial constraints. The emissions models helped the organization identify the scope of their challenge and set of relevant of solutions, plus gave teams a platform to confidently discuss capital allocation and operational decision-making to reduce emissions.

Of the optimal furnace projects listed in each scenario, the company would prioritize the least efficient furnaces in the fleet, with electrification making sense in some scenarios, and efficiency improvements in other. Since oxy-fuel technology was new for the organization, they would implement it for one furnace to confirm the potential scale savings and throughput improvement. The best furnace for this would be a furnace at the USA plant, due to availability of vendors and oxygen pipeline access. The results of that pilot could then be used to calibrate and rerun the models.

THIS PAGE INTENTIONALLY LEFT BLANK

# Chapter 4

## Conclusions

PE firms are figuring out the best ways to measure and improve each of their portfolio companies when it comes to ESG criteria, while ensuring they continue create value for future buyers and maximize returns for investors. PE shops that invest in manufacturing and industrial companies have a more difficult environmental challenge because their investments are generally more emissions-intensive due to the complex supply chains and energy-intensive operations of the companies.

We modeled emissions reductions for industrial process furnaces, which is a top source of emissions for manufacturing companies, to determine the feasibility of reaching corporate emissions reduction goal. Our optimization model showed that, in a worst-case scenario, the research host company can reduce its furnace emissions intensity by 5% by 2030 while reducing total cost and therefore creating value for their PE owners. We also show the effects of carbon pricing on the company's optimal investment strategy. A carbon price of \$100/ton and \$200/ton made more furnace upgrades profitable and led to further reductions in emissions intensity (7% and 15%, respectively). Finally, we showed that the higher electricity price from a renewable energy PPA must be coupled with carbon prices in order to change the optimal list of furnace projects. At average PPA prices and a carbon price of \$100/ton and \$200/ton, emissions intensity is reduced by 30% and 32%, respectively.

Carbon pricing allowed the host company to profitably meet their 2030 science-based emissions reduction target. Those scenarios included 50% cleaner electricity

supply through a PPA, plus carbon pricing. This indicates that it will likely not be feasible for manufacturing companies to reach a profitable science-based reduction target without either cleaner electricity and a mechanism to increase the cost of natural gas (such as carbon pricing) or new breakthroughs in emission reduction technologies. Many companies around the globe are not waiting for policy to change and are instituting their own internal carbon pricing mechanisms to fund carbon reduction investments, including customers of private equity held industrial companies. The extent to which this has and will accelerate climate action is still being studied.

Our research also shows that ignoring the effect of process improvements on manufacturing equipment upgrades greatly undervalues the financial performance of decarbonization initiatives. A main driver for cost savings came from process benefits such as scale reduction and throughput improvement. Accounting for process benefits from furnace upgrades improved cumulative savings through 2030 by 100%. Cost structures contribute directly to company earnings valuations within the PE industry, and understanding the full benefit of cost savings and value creation increases the likelihood of investment in these projects.

The complexity of a business's supply chain and operations requires detailed, granular, and accurate carbon accounting and management to understand the full scope of a company's emissions. In this study we showed that the host company's absolute emissions and emissions intensities vary greatly by country; with ranges of 75-825 kton of CO<sub>2</sub> per year and 1.25-2.9 tons of CO<sub>2</sub> per ton of steel produced. The emissions also vary depending on the product and customer, where one product produced in the USA for a customer in the USA has a carbon footprint of 1.59 tons of CO<sub>2</sub> per ton of steel, while another product produced in Peru for a customer in Chile has a carbon footprint of 2.47 tons of CO<sub>2</sub> per ton of steel. Plugging the results of our optimization model into the carbon footprint calculator showed that meeting the host company's science-based emissions targets will affect the emissions profiles of each plant differently. This becomes important to track as industrial companies deal with individual customer requirements for product carbon footprint.

The emissions models helped the organization identify the scope of their challenge

and set of relevant of solutions, plus gave teams a platform to confidently discuss capital allocation and operational decision-making for emission reduction. For this program of analysis and action to maintain momentum, companies must have a dedicated sustainability professional to lead the effort. Even with a dedicated professional, our research found that sustainability discussions and decision-making needs to occur throughout the organization, from the executive suite to the operations teams, in order to build confidence in investment decisions.

