AN EVALUATION OF THE APPLICABLE NEW LOW-CARBON TECHNOLOGIES IN INTEGRATED IRON AND STEEL PLANTS

ENTEGRE DEMİR-ÇELİK TESİSLERİNDE UYGULANABİLİR DÜŞÜK KARBONLU YENİ TEKNOLOJİLERİN DEĞERLENDİRİLMESİ

SEDA ÇİĞDEM

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To my family…

ABSTRACT

AN EVALUATION OF THE APPLICABLE NEW LOW-CARBON TECHNOLOGIES IN INTEGRATED IRON AND STEEL PLANTS

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Iron and steel production is an industrial sector that involves energy-intensive processes and has a high share of fossil fuel use. Therefore, it accounts for 7% of global greenhouse gas emissions. Existing emission reduction technologies are insufficient for reducing carbon emissions in this sector. This thesis analyzes low-carbon technologies for integrated production facilities (Kardemir, Erdemir, and İsdemir) in Türkiye. Data on emission reductions were collected from the monthly and annual activity reports published by the facilities in 2022 and 2023. The main processes that cause carbon emissions in the iron and steel production process are coke and sintering plants, blast furnaces, and basic oxygen furnaces. In addition, lime factories also cause carbon emissions to provide production that can enter blast furnaces. The emission reduction technologies obtained from the studies conducted for this sector are summarized under three main headings; alternative raw material use, non-fossil reductants/fuel substitution, and carbon capture and storage. The applicability of the investigated technologies to integrated plants in Türkiye was evaluated using the DEMATEL technique in three criteria branches (applicability, carbon reduction rate, and cost). As a result of the evaluation, it was determined that the fastest applicable, highest carbon reduction rate, and lowest cost technologies in Türkiye are alternative raw material use technologies. In the application area of alternative raw material use, it has been determined that the coal blending model technology provides a greenhouse gas emission reduction of up to 73.66% if applied in integrated plants of Türkiye. It is also seen that the carbon reduction rate for this technology is in direct proportion to cost and applicability. It has been determined that the most important criterion for selecting non-fossil reductants/fuel substitution technologies is the carbon reduction rate. It has been determined that if the non-fossil reductant technology with the highest carbon reduction rate is applied in integrated facilities in Türkiye, a 75% greenhouse gas reduction can be achieved. If the use of blast furnaces is indispensable, it has been determined that hydrogen supplementation to the tuyeres of direct furnaces also reduces greenhouse gas emission rates by 21.4%. On the other hand, it has been observed that carbon capture and storage technologies are still almost non-existent in Türkiye and that an infrastructure has not yet been established, especially for studies in the storage area. The most important obstacle to implementing this technology has been revealed to be cost. If the necessary steps are taken, greenhouse gas emission reductions of up to 93.26% can be achieved if these technologies are implemented in integrated facilities in Türkiye.

Keywords: integrated iron and steel plants, climate change, low-carbon technologies, alternative raw material use, non-fossil reductant, fuel substitution, carbon capture and storage.

ÖZET

ENTEGRE DEMİR-ÇELİK TESİSLERİNDE UYGULANABİLİR DÜŞÜK KARBONLU YENİ TEKNOLOJİLERİN DEĞERLENDİRİLMESİ

Seda ÇİĞDEM

Yüksek Lisans, Çevre Mühendisliği Bölümü

Tez Danışmanı: Prof. Dr. Merih AYDINALP KÖKSAL

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Demir-çelik üretimi enerji yoğun prosesleri içeren ve fosil yakıt kullanımında yüksek paya sahip olan bir sanayi sektörüdür. Bu nedenle küresel sera gazı emisyonunun %7'lik bir kısmını oluşturmaktadır. Mevcut emisyon azaltım teknolojileri, bu sektördeki karbon emisyonlarını azaltmak için yeterli değildir. Bu tez çalışması, Türkiye'deki entegre üretim yapan tesisler (Kardemir, Erdemir ve İsdemir) için düşük karbonlu teknolojileri analiz etmektedir. Tesislerin 2022 ve 2023 yılında yayınladıkları aylık ve yıllık faaliyet raporlarından emisyon azaltımı ile ilgili veriler toplanmıştır. Demir-çelik üretim prosesinde karbon emisyonlarına neden olan başlıca süreçler; kok ve sinterleme tesisleri, yüksek fırınlar ve bazik oksijen fırınlarıdır. Bunun yanısıra yüksek fırınlara girebilecek özellikte üretimin sağlanabilmesi için kireç fabrikaları da karbon emisyonlarına neden olmaktadır. Bu sektör için yapılan çalışmalardan elde edilen emisyon azaltım teknolojileri üç ana başlık altında özetlenmiştir; alternatif ham madde kullanımı, karbonsuz indirgeyiciler/yakıt ikamesi ve karbon yakalama ve depolama. Araştırılan teknolojilerin Türkiye’deki entegre tesislere uygulanabilirliği üç kriter dalında (uygulanabilirlik, karbon azaltım oranı ve maliyet) DEMATEL tekniği kullanılarak değerlendirilmiştir. Değerlendirme sonucunda Türkiye’de en hızlı uygulanabilir, en yüksek karbon azaltım oranına sahip ve en düşük maliyetli teknolojilerin alternatif ham madde kullanımı teknolojileri olduğu tespit edilmiştir. Alternatif ham madde kullanımı uygulamasında kömür harmanlama model çalışmalarından %73,66’ya kadar sera gazı emisyon azaltımı sağladığı kanıtlanmıştır. Ayrıca bu teknoloji için karbon azaltım oranının maliyet ve uygulanabilirlikle doğru orantıda olduğu görülmektedir. Karbonsuz indirgeyiciler/yakıt ikamesi teknolojilerinde seçim yapılırken en önemli kriterin karbon azaltım oranı olduğu tespit edilmiştir. Karbon azaltım oranı en yüksek karbonsuz indirgeyici teknolojisinin Türkiye’deki entegre tesislerde uygulanması durumunda %75 oranında sera gazı azaltımı elde edilebileceği tespit edilmiştir. Eğer yüksek fırınlar kullanılmaktan vazgeçilmez ise direkt fırınların tuyerlerine hidrojen takviyesinin de sera gazı emisyon oranlarını %21,4 oranında azaltacağı tespit edilmiştir. Diğer yandan karbon yakalama ve depolama teknolojilerinin Türkiye’de henüz yok denecek kadar az olduğu, özellikle depolama alanındaki çalışmalar için henüz bir altyapının oluşturulmadığı görülmüştür. Bu teknolojinin uygulanmasındaki en önemli engelin maliyet olduğu ortaya çıkmıştır. Gerekli adımların atılması ile Türkiye’deki entegre tesislerde bu teknolojilerin uygulanması durumunda %93,26’ya kadar sera gazı emisyon azaltımı sağlanabilir.

Anahtar Kelimeler: entegre demir-çelik tesisleri, iklim değişikliği, düşük karbonlu teknolojiler, alternatif ham madde kullanımı, karbonsuz indirgeyiciler, yakıt ikamesi, karbon yakalama ve depolama.

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SYMBOLS AND ABBREVIATIONS

Symbols

%	Percent
°C	Celsius
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Fe_2O_3	Ferric oxide
H_2	Hydrogen
kg	Kilogram
N_2O	Nitrous oxide
NH_3	Ammonia
NO_x	Nitrogen oxides
PAHs	Polycyclic Aromatic Hydrocarbons
PM_{10}	Particulate matter 10 micrometers or less in diameter
SO_2	Sulphur dioxide
VOCs	Volatile Organic Compounds

Abbreviations

ASU	Air Separation Unit
BF	Blast Furnace
BFG	Blast Furnace Gas
BOF	Basic Oxygen Furnace
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage

CCUS	Carbon Capture Utilization and Storage
CFB	Circulating Fluidized Bed
CO_{2eq} / CO_{2e}	Carbon dioxide equivalent
COG	Coke Oven Gas
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DEPG	Polyethylene Glycol Dimethyl Ethers
DFB	Double Fluidized Bed
DRI	Direct Reduced Iron
DR-NG	Direct Reduction with Natural Gas
EAF	Electric Arc Furnaces
Erdemir	Ereğli Demir ve Çelik Fabrikaları T.A.Ş.
Etc.	Et cetera
EU	European Union
FINEX	Fines INstant Extraction
FOG	FINEX off-gas
GHG	Greenhouse Gases
HPSR	Hydrogen Plasma Smelting Reduction
HyREX	Hydrogen-based Steelmaking
İsdemir	İskenderun Demir ve Çelik A.Ş.
Kardemir	Karabük Demir Çelik Sanayi ve Ticaret A.Ş.
MEA	Monoethanolamine
MOE	Molten Oxide Electrolysis
NIR	National Greenhouse Gas Inventory
POSCO	Pohang Iron and Steel Company
PSA	Pressure Swing Adsorption
R&D	Research and Development

TÇÜD	Turkish Steel Producers Association
TGR-BF	Top Gas Recycle Blast Furnace
TSA	Temperature Swing Adsorption
TVSA	Temperature/Vacuum Swing Adsorption
USA	United States of America
VM	Volatile Matter
VPSA	Two-Stage Vacuum Swing Adsorption
WSA	World Steel Association

1. INTRODUCTION

This chapter overviews the global and national environmental and commercial situation of the iron and steel sector. The problem statement, the study's rationale, importance, contributions, purpose, scope, and structure are presented.

1.1. General Overview

Iron ore is the third most abundant mineral element in the Earth's crust at 5%. The next two most abundant elements are aluminum, 8.1%, and silicon, 28% (Smil, 2016). Iron has been the most widely used element throughout history. It is the primary raw material of the iron and steel industry, and by processing this ore, more durable and higher-quality steel metal is produced. Iron and steel metals are the building blocks of industrialization and are vital to countries' economic development. Figure 1 shows the annual crude steel production chart by million tones (mt) from the World Steel Association (WSA) website covering between 2000 and 2023.

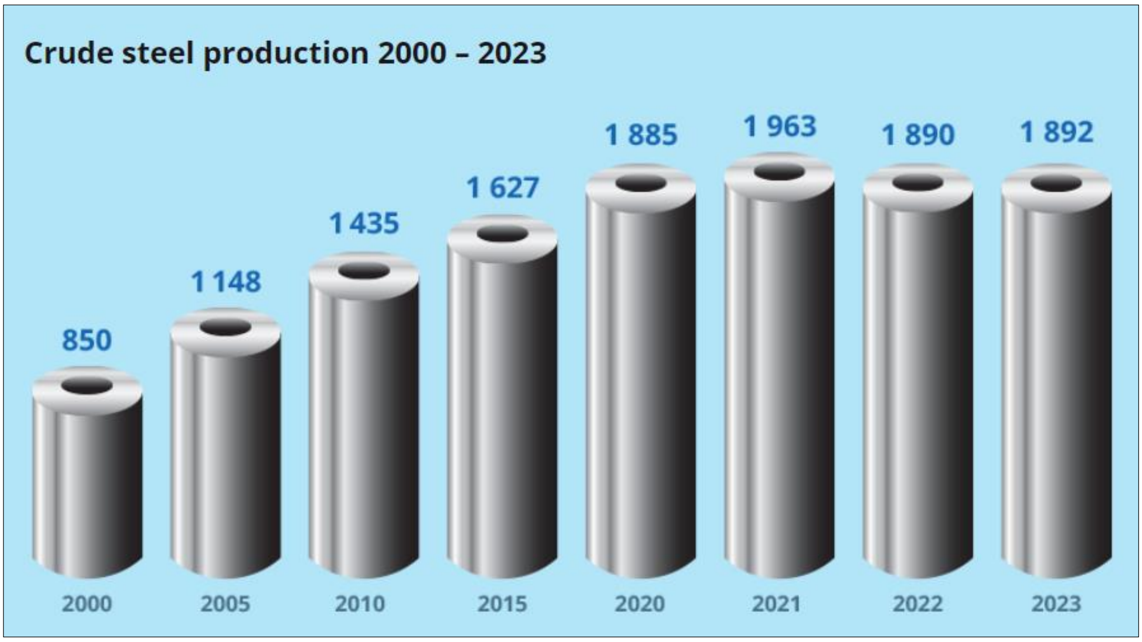

Figure 1. Annual Crude Steel Production between 2000 and 2023 (WSA, 2024)

According to the WSA, while the annual crude steel production was 850 mt in 2000, this production amount increased until 2020 and reached 1885 mt (WSA, 2024). Worldwide steel supply is projected to increase by more than one-third by 2050. With the COVID-19 pandemic in 2020, production activities were disrupted in many countries, and there were declines in the supply chain. In 2020, global crude steel production decreased by an estimated 5% compared to 2019 (International Energy Agency, 2020). In 2023, annual crude steel production remains stable at 1892 mt (WSA, 2024). The production data of the countries in the top 10 in steel production in the world in 2022 and 2023 are given in Table 1.

Table 1. Steel Production Data of Top 10 Countries in 2022 and 2023

Country	**2023**		**2022**	
	Rank	**Tonnage**	**Rank**	**Tonnage**
China	1	1019.1	1	1019.1
India	2	140.8	2	125.4
Japan	3	87.0	3	89.2
United States	4	81.4	4	80.5
Russia	5	76.0	5	71.7
South Korea	6	66.7	6	65.8
Germany	7	35.4	7	36.9
Türkiye	**8**	**33.7**	**8**	**35.1**
Brazil	9	31.8	9	34.1
Iran	10	31.0	10	30.6

China ranked first with 1,019.1 mt of crude steel production in 2022 and 2023, accounting for 54% of the global production. Türkiye ranked eighth with 35.1 mt and 33.7 mt of crude steel production in 2022 and 2023, accounting for 3% of the global production.

The iron and steel industry consumes about 7% of the global energy supply. Since the use of carbon-based raw materials and energy consumption is intensive in this sector, it contributes significantly to global GHG emissions. It is known that the iron and steel sector is responsible for about 7-9% of global GHG emissions (Renforth et al., 2024) (Kim, 2022).

Approximately 7% of the GHG released into the world's atmosphere occurs due to conventional steel production, which depends on using 70% coal as a raw material. The remaining 30% of iron production occurs through electric arc furnaces (EAF), which emit lower levels of CO_2 than BFs (Jennifer, 2022).

In Türkiye, according to the National Greenhouse Gas Inventory (NIR), the most important GHG emission sources in 2021 are cement production, with a share of 7.8%, and iron and steel production, with 2.1% (Turkish Statistical Institute, 2023).

According to the Turkish Steel Producers Association (TÇÜD), 42 crude steel production facilities in Türkiye produced 33.7 million tons of steel in 2023. Of the 42 crude steel production facilities, 13 are located in the Mediterranean region, 9 in the Marmara region, 10 in the Aegean region, 7 in the Black Sea region, and 3 in the Central Anatolia region. Of the 42 crude steel production facilities, 28 are EAFs, 11 are induction furnaces, and 3 are BFs. The map showing steel producers in Türkiye is given in Figure 2 (TÇÜD, 2023).

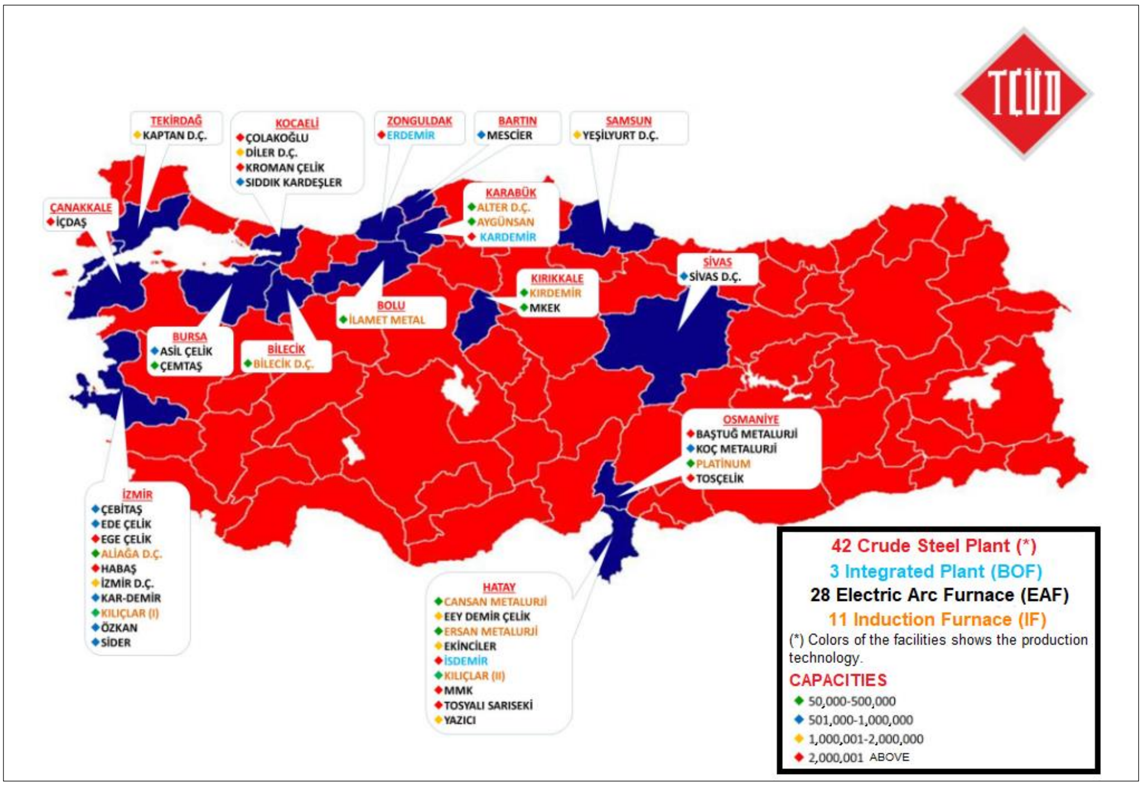

Figure 2. Steel Producers in Türkiye (TÇÜD, 2023)

Information on 2023 crude steel production from iron and steel facilities in Türkiye is presented in Table 2.

Table 2. Crude Steel Production Information of Türkiye, 2023 (KARDEMİR, 2023) (Caymaz, 2024) (Deloitte, 2023)

Type of Plants	**Manufacturers**	**Crude Steel Production**	
		Mt	**%**
BF-BOF Integrated Plants	Kardemir	2.22	6
	İsdemir	4.4	14
	Erdemir	2.8	8
	Integrated Plants Total	**9.42**	**28**
EAF/IF Plants	**EAF and IF Plants Total**	**24.28**	**72**
Grand Total		**33.7**	**100**

As can be seen in Table 2, 28% of steel production in Türkiye comes from integrated plants. At the same time, 82.7% of the total emissions in this sector are caused by integrated plants (Turkish Statistical Institute, 2023).

A "Fit for 55 Package" has been prepared as part of the agreement to materialize the European Green Deal's intermediate targets. This comprehensive package of draft laws aims to align climate, energy, transport, and taxation policies to reduce net GHG emissions by at least 55% by 2030 compared to 1990 levels (Council of the EU and the European Council, 2024). The Carbon Border Adjustment Mechanism (CBAM) has been developed to eliminate the risk of leakage of emissions within the Fit for 55 Package. The CBAM aims to ensure that high-emission products produced at low cost compete with low-emission products produced at high cost. In the first phase, the CBAM aimed to equalize the carbon prices of domestic and imported products of the cement, iron and steel, aluminum, fertilizer, hydrogen, and electricity sectors (Republic of Türkiye Ministry of Foreign Affairs Directorate for EU Affairs, 2024).

The European Green Deal and all the accompanying laws and regulations closely concern EU member states and countries with close economic trade relations with the EU. Türkiye is among the countries directly affected by this agreement due to its geographical location and deep economic ties with the EU. Therefore, to preserve its position in the EU market, Türkiye needs to follow the European

Green Deal and all the regulations introduced within this deal's scope and accelerate the industry's green transformation. In this context, it is of critical importance for Türkiye to set targets for the leading sectors identified under the CBAM, transition to sustainable practices, and reduce carbon emissions.

Since iron and steel are sectors that consume energy and raw materials intensively and harm the environment, it is necessary to reorganize conventional production methods and adapt green and new technologies to the production process. The main carbon emissions from the conventional steelmaking process, consisting of BF and BOF, result from the following events:

- Binding of carbon trapped in coke and limestone to oxygen in the air,
- Use of fossil fuels for BF heating, and
- Use of coal to power coke ovens and sintering and pelletizing plants.

More than half of the raw materials needed for production are released as waste gases and solid waste/semi-finished products. Waste gases are composed of pollutant parameters, including heavy metal elements, and are one of the most significant emissions from this sector. The rate of reuse and recovery of solid waste and/or by-products has increased in the past to reduce emissions, but significant emission reductions have not been achieved.

At the Breakthrough Technology Conference in the United Arab Emirates on 5-6 December 2023, a platform was created to increase and facilitate the interaction between researchers and engineers in developing low-CO_2 emission iron and steel production technologies. New technologies covering topics such as hydrogen use (reduction, BF injection, heating), Carbon Capture Utilization and Storage (CCUS), use of alternative carbon sources, electrification (EAF, electrolysis, heating), scrap, and efficiency were discussed at the event (WSA, 2023).

The following four production routes are used worldwide for crude steel production in the iron and steel industry:

- the classic BF-BOF route,
- the direct melting of scrap (EAF),
- smelting reduction, and

- direct reduction.

According to WSA, approximately 70% of global steel production is obtained from the conventional BF-BOF route (WSA, 2023). In Türkiye, on the contrary, most of the steel production is from electric arc furnaces (74.8%), and the remaining production comes from the BF-BOF route (25.2%) (TOBB, 2021). Since the subject of this study covers integrated iron and steel plants, an evaluation and analysis have been made for integrated plants only.

1.2. Problem Statement

Carbon-containing air emissions from integrated iron and steel plants have not been extensively studied, unlike other common air pollutants (PM_{10}, NO_x, and SO_2). The iron and steel industry is one of the most CO_2 emission sources. Studies conducted in recent years have focused on technological developments and emission reduction in BFs and coke ovens, which have the highest GHG emissions in the iron and steel industry. Carbon-containing air emissions (such as CH_4 and CO_2) contribute to increased global warming when released into the atmosphere. Therefore, carbon emissions must be reduced for large energy-intensive fossil fuel sectors.

In Türkiye, the iron and steel production facilities that cause the highest carbon emissions use the integrated method. For this reason, the fact that raw materials and raw material processing processes in integrated plants are based on fossil fuels shows the importance of decarbonization.

1.3. Objective of the Study

The main objective of this comprehensive study is to determine and evaluate a wide range of applicable technologies for reducing GHG emissions from integrated iron and steel facilities in Türkiye.

The sub-objectives of this study are listed below:

- To analyze the utilization of alternative raw materials for emission reduction,
- To analyze the effect of non-fossil reductants and/or fuel substitution on emission reduction in production processes,
- To analyze the impact of carbon capture and utilization technologies for emission reduction on carbon-containing by-products formed in production processes.

1.4. Scope of the Study

The study is based on analyses of studies conducted on worldwide low-carbon technologies and the DEMATEL technique, which enables the demonstration and analysis of causal relationships between complicating variables. The iron and steel industry is currently known to contribute about 7-8% of global GHG emissions (Zhang et al., 2024). The BF-BOF route, the conventional production method of the iron and steel industry, consumes significantly more energy than the EAF route, releasing more carbon emissions (He et al., 2017). Therefore, integrated production facilities (Kardemir, Erdemir, and İsdemir) were selected as the research area for reducing carbon emissions in the iron and steel sector in Türkiye.

