EVALUATION OF ENVIRONMENTAL BURDENS OF STEEL MANUFACTURING IN PAKISTAN

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DEDICATION

Dedicated to my parents and beloved husband, without them this accomplishment can never be achieved.

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ABSTRACT

In Pakistan, the iron and steel industry is a leading manufacturing sector that plays a significant role in the national economy and social development. However, it consumes a significant amount of energy, produces various emissions, and generates wastages. An assessment of environmental burdens may enable us to review and improve the environmental outlook of this sector. However, there is limited research on this topic. Thus, the objective of this study is to evaluate the environmental impacts of a mini steel mill (manufacturing plant). The system boundary includes scrap melting, continuous casting, and rolling processes, representing the gate-to-gate steel production. Primary data were collected from a steel production plant, located in Islamabad, Pakistan. The study utilizes SimaPro V9.4 software as the modeling tool and the Recipe method to map various impact categories. The results were discussed at both the midpoint and endpoint levels. The scrap melting process was found with higher impacts in most of midpoint impact categories, including global warming, acidification, ozone depletion, etc. This was mainly because of the energy intensive nature of melting process and coal-based energy generation at the plant. After melting, it was the continuous casting process that generated more impacts, and it was followed by the rolling process. At the endpoint (damages) level, the scrap melting caused more damage to all three areas of protection (human health, ecosystems and resources) than any other production process. The results were calculated for the scenario if the plant is run with cleaner energy sources, such as solar energy. The results were compared with the baseline scenario to show the reduced environmental impacts and discuss potential decarbonizing opportunities. Overall, this study offers valuable insights for the policymakers, practitioners and related researchers who are seeking to promote sustainable and cleaner steel production, especially in the developing world.

Keywords: Environmental sustainability, Life cycle assessment, Steel industry, Decarbonizing, Manufacturing in Pakistan

CHAPTER 1. INTRODUCTION

1.1 Historical Background

The production of steel is profoundly influenced by the current political and environmental climate, which are dominated by concerns regarding carbon dioxide (CO_2) and other fossil greenhouse gas emissions in Europe and around the world. Automobiles, structures, and infrastructure are all manufactured by the steel industry, making it a significant economic and social force [1]. However, this sector consumes a great deal of energy and accounts for 6.7% of global carbon dioxide emissions [2].

According to the World Steel Association, the construction industry accounts for approximately 51% of global steel consumption. Steel plays a crucial role in the supply chains that connect ports, factories, warehouses, and final destinations by providing the structural framework for railways, aeroplanes, automobiles, and ships, as well as cranes used for a wide variety of applications[3]. Steel's significance extends far beyond its use in industry, as it is also essential to the development and expansion of societal structures. It is essential to sustaining a productive economy because it is used in the production of so many different products. This ranges from tires and furniture to railway ties and consumer goods.

1.2 Crisis of Pakistan Steel Mills.

The steel industry contributes five percent of Pakistan's gross domestic product, making it an important economic driver. As a cornerstone of economic and infrastructure development, which in turn define contemporary societies, it is of the utmost importance. The country's steel industry is vital, but it has struggled in recent years, putting its future in jeopardy.

In Pakistan, both imports and demand for steel have increased over the past five years. According to the Pakistan Bureau of Statistics, steel imports increased by 47% between 2016–17 and 2019–20, from $1.02 billion to $1.5 billion.[4]

During this period, steel demand increased significantly in Pakistan. From 2016 to 2019, the nation's crude steel production increased by 58%, from 3.6 million metric tons to 5.7 million metric tons.

Despite the challenges it faces, the Pakistani steel sector is prepared for significant growth because to ongoing government construction initiatives and ongoing development programmes such as the China-Pakistan Economic Corridor (CPEC). The huge undertakings in the fields of energy, transportation, and communication that comprise CPEC have all played a part in helping to contribute to this upbeat prognosis. In addition, the government's construction package, which was unveiled in April of 2020, has served as a big stimulant for the steel industry by injecting financing into a wide range of different building projects all around the nation. As a direct result of these factors, Pakistan's steel production has seen a significant uptick in recent years. According to the Pakistan Bureau of Statistics, Pakistan's annual steel production touched a new high of 5.2 million tons in the fiscal year 2020-21, marking a 14.6% increase from the previous year and establishing a new record.

The demand for steel products in Pakistan is primarily being driven by the construction of new buildings and infrastructure, as well as the expansion of the industrial sector. Despite a 17% decline in steel prices due to the closure of several firms, Pakistan is still a prominent player in the global steel industry, ranking sixth in steel production. This is despite the fact that steel prices have fallen. It is abundantly obvious that Pakistan's steel manufacturing industry is having a hard time keeping up with the rising demand for steel, which keeps increasing [5].

The global output of steel has increased substantially over the years, from 1,149 million tons in 2005 to 1,625 million tons in 2015 and now to 1,875 million tonnes. According to the World Steel Association, China, India, Japan, the United States, Russia, South Korea, Germany, Turkey, Brazil, and Iran were the top 10 steel-producing nations in 2019. In contrast, Pakistan rates only 39 out of 50 countries in terms of its steel output (0.18 percent of the global total)[6].

Customers, suppliers, and members of the public are particularly concerned about the environmental problems that exist in developing countries. These organizations have a strong interest in making sure that companies, and manufacturers in particular, do everything they can to lessen the impact that their operations and products have on the environment [7].

1.3 Process of steel Manufacturing

The first stage in producing steel is melting various waste materials, including HMS, GI, pulverized refuse, and end cuttings. Steel rebars are produced by feeding a variety of scrap metals into a furnace to produce molten steel.

Using electricity from the main grid and a transformer, the induction furnace can attain temperatures between 1650 and 1700 degrees Celsius. Pouring molten steel into a ladle, where impurities are removed, produces a high-quality final product. After undergoing any necessary treatments in the ladle, the molten steel is transferred through the open gate into the tundish. After being heated in a copper mold, billets are solidified in a tundish's continuous casting machine (CCM) by passing through water-cooled rollers. After being sized with a gas torch, the billets are left to air-cool. The chemical laboratory verifies the alleged composition of each sample.

After billets are delivered to the rolling facility, they are cold rolled with coal as the energy source. As shown in Figure 1, billets are sent to a rolling facility where they endure additional processing before becoming steel rebars.

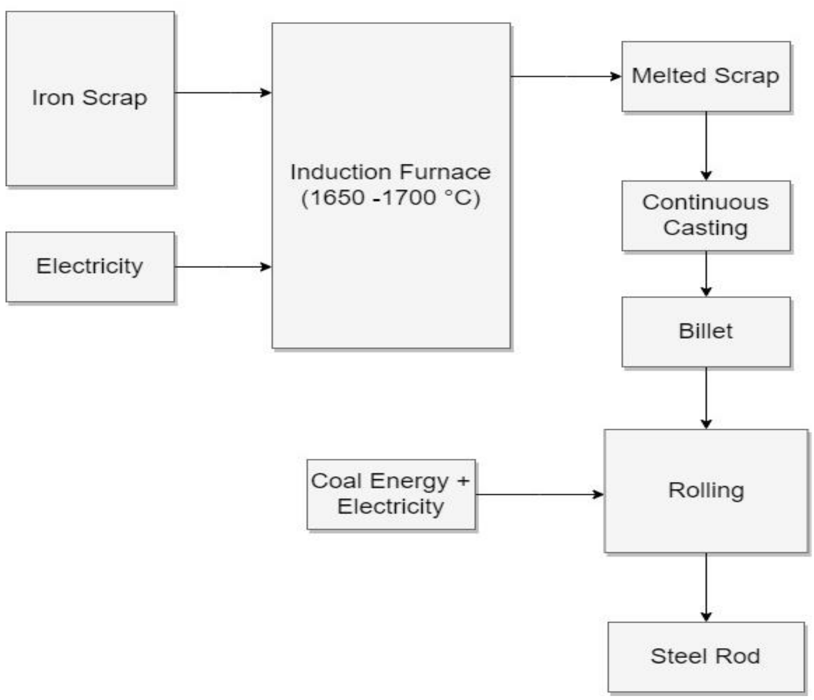

Figure 1Manufacturing Process in Mini steel industry.

1.4 Environmental Impact Assessment

The concern for nature and the environment is increasingly gaining significance within contemporary culture. An increasing number of individuals are contemplating strategies to mitigate their ecological footprint and optimize the sustainability of the natural resources and land they consume. As a result of this phenomenon, it is unsurprising that Environmental Impact Assessments (EIAs) are being increasingly carried out for a wide range of projects, plans, and programs. The Environmental Impact Assessment (EIA) is commonly recognized as a tool or procedure that methodically analyses and assesses the possible effects of proposed projects, plans, and programs on many aspects of the environment, including physical, chemical, biological, cultural, and socioeconomic factors. Consequently, it may be inferred that Environmental Impact Assessment (EIA) has the qualities of being thorough and multidisciplinary[8].

Every EIA commences with a "project screening," which identifies and eliminates insignificant activities or intentions from further consideration. Existing EIA laws in a country are frequently a factor in the screening procedure [9].

After concluding a scoping and baseline study, it is important to consider key receptors, significant effects, and project alternatives. The project's proponents can now share information with the public, consultants, government agencies, and interest groups [10].

In addition to this, it is essential to consider the potential consequences of one's actions and evaluate the importance of such forecasts. The next stage is called "mitigation," and it consists of taking actions to either avoid, decrease, or make up for the negative impacts of the situation. When all of the data have been gathered, an Environmental Impact Statement, also known as an EIS, is drafted and then subjected to quality control checks. Following the examination of the EIS, the relevant agency makes a phone call. Post-decision monitoring is a continuing examination of environmental or socioeconomic elements that takes place before the final stage of auditing, in which actual results are contrasted with expected outcomes. This review is accomplished by the methodical collection of data across several locations and times [11]

Life Cycle Assessment (LCA), also known as a three-dimensional environmental approach, Attributional Life Cycle Assessment (LCA) technique, Reliability-based Life Cycle Assessment (LCA) methodology, Material Flow Analysis (MFA), Substance Flow Analysis (SFA), Carbon

Footprint (CF), Water Footprint (FF), and Risk Assessment (RA) are some of the EIA methodologies that may be utilized.

1.5 Life Cycle Assessment

LCA is used to evaluate the environmental impact of a product or service (hence "product"); the evaluation is function-based and considers all phases of the product's life cycle. It is beneficial for both developing new products and identifying points in the life cycles of extant products where environmental impacts can be reduced. Its primary purpose is to facilitate comparisons across a vast array of products, processes, and systems, as well as across the many phases of a product's life cycle. [12]

1.5.1 Three-dimensional environmental approach

A three-dimensional Environmental Approach tries to solve the key sustainability concerns connected with manufacturing from a pollution avoidance standpoint, taking into consideration technology, energy, and material as the three essential components of production [13]

1.5.2 Attributional LCA method

It is demonstrated that decisions based on the findings of the Attributional LCA approach have specific quantifiable benefits, which are initially evaluated using the Attributional LCA approach [14]

1.5.3 Substance Flow Analysis

Substance flow analysis (SFA) aims to quantify the movement and accumulation of a specific substance, such as mercury, or a class of substances, such as inorganic nitrate compounds, in the environment [15]

1.5.4 Risk Assessment:

A risk assessment (RA) focuses on analyzing the potential for damage caused by an installation (such as a nuclear power facility) or the dangers posed by a chemical product [16]

1.5.5 Material Flow Analysis

• A material flow analysis (MFA) monitors the passage of materials in a region's economy. Typically, this refers to a basic substance, such as paper, glass, concrete, or plastic[17].

1.5.6 Carbon Footprint:

A carbon footprint (CF) is a measurement of the entire influence on the environment that a particular product, human activity, or organization has. CFs may be calculated using several methods [18].

1.5.7 Water footprint:

A water footprint (WF) assesses, among other things, the impacts of one's water consumption and environmental exposures in relation to water quality[19]

1.5.8 Steel Sector of Pakistan and EIA

Pakistan's steel industry is highly disorganized. However, nearly 80% of the market is controlled by the top 20 enterprises in the organized sector. Pakistan consumes approximately 9 million tons of steel annually. Compared to the global average, Pakistan's per capita consumption of steel is significantly lower than the global average, demonstrating the enormous growth potential of this industry. Due to its impact on manufacturing, infrastructure, and building construction, the steel industry is vital to Pakistan's economic development [20]

These industries must also take responsibility for the damage they inflict to the natural environment because of the vast amount of product they produce. It is reasonable to argue that Pakistan's overall strategy for producing energy has a negative impact on the environment since these components make up most of the country's energy mix. The production of glass in Pakistan's many sectors requires a significant amount of energy, making those industries the primary source of the country's climate change problems [20].

Recent environmental impact evaluations in Pakistan focused on the matchstick industry as well as coal-fired power stations as potential sources of pollution [21]and on managing waste of hospitals [22]. However, there is no published research on the industries that consume the majority of Pakistan's energy and resources. Since this is the phase that has the greatest impact on the environment, it is crucial to analyze the manufacturing phase of steel production in depth and offer solutions to reduce environmental impacts. Therefore, all relevant stakeholders in Pakistan should concentrate on closing the knowledge gap represented by this research gap.

1.6 Problem Statement

The steel industry is responsible for a significant quantity of energy consumption and pollution during the production process. This has a negative effect on the natural world as a direct consequence. Since there are no current inventory data for steel manufacturing in Pakistan, it is also difficult to analyze and enhance environmental performance. This complicates the analysis and improvement of environmental performance. In addition, there is no impact assessment related to the steel industry being conducted in Pakistan.

In order to improve the environmental and energy sustainability of Pakistan's steel industry, a Life Cycle Assessment will be conducted for the very first time in Pakistan's industrial sector.

1.7 Research Objectives

- The primary objective of this study was to identify and develop inventory data specific to the steel industry in Pakistan.
- A country-specific LCA was conducted, focusing on Pakistan's mini-steel sector, to gain a deeper understanding of the environmental impacts associated with all phases of the steel-making process.
- Additionally, the study aim to compare the environmental implications of the steel industry's reliance on the electric grid versus a solar system for its energy needs. By assessing the environmental impact of these different energy sources, the study sought to offer valuable insights into the potential environmental benefits and drawbacks of using renewable energy in the steel manufacturing process.

1.8 Thesis Outline

In the first chapter of the thesis, context, the steelmaking process, environmental impact assessment, and various methodologies, the Steel sector of Pakistan, the problem statement, and the primary objective of the study are briefly discussed. In Chapter 2, I conduct a literature review germane to my thesis to identify and emphasize the extant knowledge gaps. The steel industry is also extensively discussed in this chapter. The methods used in this study to achieve these objectives are discussed in Chapter 3, and Chapter 4 provides a summary of the research findings. In the concluding chapter, titled "Conclusion," the implications of this analysis are discussed, along with the study's significance, limitations, and recommendations for future research. Figure 2 illustrates the structure of this thesis.

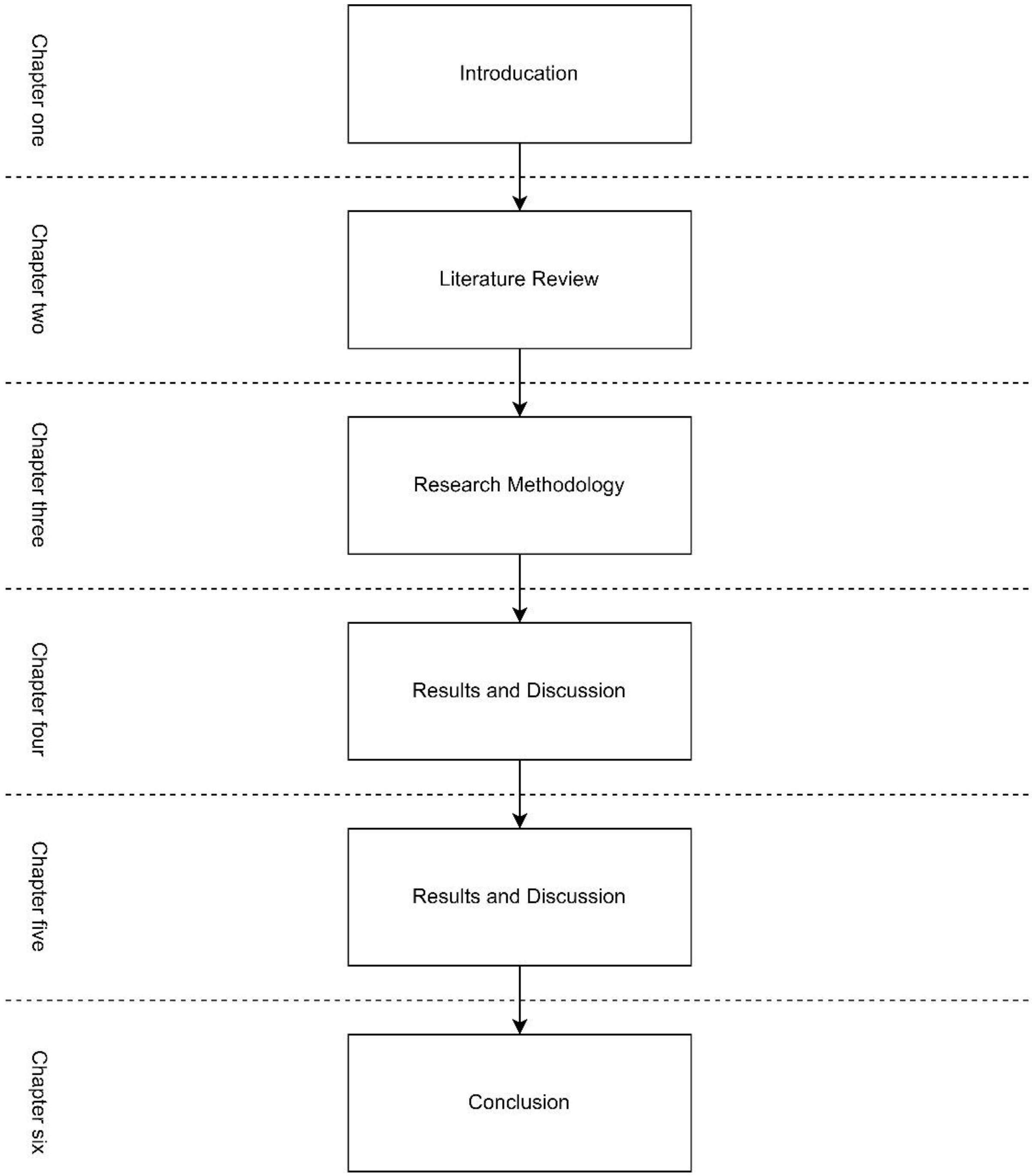

Figure 2 Thesis Structure

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

As discussed in the preceding chapter, in recent years numerous methods for evaluating environmental impacts have been developed, each with its own advantages and disadvantages. Due to its adaptability, Life Cycle Assessment (LCA) is widely utilized in academia and government. This chapter explains what LCA is, why it is significant, how it can be utilized, how it is performed, and what each step of the process entails. Numerous studies on the life cycle assessment (LCA) of glass packaging solutions have been published to learn more about its relevance to the steel industry and to identify any knowledge deficiencies.