To expand this work, we would focus on extending the optimization model. Specifically, we would focus on new emission reduction technologies and clean electricity, since these are the pathways needed to meet science-based targets for industrial companies. There is a lot of research and funding going into lowering the cost and improving the technology behind green hydrogen and carbon capture, storage, and sequestration. Incorporating these new technologies into the model would require more inputs for the cost of hydrogen, the value of sequestering carbon, and the equipment costs for these technologies. The current model includes existing electricity rates and tariff structures as a fixed input. In the future, different electricity tariff structures can be added as inputs to consider the effects they would have on the optimal selection of furnace electrification projects. More granular data, such as 15-minute interval data, for energy consumption, electricity prices, and carbon content of electricity, would increase the accuracy of the model. We are interested in understanding how optimal investment criteria may change by aligning 15-minute interval data of electricity prices, electric load for furnaces, and carbon content of electricity. This would require more granular time steps for our model, which are currently annual, and the decision variables would increase in proportion to the increase in time steps. As customers of industrial businesses refine their own sustainability requirements and begin to request or require carbon footprint targets, the model could be extended to include the willingness of customers to pay for a green premium. This would be modeled as incremental profit for investments that reduce the carbon footprint to a certain customer threshold.

THIS PAGE INTENTIONALLY LEFT BLANK

# Appendix A

## Tables

Table A.1: List of Molycop process furnaces

Plant Location	Furnace Type	Fuel
Kamloops, CAN	Bar Heating	Gas
Kansas City, USA	Bar Heating	Gas
La Joya, PER	Bar Heating	Gas
Lima, PER	Bar Heating	Gas
El Salto, MEX	Bar Heating	Gas
Kamloops, CAN	Bar Heating	Gas
El Salto, MEX	Bar Heating	Gas
Waratah, AUS	Bar Heating	Gas
Cilegon, IND	Bar Heating	Gas
Cilegon, IND	Bar Heating	Gas
Lima, PER	Bar Heating	Gas
Waratah, AUS	Heat Treat	Gas
Kansas City, USA	Heat Treat	Gas
Mejillones, CHI	Heat Treat	Gas
Lima, PER	Heat Treat	Gas
Kamloops, CAN	Heat Treat	Gas
El Salto, MEX	Heat Treat	Gas
Talcahuano, CHI	Heat Treat	Gas
Lima, PER	Heat Treat	Gas
Kamloops, CAN	Temper	Gas
Kansas City, USA	Temper	Gas
Lima, PER	Temper	Gas
El Salto, MEX	Temper	Gas
Kamloops, CAN	Temper	Gas
Waratah, AUS	Temper	Gas
Lima, PER	Temper	Gas
Talcahuano, CHI	Temper	Gas
Mejillones, CHI	Temper	Gas
Kansas City, USA	Bar Heating	Electric
Lima, PER	Bar Heating	Electric
Lima, PER	Bar Heating	Electric
Mejillones, CHI	Bar Heating	Electric
Mejillones, CHI	Bar Heating	Electric
Talcahuano, CHI	Bar Heating	Electric
Talcahuano, CHI	Bar Heating	Electric
Talcahuano, CHI	Bar Heating	Electric
Waratah, AUS	Bar Heating	Electric
Bilbao, Spain	Bar Heating	Electric
Sevilla, Spain	Bar Heating	Electric

Table A.2: Gas usage reduction percentages for each furnace from each decarbonization project type

Furnace Identifier	Efficiency	Oxyfuel	Electrification
Gas Bar Heating	0.05 - 0.25	0.10	1.0
Heat Treat	0.05 - 0.25	0.10	1.0
Temper	0.05	0.10	1.0

Table A.3: Capital expenditure values used for each furnace from each decarbonization project type

Furnace Type	Efficiency	Oxyfuel	Electrification
Gas Bar Heating	\$500,000	\$500,000	\$200,000 - \$5,000,000
Heat Treat	\$500,000	\$500,000	\$800,000
Temper	\$500,000 - \$750,000	\$500,000	\$200,000