The highest carbon emissions occur in integrated iron and steel plants' coke, sinter, iron, and steel production stages (He et al., 2017). Therefore, this study has carried out technological research for these processes. With this thesis, the studies required by the integrated plants in Türkiye for green steel production have been revealed. Other production processes, such as steel casting, hot rolling, cold rolling, galvanizing, and coating, are excluded from this study as they cause less energy consumption and carbon emissions.

In this study, the capacity information of three integrated plants currently operating in Türkiye is analyzed, and their current projects for production efficiency and emission reduction are evaluated. At the same time, emission reduction projects published in the literature in recent years are also analyzed.

The research uses the DEMATEL technique to identify appropriate technologies for integrated plants in Türkiye. Then, the results obtained from the DEMATEL technique are interpreted.

1.5. Structure of the Study

This thesis consists of six chapters. Chapter 1 provides information on the current state of the global iron and steel sector and Türkiye's position. The problem definition for the study, the purpose, and the scope of the study are given in this chapter. Chapter 2 examines the integrated iron and steel production route and carbon emission sources that constitute this study's scope. The calculation of carbon emissions in iron and steel plants is examined, and the technologies included in the research are classified and introduced. Information on production, emission, and emission reduction projects related to integrated iron and steel plants in Türkiye is also included in this chapter. Chapter 3 provides a summary of the recent studies that have been conducted in terms of the scope and purpose of the study. Chapter 4 presents the methodology of the study. The decision-making phase for the study is described, including data collection, identification of factors affecting technology selection criteria, selection and evaluation of low-carbon approaches, emission estimation in case of implementation of appropriate approaches, and evaluation of emission reduction approaches. Chapter 5 presents the detailed results of the methodology applied to the identified technology approaches and then discusses its applicability to integrated plants in Türkiye. Chapter 6 provides the final findings and recommendations.

2. BACKGROUND INFORMATION

This chapter explains the production route of integrated iron and steel plants and the processes that release carbon emissions along the route. It also provides a general definition of key carbon reduction technologies in the literature and information about the process, production, and emission reduction projects related to integrated iron and steel plants in Türkiye, which constitute the scope of the study.

2.1. Production Route of Integrated Plants

The production route of an integrated iron and steel plant begins with the preparation of raw materials. Raw materials such as iron ore, coal, limestone, and recycled steel are sent to BF and BOF to produce iron and steel (WSA, 2023). This is the most widely used steelmaking method in the world, and the key process components are as follows:

- Raw Materials Preparation (Sintering/Pelleting and Coke Making)
- Ironmaking (BF)
- Steelmaking (BOF)
- Casting & Rolling

The flow chart of the integrated iron and steel production process is shown below.

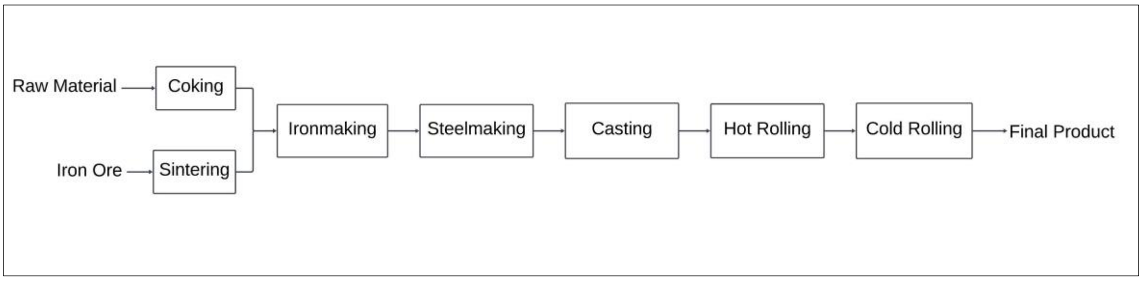

Figure 3. Flow Chart of Integrated Plants

On average, an integrated production produces 1000 kg of crude steel using 1370 kg of iron ore, 780 kg of metallurgical coal, 270 kg of limestone, and 125 kg of recycled steel (WSA, 2023).

2.2. Carbon Emission Sources of Integrated Plants

Coke production, sinter production, and BF-BOFs are considered the main sources of carbon emissions in integrated iron and steel production stages. The steps that cause carbon emissions in integrated iron and steel plants are explained below, and the processes that cause carbon emissions are indicated with flow charts.

2.2.1. Coke Plant

Coke plants emit different types of pollutants at many locations. These emissions are discharged directly from the stacks and can be released into the air from non-stack sources during various activities.

Metallurgical coke is an important component in the process of producing steel with high strength and large particle size. It is obtained by high-temperature combustion (carbonization) of coal in the absence of air. In integrated plants, metallurgical coke is produced in a coke oven, also known as a coke battery or coke plant (Bhattacharya & Datta, 2023) (Marsh & Rodríguez-Reinoso, 2006). Due to its high carbon content, coke causes CO_2 emissions during its production from coking coals and its use in BFs for reduction/fuel input. Coke plant inputs and outputs are summarized in Figure 4, with those marked in red representing carbon-containing inputs and outputs.

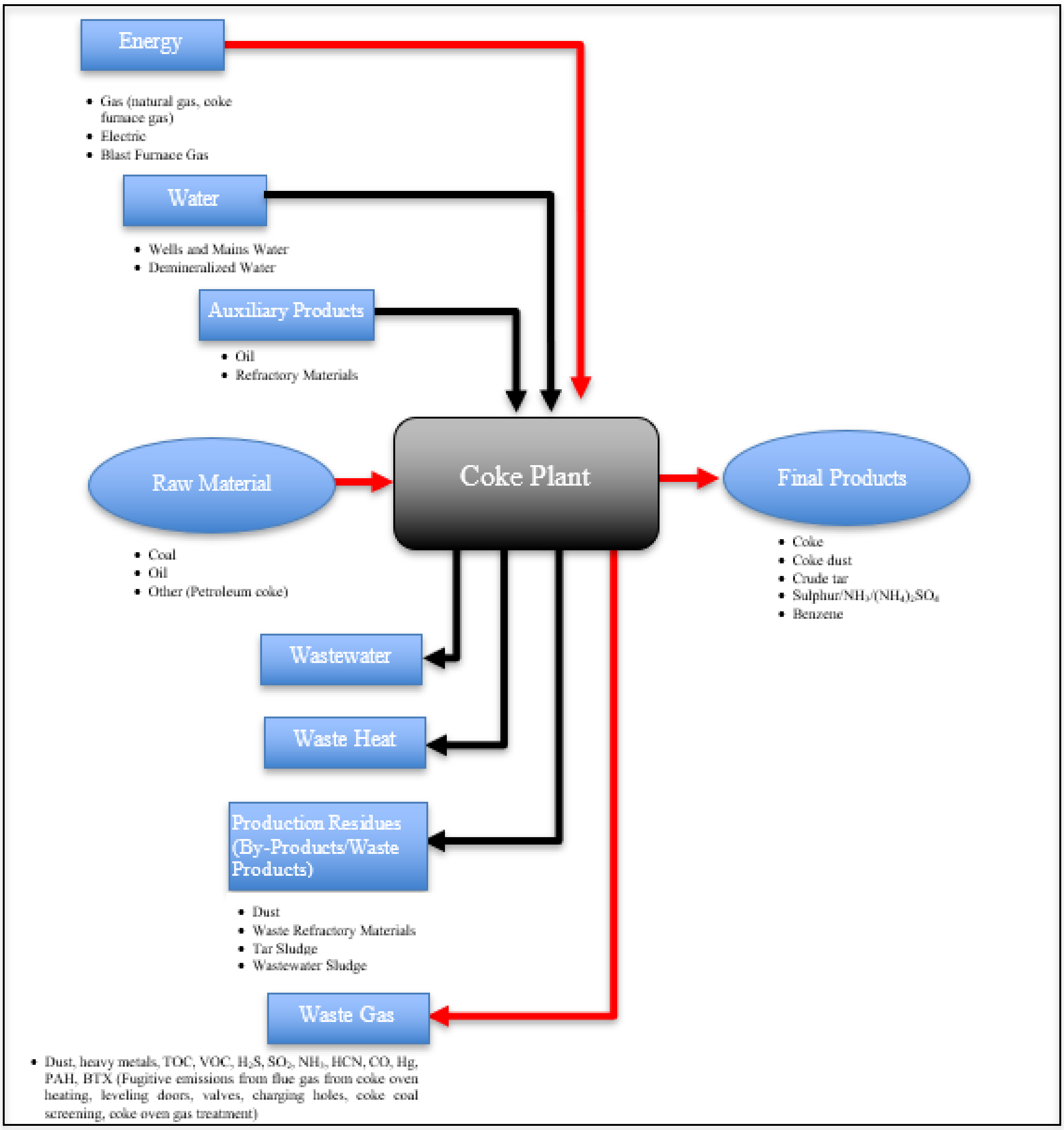

Figure 4. Coke Plant Key Inputs and Outputs

As summarized in Figure 4, the presence of carbon content in the energy, raw materials, and product streams required for coke oven operation results in carbon emissions.

2.2.2. Sinter Plant

The sintering process in integrated plants allows the fine particles of iron ore to agglomerate, allowing them to be used efficiently in BFs. Therefore, it is important in iron making. Sintering involves thermochemical reactions (Bhattacharya &

Datta, 2023) (Li & Qiu, 2022). These processes affect both the sinter itself and dust and gas emissions. The inputs and outputs of sinter plants are summarized in Figure 5, with those marked in red representing carbon-containing inputs and outputs.

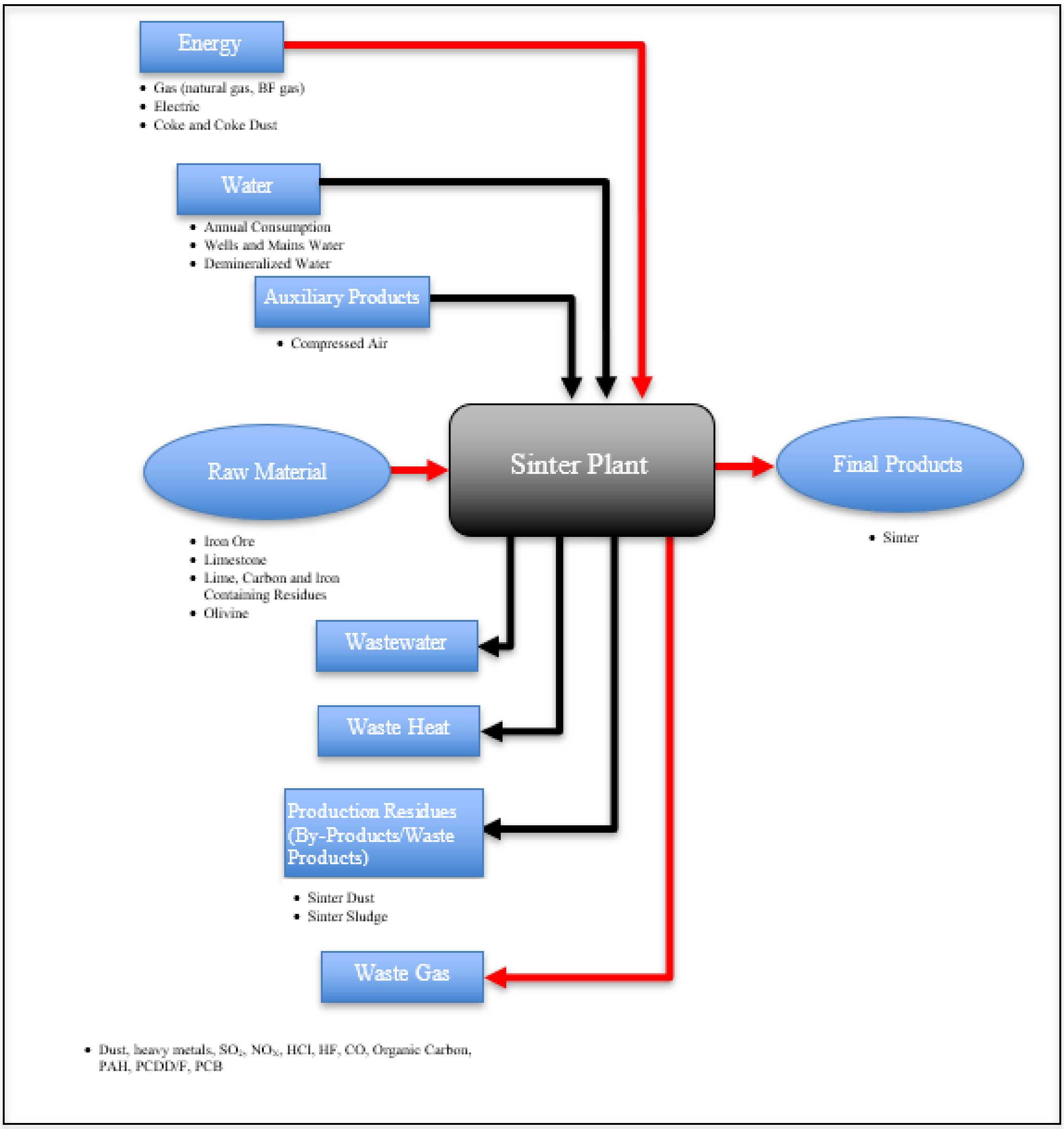

Figure 5. Sinter Plant Key Inputs and Outputs

As summarized in Figure 5, the presence of carbon content in the energy, raw material, product, and waste gas streams required for the sintering process results in carbon emissions.

2.2.3. Blast Furnace (BF)

The BF technology most commonly used in integrated plants is based on countercurrent metallurgy and is used to produce pig iron.

The iron oxides and coke fed into the furnace from the top are moved downwards while the reducing gases are moved upwards. The reduction conditions inside the furnace are created with the help of coke fed from the top, oxygen, carbon, or hydrogen-based reducing agents injected from the tuyeres. Reducing gas flows upwards and reduces and melts the top-charged charge material into hot metal. A modern BF plant consists of the following sections:

- BF proper,
- Hot blast supply equipment,
- Gas cleaning system and gas storage,
- Raw material storage and handling,
- Liquid products disposal, and
- Process control equipment.

A large amount of energy, coke, and pulverized coal is consumed at this stage. Therefore, in integrated iron and steel plants, a significant portion of emissions occur during this stage. This process consumes large amounts of energy and uses coke and pulverized coal reactions (Bhattacharya & Datta, 2023) (Suopajärvi et al., 2013). The main inputs and outputs from this process are summarized in Figure 6.

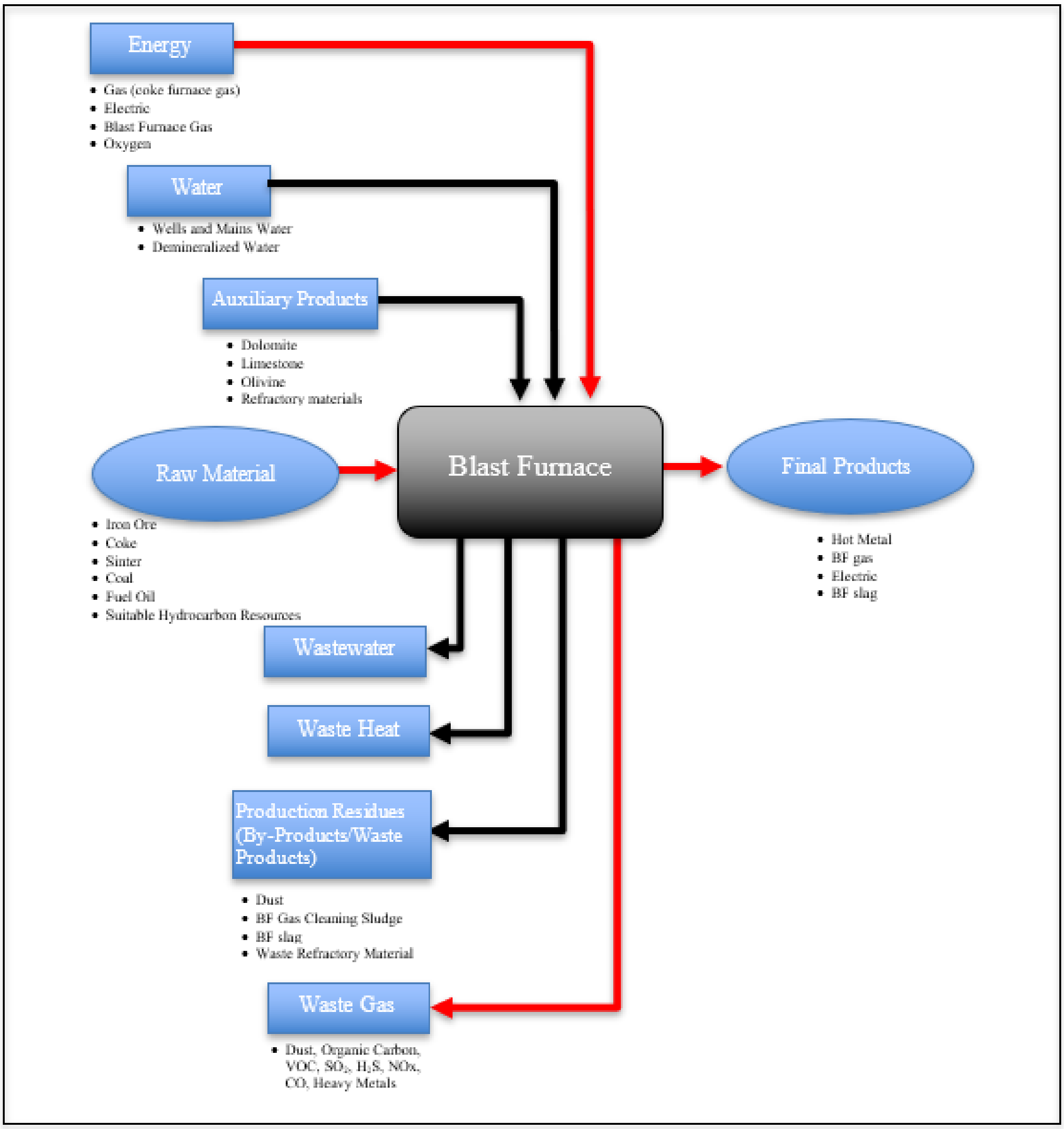

Figure 6. Blast Furnace Key Inputs and Outputs

As summarized in Figure 6, carbon emissions occur due to the presence of carbon content in the energy, raw material, product, and waste gas streams required in the BF process.

All components in BF gas can be released during charging and transportation. Raw BF gas contains particulate matter (including heavy metals and carbon), carbon monoxide (CO), carbon dioxide (CO_2), sulfur compounds, ammonia (NH_3), cyanide compounds, and Polycyclic Aromatic Hydrocarbons (PAHs).

2.2.4. Basic Oxygen Furnace (BOF)

The BOF process, also known as the oxygen converter process, is the most common method for primary steel production and produces liquid steel. The BOF process includes the following steps:

- Charging,
- Oxygen blowing,
- Refining,
- Sampling and analysis, and
- Tapping.

The first step of the BOF starts with the loading of raw materials. The main inputs are iron ore (hot metal from the BF or directly reduced iron), scrap steel, by-products such as limestone and dolomite, and oxygen. Once the raw materials are loaded, they are lowered into a lance furnace equipped with a multi-hole nozzle. Here, high-pressure oxygen is added, creating an exothermic reaction with the carbon contained in the load. The blowing of oxygen raises the temperature of the charge, melting the scrap and hot metal. This reaction produces CO gas, which is emitted as a by-product. Impurities in the hot metal, such as carbon, silicon, and manganese, also react with the oxygen to form slag. During these processes, samples can be taken to assess the quality of the steel. Finally, the slag is removed from the steel by means of a tapping hole in the furnace (Bhattacharya & Datta, 2023).

Pollutant emissions from this process occur during the charging of scrap or hot metal, oxygen blowing, tilting of the furnace during oxygen blowing, transfer of liquid steel to ladle furnaces, and slag removal. The main inputs and outputs for the BOF are given in Figure 7.

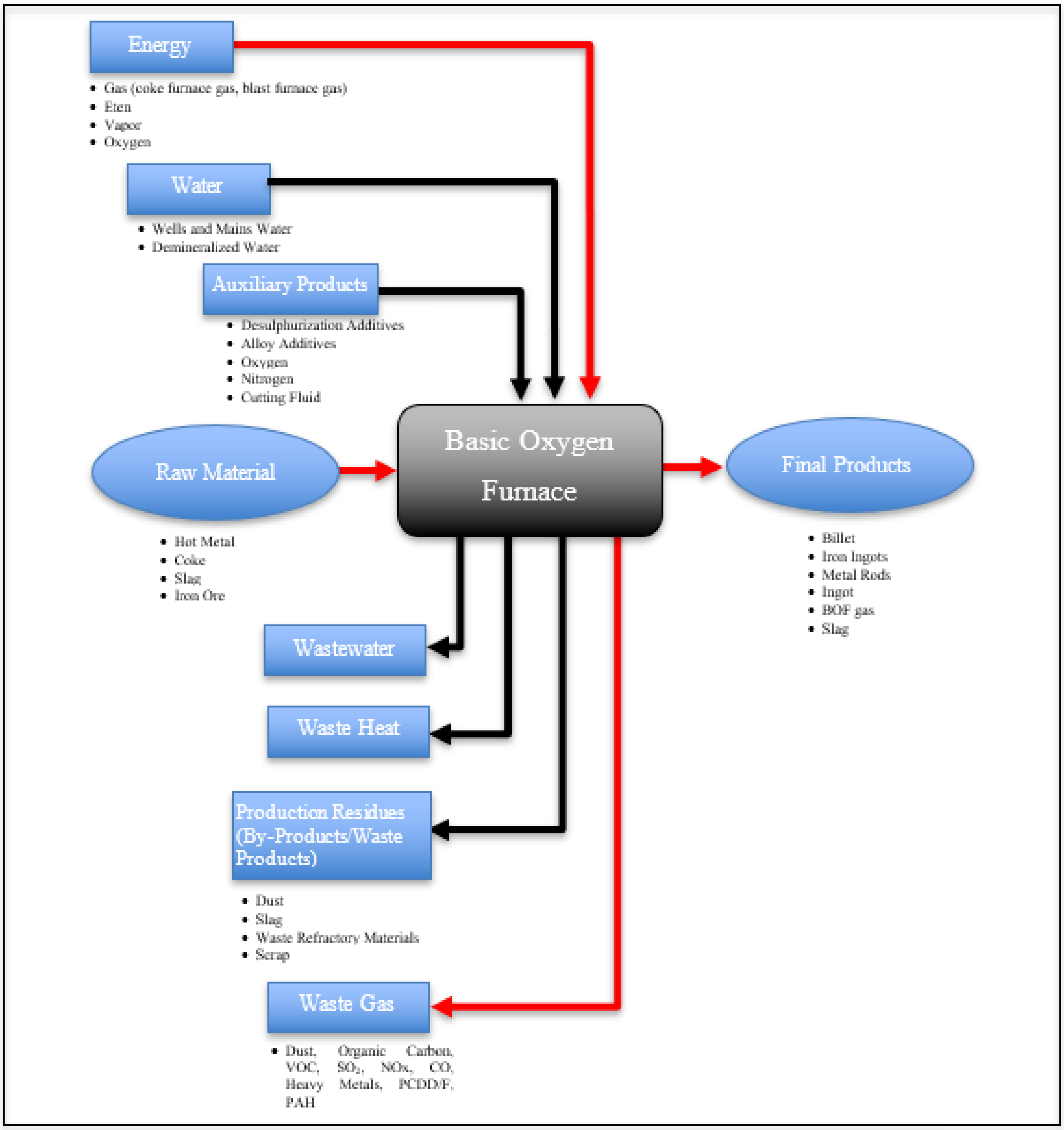

Figure 7. Basic Oxygen Furnace Key Inputs and Outputs

As summarized in Figure 7, carbon emissions occur due to the presence of carbon content in the energy, raw material, product, and waste gas streams required in the BF process.