2.2 Life Cycle Assessment

Researchers use life cycle assessment (LCA) to evaluate the environmental effects of a product, resource, or service over the span of its entire life cycle (SABS ISO, 1998). Demand for natural resources, as well as emissions and solid refuse, are examples of environmental inputs and outputs, respectively. The extraction of basic materials, their production, their use, and their disposal or recycling at the end of their useful life are all components of the technological system that constitutes the life cycle. Often, "cradle-to-grave" is used to characterize the scope of a life cycle assessment (LCA). In addition to standards, a professional code of conduct has been established for LCA methods [23].

LCA generally has four components. These include:

2.2.1 Goal and scope

The first step of an LCA analysis is defining the objectives and parameters of the study. The point of the research is outlined below. The context, intended audience, and justification for the research are all described in this section. In addition, the study's parameters are specified. Included are a breakdown of the scope of the study, the systems under review, the functional unit, the systems under review, the system boundaries, allocation approaches, data requirements, data quality requirements, key assumptions, impact assessment methodology, interpretation strategy, and reporting format. The objective of the study must be specified, including the research query, intended application, and anticipated audience. Include boundaries, implications, data requirements, and the functional unit (FU) in the scope section. The FU should provide the following information about the function supplied, amount, duration, and quantity: Rephrased as: "What?" What exactly is it? How much time remains? How precisely?[24]

2.2.2 Inventory

The results of a Life Cycle Inventory (LCI) study are based on data that is collected, examined, and calculated. At the end of the study, a technical system flow model is made. We figure out the pollution, energy needs, and material flows for each process. To consider the whole life cycle of the product, these numbers will be moved up or down to the functional unit set out in the goals and scope.

2.2.3 Impact Assessment

In the Life Cycle Impact Assessment (LCIA), category indicators are used to look at the product or production system from an environmental point of view. The LCIA also gives details for the next step, which is called "interpretation."

There are four required parts of LCIA for comparable claims: For comparative assertions, there are four mandatory elements of LCIA:

- selection of impact categories, category indicators and models
- assignment of the LCIA results (classification)
- calculation of category indicator results (characterization)
- data quality analysis

The following elements are optional:

- calculating the magnitude of category indicator results relative to a reference value (normalization)
- grouping
- weighting

2.2.4 Interpretation

At this stage of the life cycle assessment process (according to ISO 14043), the results are evaluated considering the aim and scope description, conclusions are reached, the limits of the results are given, and suggestions are made. LCAs are iterative processes because the procedures that make up an LCA are often repeated whenever new data are received or as systems are better understood. You could find out more about which inputs and outputs have the most significant effect on the environment around you if you do an analysis of the impact. With this knowledge in mind, improved data for those inputs and outputs might be obtained, which would enhance inventory analysis. The results of the LCA ought to be in line with the study's goals and the criteria it uses.

To summaries, the "goal and scope" will establish the boundaries of the study, the "inventory" will include a comprehensive listing and categorization of the various elements involved in the cycle, the "impact assessment" will describe and quantify the impacts, and the "improvement assessment" will provide the foundation for improving the existing cycle. The LCA may be approached from two major perspectives, which are as follows:

- as a conceptual thought process that guides the selection of options from design and improvement; and
- methodologically, as a way to build a quantitative and qualitative inventory of environmental burdens or releases, to evaluate the impacts of those burdens or releases, and to identify alternatives to improve environmental performance [25].

LCA approaches and procedures aid in decision-making by considering the product's production, use, and eventual disposal. It details the environmental impact at each level, allowing you to make a financially and ecologically informed decision.

2.3 TYPES OF LCA

There are three different types of LCA.

They are:

- Conceptual LCA – Life Cycle Thinking,
- Simplified LCA; and
- Detailed LCA.

The different types can be used in different ways and have strengths and weaknesses, depending upon the context in which they are used.

2.3.1 Conceptual LCA

The most fundamental application of LCA is conceptual LCA, which evaluates environmental factors using a simple list of qualitative items. Commonly, the results of a conceptual LCA are communicated in the form of qualitative remarks, images, flow diagrams, or simple scoring systems that emphasize the materials or components with the greatest impact on the environment and explain why this is the case. Conceptual LCA results cannot be used for advertising or public dissemination. Nonetheless, they may assist policymakers in determining whether an item provides an environmental benefit. Occasionally, "Conceptual LCA" is substituted with "Life Cycle Thinking" [26].

2.3.2 Simplified LCA

Simplified LCA is a way to look at the environmental impact of something, like a product or a process, throughout its entire life cycle. It takes a more basic approach by using general information and common methods for details like energy production [27]

Here's how it works in simpler terms:

- **Screening:** First, we figure out which parts of the whole process are really important or where we don't have enough information.
- **Simplifying:** Once we know what's important, we focus on those parts and don't get bogged down in the less important stuff.
- **Assessing reliability:** Lastly, we double-check to make sure that simplifying things doesn't make our results not trustworthy. We want to be sure our conclusions are still good even though we simplified some things.

2.3.3 Detailed LCA

A Detailed Life Cycle Assessment (LCA) is like taking a really close look at the environmental impact of something, like a product or service. But it's a bit more complicated and involves five steps:

- **Planning:** First, you need to plan what you're going to do. This means setting clear goals, deciding exactly what you're studying (the product or service), and figuring out where the boundaries of your study are. You also need to decide what environmental factors you're going to look at and how you're going to collect data.
- **Screening:** Next, you do a preliminary run of the LCA to get an initial idea of what's going on. If you find any issues or problems within a plan, it can be adjustable.

- **Data Collection and Treatment:** This step is all about gathering information. You might measure things, talk to experts, read books and research papers, do some math, or use databases. Once all the data is gathered it can be organized in a table.
- **Evaluation:** Now comes the part where you make sense of all that data. You group it into different categories based on its impact, like pollution or energy use. Then, you add up the numbers within each category, put everything on the same scale, and weigh how important each category is.

So, Detailed LCA is like a detailed investigation of how something affects the environment. Make a plan, take a first look, gather the data, and then figure out the big picture by sorting, adding, and ranking the data [28].

2.4 Impact assessment

When doing a Detailed Life Cycle Assessment (LCA), there are two more important steps:

- **Sensitivity Analysis:** This means checking how sensitive your results are to different factors or changes. It helps you see if small changes in your data or methods could make a big difference in your final conclusions.
- **Improvement Priority and Feasibility Assessment:** Once you know the environmental impact, you can figure out what changes would help the most and are doable. This helps decide what improvements to focus on.

Now, the planning stage of LCA is super crucial because it changes the whole study. If you start by doing a quick check (the screening LCA), it makes planning the rest of the project much easier. It helps ensure you're on the right track from the beginning.

2.5 Optional Steps in LCA

In addition to the four main steps of Life Cycle Assessment (LCA), there are three other optional steps that can help us better understand the environmental impacts: [29]

2.5.1 Normalization:

This step helps us figure out how bad the environmental damage is by comparing it to a standard measure. It's like putting the impacts into perspective, so we can see how they relate to a specific unit, making it easier to understand.

2.5.2 Grouping:

Grouping is a way to organize and prioritize the results. We group similar impacts together, like grouping all pollution impacts or impacts on different areas of the environment. This helps us focus on what's most important.

2.5.3 Weighting:

Weighting takes the different environmental impacts and gives them scores based on their importance. Then, these scores are combined into a single number, making it easier to compare and understand the overall environmental impact of different scenarios. This is typically done for the most critical impact categories.

2.6 WHO USES LCA AND WHY?

There are mainly four groups of people or organizations who use LCAs:

- **Businesses and Companies:** They use LCAs to understand the environmental impact of their products or processes.
- **Government and Regulatory Agencies:** These are government organizations that use LCAs to make rules and regulations related to the environment.
- **Non-Governmental Organizations (NGOs):** These are groups like environmental organizations and consumer advocacy groups. They use LCAs to check if businesses and governments are doing things that are good for the environment.
- **Consumers:** This includes regular people like us and also governments when they buy things. They use LCAs to make choices that are better for the environment when buying products or services[30]
- **Industry and other commercial enterprises:** In The vast majority of cases, a company is held legally liable for a product for a limited period of time. Nonetheless, legislation and public opinion are beginning to shift in the direction of holding manufacturers accountable for the effects their products and services have on the environment ("chain responsibility"). This aspect may be difficult to regulate, but the consequences for a company's or product's reputation could be severe if it is not.

Life cycle assessment (also known as LCA) is a technique that can be used to determine whether a product has a positive or negative impact on the environment. Having this information may assist public dialogues about the influence that the company has on the environment. The results of a life cycle assessment (LCA) may facilitate communication with a variety of stakeholders, including environmental organizations, communities, interested and affected parties, and government authorities. LCA is most frequently applied to the business processes of product development and design, as well as policymaking, communication, and negotiation.

2.6.1 Product Improvement

LCAs are prepared by manufacturers to serve as a basis for incorporating new features and capabilities into their products and production processes. This data is often developed for internal use and is kept hidden from public access as part of the company's strategy for maintaining its market edge. The advantage to both existing and future market participants is substantial, making the high cost of carrying out this task worthwhile[31]

2.6.1.1 Product Design

LCA is a helpful tool for comparing "old information" to forecasts and predictions for new product and service development, which is a common practice. Despite the thin line that distinguishes refinement from new design, life cycle assessments (LCAs) for products may be an effective justification tool for investments in infrastructure renewal and other areas. Formulation of Company Policy

In certain domains, LCAs have the potential to make substantial contributions to the formulation and revision of business policy. For instance, a company's approach to refuse management may be influenced by suggestions for primary material selection. Possible outcomes include decreased production of hazardous refuse, increased recycling opportunities, and less industrial waste sent to landfills. In terms of materials management and public opinion, LCAs may also dissuade businesses from utilizing raw materials and substances.

2.6.1.2 Product Information

In rare cases, government agencies may need product details for licensing or legal compliance reasons. This need may be met by LCA data, and the "documentary audit trail" generated by the analysis can serve as a means for verifying the accuracy of both the data and the conclusions made about the product.

2.7 Government and regulatory bodies

Life Cycle Assessments (LCAs) are crucial for promoting sustainable development. When governments use information from these studies, it helps them make decisions that benefit both the environment and the economy. Governments can use LCAs in various ways, such as labeling environmentally friendly products, implementing refund systems, offering subsidies, and creating policies.

- **Eco-labeling (Environmental Labeling):** Although South Africa doesn't currently have a well-established system for eco-labeling like Europe and North America, it may consider adopting one in the future. Eco-labeling is a way to indicate that a product is environmentally friendly if it meets specific environmental standards.
- **Non-Governmental Organizations (NGOs):** LCAs provide valuable information to NGOs, allowing them to inform their members and advocate for positive changes. Currently, LCAs are not widely recognized among NGOs in South Africa, and there are concerns about potential bias in these studies. This may be due to a shortage of LCA experts and a lack of clarity from the government regarding its intentions for using LCAs. In the future, LCAs might be subject to South Africa's access to information laws. If NGOs can collaborate with businesses to make essential LCA data transparent and accessible, it will facilitate the sharing of product information without complications.

2.8 Consumers

LCA data can help consumers by providing a better knowledge of the many purchase alternatives accessible to them. Because of the general public's lack of understanding of LCA, it is difficult to utilise it to make educated judgements about whether to buy environmental responsible items and the value of such products. Due to a lack of resources and experienced people, LCAs are not widely used in South Africa. LCAs on a broad range of consumer goods and services will give vital information to government and non-profit consumer advocacy groups in the future. Sharing these discoveries with the wider public may help shape consumer preferences and guide purchase choices. A poorly made washing machine, for example, might waste a lot of water and energy while adding to the worldwide phosphate pollution issue.

Data may be used to show how modifications and improvements can minimize pollution in the short and long term, enabling customers to make better selections based not only on price, but also on running expenses, emission potential, and environmental effect. This helps to achieve national environmental policies and goals.

2.9 LCA Standards

In terms of standards, Life Cycle Assessment (LCA) falls under the ISO 14000 series. The key documents within this series include:

- ISO 14040 – This document, published in 1997, covers the fundamental principles and framework for conducting Life Cycle Assessments.
- ISO 14041 – Published in 1998, this standard deals with the analysis of Life Cycle Inventory, which involves gathering data about the environmental impacts at each stage of a product's life cycle.
- ISO 14042 – Released in 2000, this standard focuses on the assessment of the environmental impacts throughout the life cycle, known as Life Cycle Impact Assessment.
- ISO 14043 – Also published in 2000, this standard addresses the interpretation of Life Cycle Assessment results, helping to draw meaningful conclusions from the collected data.

These standards provide guidelines and a structured framework for conducting LCA studies, ensuring consistency and reliability in assessing the environmental impacts of products and processes[32]

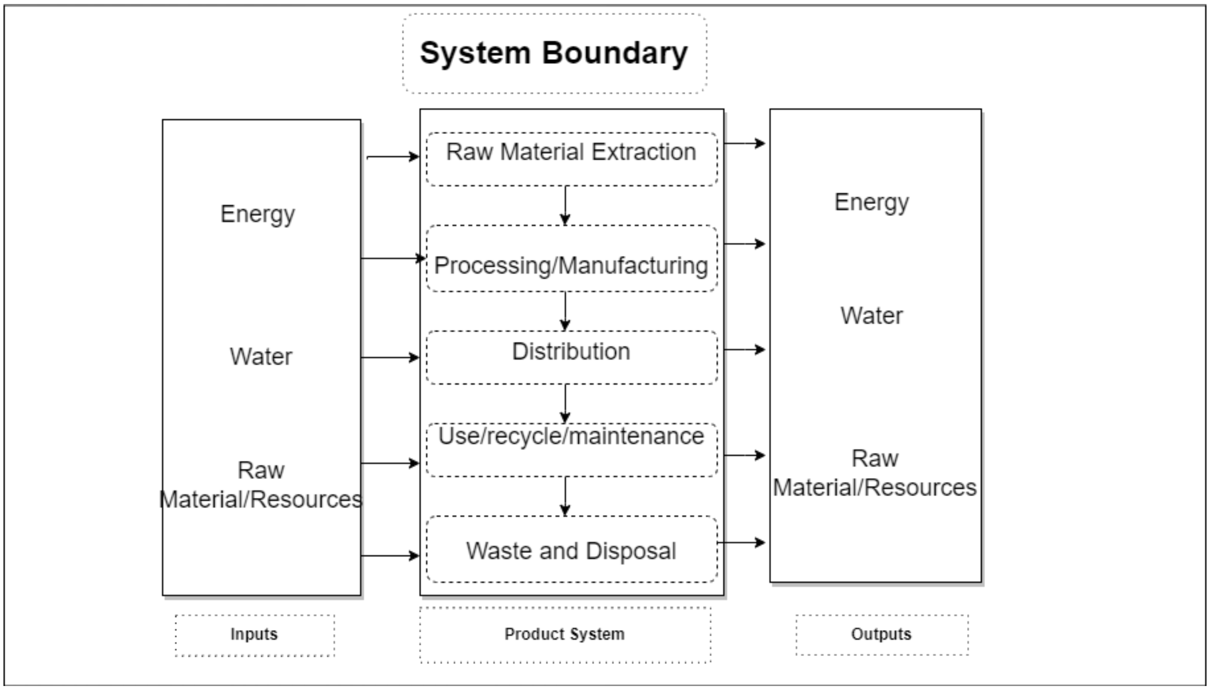

Figure 3 Life Cycle Assessment Framework based on ISO 14040 Model

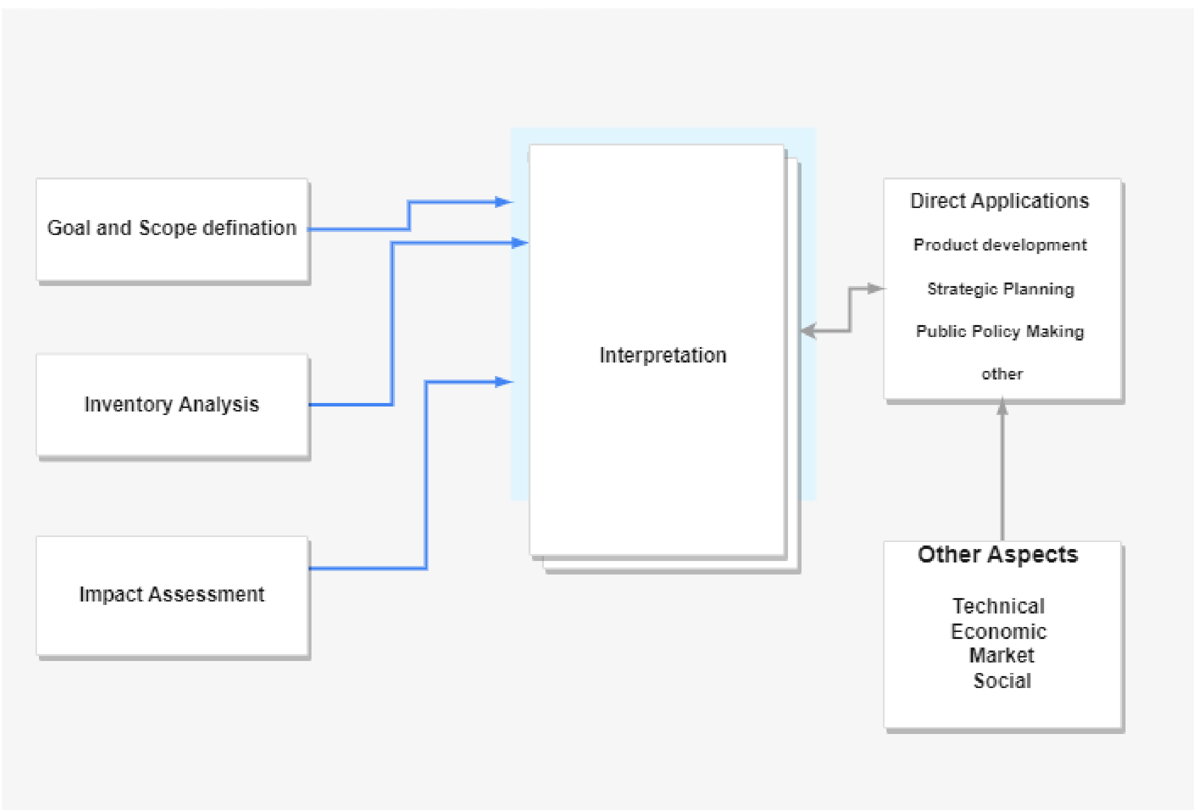

Figure 4 Life Cycle Assessment procedure.