Table A.4: Values of emissions factors used in analysis

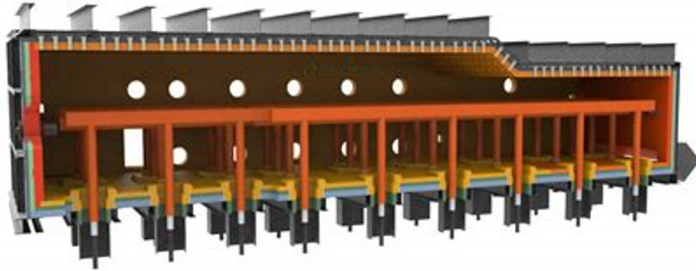
Factor Name	Value	Units	Source
Road transport	0.000233	ton CO2 / ton-mile	EPA emissions factor hub
Rail transport	0.000024	ton CO2 / ton-mile	EPA emissions factor hub
Ocean transport	0.000045	ton CO2 / ton-mile	EPA emissions factor hub
Air transport	0.001284	ton CO2 / ton-mile	EPA emissions factor hub
Waratah grid	0.00081	ton CO2 / kWh	NGER, Utility: Flow Power
Lima grid	0.00026	ton CO2 / kWh	Insight Sourcing Group
La Joya grid	0.00026	ton CO2 / kWh	Utility: SEAL/ENEL
Kansas City grid	0.0004358	ton CO2 / kWh	EPA, Utility: Evergy MO
Talcahuano grid	0.0003966	ton CO2 / kWh	Utility: ENGIE S.A.
Mejillones grid	0.0003966	ton CO2 / kWh	Utility: ENGIE S.A.
El Salto grid	0.000494	ton CO2 / kWh	Registro Nacional de Emisiones, Utility: CFE
Sevilla grid	0.00045091	ton CO2 / kWh	EU Residual Mix
Bilbao grid	0.00045091	ton CO2 / kWh	EU Residual Mix
Cilegon grid	0.0008	ton CO2 / kWh	KDL & PLN
Kamloops grid	0.0000186	ton CO2 / kWh	NIR, Utility: BC Hydro
Natural Gas	0.0502938	ton CO2 / GJ	EPA emissions factor hub
Cast High Cr	1.15	-	CRU

THIS PAGE INTENTIONALLY LEFT BLANK

# Appendix B

## Figures

Figure B-1: Example process furnaces



Example of walking beam furnace (bar heat)

---



Example of rotary hearth furnace (heat treat)



Example of induction reheat furnace

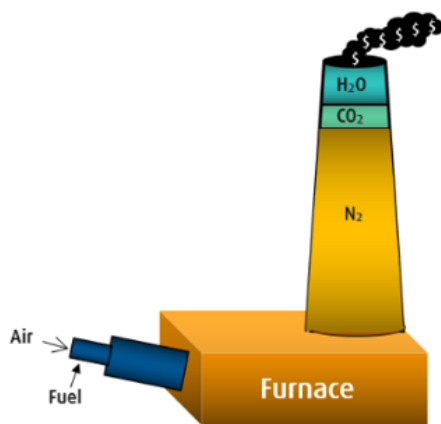
Figure B-2: Example of an oxygen lance installation for oxy-fuel technology. Source: Linde



**O<sub>2</sub> lance retrofit next to existing burners**

Figure B-3: Comparison of Air vs. Oxygen Combustion. Source: Linde

### Air Based Combustion

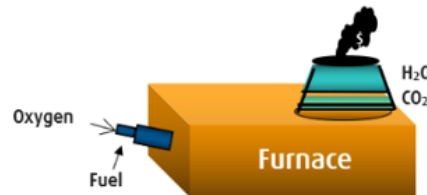


N<sub>2</sub> in air is heated and emitted in flue gas → Energy is wasted

### Oxygen Based Combustion

- 80% lower flue gas volume
- Up to 50% fuel and CO<sub>2</sub> savings\*
- Up to 90% NO<sub>x</sub> reduction\*
- Lower capital for flue gas treatment
- Fuel substitution: low C / low value fuels
- On-demand production increase