2.2.5. Crucible Furnaces (Secondary Metallurgical Plants)

Ladle furnaces are large metallurgical furnaces, usually used to smelt iron ore and produce steel at high temperatures. The combustion of fossil fuels such as coal, coke, gas, or oil usually powers these furnaces. Carbon emissions are produced and released into the atmosphere during this combustion process.

2.2.6. Continuous Casting Facilities

Continuous casting plants consist of melting, casting, and cooling stages, which require fossil fuels such as coal, coke, gas, or oil. The combustion of fossil fuels produces carbon emissions and releases the atmosphere.

2.2.7. Rolling Mills

Emissions from rolling mills mainly originate from annealing furnaces where products are made ready for processing. Here, controlling combustion, improving combustion conditions, modernization, and regular maintenance of annealing furnaces can significantly reduce emissions.

The type of fuel consumed in annealing furnaces is very important in terms of emissions. Generally, plant gases such as fuel oil, natural gas, Coke Oven Gas (COG), and Blast Furnace Gas (BFG) are used to ignite the furnaces. This produces mainly dust and combustion gases.

2.2.8. Energy Production Plants

Energy facilities within integrated iron and steel factories generally use plant gases such as natural gas, COG, and BFG. Although facility emissions vary depending on the type of fuel they consume, they mainly consist of dust and combustion gases.

2.3. Emission Calculation of Integrated Iron and Steel Plants

The GHG Protocol, an international accounting tool, is widely used by government and business leaders to understand, measure, and manage GHG emissions. The GHG Protocol provides calculation tools for different industrial sectors. Emission sources from the iron and steel industry are summarized in the following three (3) scopes.

Scope-1: Direct Emissions (Originated or controlled by the company)

- CO_2 emissions from iron and steel production processes
- GHG emissions from stationary combustion
- GHG emissions from transportation or mobile sources

Scope-2: Indirect Emissions (Emissions from purchased electricity, heat, or steam)

- GHG emissions from purchased electricity
- Allocation of emissions from co-generation

Scope-3: Other Indirect Emissions

- GHG emissions released during the use of products
- GHG emissions from the production of purchased materials
- GHG emissions from the transportation of products

This thesis examines low-carbon technologies for reducing Scope-1 process emissions from integrated iron and steel plants.

2.4. Key Carbon Reduction Practices in Iron and Steel Plants

Integrated iron and steel production is complicated to decarbonize. For this reason, studies on reducing production emissions have been conducted for a long time. These studies have been compiled, and key carbon reduction practices have been identified under three (3) main headings for this thesis:

- Alternative raw material use
- Non-fossil reductant/fuel substitution
- Carbon Capture and Storage (CCS)

These key carbon reduction practices are currently needed by the sector globally, and information on them is provided below.

2.4.1. Alternative Raw Material Use

This section presents an overview of biomass, biochar, and coal refining models as alternative raw material technologies in iron and steel production processes.

2.4.1.1. Biomass and Biochar

Metallurgical coke from the coke plant is used in BFs in the iron and steel industry. Coke significantly impacts hot metal quality and the BF process (Meng et al., 2017). Therefore, it is one of the most important raw materials BF uses in iron production. The high carbon content of coke causes CO_2 emissions. The most appropriate solution to reduce this is the widespread use of renewable and carbon-neutral materials.

Using biomass for heating and reduction in the iron and steel industry can potentially replace metallurgical coke. Biomass fuel has a higher surface area and higher porosity compared to coal fuel (Ooi et al., 2008) (Lovel et al., 2009) (Suopajärvi et al., 2017). However, the biggest problem in using biomass as fuel is its low heating value due to the abundance of oxygen and VOCs in its content (Vassilev et al., 2015) (TÜBİTAK, 2023). Therefore, the most efficient ways to convert biomass to biochar should be investigated.

It is known that the most suitable biomass for use in metallurgical processes is wood-based. However, raw woody biomass is not suitable for use in processes without any treatment (TÜBİTAK, 2023).

In order to increase the thermal efficiency of biomass, the physical properties of the biomass should be determined and subjected to a series of processes accordingly. Generally, to obtain biochar from biomass, thermochemical transformations such as pyrolysis, gasification, torrefaction and hydrothermal carbonization processes are used, which provide high temperature (300-900 °C) and limited oxygen conditions (Nidheesh et al., 2021) (Amalina et al., 2022).

Woody biomass can be upgraded to biochar through thermochemical slow pyrolysis without oxygen, as in torrefaction or pyrolysis processes (TÜBİTAK, 2023).

The appropriate use of biochar in the iron and steel industry can result in energy savings, emission reductions and cost reductions. Also, due to the purity of biochar, high-quality hot metal can be produced and provided with fewer impurities for the subsequent steelmaking process.

2.4.1.2. Coal Blending Models

Today, coal blending models are being developed to blend various coal types to produce coke of a specific targeted quality. Coal blending models are used to obtain an optimized coal blend by mixing different types of coal used in steel production with a certain quality and properties. Factors such as coal quality, combustion characteristics, ash content, VOC, sulfur content, and moisture content play an active role in determining coal blend models, taking into account the plant's needs. These models can be obtained through mathematical modeling, data analysis, and simulation techniques. Coal blending models are used in iron and steel plants worldwide and in Türkiye. However, the programs that develop these models cannot provide high levels of efficiency, so studies to increase the success of the programs continue.

2.4.2. Fuel Substitution or Non-Fossil Reductants

This section presents an overview of technologies for substituting alternative fuel or non-fossil reduction methods (hydrogen, electrolysis, and gasification) into production processes.

2.4.2.1. Reduction with Hydrogen

In iron and steel production processes, carbon-free hydrogen can be used to replace the conventional reductant coke or carbon monoxide gas. However, the majority of hydrogen needs today are met by using fossil fuels such as natural gas or coal. Greenways of obtaining hydrogen could be a good option for the iron and steel industry to decarbonize its processes. The potential of carbon-free hydrogen production with blue H_2 (fossil fuel + CCS H_2 production) and green H_2

(renewable electricity + water electrolysis H_2 production), technologies developed in recent years, is being explored (van Hulst, 2019) (Dickel, 2020).

2.4.2.2. Reduction with Gasification

Most (85%) of total CO_2 emissions in iron and steel plants occur in iron reduction processes. In this context, gasification technologies can convert biomass into synthesis gas (biosyngas) to directly reduce iron ore (Zaini et al., 2023). Gasification is when oxygen (or air) and steam are brought into direct contact with coal or other feed materials. This method consists of a series of chemical reactions that convert the feed into syngas and ash/slag. These chemical reactions occur in a gasifier, a high-temperature/pressure vessel (National Energy Technology Laboratory, 2024).

2.4.2.3. Reduction with Electrolysis

In the reduction by electrolysis method, an electric current is applied to the ore to perform electro-chemical processes to reduce the iron ore. The iron ore is dissolved in a high-temperature solvent, and an electric current is passed through it. Negatively charged oxygen ions migrate to the positively charged anode, producing oxygen bubbles. Positively charged iron ions migrate to the negatively charged cathode, where they are reduced to elemental iron. If the electricity used is carbon-free, iron is produced without CO_2 emissions (WSA, 2021).

2.4.3. Carbon Capture and Storage (CCS)

This section provides an overview of carbon capture and storage technologies. The first applications of CCS technologies began in the 1920s when CO_2 was used to separate CO_2 from methane (CH_4) gas in natural gas reserves. This technology, called CO_2 scrubber, was developed to remove impurities from methane before it was sold.

CO_2 is separated from other gases and captured during emissions-intensive processes such as iron production. The captured CO_2 is then transported via a pipeline or ship to an onshore or offshore storage location (in Europe, the former

North Sea gas fields have great potential) or used, for example, as fuel or biomass. Processes include post/pre-combustion capture and compression-transport-storage/utilization (Roland, 2020).

The first modern project to reduce anthropogenic CO_2 emissions was the Sleipner Carbon Capture and Storage (Sleipner CCS) project in the Norwegian North Sea in 1996. Launched in 1991 by Equinor under the influence of carbon taxes imposed by the Norwegian government, the project captures CO_2 separated in the natural gas refining process. It is injected into deep brine aquifers for storage and emission (CCS Technologies Program at MIT, 2016).

There are four main technologies used to capture carbon:

- Carbon absorption (primary usage)
- Retention on the surface/carbon adsorption (secondary usage)
- Carbon capture with membrane (secondary usage)
- Carbon capture with cryogenic process (theoretical)

Carbon absorption technologies are the most preferred CCS technologies for the iron and steel sector. The second option is adsorption and membrane separation technologies. Carbon capture by a cryogenic process is far from being practiced according to today's technology level and economy. Therefore, absorption and adsorption technologies in primary and secondary use in the sector are described below.

2.4.3.1. Carbon Absorption

As described above, carbon absorption technology is preferred for primary use in the iron and steel sector. Carbon absorption technology is basically based on the process of physically or chemically trapping CO_2 in another liquid or solid material. An example is trapping CO_2 molecules by dissolving them in a liquid solution. It is the oldest technology used in carbon capture and is known to be the method with the most research and development (R&D) work and progress. For this reason, this technology is expected to be the most preferred method in the near and medium future (TSKB Enerji Çalışma Grubu, 2023). Carbon absorption processes are divided into chemical and physical. Chemical absorption methods include MEA, AMP, KS-1 and KS-2, Aqua ammonia, Caustic, Dual-alkali etc. Physical absorption methods include the selexol process, rectisol process, flour process (propylene carbonate), NMP-Purisol (n-methy-2-pyrollidone), etc. In iron and steel production processes, chemical absorption can be preferred for CO_2 capture due to the low CO_2 pressure of the flue gas in BFs. It is important to characterize the process in carbon capture technologies.

2.4.3.2. Carbon Adsorption

Adsorption is often used to clean or recover gases and other chemicals in iron and steel plants. This method allows contaminants or unwanted components in the gas phase to be absorbed into the surface using an adsorbent material.

2.5. Current Carbon Reduction Practices in the World

Since using coke and coal as raw materials in integrated iron and steel plants is the main source of carbon emissions, direct and smelting reduction processes have been developed in many integrated plants worldwide. Today, these processes continue to be developed and are widely used. These processes involve the pre-reduction of ores. Below is information about widely used process technologies that help reduce carbon emissions.

COREX: This technology, developed in the 1980s by Siemens VAI (now Primetals Technologies), aims to reduce iron ore to metallic iron directly. In this process, iron ore's melting and reduction processes occur in a single unit. By developing this technology, carbon-free production is realized in many countries, reducing production costs. The first company to use this technology is Indian-based JSW Steel (JSW Steel, 2024).

FINEX: FINEX technology is an iron production technology developed by the Korean company POSCO and Primetals Technologies. This technology uses direct fluidized bed reactors. The raw material, i.e., coal, which is gasified by the smelter gasifier, becomes a reducing gas and directly reduces the iron. This process aims to obtain a more efficient result by combining the Fluidized Bed of FINMET, originating from Finland, and the Melting Gasifier of COREX, originating from Germany. For this reason, it is called FINEX (Primetals Technologies, 2024).

MIDREX: The technology for this direct reduction method was developed in the late 1960s by Midrex Technologies Inc. of the United States of America (USA). The first commercial application of this technology was realized by Kobe Steel Ltd., a steel production company based in Japan. It has subsequently continued to be used and developed in many countries (MIDREX, 2024).

HyREX: POSCO, South Korea's largest steel company, is developing its own green H2-DRI steelmaking process, branded HyREX. HyREX will replace the shaft furnace in conventional DRI technology. It uses a fluidized reduction method in which high-temperature reduction gases are evenly distributed through a distribution plate at the bottom of the reactor, which facilitates the reduction reaction by allowing the powdered iron ore to float and mix (Hasanbeigi et al., 2024).

HIsmelt: It was started to be developed by HIsmelt Pty Ltd in Australia in the 1990s. In the HIsmelt process, a mixture of coal and limestone is melted into powder in the lower zone and combustion is conducted in the upper zone by applying hot blowing enriched with oxygen. After combustion, iron ore is deposited in the lower zone while slags and combustion gases are produced in the upper zone. The first HIsmelt pilot plant was established in 2000 and continues to be used in different countries with improvements and modernizations over the years (Goodman & Dry, 2009).

2.6. Integrated Steel Plants in Türkiye

Since this study covers the examination and evaluation of integrated iron and steel plants in Türkiye, information about the Kardemir, Erdemir, and İsdemir plants is given below.

2.6.1. Kardemir

Karabük Demir Çelik Sanayi ve Ticaret A.Ş. (Kardemir) is Türkiye's first integrated iron and steel factory in Karabük province. Its foundation was laid on April 3, 1937, by İsmet İnönü, the prime minister of the time, as one of Mustafa Kemal Atatürk's national industrialization moves. Kardemir commissioned its first BF on September 9, 1939, and started production (KARDEMİR, 2019).

Kardemir also pioneered the establishment of Erdemir and İsdemir by contributing to the development of Turkish industry. Kardemir, one of the world's leading freight, passenger, light rail, and locomotive wheel manufacturers, was privatized in 1995.

Kardemir's process components include a coke plant, sinter plant, BF, steel production, and continuous casting processes.

Kardemir has a total of 5 blast furnaces, these are;

- Blast Furnace No. 1 (Fatma), which was established in 1939 and is the first blast furnace of Kardemir and Türkiye,
- Blast Furnace No. 2 (Zeynep), established in 1950,
- Blast furnace No. 3 (Ülkü), established in 1962,
- Blast furnace No. 4 was established in 2008, and
- Blast furnace No. 5 was established in 2015.

BFs consist of various parts: throat, shaft or stack, belly, bosh, and hearth (Laraia, 2019). The inner parts of blast furnaces contain refractory material to prevent the heat generated from damaging the body sheet. Refractories are exposed to various effects (mechanical and chemical, corrosion, erosion, abrasion) depending on the regions of the blast furnace (Husović et al., 2022). In 2022, Kardemir replaced all refractories in blast furnace No. 1 and made physical improvements around the furnace to repair aging blast furnaces, increase production efficiency, and prevent emission leaks. The modernization of the No. 1 furnace was completed, and the production capacity was increased (Anadolu Ajansı, 2022).

The coal used in the coke plants at Kardemir is purchased from the Zonguldak Kozlu, Karadon, and Üzülmez quarries of the Turkish Hard Coal Authority, and the amount purchased is 170,000 tons of coking coal produced annually. Coking coal is used at a rate of 10-15% in coke factories. Iron ore is purchased from various regions of Anatolia, and the annual amount is around 2,500,000 tons (KARDEMİR, 2023)

In Kardemir facilities, liquid crude iron from blast furnaces is transported by ladles or torpedoes and sent to steel production facilities. Liquid crude iron is converted into liquid steel in basic oxygen furnaces. Kardemir currently has three basic oxygen furnaces, two with a capacity of 120 tons and one with a capacity of 90 tons (KARDEMİR, 2023).

In 2022, despite the global and national economic downturn in iron and steel production and production losses due to maintenance and repair at BFs No. 1 and No. 4, Kardemir's Blast Furnace No. 5 broke its annual production record. Kardemir used 3.62 mt of ore and 1.93 mt of coal for production in 2022, producing 2.22 million tons of crude steel and 2.14 million tons of finished products. Kardemir's total carbon emission for 2022 was calculated as 5.5 million tons of CO_2e, and it was announced that it causes 2.5 tons of CO_2 emissions per ton of crude steel produced. (KARDEMİR, 2023)

2.6.2. Erdemir

Ereğli Demir ve Çelik Fabrikaları T.A.Ş. (Erdemir) was established as Türkiye's first flat steel production facility with Law No. 7462 adopted on February 28, 1960, to meet the needs of the existing industry in Türkiye and to establish and develop new branches of industry. Erdemir started its production journey on May 15, 1965, with an annual production capacity of 0.5 million tonnes of crude steel and 0.4 million tonnes of flat steel.

Erdemir's process components include coke plants, sinter plants, coal injection plants, blast furnaces, desulfurization plants, steel mills, secondary metallurgy plants, continuous casting plants, and hot and cold rolling mills.

The preparation of the raw material is conducted in the coke plants. The coking plants at Erdemir consist of coal preparation facilities, coke batteries, coke manipulation facilities, and by-product facilities. In the coke and sinter plants, raw materials are prepared to usable properties and sizes for the BF. A coal injection plant was established at Erdemir to reduce the use of coke and to utilize cheaper coals that are not suitable for coking. The ready-to-feed raw materials produced in these units and facilities are sent to Erdemir's BFs. In order for the hot ore coming out of the BF to be usable in the steel mill, it is sent to the desulfurization plant. Here, the sulfur in the hot ore content is removed. Erdemir's steel mill consists of three converters, and the desulphurized hot ore is mixed with alloying elements and converted into pure steel with oxygen. Secondary metallurgy facilities ensure that the steel produced in the steel mill is of high quality. Erdemir's secondary metallurgy facilities consist of ladle mixing, ladle furnace, degassing plant under vacuum, chemical heating, and alloying plant. High-quality steel is sent to the continuous casting plants, where it is shaped and solidified in molds. Erdemir has four continuous casting plants. Slabs obtained from the continuous casting plants are sent to hot and cold rolling mills and subjected to cutting, sizing, and annealing processes (Gümüş, 2001).

Units auxiliary to production at Erdemir include lime factories, oxygen factories, power generation and distribution facilities, dams, and water facilities. Metallurgical burnt lime and dolomite used in the steel mill converters are produced in Erdemir's three lime factories, while the oxygen requirement is met in five oxygen factories. Approximately half of the electrical energy consumption at Erdemir is provided by the Power Plant. The water requirement used in the production of liquid steel in the plant is supplied by dams (Gümüş, 2001).

Today, Erdemir produces hot and cold rolled flat steel, plate, tin, chrome, and galvanized coated steel sheets at international quality standards. With a capacity of approximately 4 mt of crude steel and 5 mt of finished products, Erdemir is one of the world's most important steel producers. It is also the only plate producer in

Türkiye and has one of the largest ports in the Black Sea Region (OYAK Maden Metlurji Şirketleri, 2024).

In 2023, it was declared that 2.11 tons of CO_2e emissions were realized at Erdemir to produce one ton of crude steel (OYAK Maden Metlurji Şirketleri, 2024).

Erdemir established new companies and transformed them into a group headed by Ereğli Iron and Steel Factories Turkish Joint Stock Company except for capacity investments in production.

Erdemir has accelerated its efforts for green steel production in recent years. The Wood Shredding Equipment, which aims to reduce CO_2 emissions by using biochar instead of fossil fuel in iron and steel production processes, was commissioned in 2023. With this equipment, efforts were made to reduce the size of the wood waste generated and stockpiled every year and to use it as secondary raw material for biochar production in the Pilot Pyrolysis Plant (OYAK Maden Metlurji Şirketleri, 2024).

In January 2002, Erdemir acquired İsdemir on the condition that it would switch to flat production. As of February 2006, Erdemir Group, a state company, started operating within OYAK Group, one of the largest group companies in Türkiye. Today, OYAK Group continues the activities of Erdemir Group based on its experience in international markets, financial strength, and contemporary management principles.

2.6.3. İsdemir

Founded on October 3, 1970, in İskenderun, İskenderun Demir ve Çelik A.Ş. (İsdemir) is an integrated iron and steel plant with the third highest steel production capacity and the largest liquid steel capacity in Türkiye. İsdemir was transferred to Erdemir in 2002 on the condition that flat product production would be started.

The company is among the world's most important steel producers, with a production capacity of 5.8 million tonnes/year of liquid steel, 3.5 million tonnes/year of flat products, 0.6 million tonnes/year of coil, and 2.5 million tonnes/year of billet finished products.

In 2023, it was declared that 2.07 tons of CO_2e emissions were realized at İsdemir to produce one ton of crude steel (OYAK Maden Metlurji Şirketleri, 2024).

İsdemir, Türkiye's only integrated steel plant capable of simultaneously producing both long and flat products, has been continuing its investments in line with the needs of the country's industry since its establishment.

In January 2002, all of İsdemir's shares were transferred to Erdemir on the condition that investments were made for the transition to flat production. After Erdemir started to operate within OYAK Group in February 2006, İsdemir also came under the umbrella of OYAK Group (İSDEMİR, 2024).

2.6.4. Projects of Kardemir, Erdemir and İsdemir

At Kardemir, feasibility studies have started for the transformation roadmap for the zero-emission target. Within the European Green Deal obligations framework, a working group has been established at Kardemir, and joint studies have been carried out with many public institutions and organizations. It carries out studies in the fields of hydrogen, carbon capture, dedusting, and reduction of hazardous waste. Research on the existing blast furnace technology, which accounts for 90% of the emission intensity in the facility, has begun. Research is also being conducted on the use of production technologies such as direct reduced iron (DRI), melting furnaces, and electric arc furnaces. Kardemir is also working on scenarios for the transition to low-carbon steel through the use of entirely new technologies. There is also research on fuel use. In order to reduce carbon emissions from electricity supply, there are feasibility studies for renewable energy (Solar Power Plant and Wind Power Plant) (KARDEMİR, 2023).

Kardemir is committed to reducing its greenhouse gas emissions in the short, medium, and long term and carries out a policy that aims to reduce greenhouse gas emissions in line with Türkiye's national zero carbon final goal by 2053. The activities carried out in this context are given in Table 3.

Table 3. Projects Conducted at Kardemir (KARDEMİR, 2023)

Project Name	Project Description	Status of Completion	Amount of Greenhouse Gas Emission Reduction
30 MW Turbo Generator Investment	Kardemir's electricity generation installed capacity with the commissioned generator increased to 107.5 MWe.	In December 2021, the investment was completed.	Annual GHG emission reduction from combustion and Scope 2 was 57,757 tCO_2.
LAC 40 Turbine Pump Commissioning	One turbine-driven feed water pump was decided to replace three electric motor feed water pumps to meet the steam boilers' feed water requirements.	It was commissioned in 2023.	It has been declared that 7,205 MWh/year of electricity savings is achieved with the commissioning of the project. The reduction in greenhouse gas emission from Scope 2 is estimated at 3,170 tCO_2.
Coke Batteries Closed Coal Charging with Ammonia Water Instead of Steam	Closed coal charging in coke batteries is planned to be done with ammonia water instead of steam.	It was commissioned in 2023.	When the project is commissioned, the annual combustion-based GHG mitigation amount is projected to be 2692 tCO_2.

Oyak Group, which includes Erdemir and İsdemir, announced the Net Zero Roadmap to contribute to Türkiye's 2053 net zero emission target. In this context, Erdemir and İsdemir stated that they aim to reduce carbon emissions per ton by 25% by 2030, 40% by 2040, and reach net zero emissions by 2050, compared to 2022, which they set as the base year (OYAK Maden Metlurji Şirketleri, 2024). Erdemir and İsdemir included their green transformation investments in the Integrated Annual Report to realize their targets within this scope.

The ongoing and completed investment projects included in the Integrated Annual Report for Erdemir and İsdemir are summarized in Table 4.