2.10 Strengths and Weaknesses of LCAs

2.10.1 Strengths

There are some important points to know about Life Cycle Assessments (LCAs) based on nearly two decades of work in Europe and North America:

- **Growing Databases:** Over the years, we've collected a lot of information in Europe and North America about materials, energy, and transportation. This information can help South Africa speed up its LCA efforts. While some data is specific to developed countries, much of it can be used in South Africa with a bit of adjustment.
- **Impact on Understanding:** LCAs can help people understand how their actions affect the wider community. Because LCAs provide data in numbers, it's easier to compare and analyze things.
- **Foundation for Sustainable Policies:** Sustainable policies and actions rely on using life cycle thinking. This means considering the whole life cycle of products and processes. It's like looking at the entire journey from beginning to end.
- **Universal Standards:** As LCAs become more common, they'll create standards that everyone can use to compare things scientifically. This will help set benchmarks for performance.
- **Environmental Monitoring:** LCAs can detect and track environmental pollution through air, water, and soil. Using scores with trustworthy data helps identify and follow these pollutants.
- **Beyond Environmental Impact Assessments**: LCAs go further than traditional Environmental Impact Assessments. They use diagrams to show how things move through different stages and processes, which helps people understand better.
- **Effective Decision-Making:** Using scores with reliable data and impact categories makes decision-making more effective and well-informed. It helps figure out what actions or products are better for the environment [33]

2.10.2 Weaknesses

There are some drawbacks and limitations when using Life Cycle Assessments (LCAs), and it's important to be aware of them:

- **Normal Operating Conditions:** LCAs mainly consider how things work under normal circumstances. They don't handle unusual events like accidents or spills well. For those, we need to use risk assessments alongside LCAs.
- **Limited and Questionable Data**: Sometimes, there's not enough data, or the data quality isn't great. This can be a problem, especially in South Africa, when comparing local studies to detailed ones from developed countries.
- **Data Shortages and Impact Categories:** Some types of impacts, like harm to ecosystems or human health, lack enough data. This makes the environmental scores less reliable.
- **Confidence in Data:** How much we trust the data greatly affects how useful the environmental scores are. It also depends on the skills of the local LCA experts.
- **Worst-Case Assumptions:** LCAs often assume the worst possible environmental effects, which might not always be accurate. For instance, they might assume all emissions are harmful, even if they're neutralized by other substances.
- **Linearity of Impact:** LCAs assume that if there's more pollution, the impact is worse. This doesn't consider variations in local conditions or critical limits.
- **Time-Consuming:** Doing a detailed LCA can take a long time, which can delay projects and decisions.
- **Changing Results:** LCAs need to be updated regularly because new information and technologies can make older results outdated.
- **Design Flaws:** If there are no clear rules and standards for how to conduct an LCA, the results can be flawed. It's essential to have guidelines and peer reviews to maintain high standards in LCA studies.

2.11 Impact Assessment Methods

The critical volumes method, one of the earliest strategies for assessing the effects of LCAs, began by classifying emissions into emission compartments (air, water, and soil). This technique is obsolete because it disregards the persistence and ultimate resting places of contaminants (their effect pathways). The CML (Centrum voor Milieukunde Leiden) 92 method was the first of its kind to concentrate on the effects of emissions, laying the foundation for numerous subsequent developments. Historically, the CML 92 technique was favored by Europeans. After being brought up to date with CML 2002, the LCA manual became a practical blueprint with step-by-step instructions for implementing LCA. The contexts in which the following common approaches to conducting impact assessments are most beneficial are listed below[34].

The different impact assessment methods used in various regions:

2.11.1 European Impact Assessment Methods:

- CML-IA Baseline
- CML-IA Non-Baseline
- Ecological Scarcity 2013
- EF 3.0 Method (Adapted)
- EF Method (Adapted)
- EN 15804+A2 Method
- Environmental Prices
- EPD 2018
- EPS 2015d
- EPS 2015dx

2.11.2 North American Impact Assessment Methods:

- BEES+
- TRACI 2.1

2.11.3 Global Impact Assessment Methods:

- Impact World+ Endpoint
- Impact World+ Midpoint
- ReCiPe 2016 Endpoint (E)
- ReCiPe 2016 Endpoint (H)
- ReCiPe 2016 Endpoint (I)
- ReCiPe 2016 Midpoint (E)
- ReCiPe 2016 Midpoint (H)
- ReCiPe 2016 Midpoint (I)

Besides these methods, there are other impact assessment approaches available, some of which focus on specific issues like water footprint. It's important to note that some of these methods have been replaced or are no longer in widespread use.

2.12 LCA Softwares

Several software tools, like GaBi, SimaPro, OpenLCA, and AMEE, can be really helpful for this task. They help us assess how products or processes affect the environment. There are different methods for this, such as AADP, CML, EDIP, and more. These methods are often called "midpoint" or "endpoint" approaches.

- Midpoint approaches look at the short-term effects, like how much carbon dioxide increases over 100 years for climate change.
- Endpoint approaches estimate the long-term impact, like how many lives could be affected or species might go extinct.

Each method has its own list of impact categories and indicators. For example, the ReCiPe method, which is a midpoint approach, looks at things like climate change, ozone depletion, and human toxicity, and it measures them in specific units, like kilograms of CO2 equivalent.

When doing a study, you choose the impact categories that make the most sense for that study. And you can compare the results using different methods by normalizing the impacts to fit those categories. This helps us understand and compare the environmental effects more easily[35]

There are several software tools available to help with conducting Life Cycle Assessments (LCAs), each with its unique features and best-fit user profiles. Let's take a closer look at three prominent LCA software tools: OpenLCA, GaBi, and SimaPro.

2.12.1 OpenLCA:

OpenLCA is an open-source LCA solution, making it an attractive option for those who are just starting in the world of LCAs and have a limited budget. However, it offers functionalities that can be valuable to users with a more technical background.

- One of the significant advantages of OpenLCA is its flexibility. Users can adjust Life Cycle Inventory (LCI) datasets, allowing them to tailor the environmental datasets to match the specific production process and inputs of their product. This flexibility is particularly useful when dealing with complex or unique products and processes.
- It also provides a range of analytical features to assess the environmental impact and performance of a product comprehensively. Users can dive deep into the environmental

datasets they add to the application, enabling advanced supply chain analysis. This means you can explore the environmental implications of your product at a detailed level.

- However, it's important to note that many LCA tools rely on LCI databases to measure impact. OpenLCA provides access to various databases, but it's essential to be aware that not all of these databases are free. Therefore, users should consider the cost associated with accessing specific databases[36]

Best Fit with OpenLCA: OpenLCA is best suited for those starting in the field of LCAs and individuals or organizations with budget constraints. However, its technical capabilities make it appealing to more advanced practitioners, LCA experts, and sustainability consultants.

2.12.2 GaBi:

GaBi is a well-established LCA tool that has been around since the mid-'90s and is widely used, especially in Germany. Similar to SimaPro, GaBi is a technically extensive solution with many potential add-ons for sustainable product development. GaBi is commonly used by LCA experts and sustainability consultants. It has its specific LCI database and allows users to conduct LCAs according to different standards. In addition to traditional LCAs, GaBi supports Life Cycle Costing and Life Cycle Reporting, making it a versatile tool for holistic sustainability assessments.

Best Fit with GaBi: GaBi is often considered a tool that best suits LCA experts and those seeking to perform complex and in-depth analyses of their product footprints. It provides the necessary tools for conducting comprehensive assessments.

2.12.3 SimaPro:

SimaPro is one of the most well-known and widely used LCA software tools, with a history spanning 30 years. It is available both as desktop software and a cloud-based solution, although the cloud-based option may not include all features. SimaPro is a technical application with numerous optional add-ons, making it incredibly versatile. It allows users to delve deeply into LCA calculations for products and production processes. This deep analysis capability sets it apart from other tools.

It is primarily used in academic settings and by experienced LCA consultants. It is designed for seasoned LCA experts who need to model and analyze complex life cycles systematically. With

SimaPro, users can measure the impact of their products and services across all stages of their life cycles.

Best Fit with SimaPro: SimaPro is best suited for academic use and for experienced LCA professionals who require advanced tools for conducting intricate life cycle analyses. It is a comprehensive software solution that is ideal for in-depth assessments.

Both OpenLCA and SimaPro have their advantages. OpenLCA is a freeware open-source tool known for being easy to use and capable of handling various aspects of LCA, including environmental and economic aspects. It provides access to different databases, making it flexible for various needs. SimaPro, on the other hand, is one of the most popular and widely used LCA software programs, offering high flexibility and transparency in generating results[37].

These tools have been recommended by experts for various types of LCA assessments, including life cycle assessment, social life cycle assessment, life cycle costing, carbon and water footprint analysis, product environmental footprint (PEF), and environmental product declarations (EPD). Researchers have even compared the results obtained from GaBi and SimaPro, highlighting their effectiveness and reliability in conducting LCA studies.

In summary, the choice of LCA software tool depends on your specific needs, budget, and level of expertise. OpenLCA is an excellent option for beginners and those with limited budgets, while GaBi and SimaPro are better suited for advanced users, experts, and consultants who require more extensive functionalities and capabilities for conducting comprehensive life cycle assessments. Each tool has its strengths, and selecting the right one will depend on your specific requirements and objectives for LCA studies [38].

Life Cycle Assessment (LCA) research conducted in the steel sector was scrutinised in great detail so that a complete perspective could be provided. The International Stainless Steel Forum was responsible for a significant LCI research project that analysed the whole life cycle of stainless steel products, beginning with the extraction of raw materials and ending with their disposal. This study included information from firms based in Europe, the United States of America, Korea, and Japan in an attempt to provide international data for use in further case studies. The data focused on stainless steel goods, including long and flat items, of austenitic and ferritic grades, and manufactured from either ore or scrap steel as the source material.

An independent cradle-to-gate LCI research of Canadian integrated and scrap-based steel mills was carried out in the early 1990s. This study was carried out in addition to the global LCI programmers. These studies are necessary for the advancement of sustainability activities within the steel industry since they give critical insights into the environmental repercussions of industrial practices [39]

2.13 Review of related LCA studies

To present a comprehensive overview of Life Cycle Assessment (LCA) studies in steel manufacturing, an extensive literature review was conducted. One notable LCI study was carried out by the International Stainless-Steel Forum, focusing on cradle-to-gate assessments of stainless-steel products. This study aimed to provide global data for further case studies and encompassed data from European, North American, Korean, and Japanese producers. The data pertained to long and flat stainless-steel products, including austenitic and ferritic grades, produced from both ore and scrap steel.

Before the international LCI initiatives, in the early 1990s, a separate cradle-to-gate LCI study was conducted, specifically examining Canadian integrated and scrap-based steel mills. These studies contribute valuable insights into the environmental impacts of steel manufacturing practices and play a crucial role in advancing sustainability efforts within the industry[39].

Another study discusses the application of Life Cycle Assessment (LCA) in the steel industry, focusing on the efforts of the American Iron and Steel Institute (AISI) to promote and implement LCA practices. LCA is described as a tool to analyze the environmental impacts of product and service systems, consisting of four key elements: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation. AISI initiated its LCA program in 1994, involving training and education, conducting LCA studies of steel products, participating in LCA projects related to steel, and supporting the development of LCA in the industry[40].

In a separate study, the utilization of Life Cycle Assessment (LCA) within the steel industry takes center stage, with a focus on the American Iron and Steel Institute's (AISI) endeavors to endorse and integrate LCA methodologies. LCA is characterized as a tool for scrutinizing the ecological consequences of product and service systems, encompassing four essential components: delineating goals and scope, conducting an inventory analysis throughout the life cycle, evaluating environmental impacts, and interpreting the results. AISI initiated its LCA program back in 1994, encompassing activities such as education and training, conducting LCA studies on steel products, active involvement in steel-related LCA projects, and supporting the broader adoption of LCA within the industry[41].

In another research endeavor, the spotlight turns to the iron and steel sector, a prominent energy-intensive industry responsible for a substantial share of global and Australian carbon dioxide (CO_2) emissions. This particular study delves into the potential for curbing CO_2 emissions within the industry by implementing carbon capture and storage (CCS) technologies. The research examines the feasibility and associated costs of integrating CCS into existing steelmaking facilities in Australia. The investigation estimates the expenses linked to capturing CO_2 emissions from various emission sources in both an integrated steel mill and a scrap mini mill [42]

Table 1 gives us 12 reviewed studies specifically related to the environmental impacts of steel rebars manufacturing and. the description, results, and shortcomings of each study are described briefly.

Sr. No	Description	Short comings	References
1	This paper presents a Life Cycle Assessment (LCA) study conducted on the iron and steel production industry in Turkey. The study employs SimaPro software and the IMPACT 2002+ impact assessment method to evaluate the environmental impacts of various processes involved in steel production, as well as the impacts associated with different final steel products. The analysis is conducted from a cradle-to-gate perspective, with a functional unit of 1 ton of final steel product. The paper	**Results:** Among the processes evaluated, the steel making process stands out as having the highest total environmental impact, followed closely by sintering. The most significant impacts are observed in the categories of human health and climate change. Surprisingly, coke production, while having the highest impact on the depletion of non-renewable energy sources, contributes negatively to the climate change category due to the avoided external energy consumption resulting from coke oven gas production on-site. When assessing	[43]

	identifies key environmental impact categories, highlights the processes with the most significant impacts, and explores different production scenarios' effects on environmental outcomes. Additionally, it offers recommendations for sustainable production practices.	different final products, hot rolled coil emerges as having the most considerable total environmental impact, followed by hot rolled wire rod, billet, and slab. Additionally, the study explores the impact of various production scenarios involving different ratios of semi-finished (billet and slab) and finished (wire rod and coil) products. It reveals that the highest impact occurs when all products are finished, with hot rolling accounting for approximately 24% of the total environmental impacts for one ton of product. The assessment results lead to suggestions for sustainable production practices. **Shortcomings:** It is important to acknowledge that this LCA study relies on certain assumptions and data accuracy collected from the study plant, despite close collaboration with plant managers. Future research should prioritize conducting sensitivity analyses to evaluate the influence of these parameters. Additionally, the study emphasizes the impact on Respiratory Inorganics and Global Warming categories, recommending priority in investment planning to reduce these environmental impacts.	