\*depending on baseline conditions



Eliminates heat up of N<sub>2</sub> in air → fuel savings

Figure B-4: The recuperator used in Molycop's USA plant



THIS PAGE INTENTIONALLY LEFT BLANK

# Bibliography

- [1] Jefferson Kaduvinal Abraham, Marcel Olbert, and Florin P Vasvari. “ESG Disclosures in the Private Equity Industry”. In: *SSRN* (2022). URL: <https://ssrn.com/abstract=4265171>.
- [2] “AIP ESG Policy Overview”. In: *americanindustrial.com/esg/* (Aug. 2022).
- [3] Binh Bui and Carolyn J Fowler. “Strategic responses to changing climate change policies: The role played by carbon accounting”. In: *Australian Accounting Review* 29.2 (2019), pp. 360–375.
- [4] Roger L Burritt, Stefan Schaltegger, and Dimitar Zvezdov. “Carbon management accounting: explaining practice in leading German companies”. In: *Australian accounting review* 21.1 (2011), pp. 80–98.
- [5] Shira Cohen, Igor Kadach, and Gaizka Ormazabal. “Why do Institutional Investors Request Climate Related Disclosures?” In: *Available at SSRN 4138869* (2022).
- [6] Anita Engels. “The European Emissions Trading Scheme: An exploratory study of how companies learn to account for carbon”. In: *Accounting, Organizations and Society* 34.3-4 (2009), pp. 488–498.
- [7] Gunnar Friede, Timo Busch, and Alexander Bassen. “ESG and financial performance: aggregated evidence from more than 2000 empirical studies”. In: *Journal of Sustainable Finance & Investment* 5.4 (2015), pp. 210–233. DOI: 10.1080/20430795.2015.1118917.
- [8] Delphine Gibassier and Stefan Schaltegger. “Carbon management accounting and reporting in practice: a case study on converging emergent approaches”. In: *Sustainability Accounting, Management and Policy Journal* 6.3 (2015), pp. 340–365.
- [9] Haslenda Hashim et al. “Optimization Model for Energy Planning with CO2 Emission Considerations”. In: *Industrial & Engineering Chemistry Research* 44.4 (2005), pp. 879–890. DOI: 10.1021/ie049766o. eprint: <https://doi.org/10.1021/ie049766o>. URL: <https://doi.org/10.1021/ie049766o>.
- [10] Rong He et al. “Corporate Carbon Accounting: A Literature Review of Carbon Accounting Research from the Kyoto Protocol to the Paris Agreement”. In: *Accounting & Finance* (2021). DOI: 10.1021/ie049766o. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/acfi.12789>.

- [11] Na Hongming et al. “Optimization of energy efficiency, energy consumption and CO2 emission in typical iron and steel manufacturing process”. In: *Energy* (July 2022).
- [12] Kwangbok Jeong et al. “Development of a multi-objective optimization model for determining the optimal CO2 emissions reduction strategies for a multi-family housing complex”. In: *Renewable and Sustainable Energy Reviews* 110 (2019), pp. 118–131. ISSN: 1364-0321. DOI: <https://doi.org/10.1016/j.rser.2019.04.068>. URL: <https://www.sciencedirect.com/science/article/pii/S1364032119302898>.
- [13] Jayanthi Kumarasiri and Abeyratna Gunasekarage. “Risk regulation, community pressure and the use of management accounting in managing climate change risk: Australian evidence”. In: *The British Accounting Review* 49.1 (2017), pp. 25–38.
- [14] Ki-Hoon Lee and Yong Wu. “Integrating sustainability performance measurement into logistics and supply networks: A multi-methodological approach”. In: *The British Accounting Review* 46.4 (2014), pp. 361–378.
- [15] Yu-Hao Lin et al. “Multi-objective optimization design of green building envelopes and air conditioning systems for energy conservation and CO2 emission reduction”. In: *Sustainable Cities and Society* 64 (2021), p. 102555. ISSN: 2210-6707. DOI: <https://doi.org/10.1016/j.scs.2020.102555>. URL: <https://www.sciencedirect.com/science/article/pii/S2210670720307733>.
- [16] Martina K Linnenluecke, Jacqueline Birt, and Andrew Griffiths. “The role of accounting in supporting adaptation to climate change”. In: *Accounting & Finance* 55.3 (2015), pp. 607–625.
- [17] Victoria Mills. “The Virtuous Cycle - A Framework for Strategic Energy Management”. In: ().
- [18] John Mulrow et al. “The state of carbon footprint calculators: An evaluation of calculator design and user interaction features”. In: *Sustainable Production and Consumption* 18 (2019), pp. 33–40.
- [19] Janek TD Ratnatunga and Kashi R Balachandran. “Carbon business accounting: the impact of global warming on the cost and management accounting profession”. In: *Journal of Accounting, Auditing & Finance* 24.2 (2009), pp. 333–355.
- [20] Hamidreza Shamsi et al. “Five-year technology selection optimization to achieve specific CO2 emission reduction targets”. In: *International Journal of Hydrogen Energy* 44.7 (2019), pp. 3966–3984. ISSN: 0360-3199. DOI: <https://doi.org/10.1016/j.ijhydene.2018.12.104>. URL: <https://www.sciencedirect.com/science/article/pii/S0360319918340722>.
- [21] Gillian Maree Vesty, Abby Telgenkamp, and Philip J Roscoe. “Creating numbers: carbon and capital investment”. In: *Accounting, Auditing & Accountability Journal* (2015).

- [22] Tian Weijian et al. “CO2 accounting model and carbon reduction analysis of iron and steel plants based on intra- and inter-process carbon metabolism”. In: *Journal of Cleaner Production* (May 2022).
- [23] Maria Cristina Zaccone and Matteo Pedrini. “ESG Factor Integration into Private Equity”. In: *Sustainability* 12.14 (2020). ISSN: 2071-1050. DOI: 10.3390/su12145725. URL: <https://www.mdpi.com/2071-1050/12/14/5725>.