Table 4. Ongoing and Completed Projects at Erdemir and İsdemir (OYAK Maden Metlurji Şirketleri, 2024)

Plant	**Project Name**	**Project Description**	**Status of Completion**
Erdemir	Erdemir 2nd Blast Furnace Renovation Project	Blast furnace renewal, considering the need for relining, ensured minimum production loss and cost.	Completed.
	Erdemir Steel Mill Converters Modernization Project	The sustainability of the steel production process has been ensured through equipment modernizations that will eliminate abrasion and deformations that would stop production.	Completed.
	Erdemir Steel Mill Secondary Dust Collection System Capacity Increase Project	Within the scope of the project, a new dust collection system was installed in addition to the existing secondary dust collection system, thus reducing dust emissions.	Completed.
	Erdemir 1st Slab Furnace Modernization Project	The furnace shell defects caused by the slab furnace have been eliminated. Thus, the use of the 4th furnace due to quality problems has been reduced, and the 1st furnace has been used more effectively in strip production.	Completed.
	Erdemir Plate Rolling Mill Housing System Renewal Project	By increasing the crushing power, production capacity and quality have been increased.	Completed.
	Erdemir 60 MW Turbo Generator Project	With the project of purchasing a new 60 MW turbo generator instead of the 2nd and 3rd turbo generators, a new generator with higher efficiency than the existing generators was implemented. Thus, it was aimed to reduce the amount of purchased electricity by producing more electricity with the same steam input.	Completed.
	Erdemir 4th Coke Battery Project	The aim is to reduce external coke purchases to zero.	Ongoing.
	Erdemir No. 5 Coke Battery Project	It aims to eliminate emission problems originating from the 3rd coke battery, to prevent additional costs that may arise due to purchasing coke from outside, and to eliminate the risks that may arise in coke production.	Ongoing.
	Erdemir Steel Mill Charging Hall Cranes Renewal Project	It is aimed to ensure the sustainability of liquid steel production by renewing the cranes that have completed their service life in the steel mill charging hall.	Ongoing.
	Erdemir New Turbo Blower Project	A new Turbo Blower is planned to be installed to ensure the safety and continuity of liquid crude iron production in blast furnaces.	Ongoing.
	Erdemir 2nd Hot Rolling Mill Investment Projects	The project aims to reduce unplanned stoppages, minimize material losses, improve product quality, and increase customer satisfaction.	Ongoing.

Plant	Project Name	Project Description	Status of Completion
İsdemir	Isdemir New 1st Blast Furnace Project	The furnace volume is planned to be increased. Thus, since the final product amount will increase, it is planned to convert the excess blast furnace gas into electricity production.	Ongoing.
	Isdemir Vacuum Degassing Plant Project	The RH-OB Twin Type Vacuum Degassing Plant has been established, which has the technology to remove gases such as hydrogen, nitrogen, and oxygen, which are expected to be at minimum levels in steel, to reduce the amount of non-metallic inclusions and to produce grades with ultra-low carbon content.	It was commissioned on April 25, 2024
	Isdemir 1st Blast Furnace Top Pressure Turbine (TRT) Project	It is aimed to provide additional electricity production by utilizing the pressure of the blast furnace gas to be produced in the new 1st blast furnace.	Ongoing.
	Isdemir 3rd Steam Boiler Retubing (Partial Pipe Replacement) and Burner Modification	In the 3rd steam boiler, pipe replacement and burner system modification are targeted. Thus, steam supply will be provided economically and safely.	Ongoing.
	İsdemir 1st Quay Ore Unloading Cranes Renewal Project	It is aimed to ensure the continuity of port activities and sustainability in steel production. In this context, new cranes will be put into operation, and more efficient working conditions will be achieved.	Ongoing.
	İsdemir Hot Rolling Mill Line length Level-1 Automation Systems Modernization Project	Software update and modernization studies are planned to ensure the information security of systems with aging operating systems.	It has been commissioned, and tests are ongoing.
	İsdemir Port Capacity Increase Investment	It is aimed to create additional port capacity by increasing the capacity of the investments to be made in İsdemir.	Ongoing.
	İsdemir New 1st and 2nd Turbo Generator Project	It is planned to increase the condenser capacities and renew the turbine rotors. In this way, it aims to increase efficiency and capacity, increase electricity production, and reduce electricity purchased from outside.	Ongoing.
	İsdemir Coke Dry Quenching Plant Steam Electricity Generation Project	It is aimed to provide additional electricity production by reducing the pressure of the total steam obtained from the Coke Dry Quenching Plant with the Back Pressure Turbine instead of the pressure reduction station.	Ongoing.

In addition to these projects, Erdemir proved that it has accelerated its net zero journey with the news it announced to the public. First, by announcing that it will conduct a hydrogen injection trial in the 1st Blast Furnace in October 2024, Erdemir showed that it has taken another step on its green transformation journey. Within the scope of this testing work, which was successfully carried out in October, a total of 2.2 tons of liquid hydrogen gas was injected into Erdemir's 1st Blast Furnace from 5 feathers for 2 days. During the trial, 0.6 kg of hydrogen was injected per ton of liquid crude iron, while this rate was increased to 1 kg in the later stages of the test. Simulations suggest that it is theoretically possible to inject up to 28 kg of hydrogen per ton of liquid crude iron, resulting in a direct reduction of 15-16% in CO_2 emissions in the furnace processes. With this testing, Erdemir broke new ground in the Turkish steel industry and became one of the three steel producers in Europe to realize this practice (Erdemir, 2024) (Anonymous, 2024) .

Secondly, they announced in the Integrated Annual Report that they have commissioned a pyrolysis plant for their work on the use of biomass with zero emission factor at various stages of the process. The pilot pyrolysis plant will produce biomass fuel as an alternative fuel to coal. Depending on the results to be obtained from the pilot pyrolysis plant, Erdemir plans to use biochar at the plant in the coming years in certain proportions instead of coal in the coal blend in the coke process, coke powder in the sinter blend in the sinter process, injection coal in the BF process and anthracite in the converter in the steel mill (Erdemir, 2024).

2.7. Closing Remarks

In this section, the production route of integrated iron and steel plants and the carbon emission sources generated in this route are explained. In integrated plants, coke and sinter plants, BFs, and BOFs, which are involved in preparing raw materials, are identified as the main carbon emission sources. In this thesis, the emission reduction technologies currently being researched for these carbon emissions are divided into three main classes. Since there are also studies on the development of technologies currently used worldwide among the technologies researched, brief information about these technologies is also given. It is known that these technologies, which are widely used worldwide, are not used in Türkiye. Information on integrated plants and carbon emissions in Türkiye is provided. Kardemir's data for 2023 was not available, but it was found that in 2022, 2.5 tons of CO_2 was emitted to produce one ton of crude steel. In Erdemir and İsdemir, this amount was 2.11 and 2.07 tons of CO_2 for 2023, respectively. It is known that modernization works and new plant installations are being carried out to reduce these emissions to zero. One of the most remarkable efforts by integrated plants in Türkiye to reduce carbon emissions was using hydrogen as a carbon-free reduction technology in one of Erdemir's BF installing a pilot pyrolysis plant to use biomass as an alternative carbon-free fuel.

3. PREVIOUS STUDIES

This chapter summarizes previous research papers on low-carbon technologies developed for integrated iron and steel production, as presented below.

3.1. Impact of Alternative Raw Material Use on Emission Reduction

The articles that have recently highlighted the impact of the use of alternative raw materials in iron and steel plants on emission reductions are summarized below. The emission reduction rates of the technologies/applications subject to the articles are summarized in a table under Section 3.1.3.

3.1.1. Biomass and Biochar

Biomass is inefficient in terms of carbon content and heating value compared to coke or injection coals used in the conventional method. Biomass contains high levels of oxygen, volatile matter (VM), and moisture, leading to unstable combustion. Therefore, raw biomass needs to be developed before utilization. The Green Growth Technology Map published by the Scientific and Technical Research Council of Türkiye (TÜBİTAK in Turkish) working group states that wood-based is the most suitable upgradeable biomass.

Wood and woody biomass can be upgraded to biochar through thermochemical slow pyrolysis in the absence of oxygen. Biomass charcoal obtained from the pyrolysis of raw biomass is expected to have broad application opportunities in iron production in the iron and steel sector. The efficiency of biochar depends on its compositional properties and pyrolysis conditions (carbonization temperature, heating rate, retention time, etc.). Increasing the carbonization temperature and extending the retention time during the production of biomass coal reduces the coal yield (TÜBİTAK, 2023).

A study has shown that replacing fossil fuel-based carbon with biomass-derived coal in the integrated steelmaking process has the potential to reduce GHG emissions of steel by 31-57% without any coal production by-products (bio-oil and electricity), and by 42-74% when these by-products are included in the emission reduction, at possible implementation and substitution rates (Norgate et al., 2012).

A study reported that using a biomass-based reducing agent in biochar pyrolyzed at 300 °C, i.e., torrefied biomass, is the most efficient method used in blast furnaces. The plant achieved a 4-15% reduction in CO_2 emissions (Wiklund et al., 2012).

In a study, the effect of biomass injection into blast furnaces instead of pulverized coal from fossil sources on the CO_2 emissions of the plant was investigated. Pelletized, torrefied or pyrolyzed biomasses were used in the study. And, a simulation was used to determine the proportions in which biochar could be used, and the simulation result showed a full replacement potential for charcoal, 22.8% for torrefied material, and 20% for raw wood pellets. As a result of the study, it was found that in-plant emissions can be reduced by 28.1% if all of the pulverized coal used in the traditional method in integrated plants is replaced with charcoal and injected into the BF. Also, it was found that maximum emission reduction of 6.4% and 5.7%, respectively, can be achieved if a determined rate torrefied material and wood pellets are used (Wang et al., 2015).

A study reported that CO_2 emissions can be reduced by 7.9% when 5% torrefied biomass is injected into the furnace with biogas instead of coke dust used in BF (Firsbach et al., 2022).

3.1.2. Coal Blending Models

To ensure efficient operation of the blast furnace and high-quality iron ore reduction in integrated plants, coal mixtures that can coke at an appropriate degree are required. Proper adjustment of coal mixtures is significant for preparing coal mixtures to increase the output quality of the BF. Laboratory and pilot test studies are utilized to ensure high performance and low cost of coal mixtures. The characteristics of the existing coal in the plant stockpiles, its compatibility with other coals to be used, the coke gas requirement of the factories, and the cost table of the plant are influential factors in the development of this technology. When these factors are appropriately analyzed, it is predicted that carbon emissions can be reduced (TÜBİTAK, 2023).

In a study, it was observed that a 50% reduction in GHG emissions could be achieved by 50% according to the results of the experiments conducted when a coal blend with a 50% charcoal mixture is provided as an input instead of 100% coke in the sintering process (Abreu et al., 2015).

A study compared the contribution of the substitution of fossil fuels in the iron and steel industry with two different types of biochar, wood and straw-based, to emission reductions. As a result of the study, it was observed that the wood-based coal mixture provided a decrease of 66.94% on the BF-BOF route. Within the scope of the study, when only the performance of the wood-based coal mixture on the BF route is analyzed, it is observed to provide a reduction of 73.66%. This is because the blast furnace is the largest source of emissions in the iron and steel production process (Meng et al., 2024).

3.1.3. Summary of Impact of Alternative Raw Material Use on Emission Reduction

Table 5 presents a summary of papers on the use of alternative raw materials by topic, year, and reduction rate.

Table 5. Emission Reduction Comparison on Alternative Raw Materials Technologies

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Reduction Rate (%)	Applicability	Cost
Biomass and Biochar						
Norgate et al., 2012	Changing of raw material input. Using biomass instead of charcoal.	Sinter Plant Coke Plant Blast Furnace	CO_2	31-57	Since it is difficult to replace all of the charcoal with regular coal, an applicable substitution rate must be determined.	Transportation is an important factor affecting cost.
Norgate et al., 2012	Changing of raw material input. Using biomass instead of charcoal and by-product utilization (bio-oil and electricity).	Sinter Plant Coke Plant Blast Furnace	CO_2	42-74	Since it is difficult to replace all of the charcoal with regular coal, an applicable substitution rate must be determined. Furthermore, the impact of by-products depends on the type of biochar.	Transportation is an important factor affecting cost.
Wiklund et al., 2012	Changing of raw material input. Pyrolyzing biochar, injecting torrefied biochar into a BF.	Blast Furnace	CO_2	4-15	The applicability depends on the characteristics of the pyrolysis unit to be integrated into the plant.	Raw material, transportation and pre-treatment costs are forecasted.
Wang et al., 2015	Using charcoal (biomass) completely instead of pulverized coal, a fossil resource injected into the BF.	Blast Furnace	CO_2	28.1	The availability of biomass and the processes required for its pre-treatment need to be investigated.	Logistical problems can increase costs. Technically, resources should be allocated for experimental testing and the establishment of pilot plants.
Wang et al., 2015	Using 22.8% torrefied material (biomass) instead of pulverized coal, a fossil resource injected into the BF.	Blast Furnace	CO_2	6.4		

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Reduction Rate (%)	Applicability	Cost
Wang et al., 2015	Using 20% wood pellets (biomass) instead of pulverized coal, a fossil resource injected into the BF.	Blast Furnace	CO_2	5.7		
Firsbach et al., 2022	Changing of raw material input. Using biomass and biogas instead of coke.	Blast Furnace	CO_2	7.9	Technical infrastructure must be provided for the torrefication process.	Heat recovery is difficult and costly.
Coal Blending Models						
Abreu et al., 2015	Modified raw material is used by mixing half of the coke input with charcoal (biomass).	Sintering	GHG	50	Chemical balance should be taken into account when preparing the mixture.	Land rights for plantations, institutional and economic factors affect the cost.
Meng et al., 2024	Modified raw material is used by mixing coke input with wood-based coal (biomass).	BF-BOF route	GHG	66.94	It is more advantageous if applied in the sintering process.	Biochar is more expensive than coke and coal. Therefore, the cost depends on the biomass market. Wood-based biochar is more affordable than other biomasses.
Meng et al., 2024	Modified raw material is used by mixing coke input with wood-based coal (biomass).	BF	GHG	73.66		

3.2. Impact of Non-Fossil Fuel Reductant/Fuel Substitution on Emission Reduction

The sintering process at the integrated plants blends coke dust, limestone, and other fossil-based additives into a material that can be charged to BFs. In addition to these materials used in the sintering process, coke gas and natural gas obtained from coke plants are used as fuel. Carbon emissions are released when these fossil-based fuels and reducing materials interact in the sinter-BF-BOF processes. Enriching these carbon-containing fuels and reducing materials with hydrogen or injecting hydrogen gas instead of directly will eliminate carbon emissions. However, one of the problems here is not the use of hydrogen but the obtaining of hydrogen in a green way. The Green Growth Technology Roadmap published by the TÜBİTAK working group states that hydrogen is not currently used as a fuel in the sintering process (TÜBİTAK, 2023).

Below is a summary of recent studies on non-fossil reduction methods and fuel substitution.

3.2.1. Reduction with Waste Plastics and Tires

The use of plastics as an alternative raw material and reducing material in the iron and steel sector has been proven to reduce carbon emissions since the early 2000s. Plastic materials, due to their carbon and hydrogen content, have the potential to replace coke used as a reducing material in integrated plants. In the traditional method, coke reacts with oxygen and carbon dioxide to produce carbon monoxide, a reducing gas. When plastic is used instead of coke, carbon monoxide and hydrogen are released as products, and these gases contribute to the reduction reaction. When plastic is used, the amount of CO_2 produced is reduced by 30% compared to the conventional method due to the reducing properties of hydrogen. Therefore, collecting and pre-treating waste plastics from the market can support sustainable production and reduce CO_2 emissions. For waste plastics to be used in processes, those with complex properties should be crushed, and those with light/thin properties should be melted. It is known that plastics are not used in the iron and steel sector in Türkiye (TÜBİTAK, 2023).

A study examined the carbon intensity of the Japanese iron and steel sector and the factors affecting the intensity. The study states that the use of waste plastics and tires in Japan's iron and steel sector is applied and has a small-scale effect on emission reduction. Although it has a negligible impact on emission concentration reduction, it is stated that the amount of waste plastics and tires used in Japan's iron and steel sector is increasing yearly. According to the report published by the Japanese Iron and Steel Federation in 2021, using 1-ton waste plastics and tires provides 3.6 tCO_2 reduction. As a result of the research, it was stated that the most significant improvement in carbon intensity can be achieved through direct reduction with hydrogen (Oda & Akimoto, 2022).

3.2.2. Reduction with Hydrogen

A study investigated the H_2 reduction reaction kinetics and fluidization properties of fine and cohesive Fe_2O_3 particles in a vibrating fluidized bed reactor. The study resulted in high Fe_2O_3 reduction rates at a low temperature of 500 °C. Fine iron ore particles can be directly converted to Fe without pre-sintering using vibro-fluidized beds and direct H_2 reduction instead of BFs. In summary, it has been observed that the use of H_2 in the direct reduction of iron ore with hydrogen provides significantly lower operating temperatures, reducing energy consumption and fossil-based CO_2 emissions by over 75% (Li et al., 2021).

South Korean company Pohang Iron and Steel Company (POSCO) currently operates the Fines INstant Extraction (FINEX) plant using a reduction gas containing 25% hydrogen and is developing a new hydrogen reduction model, Hydrogen-based Steelmaking (HyREX), to reduce iron directly. In a report, it was stated that 2.2 tons of CO_2 is emitted to produce one ton of steel using conventional methods, while the CO_2 emission from steel production reduced by hydrogen, which is completely green, is only 0.06 tons of CO_2 emission per ton of steel. In other words, approximately 97% CO_2 emission reduction will be realized (Hasanbeigi et al., 2024).

A study investigated the impact of hydrogen-based direct reduction of iron ore on CO_2 emissions. The study showed that there is significant potential for CO_2 emissions reduction if hydrogen is used as a reducing agent. Compared to the reference process of direct reduction with natural gas (DR-NG), it was concluded that the directly emitted CO_2 emissions could be reduced by up to 91% without considering the CO_2 intensity of the additional electricity required (Rechberger et al., 2020).

3.2.3. Reduction with Gasification

In one study, a fluidized bed reactor for a chemical cycle combustion/gasification process was designed, and steam-blasted pellets and charcoal (biomass) were used as fuel. Steel slags (by-product) were used as oxygen carrier solids in the study. As a result of the study, an average CO_2 yield of 75-82% was obtained for all of the tested fuels. When charcoal was used as fuel, it was reported that a CO_2 efficiency of 92% was achieved at low fuel input (Moldenhauer et al., 2020).

A study proposes a promising DRI route regarding energy and CO_2 capture. Two gasifier technologies are evaluated in this study: a steam/oxygen-blown Circulating Fluidized Bed (CFB) gasifier and a steam-blown Double Fluidized Bed (DFB) gasifier. CFB gasifiers comprise a riser where biomass is subjected to moisture evaporation, pyrolysis, and char gasification processes. DFB gasifiers are commonly known as recirculating gasifiers because a circulating hot bed material provides the heat for gasification. Since most of the combustion reaction occurs outside the gasifier, DFB gasifiers allow syngas production with lower CO_2 and higher H_2 concentrations than CFB gasifiers. The proposed system consists of a biomass dryer, a gasifier, a tar reforming/removal process, a gas heater, a DRI shaft furnace, and a CO_2 removal process. The wet biomass is first dehumidified in the drying stage. The dried biomass is then fed into the gasification process, where it is converted into raw syngas, unreacted coal, and ash. Atmospheric fluidized bed biomass gasifiers and reforming processes convert tar to H_2 and CO. This maximizes the conversion of biomass into high-quality reducing gas. Different integration scenarios are proposed for each main category based on applying an integrated biomass dryer, Air Separation Unit (ASU), electrolyzer, or electric tar reformer. For example, as proposed in the DFB-Electrolyzer-O_2 and CFB-Electrolyzer-O_2 scenarios, the addition of electrolyzer reduces the amount of CO_2 captured by 22% and 32% compared to

DFB-ASU-O_2 and CFB-ASU-O_2, respectively. As a result of the study, the electrification of the tar reformer and gas heater reduced the CO_2 produced and sequestered by approximately 29-32% (Zaini et al., 2023).

In a study, three possible FINEX off-gas (FOG) utilization methods were proposed and examined to make the reduction technology FINEX sustainable. The first case is post-combustion capture, the second case is pre-combustion capture, and the third case is pre-combustion capture followed by methanol synthesis. All of the proposed methods include CO_2 capture and it is assumed that the captured CO_2 is kept deep underground. Although the first case provides the highest CO_2 reduction with 65%, it was found to be non-economical. The second case was proven to have a CO_2 reduction of 22% and the third case 31%. As a result of the study, Case-2 was proven to be the most economical way to reduce CO_2 emissions. This is because the process uses less energy to capture CO_2 (Jeong et al., 2023).

HIsmelt is an innovative air-based direct smelting technology in which iron ore particles are preheated and pre-reduced in circulating fluidized bed reactors. Direct smelting and fluidized bed technologies can emit 20%-30% less CO_2 without the use of carbon capture and storage (Shabuddin et al., 2023).

3.2.4. Reduction with Electrolysis

Hydrogen plasma melting reduction or molten oxide electrolysis technologies have high CO_2 reduction potential but are currently of low applicability. Hydrogen plasma melting reduction is achieved by passing electricity through the reducing hydrogen gas to create a plasma arc, which gives off the heat necessary to melt the iron. Hydrogen Plasma Smelting Reduction (HPSR) reduces iron ore directly to liquid iron using ionized hydrogen plasma with the potential for 95% CO_2 reduction compared to the BF-BOF route. Molten oxide electrolysis (MOE) is an electrometallurgical technique used to produce liquid steel directly from iron ore (Shabuddin et al., 2023) (Draxler et al., 2021). In the MOE cell, an inert anode is immersed in an iron ore electrolyte and then electrified. When the cell heats up to 1600°C, electrons break the bonds in the iron oxide in the ore, producing pure liquid metal (Boston Metal, 2024). This technology can potentially reduce CO_2 by

96% compared to the conventional method (Shabuddin et al., 2023) (Draxler et al., 2021).

3.2.5. Fuel Substitution

Hydrogen is a clean fuel that leaves no by-products other than water vapor and heat. Considering the environmental impacts and limited reserves of fossil fuels, using hydrogen as a fuel and alternative energy source has been among the research topics in recent years. Studies for using and decarbonizing hydrogen in iron and steel processes started in 2020 and have been increasing yearly. Studies have shown that hydrogen can be helpful in integrated iron and steel plants' sintering processes and BFs.

Coke gas is currently used in sintering and is part of integrated iron and steel plants. Coke gas causes GHG emissions due to its carbon content. Therefore, using a gas enriched with coke gas and hydrogen gas or using hydrogen gas as a direct combustion gas is one of the leading technologies being developed. Recent studies on using hydrogen as an alternative fuel in integrated plants are summarized below.

Replacing coke, used as a reducing agent in BFs, with hydrogen produced from water electrolysis can significantly reduce emissions from iron and steel production (Bhaskar et al., 2020). In 2019, Thyssenkrupp, one of the world's largest steel producers, began testing hydrogen-based steel production at its production facility in Duisburg, Germany. At the plant, hydrogen was injected instead of coke in one of the BF flues. Results from the pilot study indicate CO_2 reductions of up to 20% (ThyssenKrupp Steel Europe, 2019).

In the study, pure H_2 injection was performed with tuyeres from the channel under the BF instead of coal, and 27.5 kg/t heated H_2 injection was performed instead of 120 kg/tons of steel pulverized coal. The study result showed that using H_2 as an auxiliary reducing gas in BFs can reduce CO_2 emission by 21.4% (Yılmaz et al., 2017).

A study developed a model to evaluate the utilization of residual gases for fuel. The model investigates the carbon emission reduction performance of Top Gas

Recycle Blast Furnace (TGR-BF) and CCS applications and their impact on Steam and Power Cogeneration System operation. After applying TGR-BF technology, the total emission reduction peaks at a top gas recovery rate of 6% (Xu et al., 2024).