		However, it does not delve into specific strategies or technologies for reducing these impacts, leaving room for further exploration and practical recommendations in subsequent studies.	
2	This paper focuses on conducting a Life Cycle Assessment (LCA) of steel production in Poland, specifically comparing integrated steel production and electric arc furnace (EAF) routes. The study employs the ISO 14044 standard for LCA methodology, utilizing SimaPro 7.3.3 software and the Ecoinvent database. It provides a comprehensive analysis of environmental impacts associated with various steelmaking processes, emphasizing pollution prevention methods for the most environmentally polluting aspects of steel production. The research draws on data from existing steel plants in Poland, offering insights into greenhouse gas emissions, fossil fuel consumption, mineral and metal depletion, electricity consumption, and their impacts on environmental categories.	**Results**: The findings of the LCA indicate significant environmental impacts associated with steel production in Poland. In the integrated steel production route, the production of pig iron in blast furnaces is identified as the primary contributor to greenhouse gas emissions and fossil fuel consumption. Additionally, the iron ore sintering process is found to be the largest source of dust and gas emissions, mineral consumption, and metal depletion within the national iron and steel industry. In the electric arc furnace route, electricity consumption emerges as the primary factor driving greenhouse gas emissions and fossil fuel consumption. Furthermore, the study explores the potential benefits of alternative fuel consumption in an iron ore sinter plant, suggesting that this approach could help reduce greenhouse gas emissions. However, it notes that the use of	[44]

		charcoal as an alternative fuel may have negative consequences such as increased land use and total energy demand. **Shortcomings:** Despite its valuable insights, the study has certain limitations. It relies on data obtained from 2010 production results, which might not fully represent current practices in the steel industry. Additionally, the study focuses primarily on the environmental impacts up to the factory gate and does not consider the entire cradle-to-grave life cycle of steel. Future research could expand the scope to include downstream phases such as product use and end-of-life disposal. Finally, the study highlights the need for pollution prevention methods related to raw material substitutions but does not provide detailed strategies or recommendations for their implementation, leaving room for further investigation and policy development in this area.	
3	This study focuses on addressing the significant issue of CO_2 emissions from steelworks, which constitute a substantial portion of industrial CO_2 emissions in China. The objective is	**Results:** The study identifies key influencing factors contributing to CO_2 emissions in steelworks, such as the CO_2 emission factor of Blast Furnace Gas (BFG), consumption rates for	[45]

	to identify the key factors influencing CO_2 emissions from steel production and propose measures for emissions reduction. The research utilizes life cycle inventory (LCI) data for iron and steel products to establish the relationship between CO_2 emissions and input variables. The Tornado Chart Tool is employed to quantify how changes in LCI input variables affect CO_2 emissions. The study then calculates the mean sensitivity of each input variable and ranks them to identify the most influential factors. Based on these findings, the paper proposes various measures to reduce CO_2 emissions from steelworks, such as optimizing processes and recycling blast furnace gas (BFG).	various stages of steel production (e.g., continuous casting, hot rolling), and the hot metal ratio of Basic Oxygen Furnace (BOF) steelmaking. Based on these findings, the research proposes several effective measures to reduce CO_2 emissions, including CO_2 capture from BFG, reducing the hot metal ratio in BOF, enhancing the recycling of BFG, and optimizing the product structure. These measures have the potential to significantly reduce CO_2 emissions in the integrated steel industry. **Shortcomings:** While this study offers valuable insights into reducing CO_2 emissions in steelworks, it has certain limitations. Firstly, the effectiveness and feasibility of these proposed measures may vary among different steelworks, and specific economic and environmental benefits are not fully explored due to a lack of data. Moreover, the study focuses primarily on CO_2 emissions and does not address other environmental impacts, limiting the comprehensiveness of its analysis. Additionally, the research could benefit from further investigations into the economic viability of the proposed measures and their applicability under	

		varying conditions in different steelworks. Nevertheless, this study provides a useful framework for identifying crucial environmental factors and potential mitigation strategies for decision-makers in the steel industry.	
4	This study focuses on the steel industry in China, which is a major contributor to pollutant emissions, particularly from the sintering process. China has introduced stringent ultra-low emission standards for particulate matter, SO2, and NOx in the steel industry, akin to those in the coal-fired power industry. The paper examines a novel ultra-low emission treatment process for sintering flue gas emissions, including various technologies like electrostatic precipitation, ozone oxidation, wet desulfurization, wet denitration, condensation dehumidification, and wet electrostatic precipitation. The study assesses the environmental impact and economic costs of this treatment process using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methods.	**Results:** Using a functional unit of 1 ton of sinter and a "cradle to gate" system boundary, the study conducts a life cycle assessment (LCA) and life cycle cost analysis (LCC) of the ultra-low emission treatment process. The environmental impact of the process is quantified at 0.1811, while the total economic cost is estimated at 172.79 RMB. Within this cost, the internal cost accounts for 34.64 RMB, and the external cost comprises 138.15 RMB. The study identifies key inputs responsible for environmental impact, such as sodium sulfite in the wet denitration process and electricity and liquid oxygen in the ozone oxidation process. **Findings:** The study's findings reveal that the package of flue gas cleaning methods effectively achieves stringent new emission standards for sintering flue gas, demonstrating the feasibility and effectiveness of this approach in	[46]

		reducing emissions. However, it also highlights that the new treatment processes themselves carry some environmental impact and financial costs. Wet denitration and ozone oxidation are identified as the most significant contributors to the environmental load, accounting for 42% and 32% of the total environmental impact, respectively. Moreover, the analysis indicates that sodium sulfite, electricity, and liquid oxygen are key inputs driving both financial and environmental costs. In conclusion, this study underscores China's commitment to reducing emissions in its steel industry and provides valuable insights into the environmental and economic performance of the latest ultra-low emission treatment process. It suggests potential avenues for further improvement, including technological innovations or material substitution to reduce key input consumption. Importantly, the study highlights the potential for similar technological innovations to be applied in other countries, contributing to the sustainability of the global steel industry.	

5	This paper presents a case study on the cogeneration of energy from waste gases generated during steelmaking processes, focusing on coke oven and Linz-Donawitz converter gases. The study is based on data obtained from an existing plant in Northern Spain, where engines are adapted to operate with these waste gases, and steam is generated using coke gas, converter gas, and natural gas. The environmental impact of this cogeneration process is assessed through Life Cycle Assessment (LCA), considering various environmental factors and providing insights into the benefits and drawbacks of using low-calorific-value and potentially toxic gases. The study explores the environmental benefits of reducing natural gas consumption and offers endpoint characterization factors for different impact categories.	**Results:** The research assesses various aspects of the cogeneration process, including operational parameters, energy production, emissions of NOX, SO2, and CO2, as well as discharges and wastes. The study also calculates environmental impact indicators, both midpoint and endpoint, for humans, ecosystems, and resources. The key environmental effects identified include contributions to climate change, ionizing radiation, human toxicity, and depletion of fossil and ozone-depleting substances. The results consistently indicate that utilizing these waste gases offers an environmental benefit. In the best scenario, the use of waste gases reduces the consumption of natural gas significantly, leading to a reduction in natural resource use and ozone depletion. **Shortcomings:** While this study provides valuable insights into the environmental benefits of utilizing waste gases for cogeneration in the steel industry, there are certain limitations. The analysis primarily focuses on environmental impacts and does not consider economic aspects, such as cost savings from using steel gas instead of	[47].

		natural gas or revenue from selling the energy produced. Furthermore, the study acknowledges that there are other factors, including downstream process competition for waste gases and their potential for alternative product valorization, which have not been fully explored. Future work could involve combining cost information with environmental data to create a more comprehensive decision-making tool. Additionally, as the study is based on a specific plant in Northern Spain, the generalizability of the findings to other regions and plants may require further investigation. Nevertheless, the study provides essential insights into the potential benefits of waste gas utilization in the steel industry, supporting sustainable practices and decision-making in the sector.	
6	This study conducts a comprehensive Life Cycle Assessment (LCA) of steel production in an integrated German steel plant. The assessment covers the entire steel production process, including the blast furnace, basic oxygen furnace, and casting rolling, and considers emissions from direct, upstream, and by-product sources.	**Results:** The study categorizes emissions into three groups: direct emissions, upstream emissions, and by-product emissions. Notable direct emissions contributors are the power plant (48% in terms of global warming potential), the blast furnace (22% in global warming potential), and the sinter plant (79% in photochemical ozone creation potential). Upstream	[3]

	The functional unit is set to 1 kg of hot-rolled coil, and the system boundaries are defined as cradle-to-gate, encompassing both the steel plant and upstream processes. The study utilizes the GaBi software and the CML 2016 database, incorporating primary data from the production year 2018.	processes, when combined, significantly impact categories such as acidification potential (69%) and abiotic depletion potential fossil (110%). The findings highlight the growing importance of the supply chain in achieving necessary reductions in environmental impact. The study underscores the significance of addressing emissions not only within steel production processes but also throughout the entire supply chain. **Shortcomings:** While this study provides valuable insights into the environmental impact of steel production, it faces certain limitations. One major limitation is the lack of detailed data on single steel production processes from existing literature, which restricts the ability to conduct a more granular analysis of impacts categorized by relevance. Additionally, the study focuses on a specific German steel plant, which may limit the generalizability of its findings to other regions or plants with different configurations and production methods. Moreover, the study does not delve into economic aspects, such as the cost implications of implementing environmental improvements in the	

		steel production process. Future research could consider expanding the scope of data collection and analysis to address these limitations and provide a more comprehensive picture of the environmental and economic aspects of steel production.	
7	This study conducts an extensive Life Cycle Assessment (LCA) of steel production in the largest integrated EU steel mill located in Taranto, southern Italy. The LCA encompasses the entire steel production process, from raw material extraction to solid steel slab production, with a cradle-to-casting plant gate approach. The analysis aims to identify environmental hotspots and potential avenues for improvement. The study highlights the substantial production of solid waste, particularly slag, which could be repurposed as secondary raw materials. Energy waste within the steelmaking process is also identified as a potential area for improvement. The impact categories are influenced by energy consumption and emissions' toxicity, but a detailed analysis suggests that LCA alone may not be	**Results** The results of the Life Cycle Assessment (LCA) shed light on several key findings and associated shortcomings. The inventory phase of the LCA identifies significant waste production, particularly in the form of BOF and BF slag, offering opportunities for waste reuse and sustainability improvements within the steel production process. The study also highlights a higher energy demand compared to other studies, suggesting potential energy-saving measures through technology upgrades. However, implementing these upgrades would necessitate substantial capital investments. Notably, the blast furnace and coke oven operations emerge as the most impactful phases, aligning with environmental restrictions imposed due to health concerns in the area. Human toxicity impacts, primarily linked to the coke oven phase, underscore the	[39]

	sufficient for toxicity assessments and should be complemented by site-specific studies. The results serve as a foundation for pollution control measures and waste reutilization scenarios to enhance the steel mill's sustainability.	importance of conducting site-specific studies to comprehensively understand toxicity-related impacts. Despite these valuable findings, the study has some shortcomings. Firstly, it has a limited scope as it primarily focuses on a specific segment of the steel production cycle, excluding downstream processes like rolling operations. Expanding the scope to encompass these downstream processes would offer a more holistic view of the environmental sustainability of steel production. Secondly, the study highlights challenges in using LCA as the sole tool for toxicity assessments, emphasizing the need for complementary site-specific studies. This underscores a limitation in relying solely on LCA for assessing certain environmental impacts. Additionally, the paper does not delve into economic considerations, such as cost-effectiveness or potential economic benefits associated with pollution control measures and waste reuse scenarios. Integrating economic analysis would make the findings more practical for decision-makers. Furthermore, while the study mentions the potential for energy exchange	

		between the steel mill and a neighboring power plant, it does not explore this aspect in detail. A more in-depth analysis of energy exchange and its environmental advantages could provide valuable insights. Finally, the study's limited regional focus on the Taranto steel mill in Italy may constrain the generalizability of its findings to other regions or steel plants with different characteristics. Expanding the analysis to a broader context would enhance the overall understanding of steel production sustainability.	
8	This paper focuses on the application of Life Cycle Assessment (LCA) to evaluate the environmental impact of the steel production process in the Tangshan stainless steel industry in China in the year 2009. The study assesses energy and material consumption throughout the production process. Three different impact assessment methods, namely EDIP, CML2001, and Eco-indicator 99 (EI99), are used to evaluate environmental impacts, including global warming potential and human health effects. The paper identifies key processes in steel production that contribute to	**Results:** The Life Cycle Assessment (LCA) results of the Tangshan stainless steel industry offer valuable insights into the environmental impacts of various processes within the sector. The study identifies iron-making, hot rolling, and sintering as the most energy-intensive and environmentally impactful processes, with iron-making standing out as the process with the most significant environmental and human health impacts. It also highlights key findings such as the relatively low iron utilization rate and recyclability of iron ore, indicating a need for improvements in scrap recycling and resource efficiency. Additionally,	[48]

	high energy consumption and environmental harm and provides recommendations for cleaner production.	processes like iron-making, sintering, and hot rolling are noted for their high energy consumption, making them crucial areas for developing cleaner production methods. Notably, blast furnace iron-making is found to have a substantial negative impact on human health, global warming, and photochemical ozone formation, prompting recommendations for technology, equipment, and management improvements to mitigate these environmental impacts. **Shortcomings:** While the study provides valuable insights, it has some notable shortcomings. Firstly, it lacks specific quantitative data on the environmental impacts assessed using the three different impact assessment methods (EDIP, CML2001, and EI99). Providing numerical results would enhance the paper's clarity and usefulness, allowing for a more precise understanding of the environmental effects. Secondly, the study is limited to a specific steel production facility in Tangshan in 2009, potentially not representing the current state of the industry or the broader steel sector in China. An update or broader analysis could provide more relevant insights	

		into the evolving steel industry. Thirdly, while the paper identifies areas for improvement, it does not delve into specific strategies or technologies that could be implemented for cleaner production. Providing actionable recommendations would be beneficial for stakeholders in the steel industry seeking to reduce their environmental footprint. Lastly, the paper could benefit from discussing the limitations and uncertainties associated with LCA in the context of steel production, such as data quality and assumptions made during the assessment. Addressing these aspects would enhance the robustness and credibility of the study's findings.	
9	This research focuses on assessing the environmental impact of China's crude steel production, a sector with significant water consumption and pollution issues. The study employs a combination of Life Cycle Assessment (LCA) and Water Footprint (WF) analysis to comprehensively evaluate the environmental burdens and potential improvements in the steel industry. The LCA examines various aspects of environmental performance,	**Results:** The study yields several key findings related to the water footprint and environmental impact of China's steel industry. Notably, it reveals that the gray water footprint, primarily associated with issues like aquatic eutrophication and carcinogens, surpasses the blue water footprint in the context of steel production. To mitigate this, optimizing indirect processes such as iron ore mining, magnesium oxide production, transportation, and electricity generation emerges as a	[49]

	while the WF analysis assesses water consumption and pollution, particularly gray and blue water footprints. The study emphasizes identifying key factors contributing to environmental burdens and proposes strategies for improvement	critical factor in reducing the gray water footprint. The study also identifies specific pollutants, including COD, Cr (VI), phosphate, BOD5, Hg, As, nitrogen oxides, particulates, and sulfur dioxide, as key substances influencing environmental improvements in the steel industry. Additionally, the research underscores the importance of accurate monitoring indicators for water footprints and suggests that the strategic location of steel industry facilities should consider regional water resources and transportation infrastructure. Furthermore, the study emphasizes the imperative of controlling pollutant emissions and offers specific recommendations for controlling various pollutants in steel production processes. **Shortcomings:** While the study provides valuable insights into the environmental aspects of China's steel industry, it acknowledges several limitations. One limitation is the need for further investigation into alternative steel production technologies beyond converter technology to offer a more comprehensive assessment. Additionally, the research predominantly focuses on the	

		environmental dimension and does not delve deeply into the economic and social dimensions of sustainable steel production, which are equally important for a holistic understanding. The study recognizes regional variations in water stress but does not provide an extensive analysis of these variations or their potential implications. In terms of future work, the research suggests addressing limitations related to dynamic databases, spatial disparities in water footprint evaluation, and the need for comprehensive sustainability assessments. It is essential to note that the study does not offer specific quantitative targets or policy recommendations for reducing the environmental burden of China's steel industry, leaving room for further policy-oriented research.	
10	This study focuses on conducting a Life Cycle Assessment (LCA) to analyze the energy consumption and environmental impact of steel production in a typical Chinese iron and steel industry. The research specifically aims to identify which processes within the steel production route contribute the most	**Results:** The study highlights several key findings related to the environmental impact of steel production processes in a typical Chinese iron and steel industry. Firstly, it identifies the blast furnace (BF) as the most significant process within the steel production route, contributing notably to CO2 and CO emissions.	[50]

	to environmental burdens. By evaluating different processes, the study aims to provide insights into the major factors affecting CO_2 and CO emissions, as well as their impact on global warming potential (GWP) and photochemical ozone creation potential (POCP).	Additionally, the BF process was found to consume the highest amount of energy among the studied processes. Furthermore, BF emerged as the major contributor to global warming potential (GWP) and photochemical ozone creation potential (POCP), emphasizing its substantial impact on these environmental factors. Interestingly, while BF was the primary source of GWP and POCP, the sintering process was responsible for the most significant impact on acidification potential (AP) and human toxicity potential (HTP). **Shortcomings:** While the study provides valuable insights into the environmental impact of steel production processes in a typical Chinese steel plant, it does not offer specific recommendations for mitigating these environmental burdens. Furthermore, the research relies on inventory data from 2009 production results, potentially lacking representation of the most current practices and technologies in the steel industry. The study also lacks an exploration of potential strategies or technologies to address the environmental impact of blast furnace processes or sintering. Additionally, it	

		primarily focuses on a specific steel production plant, which may not fully capture the variations and practices across different steel plants in China. Lastly, the paper is limited in scope as it does not address the economic or social dimensions of sustainability in the steel industry, concentrating solely on environmental impacts.	
11	This paper addresses the environmental concerns related to the production of steel balls used as grinding media in mines, with a focus on a specific producer, Craster International in Zimbabwe. The study employs a Life Cycle Assessment (LCA) to assess the environmental impacts associated with the production of these steel balls. The primary concern is the emission of greenhouse gases during production, particularly carbon dioxide, sulfur dioxide, nitrous oxides, and other trace greenhouse gases, which can have adverse effects on the environment, including flora, fauna, water bodies, and human health. The research methodology involves interviews, questionnaires, direct observations,	**Results:** The study underscores the importance of comprehending the life cycle environmental impacts associated with steel balls used as grinding media, particularly the need to mitigate greenhouse gas emissions during their production. It employs a Life Cycle Assessment (LCA) diagram to visually highlight the stages of the production process that contribute most to environmental burdens, with a specific focus on extraction and production phases. Additionally, the research identifies the presence of trace elements across all processes and emphasizes their potential environmental implications. Furthermore, the study raises concerns regarding employee exposure to hazardous emissions during steel and steel ball production, emphasizing the necessity for safety measures and mitigation strategies. It	[51]

	and measurements to gather relevant data.	offers practical recommendations, including preventive machinery maintenance, regular medical checkups for employees and the community, and the use of sensing and alarm systems to enhance safety. **Shortcomings:** While the study provides valuable insights into the environmental impact of steel ball production, it predominantly concentrates on this aspect, neglecting other crucial dimensions of sustainability, such as social and economic considerations. While it identifies areas for potential environmental impact reduction, it does not offer specific strategies or technologies to achieve these reductions, leaving practical implementation open-ended. Moreover, the paper mentions the need for further studies without delving into potential research methodologies or specific research topics for subsequent investigations. The research's specificity to one producer in Zimbabwe may limit its generalizability to other steel ball manufacturers or regions, reducing its broader applicability. Finally, the study lacks a comprehensive analysis of	

		mitigation strategies for greenhouse gas emissions and disposal scenarios for waste generated during production, which could have practical implications for the industry.	
12	This study focuses on the ship recycling industry in Bangladesh, which plays a crucial role in providing scrap metal for domestic steel products, particularly rebar for construction. The paper employs a Life Cycle Assessment (LCA) approach to evaluate the energy consumption and emissions associated with ship recycling in Bangladesh, from the transportation of retired ships to the final processing of steel scraps. It also examines the environmental impacts of producing secondary rebar from these scraps, comparing it to primary rebar production from virgin iron ore. The study assesses various unit operations within the recycling process, analyzing their effects on Global Warming Potential (GWP), resource use, human health, and ecosystem quality.	**Results:** The study reveals that secondary rebar production from ship scraps offers substantial environmental benefits, including significant energy savings of 16.5 GJ of primary energy per ton of rebar and a noteworthy reduction of 1965 kg of CO2eq in greenhouse gas emissions per ton of rebar compared to primary rebar production from virgin ore. However, it points out that activities beyond the ship recycling yards, particularly in the rerolling stage, are responsible for the most significant environmental damage. Furthermore, adverse environmental impacts within ship recycling, such as local pollution and health risks, primarily stem from the use of gas torches for cutting. To mitigate these impacts, the study recommends enhancing safety measures, protective gear, training, and cutting technology. Additionally, it suggests conducting a social life cycle assessment to evaluate the industry's social sustainability, encompassing	[52]

		worker safety, training, medical facilities, and socio-economic factors. **Shortcomings:** While the study provides valuable insights into the environmental aspects of ship recycling, it lacks an in-depth analysis of economic and social dimensions, which are crucial for a comprehensive sustainability assessment. Additionally, it identifies areas for improvement but does not offer specific strategies or technologies to address the environmental and health impacts identified, leaving practical implementation open-ended. The research primarily focuses on the ship recycling industry in Bangladesh, limiting the generalizability of its findings to other regions or countries with different practices and technologies. While acknowledging the need for a social life cycle assessment, the paper does not provide a framework or methodology for conducting one. Lastly, the study acknowledges that the ship recycling industry is not non-polluting but suggests that focusing on specific aspects of the process, such as cutting methods and protective gear, can lead to significant environmental and health improvements.	