In a study, the conversion of a coke oven gas-fired direct reduction shaft furnace (COG-DR-EAF) to a hydrogen-based shaft furnace (H_2-DR-EAF) was investigated. The study found that the COG-DR-EAF route consumes four times more electrical energy compared to the H_2-DR-EAF route. The study concluded that the H_2-DR-EAF route would result in 79% lower CO_2 emissions than the conventional BF-BOF steelmaking route if all hydrogen production is realized through the green route (Lu et al., 2024).

3.2.6. Summary of Impact of Non-Fossil Reductant/Fuel Substitution Technologies

Table 6 presents a summary of papers on the non-fossil reductant/fuel substitution by topic, year, and reduction rate.

Table 6. Emission Reduction Comparison on Non-Fossil Fuel Reductant/Fuel Substitution Technologies

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Reduction Rate (%)	Applicability	Cost
Reduction with Waste Plastic and Tires						
TÜBİTAK, 2023	Injection of waste plastics instead of coke from BF tuyeres.	Blast Furnace	CO_2	30	A pre-treatment process is required to convert plastics into blast furnace reducer elements. The pre-treated plastics are injected through the blast furnace feathers.	It requires a low cost.
Oda & Akimoto, 2022	Using waste plastic and tires instead of coke.	Integrated Plant processes except foundries	CO_2	3.6 ton CO_2	A pre-treatment process is required to convert plastics and tires into BF reducer elements.	It requires a low cost.
Reduction with Hydrogen						
Li et al., 2021	Vibro-Fluidized Bed and Direct H_2 Reduction Direct conversion to Fe without pre-sintering using a vibro-fluidized bed and direct H_2 reduction instead of BF.	Blast Furnace	CO_2	>75	Small-scale experiments for the developed vibrating fluidized bed need to be validated on a pilot scale. It is recommended to investigate the industrial scale production of the fine Fe_2O_3 feedstock prepared and used for the study. Potential green H_2 production routes should be investigated.	The cost of green H_2 production is an important factor for the realization of the study.
Hasanbeigi et al., 2024	HyREX technology with %100 green hydrogen.	BF-BOF Route	CO_2	~97	Research is needed for green hydrogen production. Adequate infrastructure for hydrogen supply needs to be in place.	The technology is costly to implement. The report puts the cost of the technology at US$ 20.4 million.

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Reduction Rate (%)	Applicability	Cost
Rechberger et al., 2020	Direct reduction of iron ore with hydrogen (DR-H_2)	Blast Furnace	CO_2	91*	Obtaining hydrogen by electrolysis may make it difficult to implement in terms of carbon footprint. For this, H_2 trials with green electricity supply should be developed.	Obtaining the electricity needed for the technology from green sources will increase the cost.
Reduction with Gasification						
Moldenhauer et al., 2020	Kimyasal döngülü gazlaştırma prosesinde biyokütlenin yakıt olarak ve çelik cürufların indirgeyici malzeme olarak kullanılması	Blast Furnace	CO_2	75-82	The steel slag used in the study has high availability in the plants.	The steel slag used in the study is low cost. Gas cleaning costs are lower compared to other technologies. The additional cost of the chemical cycle combustion plant is estimated to be very low compared to a circulating fluidized bed reactor.
Zaini et al., 2023	Electrification of Tar Reformer and Gas Heater Passing the biomass through fluidized beds and reforming processes, using an electrolyzer to provide O_2 has resulted in more efficient H_2 production than other methods. DFB-Electrolyser-O_2 or CFB-Electrolyser-O_2	Blast Furnace	CO_2	29-32	It can be difficult to implement in the first place due to the high electricity requirement. CFB has a simpler reactor configuration.	Demand for electricity is high. CFB gasifiers are expected to have lower capital costs than DFB gasifiers. The wood pellets used in the study are typically produced from sawmill residues and have the advantage of a well-established market. Log residues have the advantage of a relatively low cost and a significant untapped potential resource, especially in forest-rich countries such as Sweden.

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Reduction Rate (%)	Applicability	Cost
Jeong et al., 2023	Case 1: Amine-based absorption process captures CO_2 from flue gas. A 30 wt% aqueous solution of monoethanolamine (MEA) is used as absorbent. Case 2: Integration of the FINEX process with pre-combustion CO_2 capture. Polyethylene glycol dimethyl ethers (DEPG) solvent was used instead of MEA for absorption. This is a preferable option as it provides a higher driving force than MEA. Case 3: Pre-combustion from FOG followed by methanol production is the route. Some of the carbon in FOG is converted into methanol, providing direct emissions reduction.	Blast Furnace	CO_2	Case 1: 65 Case 2: 22 Case 3: 31	DEPG solvent can be used instead of MEA for carbon capture. DEPG has higher carbon capture performance than MEA.	Energy consumption accounts for 69% of the technology cost. The technology integrated with the FINEX process and pre-combustion capture (Case-2) is more cost-effective than the others.
Shabuddin et al., 2023	HIsmelt Iron ore particles are preheated and pre-reduced in circulating fluidized bed reactors.	Blast Furnace Route	CO_2	20-30	Direct reduction of iron with an integrated electric arc furnace (H_2DRI-EAF) is potentially the most suitable technology for integrating hydrogen. However, the availability of green hydrogen is a limitation in the implementation of this technology. It also poses a potential challenge to the use of hydrogen-based zero-carbon DRI in EAF as the steelmaking process requires some carbon in the steel.	Today, renewable hydrogen is not affordable for commercial-scale applications, leading to at least four times higher levelized costs for hydrogen-based steel production than the BF-BOF route.

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Reduction Rate (%)	Applicability	Cost
Shabuddin et al., 2023 Draxler et al., 2021	Hydrogen Plasma Smelting Reduction (HPSR) Direct reduction of iron ore to liquid iron by ionized hydrogen plasma	Blast Furnace – Basic Oxygen Furnace Route	CO_2	95	The potential for implementation is low.	Expenditures for renewable energy will constitute the cost of this technology.
Shabuddin et al., 2023 Draxler et al., 2021	Molten Oxide Electrolysis (MOE) Direct reduction by immersion and electrification of the ore in electrolyte	Blast Furnace – Basic Oxygen Furnace Route	CO_2	96	The potential for implementation is low.	There is a 50-80% increase compared to the conventional route.
ThyssenKrupp Steel Europe, 2019 Yılmaz et al., 2017	Replacement of coal feed to the BF with H_2 injection.	Blast Furnace	CO_2	20 & 21.4	It has the potential to be implemented.	Infrastructure for clean production of hydrogen and its transportation to the plant after production needs to be established.
Xu et al., 2024	TGR-BF Residual gases for fuel and top gas recovery	Blast Furnace	CO_2	6	It has the potential to be implemented.	Purchased power for the gas-steam-power system generates additional costs.
Lu et al., 2024	Using of green hydrogen instead of coke oven gas (H_2-DR-EAF route).	Blast Furnace – Basic Oxygen Furnace Route	CO_2	79	The availability of green hydrogen is a limitation in the implementation of this technology.	In the H_2-DR plant, the energy consumption of hydrogen production accounts for 87.7% of total energy consumption. Therefore, in terms of cost, energy needs to be obtained from renewable sources.

*The additional electricity required for the process is not included in carbon intensity reduction.

3.3. Impact of Carbon Capture and Storage on Emission Reduction

Under this heading, articles summarize the impact of studies on carbon capture and storage technologies on emission reduction.

3.3.1. Carbon Absorption

In a study, three methods were investigated to increase the CO_2 capture capacity of this process by treating the waste gas from the FINEX process: post-combustion capture (Case 1), pre-combustion capture (Case 2), and pre-combustion capture followed by methanol production (Case 3). Post-combustion capture uses an amine-based absorption process (Monoethanolamine (MEA) as absorbent) to remove CO_2 from the flue gas. All three (3) proposed methods reduced CO_2 emissions compared to current practice (FINEX process). Among the options, Case 1 (post-combustion capture) showed the most significant CO_2 reduction, reducing the current method emission by 35% (Jeong et al., 2023).

As carbon capture technology, POSCO uses low-concentration ammonia water to capture CO_2 from BF gas. This technology's maximum CO_2 removal rate is close to 99%. Moreover, its CO_2 absorption capacity is three times higher than monoethanolamine (MEA), one of the main absorbents (amine-based solvents) in the iron and steel industry (Yang et al., 2022).

3.3.2. Carbon Adsorption

A study investigated laboratory-scale adsorption processes for CO_2 capture from dry flue gas to achieve CCS specifications (95% CO_2 purity, 90% CO_2 recovery). Zeolite 13X was used as an adsorbent for the study, and Two-Stage Vacuum Swing Adsorption (VPSA), Temperature Swing Adsorption (TSA), and Temperature/Vacuum Swing Adsorption (TVSA) were designed. The simulated designs were systematically compared at a laboratory scale. As a result of the study, it was observed that all three adsorption designs contribute to process optimization. Many parameters were examined within the scope of the study. Regarding CO_2 recovery performance, the optimized designs VPSA, TSA, and

TVSA have CO_2 recovery rates of 91.86%, 90.27%, and 97.66%, respectively (Jiang et al., 2020).

Pressure Swing Adsorption (PSA) Technology, organic amine sorption technology, and ammonia sorption technology are among the technologies used in BFG purification in the iron and steel industry. Shougang Jingtang Company wanted to apply this technology to other processes and used PSA pressure swing adsorption technology to recover CO_2 from the residual gas of the lime kiln. The recovered CO_2 concentration was 99.8% (Yang et al., 2022).

3.3.3. Summary of Impact of Carbon Capture and Storage on Emission Reduction

Table 7 presents a summary of papers on carbon capture and storage by topic, year, and reduction rate.

Table 7. Emission Reduction Comparison on Carbon Capture and Storage Technologies

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Emission Reduction Rate (%)	Applicability	Cost
Carbon Absorption						
Jeong et al., 2023	Case 1: Amine-based absorption process captures CO_2 from flue gas. A 30 wt% aqueous solution of monoethanolamine (MEA) is used as absorbent. Case 2: Integration of the FINEX process with pre-combustion CO_2 capture. Polyethylene glycol dimethyl ethers (DEPG) solvent was used instead of MEA for absorption. This is a preferable option as it provides a higher driving force than MEA. Case 3: Pre-combustion from FOG followed by methanol production is the route. Some of the carbon in FOG is converted into methanol, providing direct emissions reduction.	Blast Furnace	CO_2	Case 1: 65 Case 2: 22 Case 3: 31	DEPG solvent can be used instead of MEA for carbon capture. DEPG has higher carbon capture performance than MEA.	Energy consumption accounts for 69% of the technology cost. The technology integrated with the FINEX process and pre-combustion capture (Case-2) is more cost-effective than the others.
Yang et al., 2022	Ammonia absorption (POSCO technology) Separation of CO_2 from low-concentration ammonia water using waste heat at low and medium temperatures.	BF Route	CO_2	99	Amine-based absorbents remain unstable after absorbing CO_2, leading to high energy consumption in the regeneration process and a bottleneck problem in industrial applications.	It has been determined that 20 USD is spent to capture 1 ton of CO_2.

Papers	Technology Description	Technology Impacted Process	Pollutant Parameter	Emission Reduction Rate (%)	Applicability	Cost
Carbon Adsorption						
Jiang et al., 2020	Two Stage Vacuum Swing Adsorption (VPSA) Separation of air into its constituent components by adsorption	BF Route	CO_2	91.86	The vacuum level is a critical issue for the technology to be applicable.	It is more advantageous than others in terms of energy consumption. Energy costs will be low.
Jiang et al., 2020	Temperature Swing Adsorption (TSA) The recovered CO_2 is heated and used as a regeneration cleaning gas.	BF Route	CO_2	90.27	The feed flow rate is a critical issue for the technology to be applicable.	It is a costly option due to high energy and power consumption.
Jiang et al., 2020	Temperature/Vacuum Swing Adsorption (TVSA) CO_2 molecules and sorbents are easily separated by vacuum and heat.	BF Route	CO_2	97.66	The feed flow rate is a critical issue for the technology to be applicable.	It is more advantageous than others in terms of power consumption. Energy costs will be low.
Yang et al., 2022	Pressure change (Pressure Swing Adsorption (PSA) Technology)	BF Route	CO_2	99.8	It has a greater applicable temperature and pressure range.	It has low energy consumption and investment costs. However, large-scale application in the iron and steel industry is still not favored.

3.4. Closing Remarks

The technologies summarized above are for the iron and steel sector. In this study, except for electric arc furnaces and induction furnaces in the iron and steel sector, the studies prepared directly for the plants working with integrated production methods were taken into consideration.

Within the scope of the effect of alternative raw materials on emission reduction, the highest emission reduction rate was achieved with the wood-based coal blend model, with a rate of 73.66% in the studies conducted for biochar and coal blend models.

In the studies evaluated within the scope of the effect of carbon-free reduction and fuel substitution on emission reduction, the highest emission reduction rate was achieved with MOE technology at 96%. However, as mentioned above, the applicability of MOE technology is low today. Therefore, combining hydrogen reduction methods with carbon capture or fluidized bed technologies that provide a suitable environment at high temperatures can provide both economical and high performance in carbon emission reduction.

Several technologies (such as FINEX) have been implemented to assess the impact of CCS technologies on emission reductions. With the technology developed by POSCO, CO_2 is separated from ammonia water with heat. Providing heat from waste heat creates an important effect for this technology. This technology has proven that 99% CO_2 recovery is achieved.

Adsorption and absorption technologies will compete with plasma and electrolysis technologies and be highly efficient in process improvements.

4. METHODOLOGY & DATA SOURCES

This study's methodology consists of three main steps: data gathering and analysis, application of the DEMATEL technique, and evaluation of results.

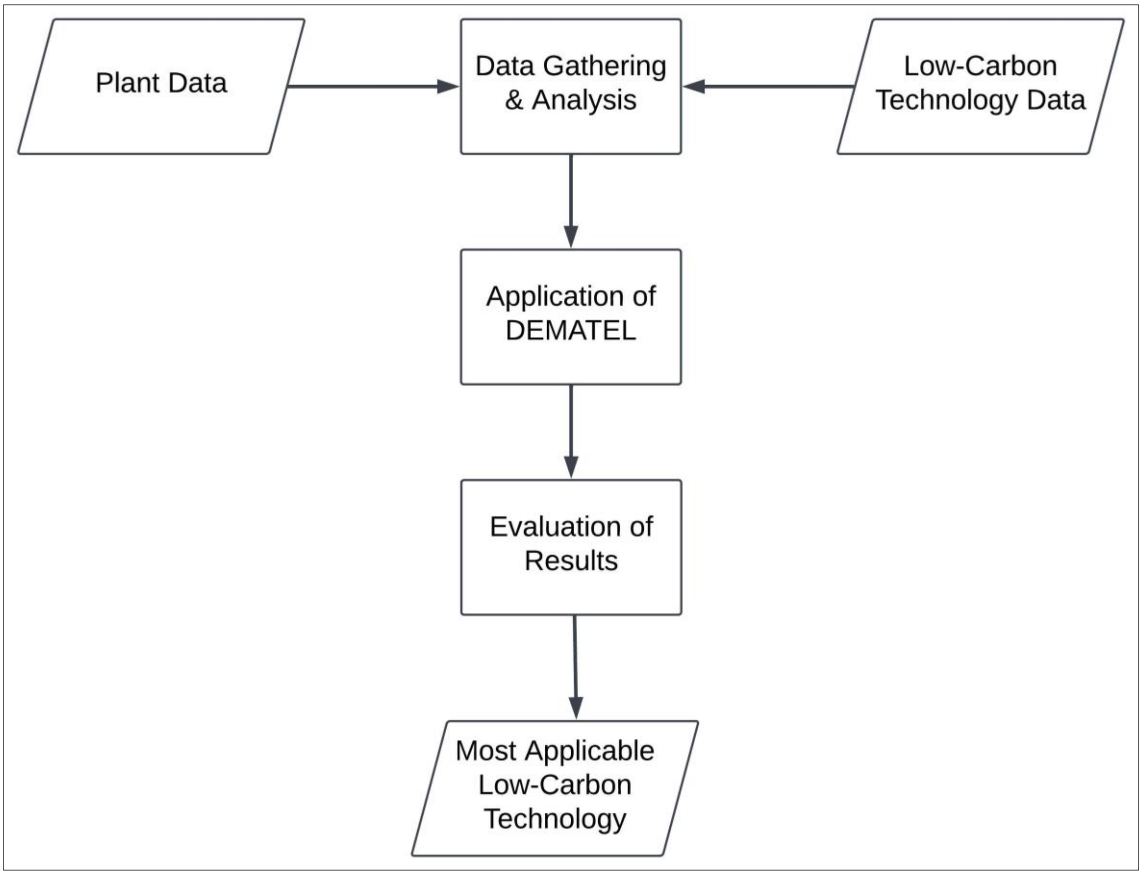

Figure 8. Methodology Flowchart of the Study

4.1. Data Gathering and Analysis

This section details and analyzes the required data to conduct the study. In the first step, the data on three integrated plants are obtained.

Process and emission information from integrated iron and steel plants in Türkiye. Process, production, and emission data for integrated iron and steel plants in Türkiye were collected from various sources. Process information on integrated iron and steel plants in Türkiye was compiled from publicly available environmental impact assessment reports, graduate studies, and publications made public by the plants. Production data on integrated iron and steel plants in Türkiye are compiled from the annual activity reports published publicly by the facilities. Process information and emission data for integrated iron and steel plants are presented in Chapter 2.

Next, data on the available low-carbon techniques are obtained. A literature review was conducted, and emission mitigation efforts that can be implemented globally in integrated iron and steel plants were summarized. The emission reduction rates of new low-carbon technologies obtained from the literature review are analyzed in Chapter 3. The techniques evaluated based on the system boundary are described below.

In this study, only the plants in Türkiye (Kardemir, Erdemir, and İsdemir) that produce steel through the integrated production route were included. Figure 9 shows the boundaries of the integrated production route included in this study. While determining the study boundary, the routes that consume the most energy and cause carbon emissions in the facility were taken into consideration. Steel casting, hot rolling, cold rolling, galvanizing, and coating processes were not included in the scope of this study due to their relatively lower energy consumption and carbon emissions.

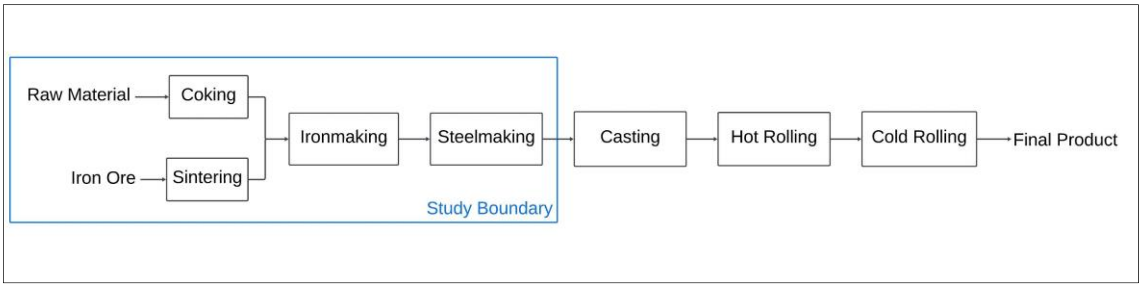

Figure 9. Main Steps of the Iron and Steel Production Route and the Study Boundary

4.2. Application of the DEMATEL Technique

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique is used for the technology selection. This method is used to select which of the three main technology applications (alternative raw material use, non-fossil fuel reductant/fuel substitution, and carbon capture and storage), which are analyzed in detail in Chapter 3, would be effective in integrated iron and steel plants in

Türkiye. The framework and calculation steps of the DEMATEL method used in this study are presented in below.

4.2.1. DEMATEL Method

Since publicly available data on integrated iron and steel plants in Türkiye is limited, most of the data required for technology assessment could not be accessed. Factors affecting technology selection were identified in line with the information obtained from publicly available sources. Then, a literature review was conducted. In order to determine the appropriate technology, it was necessary to plot the influence-importance of these factors among each other. Therefore, DEMATEL, one of the multi-criteria decision-making methods, was used to extract the influence and importance degrees of certain factors. According to the results obtained from DEMATEL, the technologies analyzed in the literature review were evaluated.

In this study, the DEMATEL method is used to select which of the three (3) main technology applications (alternative raw material use, non-fossil fuel reductant/fuel substitution, and carbon capture and storage), which are analyzed in detail in Chapter 3, would be effective in integrated iron and steel plants in Türkiye. The framework and calculation steps of the DEMATEL method used in this study are presented below.

DEMATEL method was developed by the Science and Human Relations program of the Battelle Memorial Institute in Geneva, Switzerland, between 1972 and 1976 to analyze and solve complex, interrelated problem structures (Gabus & Fontela, 1972) (Fontela & Gabus, 1976).

In complex problem structures, many main and sub-criteria affect the decision-making outcome and need to be evaluated. All criteria should be considered simultaneously to solve the complex problem in a healthy and accurate way.

The DEMATEL method helps decision-makers better understand these complex problems by visualizing all the criteria. This method allows the creation of a relationship map that reveals the internal relationships between criteria and helps visualize the causal relationships of subsystems through causality diagrams.

DEMATEL, an analytical method, creates a direct relationship matrix between variables in a system built on decision variables with internal relationships between them. Thus, the degree to which the variables influence and are influenced by each other allows us to classify the variables that constitute the system into cause-and-effect groups and to identify the major variables in the system.

4.2.2. Steps of the DEMATEL Method

Below are the calculation steps of the DEMATEL method.

Step 1 – Generating the direct relation (average) matrix:

Creating the direct relation (average) matrix is the first stage of this method. In this stage, n factors $F = (F_1, F_2, ..., F_n)$ affecting the system are determined. A scale is created to quantify the direct relation of factor F_i to factor F_j. Internal relationships between decision variables are scored using the scale given in Table 8.

Table 8. Comparison Scale of DEMATEL Method

Numerical Value Corresponding to Description	Description
0	No influence
1	Very low influence
2	Normal influence
3	High influence
4	Very high influence

The direct relation (average) matrix created in Equation (1) is denoted by **A** or a_{ij} and shows the initial direct effects that a factor utilizes and receives from other factors. The values a_{11}, a_{1j}, a_{i1}, and a_{ij} in the direct relationship matrix indicate the level at which the variables/criteria considered in the decision-making process are affected by the variable being compared. For example, the value expressed by a_{11} represents the effect of the first decision variable/criterion selected for decision-making on itself, and the impact of a decision variable/criterion on itself is considered zero (0). Similarly, a_{1j} is the value obtained by scoring the effects of the first decision variable/criterion selected for decision-making on the nth decision variable/criterion with the comparison scale in Table 8. In this equation, i and j refer to the factors influencing the application of low-carbon technologies presented in Chapter 3.

$$A = a_{ij} = \begin{bmatrix} a_{11} & \dots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \dots & a_{ij} \end{bmatrix} \quad i,j = 1,2,\dots,n \tag{1}$$

Step 2 – Normalizing the direct relation matrix:

In the created direct-relation matrix, all row and column values are summed using Equation (2), and the total value with the largest value is determined. Each element of the created direct-relation matrix is divided by the **k** value obtained by Equation (2), the value that has the largest value among the total values of the rows and columns of the matrix. Hence, a normalized direct-relation matrix is created. The normalized direct relationship matrix is represented by **M** and given by Equation (3).

$$k = max\left[max_j\left(\sum_{i=1}^{n} a_{ij}\right), max_i\left(\sum_{j=1}^{n} a_{ij}\right)\right] \tag{2}$$

$$M = \frac{A}{k} \tag{3}$$

Step 3 – Attaining the total-relation matrix:

After obtaining the normalized direct-relation matrix **M**, the total relation matrix **T** can be acquired by using Equation (4), where **I** is denoted as the identity matrix. In Equation (5), t_{ij} denotes the total degree of association of the i^{th} risk factor with the j^{th} risk factor.

$$T = M(I - M)^{-1} \tag{4}$$

$$T = \begin{bmatrix} t_{11} & \cdots & t_{1j} \\ \vdots & \ddots & \vdots \\ t_{i1} & \cdots & t_{ij} \end{bmatrix} \quad i,j = 1,2,\ldots,n \tag{5}$$

Step 4 – Producing the influential relation map:

In this step, the relationship and influence between the criteria are examined, and an influential relation map is generated. First, the formulas given in Equations (6) and (7) determine the sum (R) of each row (i) and the sum (C) of each column (j) in the total relation matrix.

$$R = [r_i]_{n\times 1} = \left(\sum_{j=1}^{n} t_{i,j}\right)_{n\times 1} \tag{6}$$

$$C = \left[c_j\right]_{1\times n} = \left(\sum_{i=1}^{n} t_{i,j}\right)_{1\times n} \tag{7}$$

The row and column sums represent the degree of influence of the criteria on the other criteria. In these equations, $\mathbf{r_i}$ is the sum of the first row in the **T** matrix and represents the sum of the direct and indirect influences from factor $\mathbf{F_i}$ to the other factors. Similarly, $\mathbf{r_j}$ is the sum of the **jth** column in the **T** matrix and represents the sum of the direct and indirect effects of the factor $\mathbf{F_j}$ from other factors.