2.14 Research Gap

A detailed review of the previously discussed LCA studies for steel production in integrated steel plants. A large industrial facility that includes all stages of steel manufacturing is known as an integrated steel mill. The refining of raw materials such as iron ore, coal, and limestone is often the first step in the manufacturing of iron and steel. Blast furnaces for smelting iron, converters for refining it into steel, and rolling mills for molding the steel into a range of goods are all found in these mills. The assessment borders specified the phases of the life cycle that were examined, and the assessment levels indicated whether the review was product-, process-, or sector-based. 10 of the 12 research were conducted in developed nations, with only 2 studies conducted in developing countries, Zimbabwe, and Bangladesh.

This shows that there have been only a few studies on the environmental effects of steel production and manufacturing in developing nations. Furthermore, no study to our knowledge has studied the environmental effects of a mini-steel company. An integrated steel mill completed all the examined investigations, with an emphasis on the product and process. Furthermore, six research exclusively used the midpoint strategy, whereas only two used both the midpoint and endpoint approaches. Six studies make use of both primary and secondary data sources. Six studies used gate-to-gate assessment boundaries, while two used cradle-to-grave assessment borders. According to the literature, there is no study that provides decarbonization suggestions. Only one study advises that renewable resources be used.

This is the first complete technical and scientific Life Cycle Assessment (LCA) carried out in a developing country like Pakistan, where assessing and analyzing the environmental implications of steel manufacturing is critical. This study focuses on Pakistan's mini-steel sector, and for the first time, an extensive LCA was performed to examine the environmental implications associated with all stages of steel manufacturing, from raw materials to finished product. There are hypotheses given regarding the extent to which there will be visible changes in the environmental effects as a result of the utilization of renewable resources.

Table 1Comprehensive Analysis of reviewed studies

Sr. No.	Country		Assessment Levels			Type of Steel Plant		Software		Assessment Approach			Data Sources		Assessment Boundaries				Year	Ref
	Developed	Developing	Sector	Product	Process	integrated	Mini	Sima Pro	Gabi	Midpoint	Impact 2002+	Endpoint	Primary	Secondary	Cradle-to-Gate	Cradle-to-Grave	Cradle-to-Cradle	Factory In Gate-		
1	✓				✓	✓		✓			✓			✓	✓				2015	[43]
2	✓				✓	✓		✓		✓		✓	✓	✓		✓			2013	[53]
3	✓			✓		✓		✓					✓	✓	✓				2010	[45]
4	✓			✓		✓		✓		✓			✓		✓				2020	[46]
5	✓			✓		✓		✓		✓		✓	✓					✓	2019	[47]
6	✓				✓	✓			✓				✓				✓		2021	[3]
7	✓				✓	✓		✓		✓			✓	✓	✓				2016	[39]
8	✓				✓	✓			✓				✓	✓				✓	2012	[48]
9	✓				✓	✓		✓		✓			✓			✓		✓	2018	[49]
10	✓				✓	✓		✓			✓		✓	✓				✓	2014	[50]
11		✓			✓	✓		✓		✓			✓					✓	2015	[51]
12		✓			✓	✓		✓			✓		✓	✓				✓	2016	[52]
Total Score	10	2	0	3	9	12	0	10	2	6	3	2	11	7	4	2	1	5		

CHAPTER 3. METHODOLOGY

In recent times, people have become more concerned about how products and industries affect the environment. This has led to a greater focus on "life cycle thinking" in environmental policymaking. One industry that has a big impact on the environment is the steel industry, especially in countries like Pakistan, which are still developing. To better understand and reduce the harmful effects of this industry, a study was conducted.

This chapter explains how the study was done. It all started with selecting a steel industry in Pakistan and then looking at how it impacts the environment. The study used a method called Life Cycle Assessment (LCA), which helps us measure the environmental effects of products and industries.

The LCA calculations were done using a software called SimaPro version 9.4, and they followed a set of rules called the ISO 14040 standard. This standard breaks down the study into four main steps:

- **Goal and Scope Definition**: This is where we decide what we want to study and what aspects of the steel industry's impact on the environment we want to look at.
- **Inventory Modeling:** In this step, we gather data and information about the steel industry, like how much energy it uses, what materials it uses, and what kind of pollution it produces.
- **Impact Assessment:** Here, we analyze all the data we collected to understand how the steel industry affects the environment. We look at things like air and water pollution, energy use, and more.
- **Interpretation:** This is the final step where we make sense of all the information we gathered. We try to understand the big picture of how the steel industry impacts the environment in Pakistan.

In a nutshell, this chapter explains how a study was done to understand the environmental impact of the steel industry in Pakistan. The study followed a structured process, using specific software and standards to collect data, analyze it, and draw conclusions about how the industry affects the environment.

3.1 Goal of the study

The aim of the study is to Perform LCA on a mini steel industry in SimaPro which is helpful to evaluate the environmental impacts.

3.2 Objectives

- The primary objective of this study was to identify and develop inventory data specific to the steel industry in Pakistan.
- A country-specific LCA was conducted, focusing on Pakistan's mini-steel sector, to gain a deeper understanding of the environmental impacts associated with all phases of the steel-making process.
- Additionally, the study aimed to compare the environmental implications of the steel industry's reliance on the electric grid versus a solar system for its energy needs. By assessing the environmental impact of these different energy sources, the study sought to offer valuable insights into the potential environmental benefits and drawbacks of using renewable energy in the steel manufacturing process.

3.3 Scope of the study

The study's scope should include a description of the most significant methodological decisions, assumptions, and constraints, as outlined in the following sections.

3.4 Functional unit

The functional unit is 1 ton of steel rebars manufactured in one year

Overall, the purpose of this detailed LCA research is to encourage informed decision-making and sustainable practices within the Pakistani steel industry.

3.5 System boundaries

The boundary chosen for this research is gate-to-gate, excluding raw material transportation since the producer has less control over these phases, and it was also difficult to get trustworthy data for these phases. This research included the complete process of steel manufacture in a factory, such as raw material processing, coal combustion, and energy consumption for melting and cold rolling operations, as well as other activities inside the facility until the final product was made. However, thanks to their limited effect in comparison to other elements, the research eliminates steel-making equipment and machinery from consideration. This method attributes no environmental impact to the product's use phase.

System boundaries also must be specified in other dimensions:

- Geographical area
- Time horizon
- Production of capital goods
- Boundaries between the life cycle of the studied product and related life cycles of other products

3.5.1 Geographical Area:

We're looking at a steel plant in Islamabad, Pakistan. This plant makes steel bars used in building with international quality standards (BS4449 and 4446). They get their raw materials like scrap metal from South Africa. For power, they use a mix of energy sources available in Pakistan.

3.5.2 Time Frame:

Our study covers one year of steel bar production in this plant.

3.5.3 Capital Goods:

We only consider the equipment and machinery used if they make a big difference in our comparison. In this case, they don't, so we're leaving them out.

3.5.4 Boundaries Between Life Cycles:

When we study one product's life cycle, we might touch on other related products' life cycles. But, for us, we're mainly looking at the technical aspects. We're not getting into the economic and social stuff. We're assuming that the demand for what this plant makes stays pretty much the same.

In simple terms, we're checking out a steel plant in Islamabad, Pakistan, for one year. They make steel bars for building stuff, following global quality standards. They get their raw materials from South Africa and use a mix of energy sources in Pakistan. We're not worried about the equipment they use because it doesn't change much in our comparison. We're mainly looking at how their steel-making process affects the environment.

3.5.5 Simplified Flowchart

the primary raw materials from which the completed steel product was made, as shown in figure 5. The model illustrates the major components and stages involved in the manufacturing of steel rebars. To make molten steel, which is then used in the fabrication of steel rebars, a variety of scrap metals are fed into a furnace. This creates steel.

During operation, the induction boiler may achieve temperatures ranging from 1650 to 1700 degrees Celsius. This is accomplished by using power from the primary grid, which is supplied by a transformer. In order to produce an end product of superior quality, the liquid steel is first poured into a ladle, which then filters out any contaminants that may be present. The molten steel is transferred from the ladle to the tundish via the open gate after it has been subjected to any required treatments in the ladle. After being heated up in a copper mould, billets are solidified in a continuous casting machine (CCM) by passing over water-cooled rollers as they make their way through the machine. The billets are sized with a gas torch and then laid aside to cool in the air once they have been measured. The chemical laboratory performs examinations on the samples to validate the information provided about their composition.

After being transported to the rolling facility, the billets go through a process called cold rolling, in which coal serves as the source of energy.

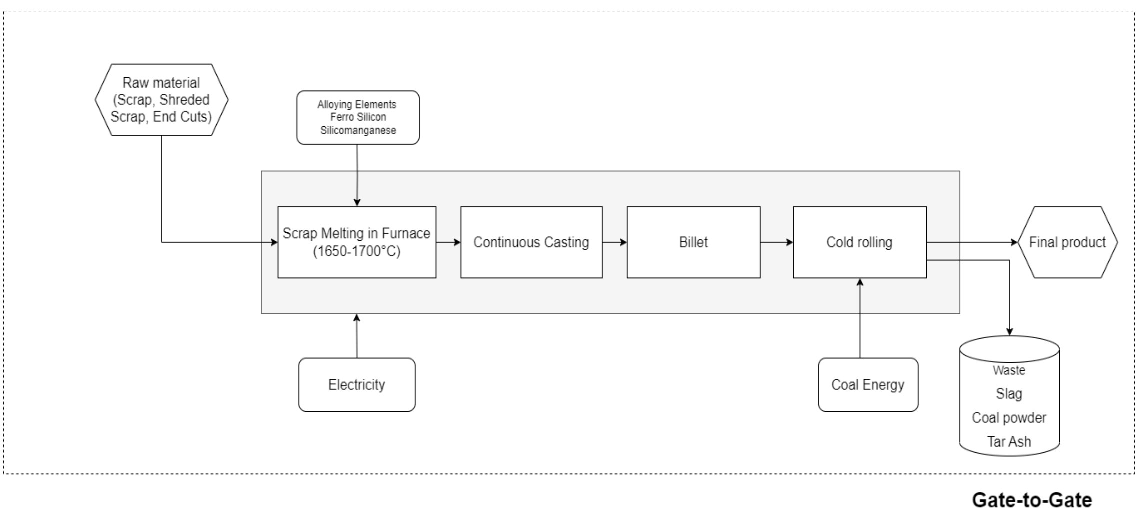

Figure 5Simplified Flow chart.

It is important to highlight, that although, the figure involves the end-of-life processes, in the model it won’t been considered.

3.6 Life cycle inventory Analysis

The Life Cycle Inventory Analysis (LCIA) plays an important role in LCA studies. This section describes the data and the detailed flowchart. The headings also involve the allocation problems, normalization, weighting and the assumptions and limitations.

3.6.1 Data

To build a proper model in SimaPro, data acquisition has an important role.

3.6.2 Primary Data.

The primary data collected information about the inputs and outputs of the instance company's manufacturing processes. This required quantifying the consumption of resources (raw materials), fuel and energy, and environmental emissions during manufacturing processes. The primary data were collected by physically visiting the facility.

To assure data integrity, the primary data capture occurred over the course of three distinct months: December 2021, May 2022, and July 2022. By gathering data during these specific periods, the study intended to capture any potential variations in the manufacturing processes and environmental impacts. The average of the primary data collected over the course of three months was used for inventory and additional analysis in this study. This methodology aided to provide a more comprehensive and accurate comprehension of the case company's environmental performance during the specified time period.

3.6.3 secondary data.

The secondary data came from scientific literature and commercial databases. Although the Eco invent database is included with the software and contains the most vital components of the model, individual data acquisition is still required.

This investigation combines primary and secondary data. Using existing research and reputable databases, the study ensured a thorough and robust analysis of the environmental impact of the manufacturing procedures [54]. In this study, the secondary data were sourced from the Eco invent Life Cycle Inventory (LCI) database. All input flows related to materials, energy, and emissions were extracted from this database and then calculated for the functional unit of analysis, as shown in Table 2.

3.7 Raw materials

We need to figure out how much raw material we need. Our goal is to produce one ton of steel rebars, and this means we'll need different amounts of scrap materials.

3.7.1 Scrap Yard Importance:

In a steel plant, the scrap yard is like a treasure trove. It's filled with various types of scrap that we use as ingredients for our steel. The type and composition of the scrap help us create the right blend. The quality of the scrap directly impacts the quality of our steel. If there are any impurities or unwanted stuff in the scrap, it can mess up our product.

The types of scrap materials we use:

3.7.2 HMS (High Melting Scrap):

This is a special type of scrap used in the furnace. It's basically old steel and iron that can be recycled. There are two main categories: HMS1 and HMS2. The big difference is that HMS1 doesn't contain galvanized and blackened steel, while HMS2 does.

Figure 6 High Melting Scrap

Both types need to meet certain thickness and size requirements to work well in the furnace. The right thickness and size make sure the furnace runs efficiently.

3.7.3 Shredded Scrap:

This type of scrap also goes into the furnace. It comes from shredders and includes bits from old vehicles and appliances. These pieces are easy to transport and sell. Shredded scrap is a big part of recycling. It's categorized based on its characteristics.

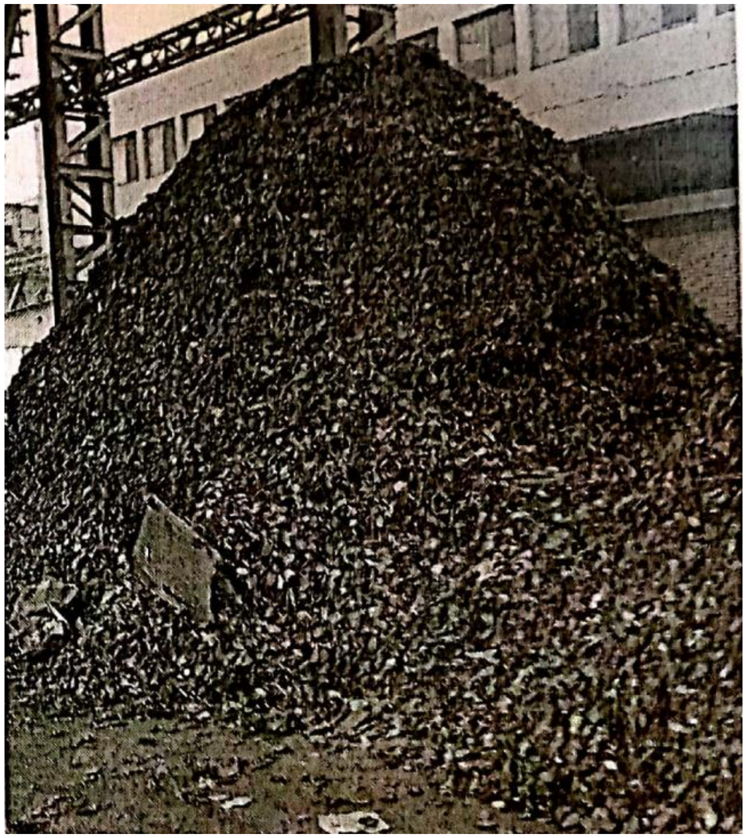

Figure 7 Shredded Scrap

The key thing to know is that shredded scrap is a mix of iron and steel, and it's magnetically separated. This type of scrap has a specific density, which helps the furnace work smoothly.

3.7.4 GI Scrap (Galvanized Iron):

GI stands for galvanized iron, and this scrap includes all sorts of steel bits. It might be from cutting pipes, plates, sheets, beams, and more. This type of scrap comes from taking apart structures, equipment, and buildings. The special thing about GI scrap is that it has a zinc coating. This coating is still there on the scrap we use.

Figure 8 Galvanized Iron Scrap

3.7.5 End Cuts:

These are also part of the mix that gets melted in the furnace. End cuts are basically leftover pieces. They're either bits that aren't useful in the rolling plant or extras from making custom-sized products.

In simpler terms, we're figuring out how much scrap we need to make one ton of steel rebars. The scrap yard is like our secret ingredient stash. We use different types of scrap, like HMS, shredded scrap, GI scrap, and end cuts. Each type has its own role. HMS is like the basic old steel, shredded scrap is bits from old stuff, GI scrap has a zinc coating, and end cuts are leftovers.

Figure 9 End cut scrap

We mix these scraps to make our steel in a big furnace. Getting the right mix and size is important to make sure the furnace works well.

3.7.6 Raw Material Processing

Once the raw materials are on hand, the next critical step in the production process is processing. In this comprehensive study, we will delve into the operations of the melting and rolling plants, where electricity plays a pivotal role in the production of steel.

3.8 Melting Plant:

The melting plant at this steel facility relies on an Induction Furnace to transform scrap metal into molten metal. This furnace stands out due to its eco-friendliness, energy efficiency, and minimal environmental impact compared to other furnace types. The magic happens through a process called induction heating. This process involves two key components: electromagnetic induction and joule heating. Importantly, this method heats the metal without direct exposure to flames, thus preventing any contamination. Inside the furnace, the temperature soars to approximately 1650-1700°C.

Figure 10 Induction Furnace in mini steel mill.

The furnace's coils are lined with fixed formers, chosen for their enhanced durability. The choice between acidic and basic lining hinges on the type of scrap being processed, with acidic lining being the preferred option in this facility. However, this lining requires periodic replacement, typically after about eight melting cycles. When it's time to replace the coils, they need to be cooled rapidly because they are made of copper, which melts at a lower temperature than the furnace. Cooling water from a specialized cooling tower is employed for this purpose.

3.8.1 Ladle:

Following the successful transformation of scrap metal into a molten state within the induction furnace, the molten metal is transported to a ladle. This facility boasts three ladles, each with an impressive 12-ton capacity. A crane is responsible for transporting the ladle to a designated platform, where the operator takes charge and fills the ladle with molten metal. The ladle plays a pivotal role in fine-tuning the composition of the molten metal. It is equipped with a 22mm diameter nozzle at its base, controlled by a slide gate and porous plug. Once the molten metal is poured into a tundish, the ladle is carefully tilted upside down to ensure that any remaining slag is removed.

3.8.2 Tundish:

The tundish is the next crucial component in the process. It is a generously sized container featuring holes or nozzles at its base. These strategically placed openings facilitate the smooth flow of molten metal into the ingot mold situated below. The tundish serves multiple functions, including regulating the flow of molten metal, preventing splashes, and ensuring a consistent and controlled stream of metal. At this facility, the tundish is capable of holding up to 2.5 tons of molten metal and boasts a pair of 12mm diameter nozzles at its base. In essence, the tundish acts as a reservoir for molten metal during the changing of ladles.

3.8.3 Continuous Casting:

From the tundish, the molten metal flows through the base's nozzles into a copper mold via a shroud. The depth of the mold is adaptable, depending on the desired product size and casting speed. This copper mold is not an ordinary one; it is hollow and equipped with a cooling system involving the circulation of water. The purpose of this cooling system is to maintain the mold's temperature at an optimal level, preventing any damage due to excessive heat. Furthermore, the mold undergoes oscillation to prevent the molten metal from adhering to the mold walls as it solidifies. This oscillation also serves the purpose of moving slag particles towards the surface, forming a removable slag layer. This process prevents defects by eliminating the formation of Al2O3, a common occurrence when Al wire is added. The oscillation is carefully controlled by the operator, as improper settings can lead to turbulence and splashing.

Figure 11 Manufacturing of billets

At this facility, the primary products produced through continuous casting are billets, which are subsequently processed in the rolling plant.

3.8.4 Industrial Cranes:

Within this facility, a fleet of overhead cranes with dual beams, allowing for both vertical and horizontal movement, plays a pivotal role. These industrial cranes are indispensable for lifting and transporting materials throughout the facility. Each crane comprises three fundamental components: the bridge, the runway, and the hoist and trolley. The bridge represents the horizontal beam that moves along a predefined path, while the runway is securely affixed to the facility's walls. The hoist and trolley function in tandem to pick up materials and precisely position them as needed. These cranes are equipped with gear systems, braking motors, and control panels to ensure seamless and precise control over their movements. Within this facility, approximately seven cranes serve different functions, each designed to accommodate specific load capacities and operational requirements.

3.8.5 Power Supply:

To ensure the seamless operation of critical equipment like the induction furnace, a robust and reliable power supply is imperative. This facility relies on a step-down transformer to convert electricity from the main grid for its needs. The transformation process begins with an 11kV supply, undergoing several stages to achieve the required 2500V and a frequency of 500-50Hz at the copper coil. To prevent overheating of the copper coil, a highly pressurized cooling system using water is employed. This high-pressure water flow effectively prevents water from evaporating under the extreme temperatures involved. The heated water is then utilized in a series of heat exchangers to transfer the heat and recycle the water efficiently. This comprehensive system integration enhances the facility's efficiency and productivity.

In simpler terms, the production process starts with scrap metal, which is then melted within an induction furnace using electricity. The composition of the molten metal is carefully adjusted within a ladle. The molten metal is subsequently channeled through a tundish, which regulates its flow and prevents splashes. From there, the molten metal enters a copper mold through a shroud in a continuous casting process. Industrial cranes facilitate the movement of materials, while a reliable power supply ensures the smooth operation of crucial equipment. This intricate system of processes and equipment is essential for the efficient and productive production of steel at this facility.

3.9 Rolling Plant

The rolling plant plays a crucial role in transforming the molten metal, previously prepared in the melting plant, into various forms of steel products, meeting the diverse needs of their customers. It is here that the molten metal undergoes a series of meticulously controlled processes, ultimately resulting in high-quality steel products that are ready for a wide range of applications.

3.9.1 Rolling Mill Machinery and Equipment:

The rolling plant is equipped with state-of-the-art machinery and equipment designed to handle the demanding task of shaping and forming molten metal into usable steel products. This includes rolling mills, which are at the heart of the operation. These rolling mills are specialized machines that apply immense pressure to the molten metal, forcing it through a series of rollers to gradually reduce its thickness and shape it into the desired forms.

The rolling mills themselves are a testament to modern engineering. They are designed to withstand extreme pressure and heat while maintaining precision and accuracy throughout the process. Rolling is a versatile process, and it can produce a wide range of steel products, including sheets, plates, bars, and various structural shapes. The ability to adjust the process parameters allows the mill to cater to diverse customer needs, producing steel products that vary in thickness, width, length, and even surface finish.

3.9.2 Quality Control:

Quality control is of paramount importance in the rolling plant at Fazal Steel Mill. To ensure that the steel products meet the highest standards, stringent quality checks are performed throughout the rolling process. These checks encompass a range of parameters, including dimensions, mechanical properties, surface finish, and visual inspection.

Modern technologies, such as automated gauging systems and non-destructive testing methods, are employed to monitor the steel's properties continuously. Any deviations from the specified standards are promptly addressed to maintain the quality of the final product.

3.9.3 Cooling and Cutting:

After passing through the rolling mill, the newly formed steel product is often at an elevated temperature. To prevent distortion and maintain dimensional accuracy, it undergoes a controlled cooling process. This process involves the use of cooling beds or water sprays that gradually reduce the steel's temperature to a suitable level for handling and further processing.

Figure 12Steel Rebars

Once the steel has cooled to the desired temperature, it undergoes precision cutting to achieve the specified lengths. This step is essential for preparing the steel products for packaging and transportation.

3.10 Life Cycle Inventory (LCI)

The table below shows the material flow of steel production.

Table 2Material Flow in steel mill

Raw Material and Fuels	Intermediate Product	Product	Waste
Iron Scrap **Electricity** **Coal energy**	Billet	Steel Rod	Slag, Tar Ash, Coal Powder

Ecoinvent's Life Cycle Inventory (LCI) library provided the secondary data for this study. As shown in Table 3, all input flows for materials, energy, and emissions were extracted from this database and computed for the functional unit of analysis. Due to the vital function that electricity played in both the melting plant and rolling plant, research was concentrated on these two facilities. All basic materials, fuel, additives, and power required to operate the systems were regarded as system components. Internal flows (or intermediate products) were excluded from the analysis.

The LCI data included not only the primary inputs but also the ancillary ones, such as lubricants and oils. The investigation also considered the gas and particle emissions of each facility. Due to the combination of primary data collected on-site and secondary data retrieved from the Eco invent LCI database, a comprehensive examination of the environmental consequences associated with manufacturing operations in the melting and rolling factories was made feasible.

Table 3Life Cycle inventory

Inputs	Induction Furnace	Continuous Casting	Coal Gasifier	Rolling
Iron Scrap	1 ton			
Ferro Silicon	0.05 ton			
Silicomanganese	0.01 ton			

Water Circulation		0.32 m3/FU		
Lubricating Oil		0.03/ton		
Bituminous coal			371/ton	
Electricity	396 kwh/ton	302kwh/ton	100 Kwh/ton	
Coal Energy			77.2 MJ/Ton	
Output				
Billet		1ton		
Steel Rod				1ton
Waste				
Slag	0.15/ton			
Tar Coal Ash			0.2/ton	
Coal Powder			0.05/ton	

3.10.1 Allocation

As to the Steel Rebars production it is just a one function so the study is not needed take into account any allocation.

3.10.2 Assumptions and limitations

In order to effectively model the complex systems within the mini steel industry, it is essential to acknowledge certain limitations. Firstly, the study imposes a time constraint by examining data on energy consumption for the initial year only. Additionally, the model does not account for the transportation expenses related to raw materials. Furthermore, the study relies on other limitations and assumptions, such as comparing the mini steel industry with two other industries in Pakistan, despite having data available for only one industry. It's crucial to note that the mini steel industry operates differently from integrated steel industries, and their environmental impacts differ significantly. Moreover, the study does not consider the use phase of the product.

3.11 Impact Categories and Assessment Method:

The chosen method for this analysis encompasses category indicators at both endpoint and midpoint levels. To provide a comprehensive overview of impacts at the midpoint level, the study covers 18 different impact categories, including Global Warming, Stratospheric Ozone Depletion, Ionizing Radiation, Ozone Formation, Human Health, Fine Particulate Matter Formation, Terrestrial Ecosystem, Terrestrial Acidification, Freshwater Eutrophication, Marine

Eutrophication, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Human Carcinogenic Toxicity, Human Non-Carcinogenic Toxicity, Land Use, Mineral Resource Scarcity, Fossil Resource Scarcity, and Water Consumption.

For endpoint damages, the midpoint impact categories are grouped into three areas of protection: Human Health, Ecosystems, and Resources. The study employs SimaPro V 9.4 as the modeling software and utilizes the ReCiPe 2016 evaluation method. This method is an extended version of ReCiPe 2008, adopting the hierarchist perspective (H). It allows for the consideration of impacts at two levels: the midpoint and endpoint levels.

3.11.1 Normalization and Weighting:

Normalization and weighting are typically employed to simplify the interpretation of results by placing them in a broader context and providing common dimensions for comparison. This is often done using the formula $N_i = I_i / R_i$, where N represents the normalized result, I is the result from the characterization, and R is a reference value. However, it's important to note that in this LCA study, normalization and weighting are not applied. The study exclusively focuses on mandatory elements within the life cycle impact assessment (LCIA) phase, which includes classification and characterization, while optional elements like normalization, grouping, and weighting are intentionally excluded. This approach allows the study to offer valuable insights into the environmental impacts associated with the steel production process without introducing additional optional elements that could potentially influence the results.

3.12 Summary

Detailed procedures for gathering and assessing information about the target industry as well as associated databases have been outlined in this section. The method of gathering data involves making many journeys to the target industry in Pakistan. Additionally, the information that is obtained is shaped via the application of mass and energy balance in accordance with the functional unit that is discussed in Chapter 3. The information that was acquired for the three different glass packaging solutions is shown in Table 3, and the second part of this chapter presents a wide variety of additional analysis scenarios.

CHAPTER 4. RESULTS AND DISCUSSIONS

In this chapter, we use the methodology of the Life Cycle Assessment to examine the effects of steel rebars on the environment. At the halfway point, we began to evaluate the relative importance of the various inputs and stages of the life cycle. The findings were also investigated at the terminal stage. In addition, for the sake of external validation and comparison, the findings were compared to those of other research that had followed a similar methodology.

Three outcomes for two cases are offered for appropriate analysis. All inputs in the first scenario (the baseline scenario) are consistent with information obtained from the Pakistani steel plant. In contrast, solar energy is used to replace on-site electrical generation in the alternate scenario. The specific outcomes for both cases are provided here. Additionally, the outcomes and effects of both situations are contrasted.

4.1 Baseline Scenario

The most polluting phase in the production of steel rebars was determined by calculating the environmental impacts per ton of final product. A Life Cycle Assessment (LCA) utilizing the Recipe 2016 midpoint (H) technique determined that the carbon footprint of steel production in the steel factory was 333 kg CO2 eq/FU (Functional Unit). The induction boiler's energy consumption and its need for electricity were significant contributors to greenhouse gas emissions. This investigation uncovered encouraging avenues for mitigating the industry's negative impact on the environment and helped identify the largest sources of greenhouse gas emissions.

Table 4 Mid Point Impact Categories

Impact category	Unit	Scrap Melting	Continuous Casting	Cold rolling
Global warming	kg CO2 eq	333.32255	173.7678509	30.51266624
Stratospheric ozone depletion	kg CFC11 eq	0.00011	6.24585E-05	5.00192E-06
Ionizing radiation	kBq Co-60 eq	25.863409	18.2539827	0.169017594
Ozone formation, Human health	kg NOx eq	0.8238918	0.356447717	0.085621498
Fine particulate matter formation	kg PM2.5 eq	0.4155884	0.197460531	0.079122315
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.860871	0.375784392	0.094428906
Terrestrial acidification	kg SO2 eq	1.0331379	0.584406851	0.176953241
Freshwater eutrophication	kg P eq	0.1292205	0.021587617	0.010099908
Marine eutrophication	kg N eq	0.0327403	0.002297655	0.000662293

Terrestrial ecotoxicity	kg 1,4-DCB	1398.6549	243.117562	17.77356268
Freshwater ecotoxicity	kg 1,4-DCB	22.160625	2.380912288	0.349707715
Marine ecotoxicity	kg 1,4-DCB	29.583272	3.153533677	0.491205577
Human carcinogenic toxicity	kg 1,4-DCB	11.21974	3.654519137	0.918399957
Human non-carcinogenic toxicity	kg 1,4-DCB	503.13051	51.46074987	16.06658087
Land use	m2a crop eq	9.0066518	2.48914951	0.279872473
Mineral resource scarcity	kg Cu eq	0.5024263	0.138231459	0.007760155
Fossil resource scarcity	kg oil eq	89.132119	54.40017879	5.57316749
Water consumption	m3	0.8546898	0.972950637	0.029599965

The results are presented in Table As viewed from a variety of perspectives, the processing of waste metal significantly exacerbated global warming, terrestrial ecotoxicity, human non-carcinogenic toxicity, and fossil resource depletion. In contrast, Continuous Casting had a greater impact on Terrestrial Ecotoxicity, Global Warming, and the Scarcity of Fossil Resources. In contrast, the effects of cold rolling were less significant at the median level and had a greater impact on the Global Warming subcategory. The environmental effects of each stage of steel production were analyzed in detail, including an evaluation of all 18 intermediate impact categories. The findings provide valuable information on the processes that cause diverse environmental effects and may be used as a foundation for future enhancements and sustainable practices in the steel manufacturing sector.

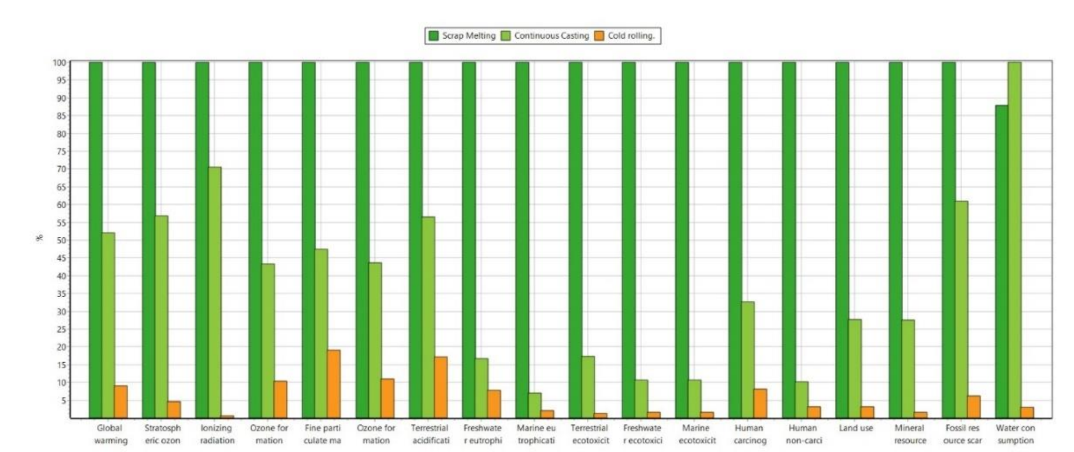

Figure 13Mid Point Results

A significant quantity of power was used, drawing from the National Grid, to melt one ton of scrap, and the graph depicts this disparity. Overall, the effects of declining fossil fuel supplies and rising temperatures on the three procedures varied considerably. The findings shed light on the impact of different additives used in the production of steel rebars. Steel rebar manufacturing might have less of an effect on the environment if different energy sources are used.

4.2 Normalized Values

The median findings, shown in Figure 8, reveal that producing 1 ton of scrap melting has a far larger environmental effect than alternative processes like continuous casting and cold rolling. Second, among the three kinds of glass containers, the freshwater eutrophication and marine eco toxicity consequences are the greatest for human carcinogenic toxicity.

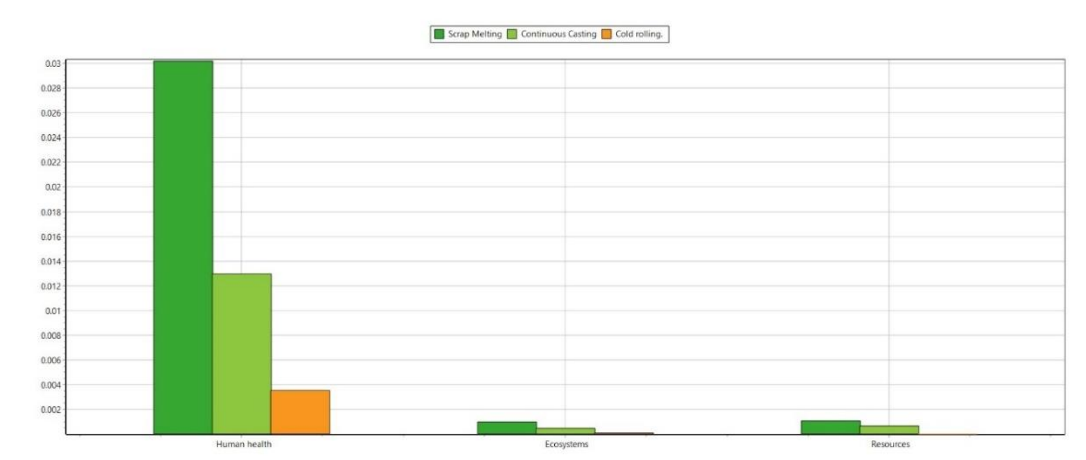

Figure 14 Normalized Results

The research performed an in-depth analysis of the data and examined how various inputs/phases contributed to the ultimate environmental effects. In this in-depth report, every stage in the production of steel rebars was analyzed. A comparative analysis of three main inputs or phases was conducted: refuse melting (impacts related to the plant's primary melting process in an induction furnace), continuous casting (impacts related to electricity consumption), and cold rolling.