Among the R+C and R-C values calculated for each row and column in the prominence-relation matrix, R+C values are called “prominence” on the horizontal axis vector, while R-C values are called “relation” on the vertical axis vector. Prominence values represent the strength of the effects the factor gives and receives, and relation values indicate the net effect the factor contributes to the system.

For example, if (r_j - c_j) is positive, factor F_j has a net effect on the other factors and can be grouped in the cause group; if (r_j - c_j) is negative, factor F_j is influenced by the other factors as a whole and should be grouped in the effect group.

Step 5 – Determining the threshold value:

Decision-makers need to set a threshold value for the level of influence to obtain an appropriate prominence-relation graph in this step. The threshold value is determined by expert opinion. It is commonly determined by averaging the values obtained in the total relation matrix.

The above steps are calculated separately for each technology analyzed in Chapter 3, and the results are presented in Chapter 5.

4.2.3. Determination of Criteria

The literature review identified three common criteria for low-carbon technologies: *carbon reduction rate*, *cost*, and *applicability*. These three criteria constitute the most important aspects of technological selection.

Carbon Reduction Rate: Measures different sub-criteria for the emission reduction of the carbon reduction technology, including the technology's carbon reduction information, the process in which the technology will be used in the facility, whether it uses green energy, etc.

Cost: Measures different sub-criteria, including the total cost (investment) to install and operate the carbon mitigation technology, including R&D, labor, equipment, installation, maintenance and repair, etc.

Applicability: Measures sub-criteria such as which process the technology will be integrated into in the facility and how sustainable the technology will be once integrated.

For each of the three main technologies given in Chapter 3, a separate assessment was conducted for each of the above-mentioned criteria. Of the three (3) technologies examined in Chapter 3, Technology-1 is named for the use of alternative feedstock, Technology-2 for Non-Fossil Fuel Reductants/Fuel substitution, and Technology-3 for Carbon Capture and Storage.

Considering the factors affecting the technology selection criteria, the comparison scale given in Chapter 4 (see Table 8) was used, and a direct-relation matrix **A** was created for each main technology. Then, direct relation matrices were normalized by dividing by the **k** value in Equation (2) in Chapter 4.

The total relation matrix was obtained by using the normalized matrices obtained from Equation (4).

Influential-relation maps were created for each technology, and the decision stage was developed according to the results obtained using Equation (6) and Equation (7).

4.3. Evaluation of Results

The evaluations regarding the use of alternative raw materials, non-fossil fuel reductant/fuel substitution, and CCS technologies were performed according to the DEMATEL method. The analysis of the technologies for which importance-relationship graphs were extracted.

The outputs obtained from the importance-relationship graphs for each technology are compared with the projects of integrated plants in Türkiye. The carbon mitigation technologies required by the integrated plants in Türkiye are presented as a recommendation, along with their mitigation ratios.

4.4. Closing Remarks

In this section, the methodology of the study and the steps performed are explained. In this study, the study boundaries were specified, and data on integrated iron and steel plants were collected and analyzed within these boundaries. The data collection phase was conducted under two (2) separate headings: new and low carbon technologies used worldwide and existing process technologies of integrated iron and steel plants in Türkiye. According to the literature review, new low-carbon technologies used in integrated iron and steel plants worldwide are categorized under three (3) main headings: *alternative raw material use*, *non-fossil fuel reductant/fuel substitution,* and *CCS*. Criteria were determined for each of these main technologies, and then the DEMATEL method was used to see the importance-relationship graph for these criteria. With the findings obtained from the DEMATEL method, the method applied to recommend the most appropriate carbon reduction technology considering the identified needs of integrated plants in Türkiye is explained.

5. RESULT AND DISCUSSION

This chapter presents the analysis of the decision variables determined using the methodology defined in Chapter 4 for the technologies whose carbon reduction rates are given in Chapter 3, and their applicability to integrated plants in Türkiye is discussed.

4.1. DEMATEL Method Findings & Observations

The names of the three (3) main technology topics in Section 3 are abbreviated as follows:

- Alternative raw material use, Technology-1;
- Non-fossil fuel reductants/Fuel substitution, Technology-2; and
- Carbon capture and storage, Technology-3.

For these technology topics, the DEMATEL method was applied according to the information obtained from the literature review and the status of integrated facilities in Türkiye. The study findings are given below.

4.1.1. DEMATEL Method for Technology-1

The decision variables of Technology-1 (Raw material use) summarized in Section 3.1 were identified, and numerical evaluations given in Table 9 were determined using the relationship scale to reveal their relationship.

Table 9. Evaluation of the Relation of Criteria for Technology-1

Influencing Criteria	**Scale**				**Influenced Criteria**
	0	**1**	**2**	**3**	
Carbon reduction rate			X		Cost
Carbon reduction rate				X	Applicability
Cost		X			Carbon reduction rate
Cost				X	Applicability
Applicability		X			Carbon reduction rate
Applicability		X			Cost

Accordingly, the direct relation (average) matrix for **A** Technology-1 is given in Table 10.

Table 10. Direct Relation (Average) Matrix for Technology-1

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	0	2	3
	Cost	1	0	3
	Applicability	1	1	0

Each element of the direct relation matrix prepared for Technology-1 above is divided by the value of **k** described in Chapter 4 to obtain a normalized matrix, which is given in Table 11.

Table 11. Normalization Matrix for Technology-1

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	0.0000	0.3333	0.5000
	Cost	0.1667	0.0000	0.5000
	Applicability	0.1667	0.1667	0.0000

The steps described in Chapter 3 were applied to the normalized matrix **M**, and the total relation matrix T obtained is shown in Table 12. Detailed calculation steps for the total relation matrix are given in Appendix 1.

Table 12. Total Relation Matrix for Technology-1

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	0.2453	0.5660	0.9057
	Cost	0.3396	0.2453	0.7925
	Applicability	0.2642	0.3019	0.2830

The influential-relation graph of the values obtained in Table 12 is given in Figure 10.

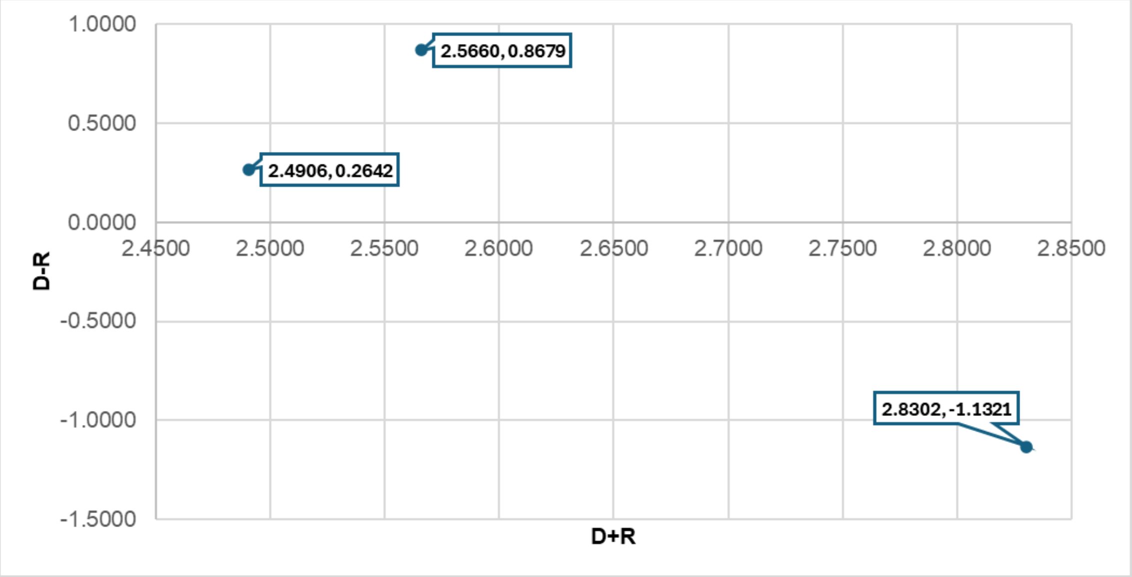

Figure 10. Influential-Relation Diagram for Technology-1

The influence-relationship graph of the criteria determined for Technology-1 was created by determining the D+R and D-R values. In Figure 10, the criterion with the highest D+R value belongs to the "applicability" factor with a value of 2.8302, and it is clearly shown that this factor has the highest impact on technology selection. The other two criteria affecting technology selection are carbon reduction rate and cost, respectively, in order of impact-importance. The applicability criterion has the highest impact on the other two criteria in technology selection.

There are two criteria with positive D-R values: carbon reduction rate and cost. In other words, the applicability criteria are influenced by the carbon reduction rate and cost criteria, with the carbon reduction rate criteria having the highest degree of influence.

4.1.2. DEMATEL Method for Technology-2

The decision variables in Technology-2 (non-fossil fuel reductants/fuel substitution) summarized in Section 3.1 were identified. The numerical evaluations given in Table 13 were determined using the relationship scale to reveal their relationship.

Table 13. Evaluation of the Relation of Criteria for Technology-2

Influencing Criteria	**Scale**				**Influenced Criteria**
	0	**1**	**2**	**3**	
Carbon reduction rate				X	Cost
Carbon reduction rate			X		Applicability
Cost			X		Carbon reduction rate
Cost				X	Applicability
Applicability			X		Carbon reduction rate
Applicability		X			Cost

Accordingly, the direct relation (average) matrix **A** for Technology-2 is given in Table 14.

Table 14. Direct Relation (Average) Matrix for Technology-2

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	0	3	2
	Cost	2	0	3
	Applicability	2	1	0

Each element of the direct relation matrix prepared for Technology-2 above is divided by the value of **k** described in Chapter 4 to obtain a normalized matrix, which is given in Table 15.

Table 15. Normalization Matrix for Technology-2

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	0.0000	0.6000	0.4000
	Cost	0.4000	0.0000	0.6000
	Applicability	0.4000	0.2000	0.0000

The steps described in Chapter 3 were applied to the normalized matrix **M**, and the total relation matrix T obtained is shown in Table 16. Detailed calculation steps for the total relation matrix are given in Appendix 1.

Table 16. Total Relation Matrix for Technology-2

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	1.8947	2.2368	2.5000
	Cost	2.1053	1.7632	2.5000
	Applicability	1.5789	1.4474	1.5000

The influential-relation graph of the values obtained in Table 16 is given in Figure 11.

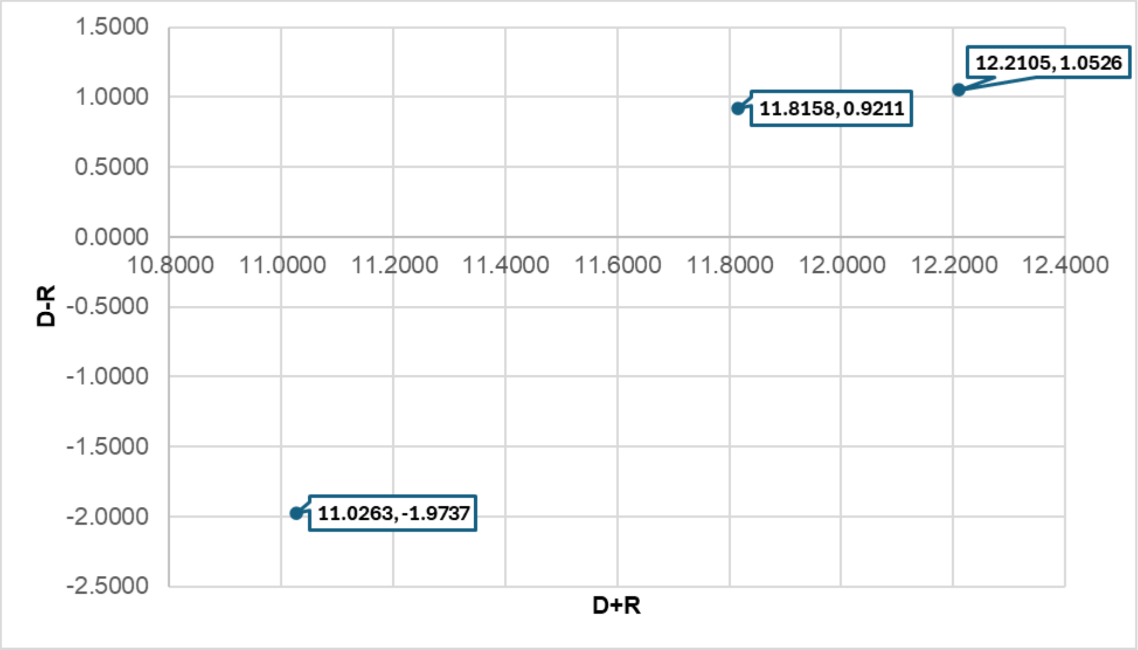

Figure 11. Influential-Relation Diagram for Technology-2

The influence-relationship graph of the criteria determined for Technology-2 was created by determining the D+R and D-R values. In Figure 11, the criterion with the highest D+R value is the “carbon reduction rate” factor, with a value of 12.2105. This factor has the highest impact on technology selection, and the carbon reduction rate criterion has the highest impact on the other two criteria. This may be because the carbon reduction rate should be paid more attention to in decision-making since the applications examined under Technology-2 will reduce the costs in this area considering today’s technology and the level of technology development in the future, and some methods are not very difficult to integrate into the facilities.

Two criteria with positive D-R values are carbon reduction rate and cost. In other words, the applicability criteria are influenced by the carbon reduction rate and cost criteria, with the carbon reduction rate criteria having the highest degree of influence. The cost has less impact on the applicability than the carbon reduction rate.

4.1.3. DEMATEL Method for Technology-3

The decision variables in Technology-2 (non-fossil fuel reductants/fuel substitution) summarized in Section 3.1 were identified. The numerical evaluations given in Table 17 were determined using the relationship scale to reveal their relationship.

Table 17. Evaluation of the Relation of Criteria for Technology-3

Influencing Criteria	**Scale**				**Influenced Criteria**
	0	**1**	**2**	**3**	
Carbon reduction rate				X	Cost
Carbon reduction rate		X			Applicability
Cost				X	Carbon reduction rate
Cost			X		Applicability
Applicability				X	Carbon reduction rate
Applicability			X		Cost

Accordingly, the direct relation (average) matrix **A** for Technology-3 is given in Table 18.

Table 18. Direct Relation (Average) Matrix for Technology-3

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	0	3	1
	Cost	3	0	2
	Applicability	3	2	0

Each element of the direct relation matrix prepared for Technology-3 above is divided by the value of **k** described in Chapter 4 to obtain a normalized matrix, which is given in Table 19.

Table 19. Normalization Matrix for Technology-3

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	0.0000	0.5000	0.1667
	Cost	0.5000	0.0000	0.3333
	Applicability	0.5000	0.3333	0.0000

The steps described in Chapter 3 were applied to the normalized matrix **M**, and the total relation matrix **T** obtained is shown in Table 20. Detailed calculation steps for the total relation matrix are given in Appendix 1.

Table 20. Total Relation Matrix for Technology-3

Decision Variables		**Influenced criteria**		
		Carbon reduction rate	**Cost**	**Applicability**
Influencing criteria	**Carbon reduction rate**	1.0000	1.2500	0.7500
	Cost	1.5000	1.0625	0.9375
	Applicability	1.5000	1.3125	0.6875

The influential-relation graph of the values obtained in Table 20 is given in Figure 12.

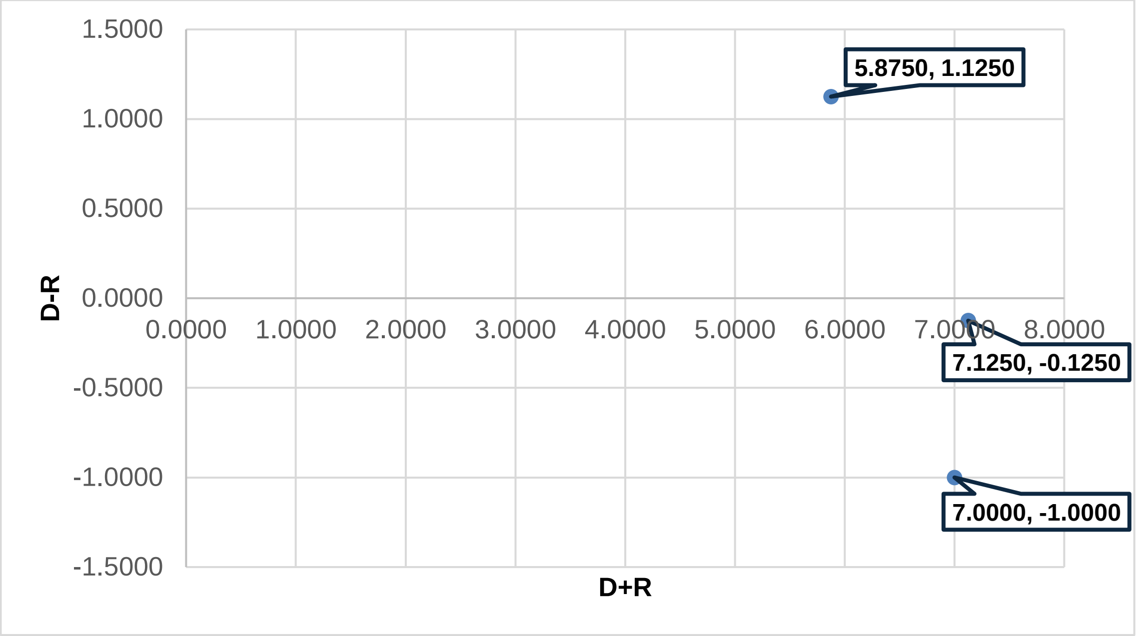

Figure 12. Influential-Relation Diagram for Technology-3

The influence-relationship graph of the criteria determined for Technology-3 was created by determining the D+R and D-R values. In Figure 12, the criterion with the highest D+R value is the “cost” factor, which is 7.1250. This factor has the highest impact on technology selection, and the cost criterion has the highest impact on the other two criteria in technology selection. Cost is the most influential factor in decision-making for Technology-3 because the applications examined under this technology require high energy consumption, collaboration of appropriate R&D teams, and state-of-the-art equipment.

The only criterion with a positive D-R value is applicability. In other words, the applicability criteria influence the cost and carbon reduction rate, with the cost criteria having the highest influence. The carbon reduction rate has less impact on the applicability than the cost. Many methods with high applicability in Technology-3 would reduce the cost, but this is not possible in today's conditions. Since the applications under Technology-3 require a lot of costs, applicability is nowadays in a position that affects other criteria.

4.1.4. DEMATEL Method Results

The evaluation of the important criteria in selecting mitigation practices for each technology is given above. The essential criteria in selecting between the applications in Technology-1 (raw material use), Technology-2 (non-fossil fuel reductants/fuel substitution), and Technology-3 (CCS) and examining their weights in the decision-making phase are presented below.

According to the DEMATEL result, the most important criterion for Technology-1 is applicability, followed by carbon reduction rate and cost. The applicability factor primarily affects the carbon reduction rate and cost factors. In this context, it is important to determine the accessibility of raw biomass and feasible substitution rates/pre-treatment processes when selecting Technology-1. For example, biomass logistics may increase the cost, or it may be necessary to set up pilot plants to reach the appropriate substitution rate. The parameters affecting the applicability factor in Technology-1 can be the required carbon temperature and retention time during char production from biomass. Since the efficiency of biochar depends on its compositional characteristics and pyrolysis conditions (carbonization temperature, heating rate, retention time, etc.), these parameters directly affect the carbon reduction rate. Among the issues currently being worked on in Technology-1 is the development of various computer-aided programs to easily analyze biomass and coal mixing ratios. Thus, it is aimed to increase the applicability of Technology-1 to plants. However, issues such as the availability of biomass, the research, and the logistics of the process steps required for pre-treatment may cause obstacles to the applicability of this technology (Wang et al., 2015). The biomass charcoal from pyrolysis of raw biomass is expected to have wide application possibilities in iron production in the iron and steel industry, considering the above risks associated with all criteria.

The increasing number of studies developed in the field of artificial intelligence and software in Türkiye and the fact that the software infrastructure required for this technology is adequate and ready for R&D studies try to keep the applicability of this technology at a high level. Moreover, in the Green Technology Roadmap prepared for the Turkish iron and steel sector, it is stated that the level of readiness in Türkiye for the new low-carbon technologies examined under

Technology-1 is close to the global level and will be applicable by 2026 (TÜBİTAK, 2023).

The DEMATEL method application for Technology-2 shows that the most critical decision maker is “carbon reduction rate” followed by “cost”. Also, the “applicability” criterion is influenced by other criteria. In other words, the carbon reduction rate of the technology selected for the facilities should be determined according to the price and performance ratio. The applicability level of the applications included in Technology-2 and suggested is affected by the “cost” and “carbon reduction rate”. In other words, it will be at a high level of applicability for a system with a high price and performance ratio in the facility. Alternative reduction is based on alternative energy sources and materials. As renewable energy resources are rapidly increasing in Türkiye and this situation may allow alternative reducing agents such as hydrogen to be obtained green, the cost and applicability of the DEMATEL method may have a lower impact than the “carbon reduction rate.”

According to the results of the DEMATEL method, the most critical decision maker for Technology-3 is cost, followed closely by the carbon reduction rate. In the Green Roadmap prepared for the Turkish iron and steel sector, it is envisaged that the studies within the scope of Technology-3 will only be ready between 2030 and 2035 (TÜBİTAK, 2023). One of the main reasons for this is the high cost of infrastructure, transportation, machinery, and equipment for the carbon capture and storage technology methods developed in the world and Türkiye. The use of energy-intensive technologies to capture carbon, the construction of pipeline infrastructure for storage, and the need for secure storage areas make this technology more expensive than others. One of the reasons for the high cost of Technology-3 is the renewable energy infrastructure needed to achieve green hydrogen. Providing electricity from renewable energy can reduce the cost of this technology. Apart from this, there are not enough studies in Türkiye to ensure that solvent, sorbent, or membrane technologies used in carbon capture are feasible and cost-effective. Therefore, CCS implementation in Türkiye is expected to take longer than in Technology-1 and Technology-2.

4.2. Assessing the Selected Applicable Low-Carbon Technologies

In this section, based on the findings from the DEMATEL method, the selection of the technology applications given in Chapter 3 was conducted. Looking at the projects completed and ongoing by Kardemir, Erdemir, and İsdemir in 2023 (see Table 3 and Table 4), it is remarkable that emission reduction works were conducted in coke batteries and modernization works were undertaken in BFs. Apart from modernization efforts, the Erdemir plant's establishment of a pilot pyrolysis plant to obtain an alternative carbon source from biomass and the project to feed hydrogen fuel to its BF are noteworthy. As a result, Erdemir accelerated its work on carbon capture and alternative carbon-free fuel trials in addition to the blast furnace line renewal projects. According to publicly available data from Kardemir and İsdemir, although innovative low-carbon technologies are mentioned as projects to reduce carbon emissions at their facilities, it is understood that the projects that have been implemented/completed are mostly modernization works. Although there is a reduction in carbon emissions through modernization, more stringent technologies need to be integrated into the facilities for Kardemir and İsdemir. It is also understood that all three plants have not given up the coke battery and want to achieve economical coke.

Currently, the aim is to reduce emissions from coke batteries in all three integrated facilities and to reduce emissions by modernization in BFs. The most effective carbon reduction technology application for coke batteries and blast furnaces is the applications including the CCS method explained under the heading of Technology-3. However, CCS technology (Technology-3) will remain costly in the short term due to the high energy consumption of carbon capture applications and the lack of studies for storage areas, as seen in the result of the DEMATEL method. Therefore, it is envisaged that studies should be started on applying alternative raw materials to substitute coke for emission reduction and using alternative reducers called Technology-1 and Technology-2 as low-carbon technology in integrated facilities in Türkiye.

As a result of the evaluation of the information obtained from the DEMATEL method, it is concluded that feasibility is the effective factor in the selection for Technology-1. The factors affecting feasibility in Technology-1 are explained in Section 5.1.4. Accordingly, one of the studies presented in Section 3.1.2, where a wood-based coal mix achieved a 73.66% reduction in the BF route, was considered as a feasible technology in Türkiye. This technology can be integrated into three integrated plants in Türkiye (Kardemir, Erdemir and İsdemir). If this technology is applied to the plants in Türkiye, the amount of carbon reduction is calculated and given in Figure 13.

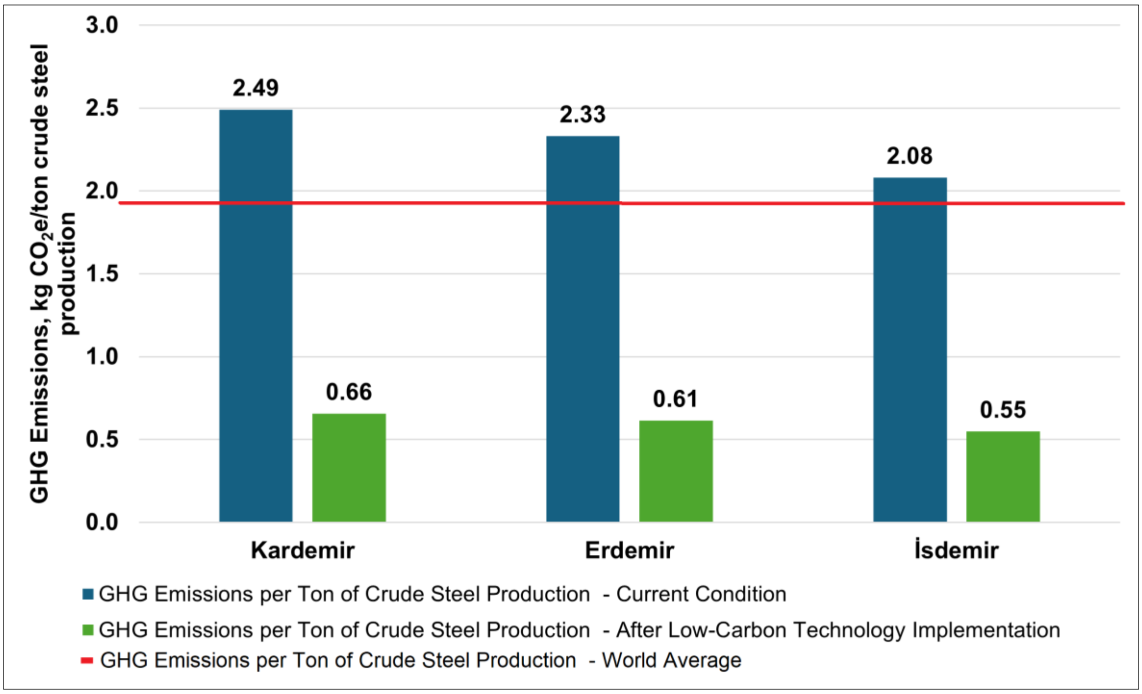

Figure 13. The Impact of Technology-1 on Emission Reduction and World Average

As can be seen in Figure 13, implementing the study of Meng et al.;

- It is estimated that Kardemir emits 2.49 tons of CO_2 to the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 1.83 tons.
- It is estimated that Erdemir emits 2.33 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 1.72 tons.
- It is estimated that İsdemir emits 2.08 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into

integrated iron and steel processes in Türkiye, this emission amount could be reduced to 1.53 tons.

As a result of the evaluation of the information obtained from the DEMATEL method, the carbon reduction rate is the most influential criterion in Technology-2 selection. Many technologies described under Technology-2 have a high carbon reduction rate but require a very high level of technology. According to the result, cost affects other factors in the DEMATEL method, so it is necessary to select technologies with high carbon reduction rates and low cost under the Technology-2 heading for integrated plants in Türkiye. Therefore, among the technologies listed in Section 3.2 of this report, the study of Li et al. for alternative reductant and the study of Yılmaz et al. for fuel substitution should be expected to be the most suitable technology for integrated plants in Türkiye.

Among the technologies detailed in Section 3.2, the use of the vibro-fludized beds and direct reduction with H_2 has been proven to reduce GHG emissions by 75% (Li et al., 2021). The change in emission amounts when this technology is integrated into three (3) integrated facilities in Türkiye (Kardemir, Erdemir, and İsdemir) is shown in Figure 14.

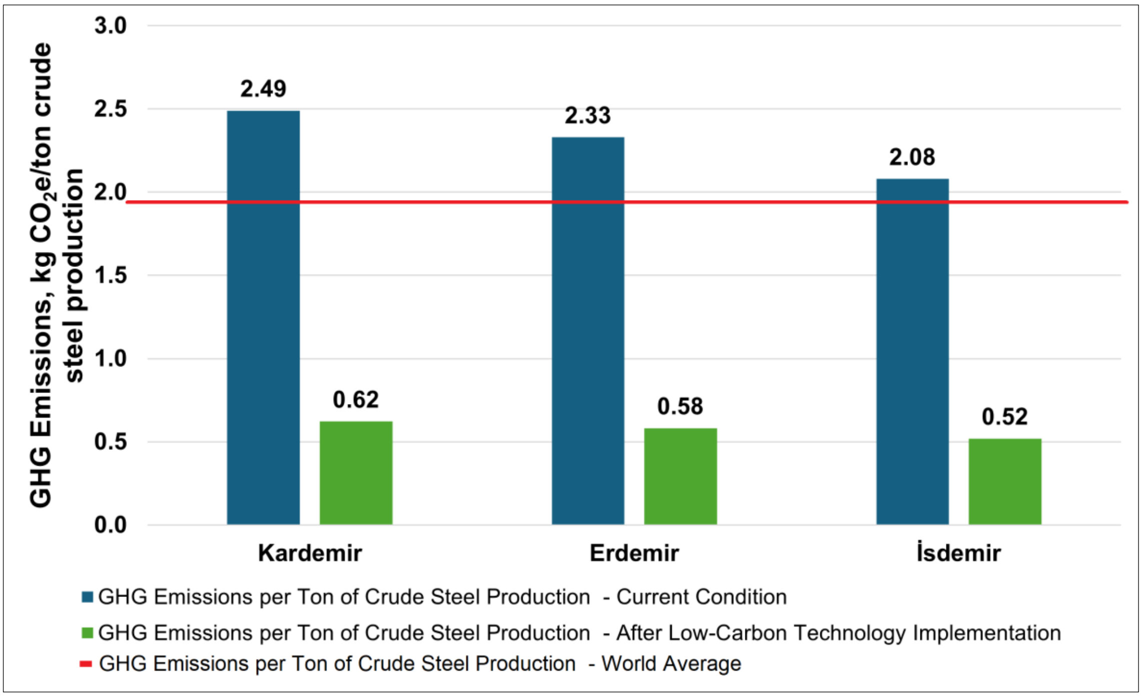

Figure 14. The Impact of Technology-2 using vibro-fludized beds and H_2 technique on Emission Reduction and World Average

As can be seen in Figure 14, implementing the study of Li et al.;

- It is estimated that Kardemir emits 2.49 tons of CO_2 to the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 1.87 tons.
- It is estimated that Erdemir emits 2.33 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 1.75 tons.
- It is estimated that İsdemir emits 2.08 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 1.56 tons.

The application in the study of H_2 injection into the BF in Section 3.2 has been proven to reduce GHG emissions by 21% (Yılmaz et al., 2017), and the change in emission amounts when this technology is integrated into three integrated facilities in Türkiye (Kardemir, Erdemir, and İsdemir) is shown in Figure 15.

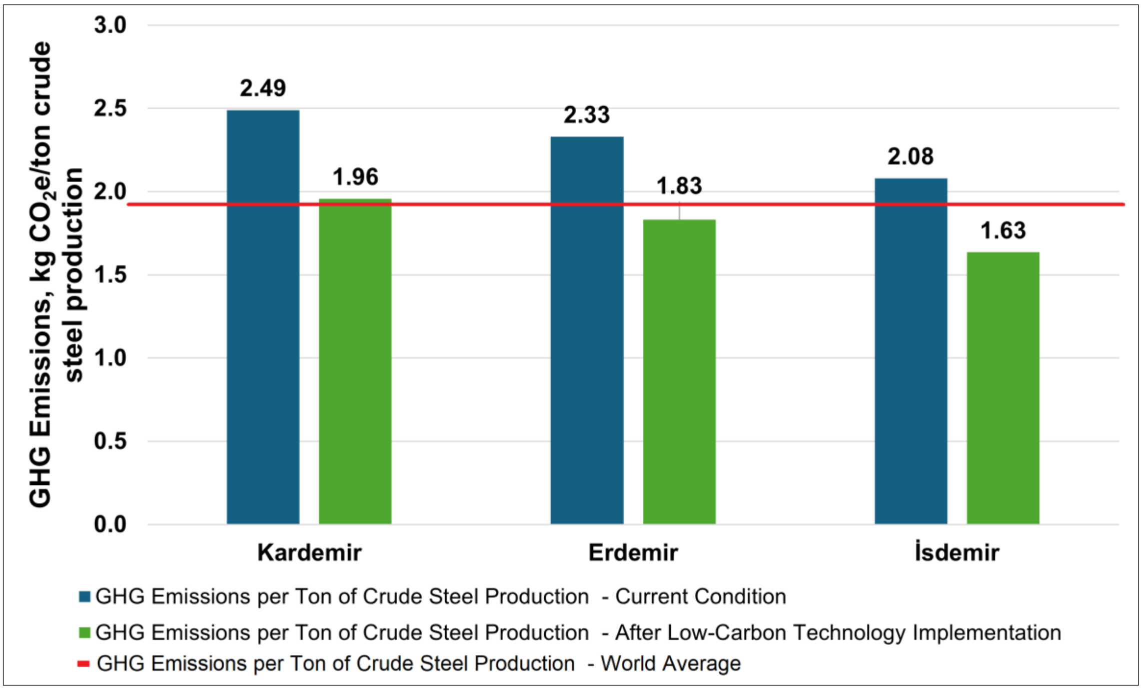

Figure 15. The Impact of Technology-2 using H_2 injection into BF technique on Emission Reduction and World Average

As seen in Figure 15, in the case of the implementation of the study involving the injection of hydrogen into BFs;

- It is estimated that Kardemir emits 2.49 tons of CO_2 to the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 0.53 tons.
- It is estimated that Erdemir emits 2.33 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 0.50 tons.
- It is estimated that İsdemir emits 2.08 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, this emission amount could be reduced to 0.44 tons.

As a result of evaluating the information obtained from the DEMATEL method, cost is the most influential criterion in Technology-3 selection. Many technologies described under Technology-3 have a high carbon reduction rate but require a very high level of technology. According to the result, applicability affects other factors in the DEMATEL method, so selecting applicable and low-cost technologies is necessary under the Technology-3 heading for integrated plants in Türkiye. Therefore, among the technologies listed in Section 3.2 of this report, the study of Jiang et al. should be expected to be the most suitable technology for integrated plants in Türkiye in the long term.

Among the technologies detailed in Section 3.2, VPSA, TSA, and TVSA adsorption technologies used in the study have been proven to reduce GHG emissions by 92%, 90%, and 98%, respectively (Jiang et al., 2020). The change in emission amounts when this technology is integrated into three integrated facilities in Türkiye (Kardemir, Erdemir, and İsdemir) is shown in Figure 16, Figure 17, and Figure 18.

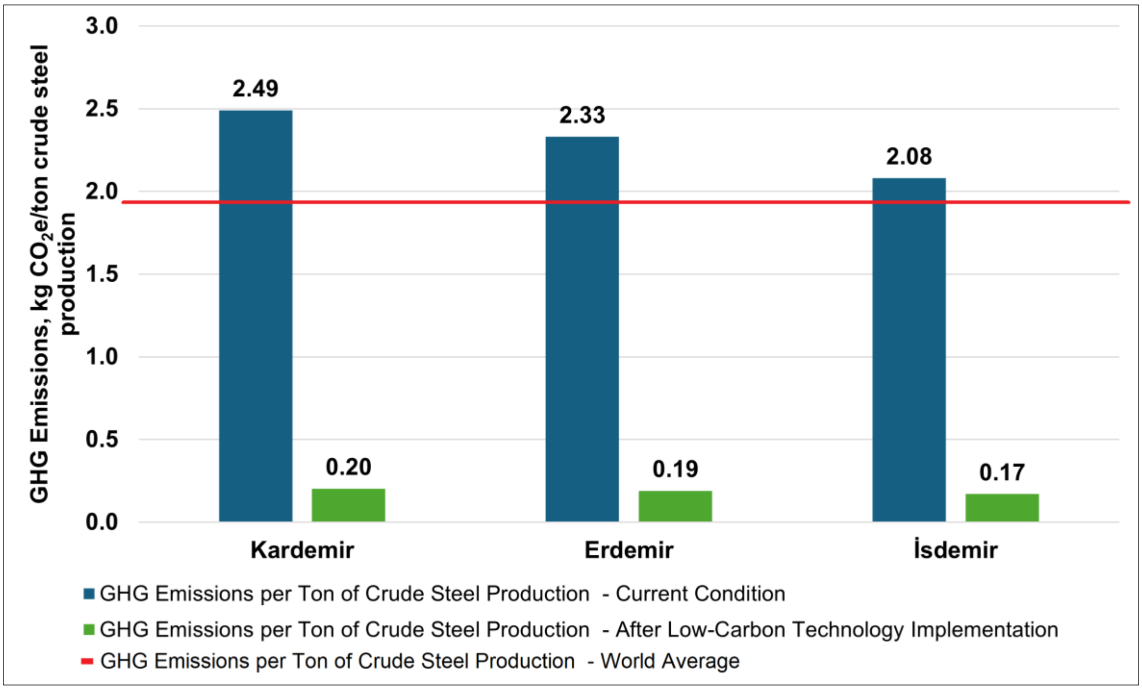

Figure 16. The Impact of Technology-3 using VPSA adsorption technique on Emission Reduction and World Average

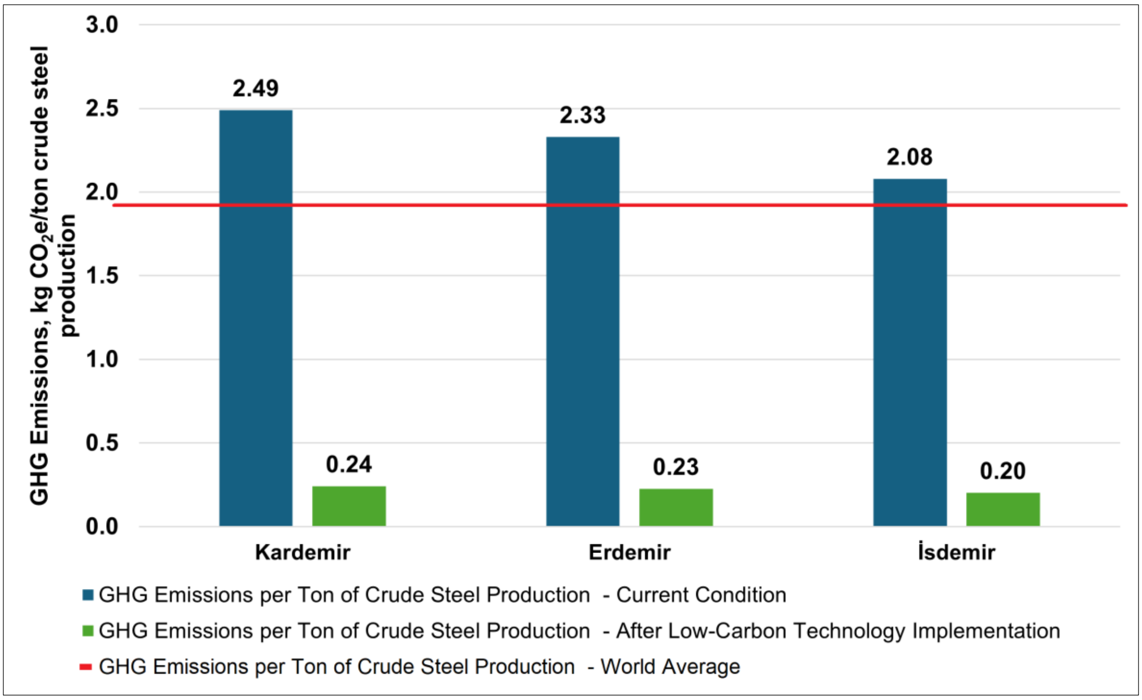

Figure 17. The Impact of Technology-3 using TSA adsorption techniques on Emission Reduction and World Average

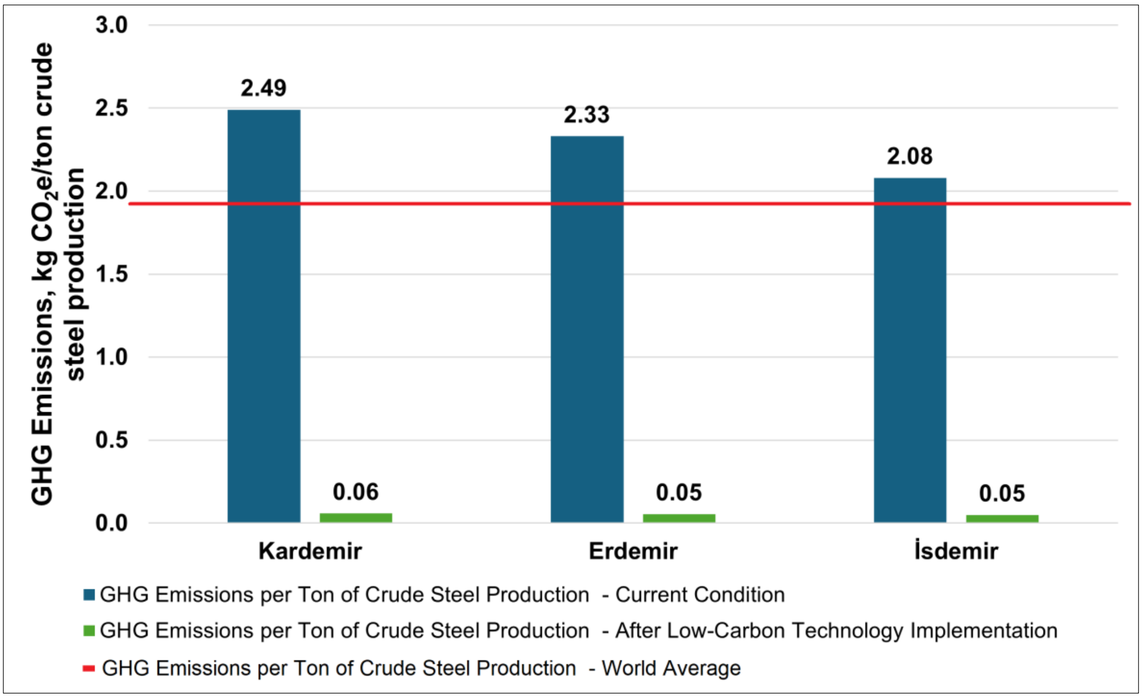

Figure 18. The Impact of Technology-3 using TVSA adsorption technique on Emission Reduction and World Average

As can be seen in Figure 16, Figure 17, and Figure 18, implementing the VPSA, TSA and TVSA adsorption techniques;

- It is estimated that Kardemir emits 2.49 tons of CO_2 to the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, emission reductions of 2.29 tons, 2.25 tons, and 2.43 tons can be achieved for VPSA, TSA, and TVSA, respectively.
- It is estimated that Erdemir emits 2.33 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, emission reductions of 2.14 tons, 2.10 tons, and 2.28 tons can be achieved for VPSA, TSA, and TVSA, respectively.
- It is estimated that İsdemir emits 2.08 tons of CO_2 in the atmosphere to produce 1 ton of crude steel. If the proposed technology is integrated into integrated iron and steel processes in Türkiye, emission reductions of 1.91 tons, 1.88 tons, and 2.03 tons can be achieved for VPSA, TSA, and TVSA, respectively.

4.3. Closing Remarks

In this section, the DEMATEL method is applied to all three (3) technologies, and the results are analyzed. The technology selection in integrated iron and steel plants in Türkiye depends on the applicability of that technology to the plant (*applicability*), the technology operating in economic conditions (*cost*), and the carbon emission reduction performance (*carbon reduction rate*). Basically, the BF-BOF process, which causes the most intense carbon emission in the integrated iron and steel plant process, is due to the use of coke. To choose which technology would be suitable for reducing emissions in this route, DEMATEL, the methodology explained in Chapter 4, was applied. The results obtained from the DEMATEL technique were analyzed for each main technology.

In case Technology-1 is implemented, the criteria to be considered is *applicability*. As a result of the studies, biomass was found to be an alternative technology that is generally economical and has a high carbon reduction potential. Factors affecting the applicability of biomass to plants include efficiency, availability, logistics, and determination of substitution rates. These factors can be taken into consideration, and biomass can be integrated into plants at a high carbon reduction rate and low cost. As a result, the studies being carried out for Technology-1 have the potential to pave the way for its implementation in integrated plants in Türkiye in the short and medium term.

In case Technology-2 is implemented, the measure to be considered is the *carbon reduction rate*. This is because the availability of carbon-free fuels and reductants through renewable energy has recently been on the rise, which has reduced the cost. Reducing the cost through access to renewable energy has accelerated the transition to focusing on how to increase the carbon reduction rate. Therefore, in Technology-2, the technologies with the lowest energy consumption and high carbon reduction should be selected.

It was revealed that the criterion to be considered in the application of Technology-3 is the *cost*. This is because carbon capture technologies require high energy consumption. In addition, safe transportation and storage areas are needed to store the carbon after capture. Therefore, implementation in Türkiye may take a long time.