The results demonstrate that the process of melting waste metal has negative effects on human health, the environment, and available resources. Continuous casting has less of an impact on human and environmental health and the environment. During cold rolling, there is no difference in the impact on human or environmental health or the amount of material consumed. When all three kinds of safety are considered, the cold rolling process stands out as the most secure.

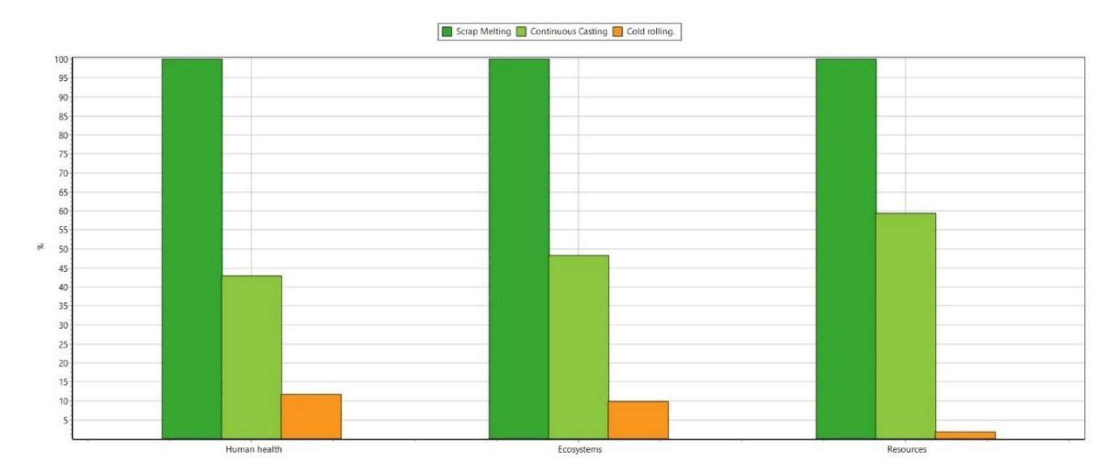

Figure 15Damage Assessment

The normalized results at the endpoint level indicated that the human health is the area of protection which is highly impacted by the three processes as illustrated in figure 16.

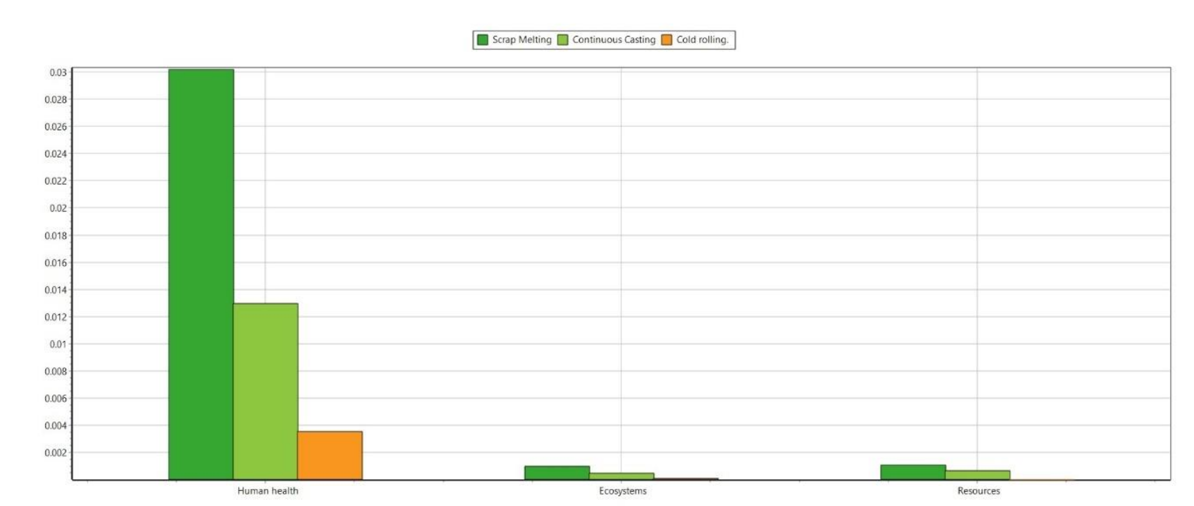

Figure 16 Normalized Results at end point

Additionally, the final score provides us with a quick snapshot of the effects of each operation. As can be seen in Figure 17, the most damaging effect on the environment was caused by scrap melting.

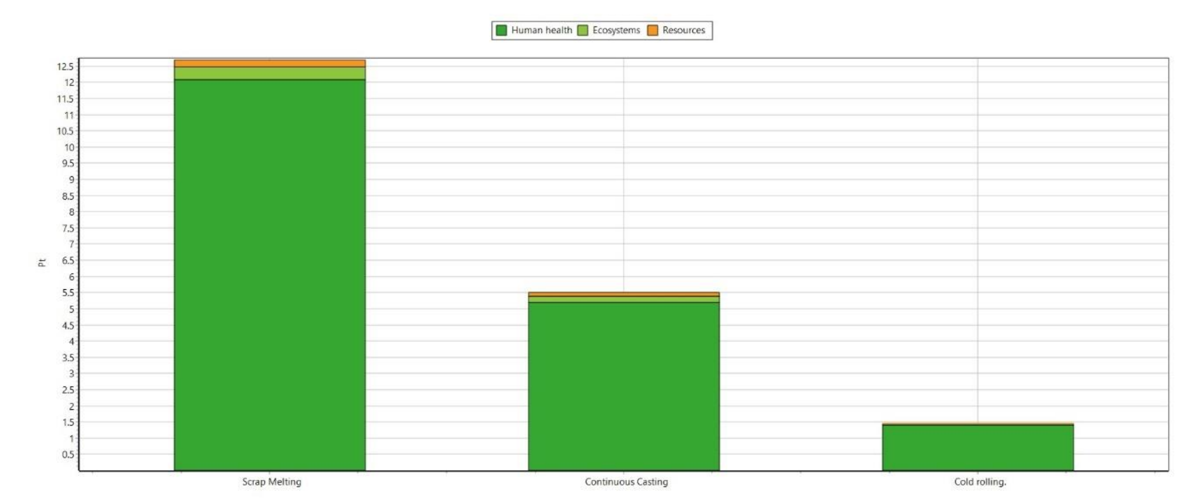

Figure 17 Single Score results at end point

Extraction and refining of primary materials were found to have the greatest impact on the environment, while air, water, and sediment emissions from industrial processes had the greatest impact on human health. Energy consumption in the billet manufacturing process was a significant contributor to environmental devastation.

4.3 Alternative scenarios and analyses

The research analyzed the environmental effects of three potential process solutions at the level of a Pakistani manufacturing facility. Since Pakistan is an impoverished country with limited resources, its energy balance has historically been less environmentally favorable than that of many industrialized countries. In order to evaluate the impact of the national grid's energy balance, two distinct scenarios were devised for each procedure. In the event that 100% solar energy was utilized and no electricity was extracted from the grid, these scenarios calculated the median environmental consequences across all 18 categories. The factory's entire energy requirements were met by solar energy, a renewable resource. This study aimed to demonstrate the environmental and economic benefits of converting the steel production process in Pakistan to utilize renewable energy sources such as solar power.

Table 5Mid point impact categories for Solar Analysis

Impact category	Unit	Scrap Melting (Solar Analysis)	Continuous Casting (Solar Analysis)	Cold rolling. (Solar Analysis)
Global warming	kg CO2 eq	105.1282	2.95799	0.782537
Stratospheric ozone depletion	kg CFC11 eq	2.83E-05	1.22E-06	3.24E-07
Ionizing radiation	kBq Co-60 eq	1.687877	0.200807	0.053124
Ozone formation, Human health	kg NOx eq	0.363011	0.009951	0.002633
Fine particulate matter formation	kg PM2.5 eq	0.173237	0.012491	0.003305
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.374515	0.010236	0.002708
Terrestrial acidification	kg SO2 eq	0.305742	0.031517	0.008338
Freshwater eutrophication	kg P eq	0.108796	0.004635	0.001226
Marine eutrophication	kg N eq	0.029911	0.00014	3.72E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1422.407	188.8401	49.95769
Freshwater ecotoxicity	kg 1,4-DCB	22.7859	2.060796	0.545184
Marine ecotoxicity	kg 1,4-DCB	30.24996	2.64258	0.699095
Human carcinogenic toxicity	kg 1,4-DCB	8.286242	1.0668	0.282222
Human non-carcinogenic toxicity	kg 1,4-DCB	491.436	30.96764	8.192497
Land use	m2a crop eq	5.94381	0.153265	0.040546
Mineral resource scarcity	kg Cu eq	0.56668	0.134697	0.035634
Fossil resource scarcity	kg oil eq	17.32557	0.728167	0.192637
Water consumption	m3	0.275547	0.530636	0.008105

As a result of changing to renewable energy, there has been a significant change in the impact categories. While Continuous Casting and Cold Rolling significantly reduce their environmental impacts, Melting Scrap has persistently high environmental impacts. This indicates that the environmental impacts of Continuous Casting and Cold Rolling processes could be significantly mitigated by replacing coal-based electricity with solar energy.

Even though solar energy had a lesser impact on the continuous casting and cold rolling processes, the findings demonstrated that the waste melting process was significantly affected.

Continuous casting only impacts water consumption if solar energy is used, and chilly rolling has negligible effects at best. The potential environmental benefits of converting some steel production operations to solar energy are illustrated graphically. The findings emphasize the need for the steel industry to adopt more eco-friendly practices and reduce their total environmental impact by transitioning to renewable energy sources such as solar.

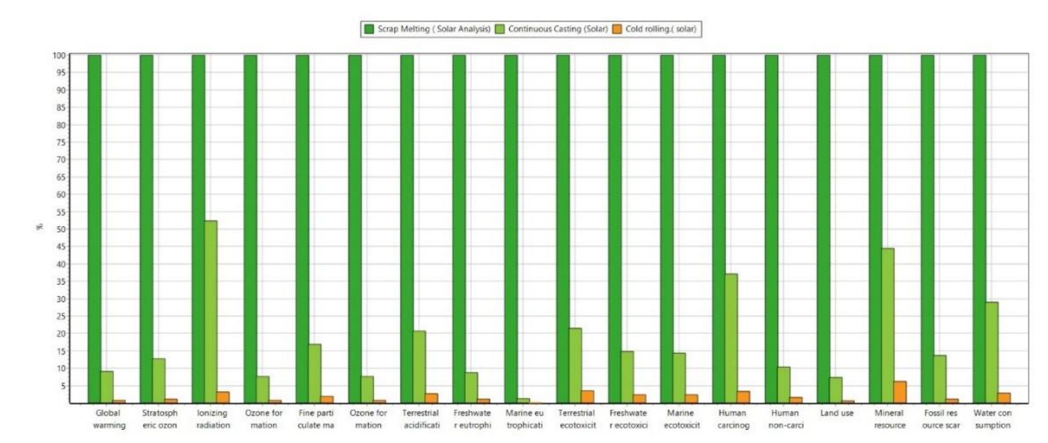

Figure 18 Midpoint results in case of solar

4.3.1 Normalized results

Figure 8 provides normalized results at the midpoint level, revealing that the production of 1 ton of recycled metal with solar energy has the greatest impact on freshwater ecotoxicity and human carcinogenicity. Changes are made to the impacts compared to the baseline scenario. Less significant are the effects of continuous casting and cool processing.

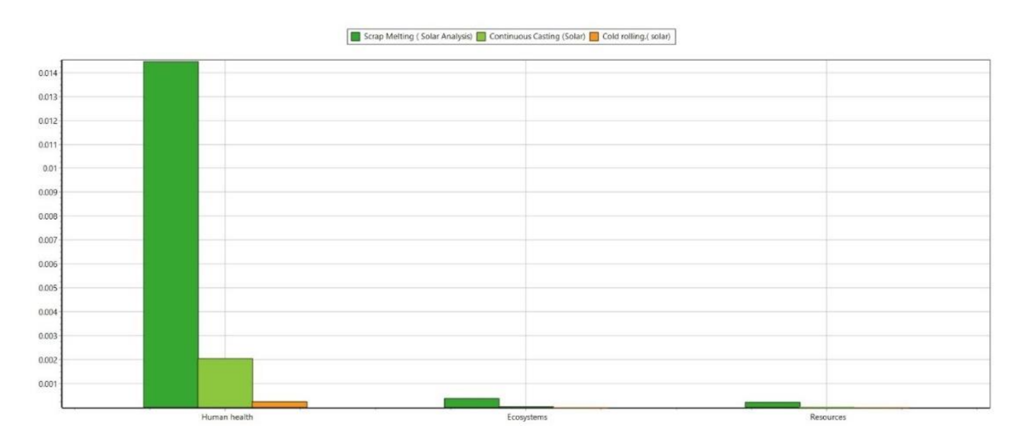

Figure 19Normalized results at endpoint

4.4 Alternative Scenario, 50% solar and 50% electricity

In this instance, the process of melting scrap required the use of electricity, whereas the processes of continuous casting and cold rolling required the use of energy derived from the sun. The information on solar power was obtained from the eco innovate data store. Midpoint graph

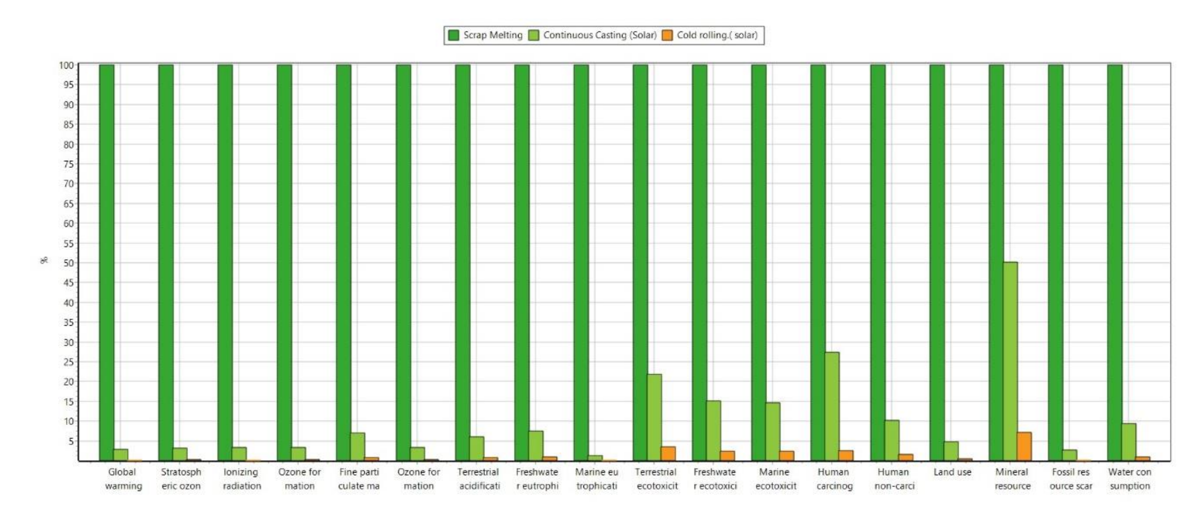

Figure 20Midpoint results at with 50% solar and 50% electricity.

The point in the figure that represents the middle illustrates that the melting of trash has a considerable influence, while the other two processes have a lower impact. In terms of the end point level, the influence of continuous casting on human health is insignificant, but the impact of cold rolling has an impact on human health, although one that is low in compared to the usage of electricity.

Figure 21Normalized Results

Cold rolling has no impact on human health at all. However, the findings for processes show that if we change the source of energy, the impacts on the environment will be substantially less severe. This is concluded that human health has a high impact score globally.

4.5 Solar system implications

4.5.1 Understanding the Traditional Mini Steel Industry

In a conventional mini steel industry, scrap metal is the primary raw material. The scrap is melted using induction furnaces, which consume substantial electricity generated from non-renewable sources. The molten metal is then cast into continuous billets or blooms before undergoing cold rolling to produce steel bars of varying shapes and sizes.

4.5.2 The Environmental Impact of Traditional Steel Production

Traditional steel production is resource-intensive and results in substantial greenhouse gas emissions. The burning of fossil fuels in conventional power plants for electricity generation releases large quantities of CO2 and other greenhouse gases into the atmosphere. Additionally, the process of melting scrap in induction furnaces contributes to air pollution due to the release of volatile organic compounds and other harmful substances.

The cumulative environmental impact of these activities is significant, making the steel industry one of the major contributors to global carbon emissions. Adopting sustainable practices in the steel industry is, therefore, essential to mitigate climate change and reduce its ecological footprint.

4.5.3 Advantages of Solar Clean Energy Integration

Transitioning from fossil fuels to solar clean energy offers numerous advantages for the mini steel industry:

4.5.3.1 Carbon Emission Reduction:

Solar energy is a clean and renewable resource that produces less greenhouse gas emissions during operation. By harnessing solar power for electricity generation, the steel industry can significantly reduce its carbon footprint and contribute to global efforts to combat climate change.

4.5.3.2 ***Cost Savings****:*

Although the initial setup costs for solar power systems can be significant, the long-term benefits outweigh the expenses. Once installed, solar panels have low operating and maintenance costs, allowing the steel plant to save on electricity bills in the long run.