According to the decision-making criteria resulting from the DEMATEL technique, the technologies selected for the plants in Türkiye were Meng et al. for Technology-1, Li et al. and Yılmaz et al. for Technology-2, and Jiang et al. for Technology-3. According to the Annual Reports published by Kardemir, Erdemir, and İsdemir, the emission reductions in the case of the application of the selected technologies in the declared emission amounts are presented with graphs (see between Figure 13 and Figure 18). According to this,

- If the study by Meng et al. is applied in Türkiye, it will result in an emission reduction of 74%, resulting in 1.83 tCO_2e at Kardemir, 1.72 tCO_2e at Erdemir and 1.53 tCO_2e at İsdemir. If this study is implemented, it will be necessary to develop programs to determine the most appropriate coal mixing ratios in cooperation with software and artificial intelligence experts in Türkiye.
- If the study by Li et al. is implemented in Türkiye, it will provide an emission reduction of 75%, resulting in an emission reduction of 1.87 tCO_2e at Kardemir, 1.75 tCO_2e at Erdemir and 1.56 tCO_2e at İsdemir.

- If the study by Yılmaz et al. is implemented in Türkiye, it will provide an emission reduction of 21%, resulting in 0.53 tCO_2e at Kardemir, 0.50 tCO_2e at Erdemir and 0.44 tCO_2e at İsdemir. During and after the signing of the Paris Agreement, investment in renewable energies in Türkiye has been increasing daily. Accordingly, hydrogen is expected to be obtained from renewable sources and become widespread in Türkiye in the short term.
- Finally, suppose the emission reduction rate of all three applications selected from carbon capture technologies in the study of Jiang et al. is averaged. In that case, it will provide an emission reduction of 93% when implemented in Türkiye. Since carbon capture technologies are energy intensive, Türkiye has not yet been able to meet this energy demand from non-fossil sources.

6. CONCLUSION AND RECOMMENDATIONS

The iron and steel sector significantly contributes to the GHG emissions in the atmosphere with its high energy consumption and production processes. With the adverse effects of climate change, the European Union has made legal arrangements and published the Green Deal to make the European continent climate resilient and minimize the impact of climate change. The European Green Deal applies to the EU and its cooperating countries. Türkiye, the EU's largest trading partner, has also had to adapt to these regulations. Among the five energy-intensive sectors in the Green Deal, the iron and steel sector has also become one of the sectors that must adapt to climate change. Therefore, Türkiye's iron and steel production facilities must integrate new technologies into their processes to reduce carbon emissions.

Integrated iron and steel plants include energy-intensive processes such as BF, coke, and sintering plants, which are also carbon emission-intensive. The use of hard coal and coke as raw materials in integrated iron and steel plants, the operation of lime factories that cause carbon emissions to make the raw material ready for the BF, and the intensive use of energy to obtain pure iron in the BF-BOF maximize carbon emissions in this facility.

The current emission reduction projects of integrated production facilities in Türkiye are modernization projects in BFs and studies on energy efficiency. Unlike İsdemir and Kardemir, Erdemir started integrating new low-carbon technologies into its plant by 2024. Erdemir's use of hydrogen and biomass in the process should be an example for İsdemir and Kardemir. One of the reasons for conducting this study is to examine the new low-carbon technologies developed around the world and to provide a recommendation for the applicability of the projects currently used and planned to be used in Türkiye.

Studies on new low-carbon technologies in integrated iron and steel plants are analyzed, and these technologies were grouped under three main headings: alternative raw material use, non-fossil fuel reductants/fuel substitution, and CCS. The DEMATEL technique, one of the decision-making methods, was utilized to select the applicable technologies for Türkiye. Three effective criteria in decision-making, applicability, cost, and carbon reduction rate, were determined using the DEMATEL technique.

In the studies on the impact of alternative raw material use on emission reduction, the applicability criterion was found to be the most dominant criterion in the decision-making process. Alternative raw material applications are generally not based on a costly material. The more applicable methods can be used to obtain coking coal as an alternative raw material in integrated plants, the more carbon reduction will be achieved. Computer software and programs should be developed and used to adjust the coking coal mixture ratio.

Studies on coking coal blend ratios to improve performance quality and reduce carbon emissions are highly recommended for modernizing BFs in integrated plants in Türkiye. For this purpose, cooperation between personnel working in the iron and steel industry and academicians in universities' computer and software departments can be suggested. The more successful the development in this area, the better the emission reduction will be in adjusting the coking coal and using it in the plant.

The carbon reduction rate was the most important criterion for selecting among the technology applications examined in the non-fossil fuel reductants/fuel substitution field. The application with the highest carbon reduction rate should be selected. When vibrating fluidized beds are used instead of BFs and hydrogen is used, high carbon emission reduction can be achieved at low temperatures without the need for pre-sintering. Integrating vibrating fluidized bed reactors into BF modernization projects in Türkiye and using hydrogen to reach pure iron may be recommended.

Cost is a consideration when choosing between CCS technology applications. The high cost of the reactors that need to be developed for carbon capture and the lack of a safe site to store the carbon after capture make this technology unfeasible in Türkiye.

Based on the results of this study, it can be understood that the use of alternative raw materials and the technologies developed for non-fossil fuel reductants/fuel substitution can be used in integrated plants in Türkiye in a short period and impact efficiency. On the other hand, it is understood that there is not enough R&D infrastructure for the application of CCS technologies in Türkiye.

Many studies need to be completed to integrate CCS technologies into the processes of integrated plants in Türkiye. Providing the necessary R&D infrastructure and studies for carbon capture and determining safe storage sites for carbon storage are very important issues. These issues can be realized in the long term with financial support and policy structuring. Therefore, it is not a preferable technology for the near future.

Recommendations for future work can be listed as:

- Due to data collection challenges, data on the type and amount of fuel used by Kardemir, Erdemir, and İsdemir plants could not be obtained. More detailed data can be collected by contacting the technical team of these facilities. Facility-specific recommendations can be made by determining the amount of emissions specific to each process.

- By contacting the technical units of Kardemir, Erdemir, and İsdemir facilities, surveys that are part of the DEMATEL technique applied for technology selection can be made by technical experts. In this way, technology selections can be made by obtaining more accurate and precise results from the DEMATEL technique.

- The literature data collected in this study could not be put into practice. For this reason, it could not be estimated what percentage of efficiency would be obtained in case of its implementation in facilities in Türkiye. To be put into practice, pilot application studies should be conducted first. Joint studies can be conducted between the facilities and universities for pilot applications.

- Laboratory studies should be conducted to examine the effect of alternative raw materials on carbon emissions and to implement low-carbon raw materials. Joint work between facilities and universities can accomplish this. Thus, the impact of alternative raw material applications can be concretely seen with studies and pilot applications conducted in laboratory environments.

- Joint work between facilities, manufacturing industries, and universities can be conducted to provide high-quality, low-carbon reduction processes using hydrogen in blast furnaces. A small-scale blast furnace process may need to be established for pilot applications. For this, projects that can receive contributions from the state can be applied, collaborations can be established in the industry to produce units, and pilot applications can be conducted. Thus, the effect of carbon-free reduction applications can be seen concretely.

- This study evaluated studies on the decarbonization of processes from which iron is extracted to be converted into steel. Future studies on decarbonization applications can be conducted in the field of steel production.

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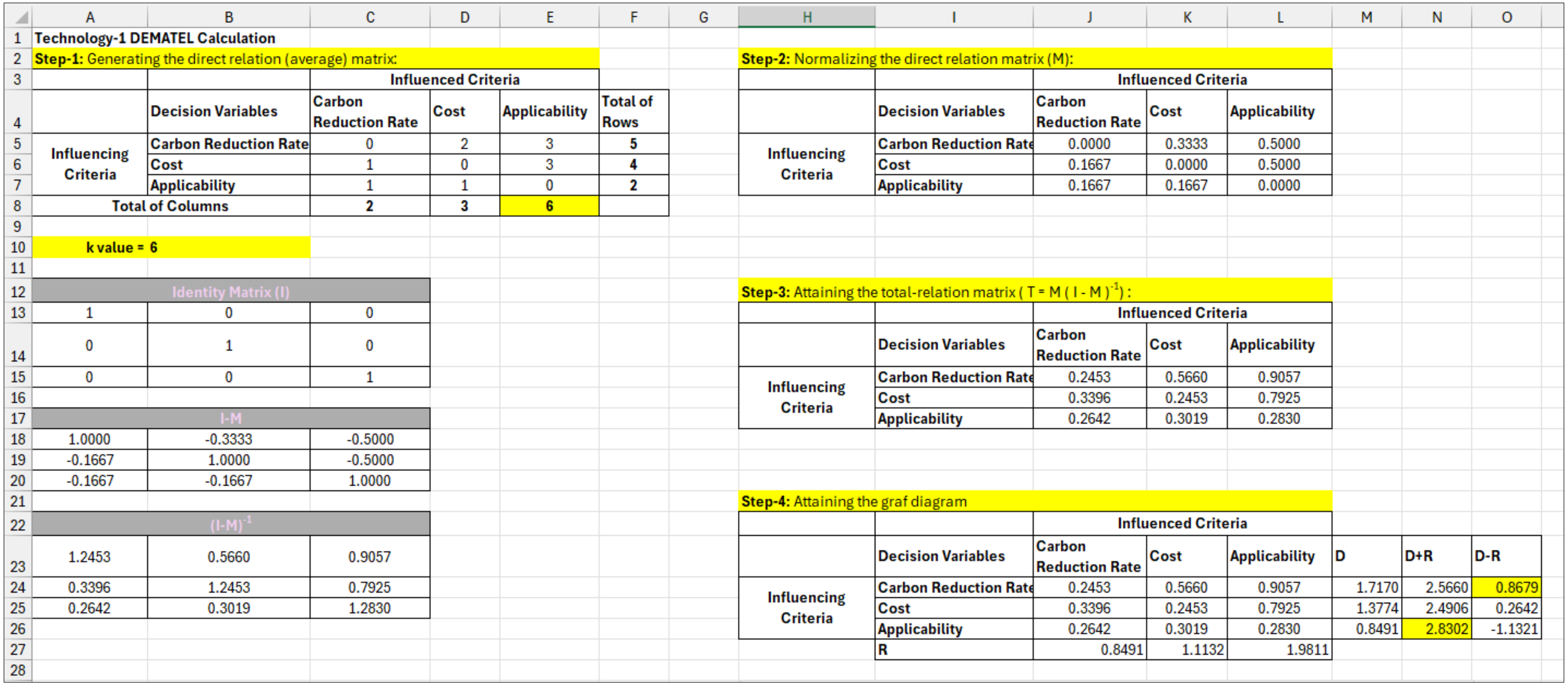
APPENDICES

Appendix 1 – DEMATEL Method Calculations

Technology-1 DEMATEL Method Calculations



Technology-1 DEMATEL Calculation

Step-1: Generating the direct relation (average) matrix:

		Influenced Criteria			
	Decision Variables	**Carbon Reduction Rate**	**Cost**	**Applicability**	**Total of Rows**
Influencing Criteria	**Carbon Reduction Rate**	0	2	3	**5**
	Cost	1	0	3	**4**
	Applicability	1	1	0	**2**
Total of Columns		**2**	**3**	**6**	

k value = 6

Identity Matrix (I)

1	0	0
0	1	0
0	0	1

I-M

1.0000	-0.3333	-0.5000
-0.1667	1.0000	-0.5000
-0.1667	-0.1667	1.0000

$(I-M)^{-1}$

1.2453	0.5660	0.9057
0.3396	1.2453	0.7925
0.2642	0.3019	1.2830

Step-2: Normalizing the direct relation matrix (M):

		Influenced Criteria		
	Decision Variables	**Carbon Reduction Rate**	**Cost**	**Applicability**
Influencing Criteria	**Carbon Reduction Rate**	0.0000	0.3333	0.5000
	Cost	0.1667	0.0000	0.5000
	Applicability	0.1667	0.1667	0.0000

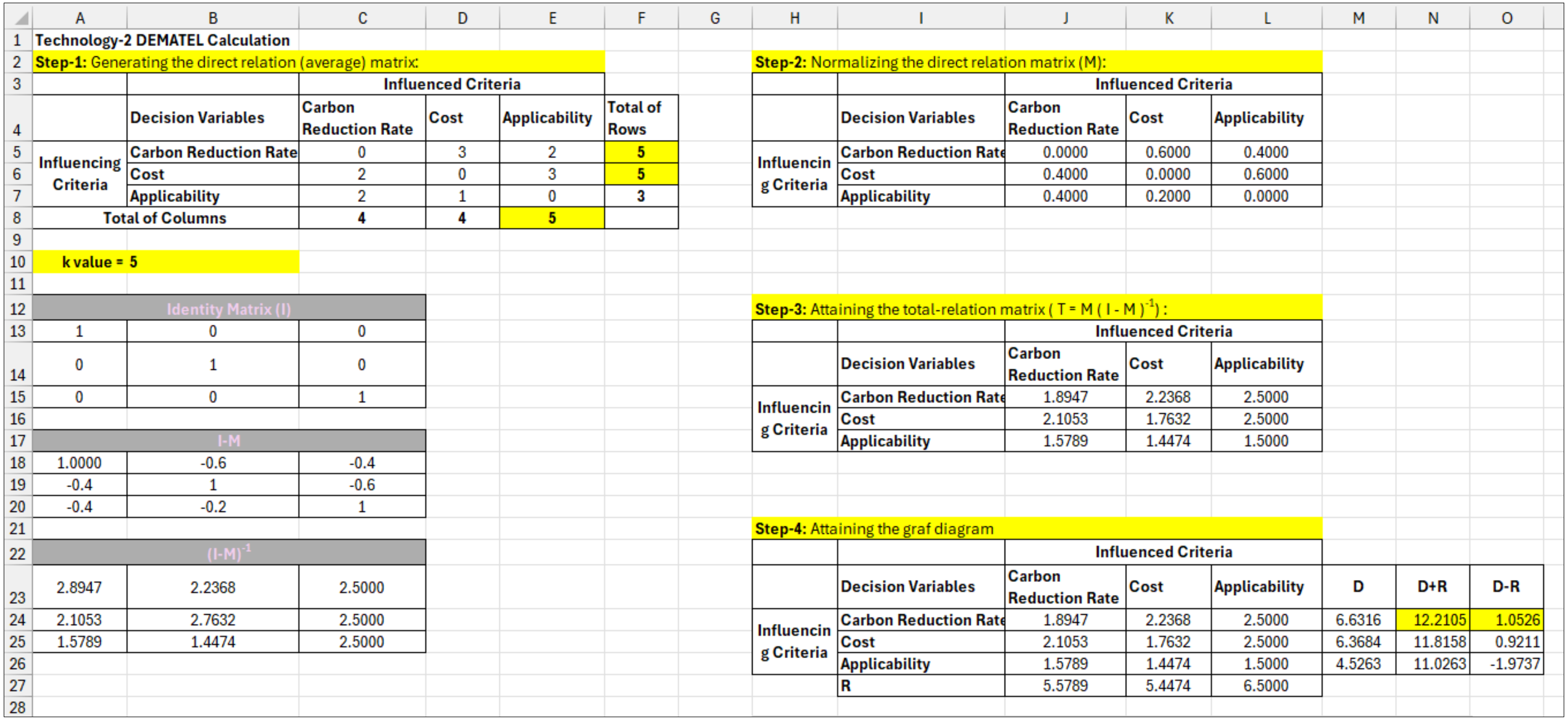
Step-3: Attaining the total-relation matrix ($T = M(I-M)^{-1}$) :

		Influenced Criteria		
	Decision Variables	**Carbon Reduction Rate**	**Cost**	**Applicability**
Influencing Criteria	**Carbon Reduction Rate**	0.2453	0.5660	0.9057
	Cost	0.3396	0.2453	0.7925
	Applicability	0.2642	0.3019	0.2830

Step-4: Attaining the graf diagram

		Influenced Criteria					
	Decision Variables	**Carbon Reduction Rate**	**Cost**	**Applicability**	**D**	**D+R**	**D-R**
Influencing Criteria	**Carbon Reduction Rate**	0.2453	0.5660	0.9057	1.7170	2.5660	0.8679
	Cost	0.3396	0.2453	0.7925	1.3774	2.4906	0.2642
	Applicability	0.2642	0.3019	0.2830	0.8491	2.8302	-1.1321
	R	0.8491	1.1132	1.9811			

Technology-2 DEMATEL Method Calculations



Technology-2 DEMATEL Calculation

Step-1: Generating the direct relation (average) matrix:

		Influenced Criteria			
	Decision Variables	Carbon Reduction Rate	Cost	Applicability	Total of Rows
Influencing Criteria	Carbon Reduction Rate	0	3	2	5
	Cost	2	0	3	5
	Applicability	2	1	0	3
Total of Columns		4	4	5	

k value = 5

Identity Matrix (I)		
1	0	0
0	1	0
0	0	1

I-M		
1.0000	-0.6	-0.4
-0.4	1	-0.6
-0.4	-0.2	1

$(I-M)^{-1}$		
2.8947	2.2368	2.5000
2.1053	2.7632	2.5000
1.5789	1.4474	2.5000

Step-2: Normalizing the direct relation matrix (M):

		Influenced Criteria		
	Decision Variables	Carbon Reduction Rate	Cost	Applicability
Influencing Criteria	Carbon Reduction Rate	0.0000	0.6000	0.4000
	Cost	0.4000	0.0000	0.6000
	Applicability	0.4000	0.2000	0.0000

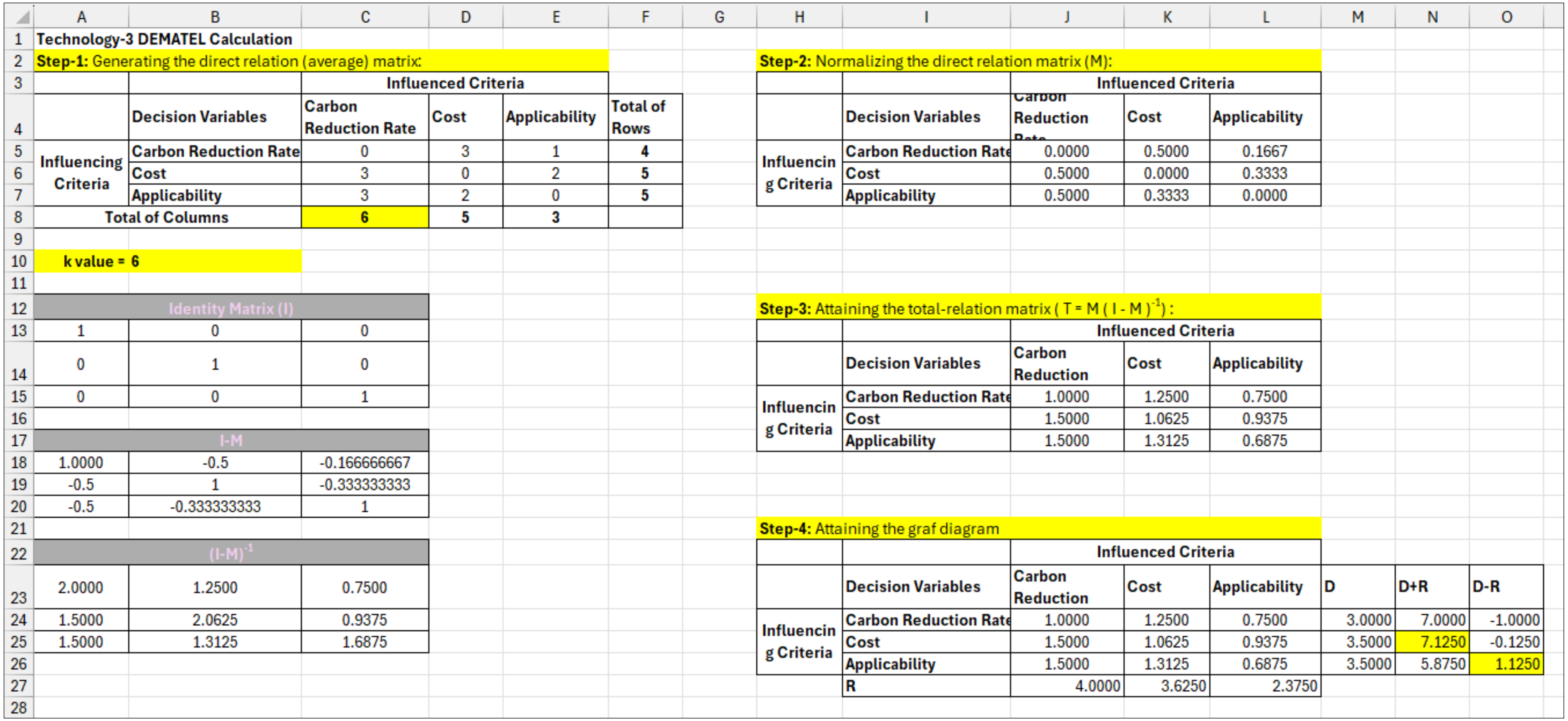
Step-3: Attaining the total-relation matrix ($T = M (I - M)^{-1}$) :

		Influenced Criteria		
	Decision Variables	Carbon Reduction Rate	Cost	Applicability
Influencing Criteria	Carbon Reduction Rate	1.8947	2.2368	2.5000
	Cost	2.1053	1.7632	2.5000
	Applicability	1.5789	1.4474	1.5000

Step-4: Attaining the graf diagram

		Influenced Criteria					
	Decision Variables	Carbon Reduction Rate	Cost	Applicability	D	D+R	D-R
Influencing Criteria	Carbon Reduction Rate	1.8947	2.2368	2.5000	6.6316	12.2105	1.0526
	Cost	2.1053	1.7632	2.5000	6.3684	11.8158	0.9211
	Applicability	1.5789	1.4474	1.5000	4.5263	11.0263	-1.9737
	R	5.5789	5.4474	6.5000			

Technology-3 DEMATEL Method Calculations



Technology-3 DEMATEL Calculation

Step-1: Generating the direct relation (average) matrix:

		Influenced Criteria			
	Decision Variables	Carbon Reduction Rate	Cost	Applicability	Total of Rows
Influencing Criteria	Carbon Reduction Rate	0	3	1	4
	Cost	3	0	2	5
	Applicability	3	2	0	5
Total of Columns		6	5	3	

k value = 6

Identity Matrix (I)		
1	0	0
0	1	0
0	0	1

I-M		
1.0000	-0.5	-0.166666667
-0.5	1	-0.333333333
-0.5	-0.333333333	1

$(I-M)^{-1}$		
2.0000	1.2500	0.7500
1.5000	2.0625	0.9375
1.5000	1.3125	1.6875

Step-2: Normalizing the direct relation matrix (M):

		Influenced Criteria		
	Decision Variables	Carbon Reduction Rate	Cost	Applicability
Influencing Criteria	Carbon Reduction Rate	0.0000	0.5000	0.1667
	Cost	0.5000	0.0000	0.3333
	Applicability	0.5000	0.3333	0.0000

Step-3: Attaining the total-relation matrix ($T = M (I - M)^{-1}$) :

		Influenced Criteria		
	Decision Variables	Carbon Reduction	Cost	Applicability
Influencing Criteria	Carbon Reduction Rate	1.0000	1.2500	0.7500
	Cost	1.5000	1.0625	0.9375
	Applicability	1.5000	1.3125	0.6875

Step-4: Attaining the graf diagram

		Influenced Criteria					
	Decision Variables	Carbon Reduction	Cost	Applicability	D	D+R	D-R
Influencing Criteria	Carbon Reduction Rate	1.0000	1.2500	0.7500	3.0000	7.0000	-1.0000
	Cost	1.5000	1.0625	0.9375	3.5000	7.1250	-0.1250
	Applicability	1.5000	1.3125	0.6875	3.5000	5.8750	1.1250
	R	4.0000	3.6250	2.3750			