4.5.3.3 Energy Independence:

Relying on solar power grants the mini steel industry greater energy independence, reducing its exposure to fluctuating fossil fuel prices and potential supply disruptions. Relying on solar power offers significant benefits to the mini steel industry, particularly in terms of energy independence and mitigating the risks associated with fluctuating fossil fuel prices and supply disruptions. Let's explore this aspect further:

4.5.3.4 ***Stability in Energy Costs****:*

One of the most significant advantages of utilizing solar power is the stability it provides in energy costs. Unlike fossil fuels, solar energy is abundant and free, with the primary expense being the initial setup and installation of solar panels and associated infrastructure. Once the solar power system is in place, the ongoing operational costs are minimal, limited mainly to maintenance and occasional upgrades.

4.5.3.5 Protection Against Price Volatility:

The prices of fossil fuels, especially coal and natural gas, are subject to market forces, geopolitical tensions, and other factors that can lead to price fluctuations. Such price volatility can significantly impact the operating costs of the mini steel industry, making budgeting and financial planning more challenging. By generating its electricity from solar power, the industry can insulate itself from these price fluctuations and ensure more predictable and stable energy expenses.

4.5.3.6 Reduced Reliance on Fossil Fuels:

A solar-powered mini steel industry reduces its reliance on fossil fuels for electricity generation. This not only lessens its contribution to carbon emissions and climate change but also reduces its dependence on non-renewable resources that might become scarcer and costlier over time. By embracing clean energy alternatives like solar, the industry can enhance its long-term sustainability and resource efficiency.

4.5.3.7 Resilience to Supply Disruptions:

The traditional steel industry, which heavily relies on electricity from the grid powered by fossil fuels, is vulnerable to supply disruptions caused by natural disasters, accidents, or infrastructure failures. Such disruptions can lead to downtime, production delays, and significant financial losses. Solar power, being a decentralized and distributed energy source, can provide a more resilient and self-sufficient energy supply for the mini steel industry. Even during grid failures or supply disruptions, a solar power system with energy storage can continue to provide electricity to critical operations, ensuring continuity and productivity.

*4.5.3.8 **Green Image and Market Advantage**:*

Embracing solar clean energy can enhance the mini steel industry's reputation as a responsible and environmentally conscious enterprise. In an era when consumers and businesses increasingly prioritize sustainability, companies that demonstrate a commitment to green practices and renewable energy are likely to gain a competitive advantage in the market. This can lead to increased demand for sustainably produced steel products and attract eco-conscious clients and investors.

*4.5.3.9 **Meeting Environmental Regulations**:*

Governments and regulatory bodies worldwide are placing more stringent environmental regulations on industrial sectors to curb pollution and carbon emissions. By transitioning to solar power and reducing its carbon footprint, the mini steel industry can position itself to comply with existing and future environmental regulations, avoiding potential penalties and legal challenges.

*4.5.3.10 **Contributing to Climate Goals**:*

The steel industry's significant carbon footprint makes it a key player in the global efforts to combat climate change. By adopting solar clean energy, the mini steel industry can contribute to national and international climate goals and align its operations with the global push for a sustainable, low-carbon future.

4.5.3.11 Enhanced Reputation:

Embracing sustainable practices can enhance the reputation of the steel company, attracting environmentally conscious customers and investors who prioritize eco-friendly products and businesses.

4.5.4 Implementing Solar Clean Energy in the Mini Steel Industry

Integrating solar clean energy into the mini steel industry requires careful planning and a step-by-step approach:

- **Energy Audit:** The first step is to conduct a comprehensive energy audit of the steel plant to assess its energy requirements and identify potential areas for solar power integration.
- **Solar Feasibility Study**: Engage experts to conduct a solar feasibility study to determine the optimal size and location for solar panels, considering factors such as sunlight availability, shading, and land availability.
- **Solar Power System Installation:** Based on the feasibility study, install solar panels and related infrastructure to capture and convert sunlight into electricity.
- **Energy Storage Solutions:** Implement energy storage solutions like batteries to store excess solar power generated during peak sunlight hours for use during non-sunny periods or during peak energy demand.
- **Hybrid System Integration:** In situations where solar energy alone may not meet the entire energy demand, consider a hybrid system that combines solar power with other renewable sources like wind or biomass to ensure a continuous and stable energy supply.
- **Smart Grid and Energy Management**: Invest in smart grid technologies and energy management systems to optimize the distribution of solar power within the steel plant, ensuring efficient utilization and reducing wastage.
- **Training and Education:** Provide training and education to the workforce on the new solar-powered system and its benefits, fostering a culture of sustainability within the company.

4.6 Overcoming Challenges

Despite the numerous benefits, transitioning to solar clean energy in the mini steel industry comes with some challenges:

- **Initial Investment:** The upfront capital required for installing solar power infrastructure can be significant. Securing funding or accessing renewable energy grants and incentives can help mitigate this challenge.

- **Land Availability:** Adequate land space is required to accommodate solar panels, which might be a constraint for some steel plants. Innovative solutions such as rooftop solar installations could be considered where land availability is limited.
- **Energy Storage Costs:** Energy storage solutions, like batteries, add to the overall implementation costs. However, advancements in battery technology and economies of scale are continually reducing storage-related expenses.
- **Energy Intensity:** The steel production process is energy-intensive, and solar energy might not be sufficient to meet the entire demand, especially during periods of peak production. Integrating a hybrid system with other renewable energy sources could address this issue.
- **Policy and Regulatory Support:** Government policies and regulations that promote renewable energy adoption and incentivize sustainable practices can play a crucial role in facilitating the implementation of solar clean energy in the steel industry. Engaging with policymakers and advocating for supportive measures can create a conducive environment for the steel sector's transition to clean energy.

CHAPTER 5. IMPLICATIONS AND RECOMENDATIONS

It is the first and only study that has been based on the LCA for manufacturing steel rebars solutions in Pakistan, and as such, it has various consequences for all stakeholders involved, specifically for practitioners, decision-makers, and researchers who are relevant to the problem.

The data from the LCA, along with a comparative examination of the production of steel rebars in a mini steel mill and a debate based on several potential outcomes, were utilized to determine the key environmental hotspots. For example, it was found that the most significant contributors to the environmental implications were associated with the processing of scrap metal. the consequences on the environment caused by the casting process. In general, the melting plant has the greatest negative effects on the surrounding environment. This suggests significant findings in an indirect way.

In addition, this study analyzed the environmental implications based on the manufacturing plant's existing energy-mix in comparison with a scenario in which all the Electricity changes with a renewable source of energy. The findings showed that the alternate scenarios, which expected that all of the electricity changes with solar energy, would have less of a negative impact on the environment. The implications of this finding are wide-ranging. In another scenario, combining electric and solar power to meet requirements demonstrates a more environmentally friendly approach. This hypothesis capitalizes on the benefits of both solar energy and electricity. When comparing the overall cost and availability of electricity versus solar energy, electricity proves to be cost-effective and more readily accessible. Consequently, a balanced approach of utilizing 50% electricity and 50% solar energy emerges as a pragmatic solution. To summarize, this study's findings hold potential value for researchers in related fields, especially in developing nations. Further investigations may be conducted at other small-scale steel manufacturing plants, allowing for comparative analysis with this study's results and potentially recommending adjustments to manufacturers.

CHAPTER 6. CONCLUSION:

The steel industry and the iron-making process are exceedingly energy-intensive. Environmental life cycle assessment (LCA) implementation enables steel manufacturers to improve their production process by minimizing environmental impacts. This was the first study to assess the life cycle of all processes at a Pakistani mini-steel facility and evaluated the environmental impact of iron and steel technologies. The environmental impacts of steel production in Pakistan were estimated using a gate-to-gate boundary. Both the midpoint and the endpoint are calculated. It was determined that the melting plant's energy consumption had the most significant environmental impact on human health. We compared electricity to solar energy, a renewable energy source. Compared to the electricity demand, the impact is negligible. The induction furnace system had the highest energy demand of the complete steel production system, and fossil fuel consumption was the primary source of environmental impacts. Coal and electricity were significant contributors to greenhouse gas emissions. By adopting solar energy, steel manufacturers can establish themselves as leaders in the struggle against climate change, enhance their reputation, and promote innovation in the industry. Integration of solar energy into the steel industry is possibly the most interesting way to decarbonize the sector and reach the 2050 goal of net-zero emissions. The induction furnace route will likely dominate steel industries for at least a few decades due to its low cost. There are global efforts to supplant the electricity grid with renewable energy sources. However, significant process and product quality research and development is required. Some solar-integrated facilities are expected to be commercially available by 2030, assuming all goes well. Few processes have the potential to be developed for the steel industry to reach its net-zero emission goal. However, the direct reduction of iron using an integrated electric arc furnace is the most mature technology currently available. Using solar to maintain energy equilibrium in steelmaking presents obstacles. In addition, the steelmaking process necessitates the presence of carbon in the steel, which poses a challenge for the use of alternative energy sources. Although implementing such a system presents challenges, the long-term benefits in terms of cost savings, environmental impact, and energy independence make it a worthy endeavor.

REFERENCES

1. Chisalita, D.-A., et al., *Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology.* Journal of cleaner production, 2019. **211**: p. 1015-1025.
2. Ryberg, M.W., P. Wang, S. Kara, and M.Z. Hauschild, *Prospective assessment of steel manufacturing relative to planetary boundaries: calling for life cycle solution.* Procedia CIRP, 2018. **69**: p. 451-456.
3. Backes, J.G., et al., *Life cycle assessment of an integrated steel mill using primary manufacturing data: actual environmental profile.* Sustainability, 2021. **13**(6): p. 3443.
4. Qazi, A., M. Shoaib, and M. Faisal, *Russia–Ukraine War and the Indo-Pacific: A Perspective from Pakistan.* Journal of Asian and African Studies, 2023: p. 00219096231176743.
5. *Steel industry warns of business closure*. Available from: https://tribune.com.pk/story/2398559/steel-industry-warns-of-business-closure.
6. Committee, N.S.A., *Annual Report of the National Screening Advisory Committee (NSAC) 2021.*
7. Klassen, R.D. and D.C. Whybark, *Environmental management in operations: the selection of environmental technologies.* Decision sciences, 1999. **30**(3): p. 601-631.
8. Gräf, A., *Environmental and Social Impact Assessment with Public Participation-A company's view.* 2011.
9. Glasson, J. and R. Therivel, *Introduction to environmental impact assessment*. 2013: Routledge.
10. Therivel, R. and P. Morris, *Methods of environmental impact assessment*. 1995: UBC Press.
11. Glasson, J., *Socio-economic impacts 1: overview and economic impacts.* Methods of Environmental and Social Impact Assessment, 2017: p. 475-514.
12. Shaked, S., et al., *Environmental life cycle assessment*. 2015: CRC Press.
13. Yuan, C., Q. Zhai, and D. Dornfeld, *A three dimensional system approach for environmentally sustainable manufacturing.* CIRP annals, 2012. **61**(1): p. 39-42.

14. Plevin, R.J., M.A. Delucchi, and F. Creutzig, *Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers.* Journal of Industrial Ecology, 2014. **18**(1): p. 73-83.
15. Zhang, L., Z.-W. Yuan, and J. Bi, *Substance flow analysis (SFA): A critical review.* Acta Ecologica Sinica, 2009. **29**(11): p. 6189-6198.
16. Aven, T., *Risk assessment and risk management: Review of recent advances on their foundation.* European Journal of Operational Research, 2016. **253**(1): p. 1-13.
17. Sendra, C., X. Gabarrell, and T. Vicent, *Material flow analysis adapted to an industrial area.* Journal of Cleaner Production, 2007. **15**(17): p. 1706-1715.
18. Liu, J., et al., *Carbon Footprint of a Large Yellow Croaker Mariculture Models Based on Life-Cycle Assessment.* Sustainability, 2023. **15**(8): p. 6658.
19. Ding, G.K. and S. Ghosh, *Sustainable water management-A strategy for maintaining future water resources.* Encyclopedia of sustainable technologies, 2017.
20. Murphy, P., *Intelligence and Security Committee Annual Report 2005-2006*. Vol. 6864. 2006: The Stationery Office.
21. Rasheed, R., et al., *Life cycle assessment of a cleaner supercritical coal-fired power plant.* Journal of Cleaner Production, 2021. **279**: p. 123869.
22. Ahmad, R., et al., *LCA of hospital solid waste treatment alternatives in a developing country: the case of district Swat, Pakistan.* Sustainability, 2019. **11**(13): p. 3501.
23. Brentrup, F., J. Küsters, H. Kuhlmann, and J. Lammel, *Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. Theoretical concept of a LCA method tailored to crop production.* European Journal of Agronomy, 2004. **20**(3): p. 247-264.
24. Leiter, M.P. and A.B. Bakker, *Work engagement: introduction.* Work engagement: A handbook of essential theory and research, 2010. **1**(9).
25. Fava, J.A., *LCA: concept, methodology, or strategy?* Journal of Industrial Ecology, 1997. **1**(2): p. 8-10.
26. Huhtala, A., *Special issue on cleaner production financing*. 2003, Elsevier. p. 611-613.
27. Hochschorner, E. and G. Finnveden, *Evaluation of two simplified life cycle assessment methods.* The International Journal of Life Cycle Assessment, 2003. **8**: p. 119-128.

28. Hauschild, M.Z., *Introduction to LCA methodology*. Life cycle assessment: Theory and practice, 2018: p. 59-66.
29. Sala, S., A.K. Cerutti, and R. Pant, *Development of a weighting approach for the Environmental Footprint.* Publications Office of the European Union: Luxembourg, 2018.
30. Bjørn, A., M. Owsianiak, C. Molin, and M.Z. Hauschild, *LCA history.* Life cycle assessment: theory and practice, 2018: p. 17-30.
31. Clark, G. and B. de Leeuw, *How to improve adoption of LCA.* The International Journal of Life Cycle Assessment, 1999. **4**: p. 184-187.
32. Finkbeiner, M., et al., *The new international standards for life cycle assessment: ISO 14040 and ISO 14044.* The international journal of life cycle assessment, 2006. **11**: p. 80-85.
33. Van Gulck, L., L. Wastiels, and M. Steeman, *How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978.* The International Journal of Life Cycle Assessment, 2022. **27**(12): p. 1249-1266.
34. Morris, P. and R. Therivel, *Methods of environmental impact assessment*. Vol. 2. 2001: Taylor & Francis.
35. Bradley, T., et al., *5.18-Life Cycle Assessment (LCA) of Algae Biofuels.* Comprehensive Renewable Energy, Second Edition: Volume 1-9, 2022: p. 387-404.
36. Silva, D., et al. *How important is the LCA software tool you choose Comparative results from GaBi, openLCA, SimaPro and Umberto*. in *Proceedings of the VII Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica, Medellin, Colombia*. 2017.
37. Olagunju, B.D. and O.A. Olanrewaju, *Comparison of life cycle assessment tools in cement production.* South African Journal of Industrial Engineering, 2020. **31**(4): p. 70-83.
38. Herrmann, I.T. and A. Moltesen, *Does it matter which Life Cycle Assessment (LCA) tool you choose?–a comparative assessment of SimaPro and GaBi.* Journal of Cleaner Production, 2015. **86**: p. 163-169.
39. Renzulli, P.A., et al., *Life cycle assessment of steel produced in an Italian integrated steel mill.* Sustainability, 2016. **8**(8): p. 719.
40. Chubbs, S.T. and B.A. Steiner, *Life cycle assessment in the steel industry.* Environmental Progress, 1998. **17**(2): p. 92-95.
41. Wiley, D.E., M.T. Ho, and A. Bustamante, *Assessment of opportunities for CO2 capture at iron and steel mills: an Australian perspective.* Energy procedia, 2011. **4**: p. 2654-2661.

42. Shahabuddin, M., G. Brooks, and M.A. Rhamdhani, *Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis.* Journal of Cleaner Production, 2023: p. 136391.
43. Olmez, G.M., F.B. Dilek, T. Karanfil, and U. Yetis, *The environmental impacts of iron and steel industry: a life cycle assessment study.* Journal of Cleaner Production, 2016. **130**: p. 195-201.
44. Gajdzik, B. and W. Sroka, *Resource Intensity vs. Investment in Production Installations—The Case of the Steel Industry in Poland.* Energies, 2021. **14**(2): p. 443.
45. Huang, Z., X. Ding, H. Sun, and S. Liu, *Identification of main influencing factors of life cycle CO2 emissions from the integrated steelworks using sensitivity analysis.* Journal of Cleaner Production, 2010. **18**(10-11): p. 1052-1058.
46. Cui, L., et al., *Life cycle assessment of ultra-low treatment for steel industry sintering flue gas emissions.* Science of the Total Environment, 2020. **725**: p. 138292.
47. García, S.G., V.R. Montequín, R.L. Fernández, and F.O. Fernández, *Evaluation of the synergies in cogeneration with steel waste gases based on Life Cycle Assessment: A combined coke oven and steelmaking gas case study.* Journal of Cleaner Production, 2019. **217**: p. 576-583.
48. Yingjun, H., Z. Zheng, L. Suqin, and C. Daqiang. *A case study of LCA for environmental protection in steel company*. in *2012 Third International Conference on Digital Manufacturing & Automation*. 2012. IEEE.
49. Ma, X., et al., *Life cycle assessment and water footprint evaluation of crude steel production: A case study in China.* Journal of environmental management, 2018. **224**: p. 10-18.
50. Hu, J.Y., F. Gao, Z.H. Wang, and X.Z. Gong. *Life cycle assessment of steel production*. in *Materials Science Forum*. 2014. Trans Tech Publ.
51. Gudukeya, L. and C. Mbohwa. *Life cycle assessment of steel balls*. in *2015 International Conference on Industrial Engineering and Operations Management (IEOM)*. 2015. IEEE.
52. Rahman, S.M., R.M. Handler, and A.L. Mayer, *Life cycle assessment of steel in the ship recycling industry in Bangladesh.* Journal of Cleaner Production, 2016. **135**: p. 963-971.
53. Burchart-Korol, D., *Life cycle assessment of steel production in Poland: a case study.* Journal of cleaner production, 2013. **54**: p. 235-243.

54. Ahmad, S., K.Y. Wong, and R. Ahmad, *Life cycle assessment for food production and manufacturing: recent trends, global applications and future prospects.* Procedia Manufacturing, 2019. **34**: p. 49-57.